METHODOLOGY FOR

FLOOD HAZARD

MODELLING AND MAPPING FOR GEORGIA (HYDRAULIC MODELLING)

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Flood Hazard

modelling and mapping
for georgia
(hydraulic modelling)

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The seven-year USD 73.6 million programme on reducing the risk of climate-driven disasters is implemented by the United Nations Development Programme (UNDP) and benefits from the USD 27 million grant from the Green Climate Fund (GCF), a USD 5 million grant from the Swiss Government, a USD 3.6 million grant from the Government of Sweden and USD 38 million in co-financing from the Government of Georgia. The programme consists of three interrelated projects:

GCF funded: Scaling-up a Multi-Hazard Early Warning System and the Use of Climate Information in Georgia

SDC funded: Strengthening Climate Adaptation Capacities in Georgia

SIDA funded: Improved Resilience of Communities to Climate Risks

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ABBREVIATIONS

Abbreviation	Meaning
ALOS	Advanced Land Observing Satellite
ASTER GDEM	Advanced Spaceborne Thermal Emission and Reflection Radiometer-Global DEM
ASAR	Advanced Synthetic Aperture Radar
ASF	Alaska Satellite Facility
AoI	Area of interest
APRSFs	Areas at potential risk of significant flooding
APSFR	Areas of potential significant flood risk
ABWS	Artificial Water-bearing Structure
CPC	Climate Prediction Centre
CSO	Combined sewer overflow
CEMS	Copernicus Emergency Management Service
DB	Dam breaks
DHI	Danish Hydraulics Institute
DSS	Data Storage System
DSW	Diffusive wave approximation of shallow water
DEM	Digital Elevation Model
DSM	Digital Surface Model
DTM	Digital terrain model
EWS	Early Warning System
EMS	Emergency Management Service
EVI	Enhanced Vegetation Index
EIAs	Environmental impact assessments
EIEC	Environmental Information and Education Centre
EFAS	European Flood Awareness System
ESA	European Space Agency
EU	European Union
EUFD	European Union Flood Directive
XML	Extensible Markup Language
FHWA	Federal Highway Administration
FHRM	Flood hazard and risk mapping

FIA	Flood impact analyses
FSI	Flood Susceptibility Index
GEBCO	General bathymetric Chart of the Oceans
GML	Geography Markup Language
GFI	Geomorphic Flood Index
DFD	German Remote Sensing Data Centre
GSMaP	Global Satellite Mapping of Precipitation
GUI	Graphical user interface
GHG	Greenhouse gas emissions
IFM	Integrated flood management
IMERG	Integrated Multi-satellite Retrievals for GPM
IWRM	Integrated water resources management
ICOLD	International Commission on Large Dams
IDW	Inverse distance weighted
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
LSWI	Land Surface Water Index
LiDAR	Light Detection and Ranging
METI	Ministry of Economy, Trade, and Industry
MRDI	Ministry of Regional Development and Infrastructure
MERIT	Multi-Error-Removed Improved-Terrain
NEA	National Environmental Agency
AWBS	Artificial water bearing structure
POT	Peak over threshold
PCPM	Polish Centre for International Aid
PERSIANN	Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks
PFRA	Preliminary flood risk assessment
RTC	Radiometric Terrain Corrected
RR	Rainfall-runoff
RT	Real time
ResSim	Reservoir simulation model
RMSE	Root mean square error
ST	Sediment transport
SWE	Shallow water equations

SRTM	Shuttle Radar Topography Mission
SO	Structure operations
SDC	Swiss Agency for Development and Cooperation
HEC-RAS	The Hydraulic Engineering Centre's River Analysis System
MFHMM	The Methodology Flood Hazard Modelling and Mapping
TIN	Triangulated irregular network
UNFCCC	United Nations Framework Convention on Climate Change
WFD	Water Framework Directive
WQ	Water quality
WMO	World Meteorological Organisation

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Introduction

1.1 Background and Context

Flood hazard mapping in Georgia have taken place primarily within the context of international projects. There are several examples of this such as the Adaptation Fund's Climate Resilient Flood Management Practices in Georgia project, managed by UNDP, and focusing on flood hazard activities in the Rioni River basin. Some other funded activities by other donors have been undertaken which have resulted in flood hazard maps for the project's target areas. It should be noted that all of these flood hazard mapping activities have been undertaken for fluvial flood sources and that none have addressed pluvial, coastal, groundwater or artificial water bearing structures (AWBSs) vis-à-vis flood sources. In all of these cases, the main hydraulic modelling effort has been undertaken by international experts and, therefore, the experience of national stakeholders is limited to their input within the framework of these projects. Finally, it should be added that international donors have applied methods and practices from their respective countries in these projects and so the methodology for the implementation of flood hazard models for mapping purposes is not unique while every project has at the same time implemented a different approach.

1.2 Purpose and Structure of the document

The objective of this report is to present a suggested methodology for flood modelling required within the framework of flood hazard and risk mapping. The Methodology Flood Hazard Modelling and Mapping (MFHMM- hydraulic modelling) is based on international practices and considers the requirements of the European Union Floods Directive (2007) requiring member states to undertake a three-stage process in the analysis and management of flood risk for all flood types and for different probability events.

Within this document, the proposed methodology for both the preliminary flood risk assessment (PFRA) and the flood hazard and risk mapping (FHRM) is proposed for the five sources of flooding: fluvial, pluvial, groundwater, sea water and artificial water-bearing infrastructure flooding. There are several points to note:

- While both the PFRA and the FHRM is outlined in the methodology, more focused is on the

FHRM. This is because the latter will be undertaken in all the river basins in Georgia and, therefore, the PFRA will not be undertaken at this stage. The main purpose of the PFRA is to identify the areas of potential significant flood risk (APSFR) that will be further analysed within the FHRM. Because the FHRM will be undertaken for all the river basins, there is no need to undertake the PFRA.

- Nonetheless, the methodology for the PFRA is described briefly because this assessment will be reviewed in the future as required by the EUFD.
- The methodology is described from a hydraulic modelling point of view while the hydrological side of the methodology will be covered in a separate methodology for hydrological modelling. It should be noted, however, that this separation between hydrological and hydraulic modelling, while it is evident in fluvial and pluvial flooding, may not be that obvious for other sources of flooding such as groundwater flooding, sea water flooding or artificial water-bearing structure flooding. The utmost of care is given to describing the hydraulic modelling processes for all the sources of flooding.

The methodological approach is based on international best practices, the consultant's experience and on the approach followed by EU member states.

The MFHMM-Hydraulic modelling document outline will include the following sections:

- Stakeholder mapping.
- Review of relevant international legislation (including EU directives, WMO guidelines and other commitments).
- Review and in-depth comparative analysis of international and national best practice in flood hydraulic hazard modelling, mapping, and assessment.
- Data requirements and data availability for flood hydraulic hazard modelling and mapping.
- Data availability for flood hydraulic hazard modelling and mapping.
- Methodology for flood hazard modelling and mapping divided into two parts – the Preliminary Flood Risk Assessment and the Flood Hazard and Risk Mapping – with the FHRM further sub-divided into flooding mechanisms and providing information about each source of flooding for both stages of the assessment

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Stakeholder Mapping

2.1 Stakeholders

2.1.1 Map Production Stakeholders

In Georgia, the main stakeholder with hydraulic modelling responsibilities within flood hazard assessment is the National Environmental Agency (NEA). The NEA is under the Ministry of Environmental Protection and Agriculture and is the main agency responsible for hazard assessment and forecasting within the early warning system in Georgia. The NEA has several departments, including the department of hydrometeorology which is in charge of the implementation of fluvial hydraulic models for flood hazard assessment purposes. The flood maps resulting from coastal, pluvial and AWB flood sources would also be managed by the NEA's department of hydrometeorology whereas ground-water source flooding would be cover by the NEA's department of geology.

There are some other stakeholders to consider from a hydraulic modelling point of view in Georgia in terms of existing technical capacities. These other stakeholders are from research institutes; in particular, the role of the Institute of Earth Sciences and the Seismic Monitoring Centre of Ilia State University in Tbilisi should be highlighted. This institute has capabilities in two-dimensional hydraulic modelling and have implemented models for flood mitigation and assessment purposes (https://ies.iliauni.edu.ge/?news=nino-jvania-street-report&lang=en).

The role of the Ministry of Regional Development and Infrastructure (MRDI) should also be noted as it is the main body responsible for the design of river and flood protection measures with responsibilities for flood hydraulic modelling to a high level of detail as required for design. It should be noted that the MRDI currently outsources its modelling needs.

There are also some other stakeholders worth considering from a data collection point of view as required for hydraulic modelling purposes. These stakeholders will be outlined in the section on expertise below.

2.1.2 Map Dissemination

The main flood hazard dissemination responsibility would fall under the Environmental Information and Education Centre (EIEC):

- The Environmental Information and Education Centre (EIEC) was established in 2013 under the Ministry of Environmental and Natural Resources Protection (now MEPA) and has the

responsibility to organise and administer an environmental information system in cooperation with state organisations as well as academic, non-governmental and international organisations and the business sector with relevant competencies. Further, the centre collects and shares environmental information, it collects information on ongoing and completed environmental projects in Georgia to create a database and ensure its publicity, it collects statistical data related to the field of environmental protection and it establishes and maintains an environmental library to facilitate access to environmental information through the website and other information sources (internet, information networks, media, etc.) in order to facilitate education on the environment and sustainable development and promote public awareness within the competence of the Ministry of Environment Protection and Agriculture (MEPA). Therefore, the EIEC would have particular roles and responsibilities for the dissemination of flood hazard maps.

- Emergency Management Service (EMS) has the responsibility to establish a database of natural and non-natural hazards and risks.

2.1.3 Main Users

Flood hazard information is critical for different activities and different users. The following users for flood hydraulic model results (flood mapping and hazard assessment) in Georgia have been identified:

- The general population. In the European Union, flood maps for all areas at risk have to be published for the information of all stakeholders and for the general population.
- The Department of Spatial Planning and Construction Policy of the Ministry of Regional Development and Infrastructure is in charge of the development, implementation, coordination, management and monitoring of spatial, urban planning and construction activities. The use of flood hazard mapping for planning purposes, including strategic planning, disaster risk management and spatial planning should be noted.
- The Ministry of Regional Development and Infrastructure (MRDI) is the main stakeholder in Georgia with responsibility for infrastructure and risk mitigation. The MRDI is in charge of the regional development policy, the introduction of water supply systems and the development of an integrated state policy on the development and design of the secondary and international road network. Additionally, the MRDI is in charge of municipal planning in accordance with the State Strategy on Regional Development. The use of flood hazard mapping and information should be included in the development of policies and municipal planning and vice-versa since municipal planning information and information regarding new roads would be relevant from a flood hazard mapping point of view.
- The Emergency Management Service (EMS) is a civil protection organisation in Georgia and is the main agency responsible for emergency management and the communication of and response to warnings. The use of flood hazard maps for rescue and management purposes should be noted. The EMS requires hazard maps that enable disaster risk reduction measures at the community level as well as hazard maps that guide evaluation planning down to the level of streets and individual properties. The role of the EMS in emergency management and its main

responsibilities during major incidents and infrastructure failure incidents should also be noted. These incidents require significantly detailed information about hazards.

- Local municipalities in Georgia have the responsibility of assessing the local hazard risk and implementing disaster risk reduction activities as well as initiating the response to any emergency.
- Business, industry, and the agriculture sector. As per the general population and for the development of contingency planning purposes, having information about a potential flood risk is critical for businesses, industries, and the agriculture sector.
- Research institutes and academia. For further research into flooding mechanisms and for the provision of more information, it is key that academia receives flood hazard information.
- Insurance companies. For the calculation of insurance premiums, flood hazard information is key for the insurance sector.
- NGOs/civil society organisations: several key NGOs operate in Georgia and the Caucasus region such as CENN, REC Caucasus and the Red Cross. In order to properly organise their humanitarian and support activities, the use of flood hazard maps would be beneficial.

The type of information and the level of detail that each of these users may require is outlined in the following sections.

2.1.4 Data and Expertise Provision

Some other stakeholders may further be identified in terms of data and expertise provision:

- The Climate Change Division of the MEPA undertakes assessments of climate change impacts on sectors of the economy and ecosystems and prepares relevant predictions, develops a national plan for adaptation to climate change, coordinates the national communications to the UNFCCC and provides an inventory of greenhouse gas emissions (GHG).
- The Ministry of Regional Development and Infrastructure (MRDI), due to its role in the flood risk management cycle, it is an important source of data and expertise.
- The Department of Spatial Planning and Construction Policy of the Ministry of Economy and Sustainable Development is an additional important source of data and expertise due to its role in the flood risk management in Georgia.
- DELTA: under the Ministry of Defence, DELTA operates and maintain a C-Band dual-polarisation weather radar station in Eastern Georgia.
- The Environmental Assessment Department of the Ministry of Environmental Protection and Agriculture is in charge of undertaking and managing environmental impact assessments (EIAs) of significant items of infrastructure in Georgia.
- The Georgian Water and Power company has the responsibility to provide water and wastewater services to the population of Tbilisi and Mtskheta as well as to state organisations and industrial and commercial objects.
- The State Hydrographic Service of Georgia under the Ministry of Economy and Sustainable Development of Georgia is the national coordinator of navigational warnings in Georgia. The ser-

vice also provides hydrographic, hydro-meteorological, maritime cartography and international navigation services.

- The Environmental Information and Education Centre (EIEC) has responsibilities for data dissemination.
- The Public Registry within the Ministry of Justice of Georgia has information for flood hazard mapping that can be of relevance, especially with regard to the existent DEM and orthophotos (see also below).
- The Emergency Management Service (EMS), due to its involvement in the disaster management cycle, it is another important source of data and expertise.
- Academia and the research community have an important contribution to make in terms of the provision of data and expertise.
- The Ministry of Economy and Sustainable Development of Georgia is also relevant, especially since the Ministry of Energy was merged into the Ministry of Economy (in 2017).
- Dam and reservoir operators.
- Municipal authorities.
- NGOs.

2.2 Stakeholder/User Needs

As noted, flood hazard information can be used for many purposes such as planning, identifying flood mitigation target areas, or raising public awareness about local flood risks. Considering the stakeholders outlined above, the level, detail and type of information yielded by a hydraulic modelling exercise within a flood hazard assessment would depend on the use of the flood hazard information itself.

Table 1 below summarises the information for each user and the requirements.

Table 1. Type and Level of Flood Hazard Information Requirements

Stakeholder	Type of Information	Purpose	Action	Scale	Grid Size (m)
General public	Flood awareness.	General area to avoid.	What areas require more detailed engineering studies.	1:50,000	90 m
Ministry of Economy and Sustainable Development	Preparedness and resilience investment needs. National view of most likely risk.	Identify new flood mitigation and warning schemes. Planning zones definitions (including permitted and restricted development in each zone).	Commission specific detailed studies in high-risk areas/ catchments.	1:500-1:1.000	15 m

MRDI	Avoidance areas for new infrastructure.	Planning of rural infrastructure locations (zoning away from high-risk areas).	Flood hazard mapping. Flood modelling. Optioneering.	1:500-1:1,000	10 m
MRDI	Avoidance areas for new infrastructure. Asset management scenarios.	Design of risk-informed climate-proofed infrastructure (all infrastructure).	Flood hazard mapping. Flood modelling. Optioneering.	1:500-1:1,000	10 m
MRDI	Flood mitigation.	Detailed design of hazard and risk mitigation measures using hazard and risk models.	Flood hazard mapping. Flood modelling. Optioneering.	1:500-1:1,000	10 m
MRDI	Asset management scenarios.	Asset management – Portfolio Risk Assessment for long-term management of infrastructure.	Location and targeting post-event repairs. Identify and target maintenance investment.	1:500-1:1,000	15 m
MEPA/NEA	Sensitive regions and locations or river reach.	Identify new information, (data collection) needs, e.g., gauging stations.	Install new monitoring and flood warning systems. Collect long-term flood records.	1:500-1:1,000	15 m
MEPA/NEA	Further information about flood hazard zones.	Identification of key areas to address. Resource identification.	Collection of data. Management of resources.	1:500-1:1,000	15 m
MEPA	Exposure of agriculture assets.	Identify less risky locations for agriculture.	Invest in local protection/preparedness.	1:5,000 – 1:10,000	30 m
MEPA	Climate Change Unit.	Reporting to UNFCC on climate change impacts.	Preparation of national communications.	1:5,000 – 1:10,000	30 m
MEPA/NEA	Water quality.	Identification of water quality issues.	Collection of data and management of resources.	1:5,000 – 1:10,000	30 m
EMS	Flood hazard communication.	Location of evacuation centres and routes. Areas that require more detailed engineering studies.	Targeting event/incident response.	1:500-1:1,000	15 m
Business, industry, and agriculture sector	Exposure of existing assets.	Identify less risky locations for investment.	Invest in local protection/preparedness.	1:5,000 – 1:10,000	30 m
Research stakeholders	Areas and mechanisms to study further.	Targeted research proposals. New data collection.	Study, analyse and publish findings relevant to flood risk.	1:5,000 – 1:10,000	30 m
Insurance companies	Exposure of portfolio (customers).	New markets or tailored insurance products to risk.	Set premiums relative to risk.	1:5,000 – 1:10,000	30 m

2.3 Information Dissemination

The dissemination of information vis-à-vis flood mapping and hazard assessment is critical. As outlined above, within the European Union Flood Directive it is compulsory for all states to disseminate the results of their flood studies. One of the most effective ways for communicating flood hazard information is through flood maps. Flood mapping to be disseminated should:

1. Be tailored for specific audiences and purposes.
2. Be paired with local information to which the community can relate.
3. Include information about historical floods.
4. Consider cartographic aspects and avoid technical terminology for ease and speed of comprehension.
5. Be provided online through traditional media and public meetings and be promoted regularly as a continuous reminder of flood hazards.
6. Use real-time gauge levels to contextualise historical or extreme floods shown on the map.
7. Use property-specific searchable web mapping services.
8. Be complemented with information about the consequences of flooding and tangible protective actions.

2.4 Partners and Networks

No significant partners or networks have been identified in Georgia for flood hazard mapping. There are, however, some European or global networks worth considering.

- EFAS: the aim of the European Flood Awareness System (EFAS) is to support preparatory measures before major flood events strike, particularly in the large trans-national river basins and throughout Europe in general. EFAS is the first operational European system monitoring and forecasting floods across Europe. While the main objective of EFAS is to provide forecasting information, it has also developed a range of flood hazard products. As far as the consultant is aware, the NEA is an EFAS user.
- Associated Programme on Flood Management: the APFM supports countries in the implementation of integrated flood management (IFM) within the overall framework of integrated water resources management (IWRM) to maximise net benefits from the use of floodplains and minimise loss of life and impacts. The APFM provides training and capacity building to national hydro-meteorological agencies and other stakeholders. It also supports the implementation of projects in some countries.
- Copernicus Emergency Management Service (CEMS): the Copernicus Emergency Management Service (EMS) provides information for emergency response for different natural and man-made disasters and other humanitarian disasters as well as prevention, preparedness, response, and recovery activities. There are obvious reasons to participate in the CEMS service from an EWS

and forecasting point of view. However, it would be important to consider the CEMS network in terms of data acquisition for calibration and validation purposes.

- The International Charter on Space and Major Disasters is a worldwide collaboration among space agencies through which satellite-derived information and products are made available to support disaster response efforts. The charter has been operational since November 2000. There are obvious reasons to participate in this charter from an EWS and forecasting point of view. However, it would be important to consider the International Charter on Space and Major Disasters network in terms of data acquisition for calibration and validation purposes.

2.5 Expertise

As noted above, there are several stakeholders that may play an important role in flood hazard and risk assessment.

- NEA: the role of the National Environmental Agency has already been noted in this deliverable and in other deliverables by this consultant. The NEA has the responsibility of developing flood hazard maps.
- The Climate Change Division of the MEPA can provide information about climate change projections for flood hazard mapping purposes in terms of expected changes in precipitation, temperature, sea-level and wind (for wave modelling).
- The Ministry of Regional Development and Infrastructure (MRDI): as noted above, the MRDI has several roles and responsibilities relevant for flood hazard mapping. The information regarding new road development, new key infrastructure and municipal plans can be relevant for the implementation of flood hazard maps.
- DELTA: as noted above, DELTA operates a weather radar station in Eastern Georgia. Due to the difficulty in obtaining sub-daily data for modelling purposes, the acquisition of data from DELTA would be important.
- The Environmental Assessment Department of the Ministry of Environmental Protection and Agriculture: The Environmental Assessment Department has information about previous environmental impact assessments (EIAs) undertaken in Georgia. This will be the case for major dams, flood defences and infrastructure projects. In some cases, hydrological and hydraulic assessments and studies have to be undertaken for environmental impact assessments. The acquisition of this information will be critical in some cases, especially for the assessment of AWBs.
- Georgian Water and Power: as overseeing the urban-drainage network in Tbilisi and some other urban areas, it is possible that some information regarding pluvial flooding and/or information about the urban drainage network is available.
- The State Hydrographic Service of Georgia: this service operates the tide gauges in Georgia, and they have been involved in recent research projects, including wave climate projects,

that will be of interest to the project.

- The Public Registry: within the Ministry of Justice of Georgia, the Public Registry (as will be discussed below) has information for flood hazard mapping that can be of relevance, especially with regard to the existing DEM and orthophotos. Additionally, the Public Registry plays a major role in flood risk issues. Information regarding building outlines will be critical for the implementation of pluvial models. This will be acquired through the risk modelling expert.
- The Emergency Management Service: as previously noted, the EMS is the main civil protection agency in Georgia. The EMS can provide expertise and information regarding previous flood events. It should be noted that it is highly recommended to include the EMS in any flood hazard activity as it has information and data about previous flooding and the dynamics in specific watercourses. Its involvement in the implementation of the flood risk management project in the Leghvtakhevi River should be noted. The EMS collects disaster risk management information from municipalities that would be of significant benefit for hazard modelling. Additionally, the EMS is one of the main users of flood hazard maps and the associated risk assessments as noted above.
- Academia and the research community: as noted, there are several relevant research and university institutions in Georgia that can provide expertise and data for flood hazard mapping purposes. The Hydrological Institute within Ilia State University, for instance, used to have a hydrological station on the Vere River (which was destroyed in the Tbilisi flooding in June 2015), and the Institute of Earth Sciences and the Seismic Monitoring Centre of Ilia State University has some expertise in hydrological and hydraulic modelling. It should be noted that it will be important to involve these institutions in the implementation and development of flood hazard maps.
- The Ministry of Economy and Sustainable Development of Georgia: The Ministry of Economy and Sustainable Development of Georgia will also be relevant, especially regarding the acquisition of information for dams.

2.6 Stakeholder engagement Strategy

As previously noted, there are several instances where the data possessed by these stakeholders would be highly valuable for flood hazard modelling and mapping purposes. Different strategies can be outlined in order to involve these organisations. It should be highlighted that while some of them would benefit directly from the use of these data for flood management purposes, some other would not and, therefore, a strategy has to be devised in order to ensure their collaboration. On the other hand, due to the government nature of most of these stakeholders, they most likely would have to hand over the data to the NEA. This issue could be different for private organisations or other types of stakeholders.

Several means could be considered as recommendations vis-à-vis data provision. Some of the above-

mentioned stakeholders can be included in the stakeholder engagement plan as described below. The creation of a so-called Technical Advisory Working Group would facilitate the provision of information on the part of some of these stakeholders. Finally, there is the strong assumption that all of the abovementioned organisations would be interested in the development of flood hazard and risk mapping and, therefore, the organisation of workshops in order to inform them about the main purpose of the project's activity will facilitate the acquisition of this information.

Nonetheless, a thorough and detail data acquisition campaign should be organised. As will follow in detail below in sections 5 and 6, there are numerous items of data missing for some flood sources and it will be important to draw up a detailed plan for the acquisition of this information.

It is highly recommended that this plan is implemented by the NEA in close collaboration with international experts. All of the abovementioned stakeholders should be contacted, and a workshop organised for information gathering purposes. Presentations should be given outlining the purpose of flood hazard activity, data sources requirements, data availability and the expected results. This workshop should be organised at the earliest possible time.

2.6.1 Stakeholder Engagement Plan and Integration Methods

Flood hazard and risk mapping address strategies and activities in several sectors such as agriculture, spatial planning, or crisis management. In this complex field, a well-balanced focused participation strategy on different levels is essential in order to mainstream flood hazard and risk information.

It is important to consider participation as a strategy on different levels and a connection to other responsibilities and processes. A benefit of the use of different forms of participation on different levels is the activation of parties in the field and the integration of the concept of flood hazard and risk alongside the associated flood risk management with the stakeholders' own procedures and planning. Effectiveness and efficiency will be strengthened by connecting flood hazard issues to the existing responsibilities and processes on different levels, in different sectors and in different time scales.

Due to the different levels of partners and stakeholders, a multi-level governance is, therefore, required in flood hazard mapping and information as well as a shifting between vertical and horizontal approaches for the preparation of decisions, decision making and measures. All of this depends highly on a solid system of communication, knowledge exchange and dialogue. Not only are institutions and stakeholders in the field of water management involved but related institutions and stakeholders in the field of

spatial planning, crisis management (civil protection) and/or economic affairs are also playing a part. Therefore, a multi-level (and multi-sector) approach for flood hazard and risk mapping and management would be recommended (Figure 1).

Figure 1. Example for the Structure of Multi-level Engagement (Source: modified from EU IPA 2010[1])

Although this multi-level cooperation one way or another exists in Georgia, it is recommended that an analysis is performed in order to identify weak points within activities of information exchange, cooperation and coordination and decide what can be done vis-à-vis improvement.

Stakeholder involvement and the participation processes can build upon this multi-level engagement. Involving already known institutions in multi-level governance, where the cooperation already exists, is a basis for participation processes. However, this cooperation within multi-level governance should be extended by involving additional stakeholders (such as civil society groups, municipalities, NGOs, etc.) and the general public. There are different responsibilities for initiating and performing participation processes, depending on the level of flood hazard governance, at these various levels. For instance, at the national level, the NEA should invite appropriate participants for a dialogue for plans and activities at the national level. The participation process at the regional and the local levels may involve completely different institutions or persons but a close cooperation among all of the different levels should be established.

In order to implement a stakeholder engagement plan, the following approach is recommended:

- Identification and selection of stakeholders: the main stakeholders have been identified in previous sections. Nonetheless, a more detailed analysis undertaken by the main stakeholder in flood hazard mapping (NEA) should be done in order to ensure that all relevant stakeholders are identified.

  In order to identify the relevant stakeholders, it would be interesting to make use of flood hazard mapping and identify flood-prone areas for local level involvement. In this case, the following should be distinguished:

  - The territory directly impacted by the inundation.
  - The vulnerability of the area impacted and its infrastructure (roads, railway, electricity, etc.).
  - The resilience of the territory.

1. Guidance document on the participation of the public and stakeholders in flood risk management, EU IPA 2010 TWINNING PROJECT.

Nonetheless, in a flood hazard engagement plan, the following main stakeholders for flood hazard mapping could be:

- Different administrations (regional, municipal-local level).
- Politicians (regional, municipal-local level).
- Interest groups (chamber of commerce, forestry and agriculture, tourism, hunting, fishery, etc.).
- Landowners/leaseholders.
- The general public that is affected by floods or interested in decisions that can play a decisive role in the interactions with the previously mentioned stakeholders.
- The private sector which may play a major role during flood crises.
- Education and health facility managers if not represented in the administrations previously outlined.
- NGOs.
- Network operators (electricity, fuel, roads, etc.).

Additionally, recommendations for the inclusion of further stakeholders should be considered because the selected stakeholders that are involved in the flood hazard mapping as initiators of a process or as members of the team may on some occasions also recommend the inclusion of further key players of a region.

- Roles of stakeholders: the stakeholders in the engagement plan can have different roles:
  - Initiators: stakeholders involved in the development or financing of the flood hazard mapping activity.
  - Shapers: have a role in consolidating the flood hazard planning and management, supporting it, or directing it at an early stage.
  - Informants: secondary data providers, interviewees, focus groups etc.
  - Central: play a central role during a project, especially as part of an advisory group.
  - Reviewers: contribute to the final output (workshops, questionnaires, etc.).
  - Recipients: not directly involved in the flood hazard mapping project but assumed to have an interest in the outcome.
  - Reflectors: give feedback to flood hazard mapping results and ideas for further activities on this context.
  - Indirect: not directly involved but may be influenced by the outcome of the flood mapping project or activity.
- Analysis: there are several analyses that can be undertaken in order to better understand the relationship between different stakeholders in the flood hazard sector. One of these analyses is a sociogram where interviews are done in order to find out more about these relationships The basis for the interviews is an interview manual which is used in a flexible way during the interviews. The interviewees are questioned about their interactions with other stakeholders,

examples of cooperation and conflict potential and their role in flood hazard mapping as well as their perceptions, concerns, and interest. An example of such a study in the UK is provided below in Figure 2.

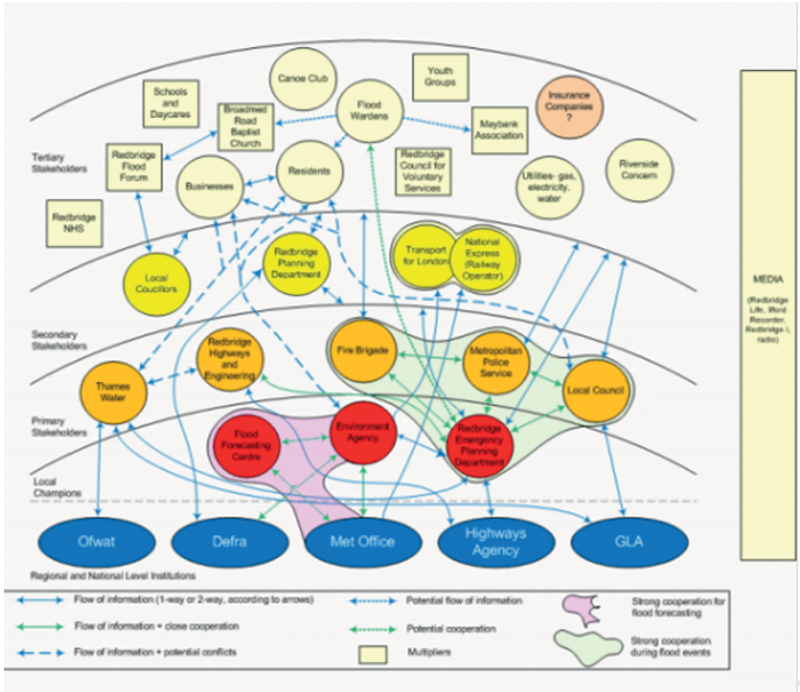

Figure 2. Sociogram Example (Source : Evers et al., 2011[2])

- Implementation of methods for engagement: there are different methods for engagement and their purpose, and the target group will vary depending on the stakeholder:
    - Media contact: can be used with all the stakeholders and with the general population.
    - Panel interviews on TV/radio: the main target group for this will be the general population and it can be undertaken though panels with some of the key stakeholders.
    - Website/brochure with risk maps: for the general population. It disseminates the flood risk information to the general public.
    - Newsletters: showing information on the progress of the flood hazard and risk activities, targeting stakeholders, officials, and the general public.
    - Road shows: targeting the general public and disseminating information through informal events.
    - Workshops: targeting key stakeholders. They can be organised at different levels and have different purposes. There can be one start-up workshop to describe the initiation of the activities, update workshops to describe different activities completed and closure workshops to present the results of the flood hazard mapping activity.

2. M. Evers, C. Maksimovic, A. Jonoski, L. Lange, S. Ochoa Rodriguez, A. Dinkneh Teklesadik, C. Makropoulos. (2011): *Decentralised Integrated Analysis and Enhancement of Awareness through Collaborative Modelling and Management of Flood Risk* [DIANE-CM], CRUE Final Report II-1.

- Feedback: Participants need feedback in order to show if their involvement had any effect. For stakeholders, this feedback can be rather easily given after the end of a dedicated workshop or in written form. There are also other ways of ensuring that feedback is received:
    - Websites of the main authorities (such as the NEA via a dedicated portal).
    - Via social networks.
    - Through official publications of the political-administrative authorities (official gazettes).
    - Newspaper articles.
    - Through consultations.
    - Through direct feedback; for instance, after a workshop or a discussion event.

03

Review of Relevant International Legislation

3.1 WMO Requirements

The World Meteorological Organisation (WMO) is dedicated to international cooperation and coordination on the state and behaviour of the Earth's atmosphere, its interaction with the land and oceans, the weather, and the climate it produces and the resulting distribution of water resources (www.wmo.int). There are no direct WMO requirements for hydraulic modelling or flood mapping, although there are several documents worth noting:

- Issue 19 of the *Integrated Flood Management Tools Series: Flood Forecasting and Early Warning*.
- Issue 20 of the *Integrated Flood Management Tools Series: Flood Mapping*.

In the Issue 19 publication, the requirements for flood forecasting model implementation are outlined from a flood analysis and hazard point of view. In the Issue 20 publication, the steps to produce flood maps are described. The suggested approach in both guidelines will be outlined.

3.1.1 Flood Mapping

The main suggested flood mapping methodology by the WMO is outlined in Figure 3.

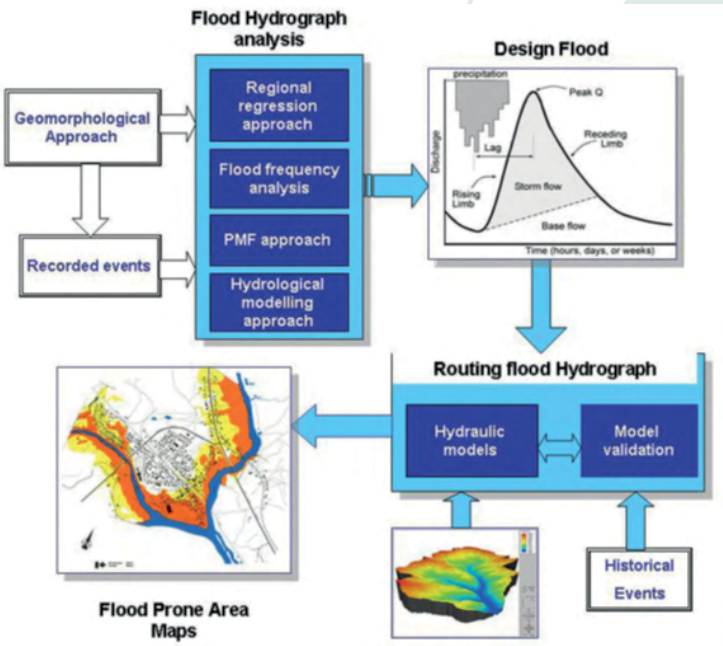

Figure 3. Modelling Approach in Flood Mapping (Source: WMO IFMTS 20, 2013)

The suggested methodology makes use of different approaches, including a geomorphological and recorded event approach to support hydrological modelling (flood hydrograph analysis). The flood information is then used for flood routing through hydraulic models while considering the calibration and the validation of the results throughout the whole process. Therefore, this suggested methodology is in agreement with international best practices.

In the sections below, the proposed methodology by the WMO will be analysed per flood mapping stage.

3.1.2 Institutional and Legal Requirements

Issue 20 of the aforementioned WMO publication provides recommendations regarding the institutional and legal requirements for undertaking flood mapping. It is recommended that institutional, administrative, and programmatic decisions take place before the technical parts of a programme of a flood mapping exercise can be implemented alongside highlighting the need for active stakeholder participation before legal and administrative mechanisms can be developed. The recommended steps before any flood hazard assessment are undertaken are:

- Stakeholder participation.
- Legal mechanisms.
- Administrative mechanisms and institutional arrangements.
- Developing a flood mapping programme.

Recommendations for each of these steps are provided. These activities are paramount in order to ensure that the flood hazard assessment and mapping programme is successful.

3.1.2.1 Flood Mapping Process: Concept and Implementation (Technical)

The flood mapping methodology proposed by the WMO in principle follows the same methodology as the outlined one in the international best practices section (4.1).

3.1.2.2 Data Sources

The WMO recommends analysing and processing several data sources, including topographical, surface elevation, information about past flood events and disasters, hydrological and hydraulic data, land-use and land cover data, and social and socio-economic data. More information is provided for each of the sections below.

3.1.2.3 Topography

The flood mapping recommendations for topographical data describe three main inputs for these data; namely: (1) topographic maps, (2) aerial photography, orthophoto maps and (3) satellite imagery.

3.1.2.4 Surface Elevation

As previously mentioned, the WMO recommendations give the surface elevation data the highest importance in terms of flood mapping results. Several data sources are recommended for surface elevation data:

- Topographic maps with contour lines (limited accuracy).
- Digital terrain models (DTMs) recommended global data sources for preliminary mapping and LiDAR (or similar accuracy) for detailed mapping.

Topographic map sources are just recommended for limited cases for the development of a digital terrain model (DTM) of the ground surface. Additionally, the quality of a DTM derived by photogrammetric (orthophoto) methods give the elevation with a maximum accuracy of +/- 1.0 m and the WMO recommendations do not consider this sufficient for detailed flood mapping. On the other hand, LiDAR provides the desired level of accuracy, although it is more expensive that other sources. LIDAR data can be used to determine a DTM with a spatial resolution of 1 to 2 m and an error in the elevation height of less than +/- 10 cm.

Regarding topographical surveys in watercourses, it is recommended that cross sections of the expected inundated part of the flood plains and the river are surveyed in 1D hydraulic models with a recommendation of keeping the distance of the river profiles below 100 m with a further refinement at hydraulic structures like bridges, weirs, and sudden changes in the riverbed. The recommendations for 2D modelling include the definition of break-lines at all discontinuous changes of the topographic height.

3.1.2.5 Past Flood Events and Disasters

The WMO is recommending the acquisition of any data related to past flood events and disasters, including information from international and national databases and at the local level vis-à-vis newspaper archives, information from local authorities, interviews with elderly people or flood marks.

3.1.2.6 Hydrologic Data

Hydrologic data are relevant in order to estimate peak discharge for the construction of hydrographs or

for the estimation of discharge-frequency relations. Hydrologic data are commonly available at:

- The Hydro-meteorological Service (rainfall and discharge measurements).
- Water authority, in relation to water use.
- Hydro-electric power stations.
- Discharge data and associated metadata.

3.1.2.7 Hydraulic Data

Hydraulic data describe the discharge conditions in and around the channel. Three spatial sections and the respective roughness are relevant: flood plain – riverbank – riverbed (cross section). This is well described in many standard hydraulic textbooks like the well-known *Open Channel Hydraulics* (Ven Te Chow, 1959) or many publicly available scripts (e.g., Goodwill & Sleigh, 2007).

One of the most relevant inputs for hydraulic models is the roughness distribution, representing the flow resistance of the flood plain and the riverbed. A reliable evaluation of the roughness parameters needs good experience. Aerial images, land-use maps and biotope distribution maps can be used for a first classification of roughness zones, but results require a thorough field check. The best basis to evaluate the roughness in the riverbed would be through taking bed material samples at various locations of the aquatic zone and determining the grain size distribution curve in the laboratory. But often, only visual control of the bed material is possible. An intermediate solution is the "transect-by-number" sample of the armour layer (Anastasi 1984; for application see Bunte & Abt, 2001).

For the validation/verification of the hydraulic model, recorded water levels and delineation lines of the inundated area should be available for historical floods and at normal flow conditions. The flow conditions below bank-full discharge serve for the validation and the verification of the roughness parameters in the riverbed. They are much easier to provide (e.g., during a bathymetric survey of the riverbed) than the water stages of a flood.

3.1.2.8 Land-use and Cover

Land-use and land-cover data are mainly used for hydrological and hydraulic modelling.

Resources might be available through:

- National statistical bureau: land-cover and land-use maps.
- Satellite data: land classification.
- Airborne photography: for land-use and land-cover mapping.

3.1.2.9 Social and Socio-economic Data

Social and socio-economic data are used for the assessment of exposure and vulnerability and ultimately for the assessment of risks in a given location. Information is available from:

- National statistical bureau: data often aggregated to variable grid size (per km 2, ha) or per administrative unit (county, municipality).
- Satellite information.
- Studies for the vulnerability information of communities: require a detailed analysis of the built environment, the distribution of the population, economic activities, etc.
- Insurance companies.

3.1.2.10 Assessment and Mapping

The WMO, although recognising the role of other approaches for local mapping in particular locations (such as the historical and the geomorphological approaches), recognises the need for following a hydrological-hydraulic modelling approach for flood mapping. This is especially the case if extreme events are considered as it is the case for a flood hazard assessment.

3.1.2.11 Determination of Discharge and Hydrographs

The determination of discharge and hydrographs is a key step in the implementation of flood modelling for flood hazard mapping. The following steps are recommended by the WMO for this purpose:

Step 1.

Delineation of the study area: recommending the estimation and modelling of the discharge and respective hydrographs of a river preferably for the whole watershed or sub-watershed boundaries.

Step 2.

Selection of modelling approach for discharge simulation: the WMO recommends either a statistical approach (using data recorded at gauging stations along the river) or the use of a modelling approach (when long data records are not available) using hydrological rainfall-runoff models.

Step 3.

Data collection and collation for model setup: the requirement for the collection of the spatial and temporal input data from as many sources as possible to be used for the model setup and the calibration and the verification of the model parameters.

Step 4.

Model validation: it is recommended that the data to validate the model should include the following:

- Peak flood discharges developed at gauging stations or computed.
- Rainfall distribution and total rainfall values.
- Rainfall and soil moisture conditions before the storm for single-event analysis.

Step 5.

Flood discharge simulation for design storm events: to be undertaken with the validated models.

3.1.3 Determination of Hazards in Flood-prone Areas

As noted above, several approaches are described for the determination of hazards in flood-prone areas, although preference is given to the modelling approach. The historical and geomorphological approaches will be briefly described for illustration purposes.

3.1.3.1 Historical Approach

The historical approach provides information on known areas that have been inundated in the past by flood waters from rivers or from the sea. The delineation of the flood mapping is undertaken combining all of the historical information available while highlighting the importance of satellite information for more detailed mapping.

3.1.3.2 Geomorphologic Approach

The geomorphic approach provides independent flood information based on surface features found on the ground and their interpretation and this approach may provide information for events where peak flows have been observed that exceeded the 100-year flood discharge calculated by regional analysis. The geomorphologic method is based on mapping the geomorphologic evidence associated with a river or a stream. Using the geomorphologic approach is only recommended for providing a first assessment of past flood activity and outlining the previously flooded areas. It is not recommended to use these data for potential future events without additional investigations and the WMO recommends just using this approach as a starting point for a modelling approach.

3.1.3.3 Modelling Approach

The modelling approach methodology proposed by the WMO does not deviate from the international best practices as outlined above. The following steps are recommended for the implementation of the modelling approach for reasons of quality and efficiency:

Step 1.

Delineation of the study area: the first recommended step is the delineation of the study area for boundary location purposes. This is equivalent to the scoping stage as described above.

Step 2.

Selection of the modelling approach for fluvial flow simulation: within this step, it is recommended that the modelling approach is decided, considering either 1D or 2D models, steady or unsteady regimes, the appropriate approach for the flow roughness and how the hydraulic structures are going to be managed.

Step 3.

Data collection and collation for model set-up: providing recommendations in line with all of the data described above.

Step 4.

Model calibration and validation: highlighting the importance of the calibration results. A margin of error of less than +/- 5 cm within the observed flood depths and the modelling results is recommended, providing those reliable observations are available.

Step 5.

Flow simulation for the flood events: to be based on the validated models.

Step 6.

Determination of the inundated area: combining the water level results (step 5) with the DTM of the ground surface and the calculated water levels. Most models undertake this process automatically.

3.1.4 Flood Forecasting

As previously described, the WMO also provides information and recommendations regarding the implementation of flood forecasting models. Although this is not the main purpose of this report, a brief summary of the recommendations and the suggested steps are outlined here because the flood models to be implemented within the flood hazard assessment will be the basis for the flood forecasting platform.

3.1.4.1 Requirements for Analytical Flood Studies

Flood analysis is essentially required to identify the characteristics of the relevant flood hydrograph for the catchment in question. In effect, the hydrograph provides the complete integrated picture of rainfall and catchment characteristics. The necessary information for analytical studies is obtained from:

- Daily recording rain gauges.
- Water level recorders with rated sections or measuring structures to provide river discharge measurements.
- Climatological data; particularly, to provide an estimation of evaporation losses and the water balance.
- General topographical and land-use mapping to define catchment characteristics.
- Detailed topographic survey of the river and the adjacent flood plain (the flood corridor or the functional flood plain).
- Identifying the areas at risk which may require a more detailed topographical survey and accurate flow measurement.

These data provide the building blocks for model studies, the calibration of models and the identification of flood warning system requirements. Although similar to general flood studies, the focus on an operational forecasting and warning system requires accurate knowledge of the timing of flood response and the speed of flood movement. It is, therefore, essential to have access to sets of information (at the very least, rainfall and flow) from various contributing portions of the catchment; particularly, data from its upper reaches. The essential requirements are as follows:

- Measurement of rainfall and runoff from the main upland portions of the catchment (watershed) to define early flood generation.
- Measurement of rainfall, runoff, and timing close to the major confluence points within the river system to identify the time of travel and the relative significance of different catchment contributions.
- Measurement of river levels, flows and flood plain characteristics upstream of high-risk areas.
- Identification of drainage congestion problems in lowland areas needing accurate water level measurement and timing.
- Local rainfall data in areas of drainage congestion and urban areas to identify pluvial flood risk.

3.1.4.2 Model Calibration and Data Requirements

Ideally, the objective of calibration is to remove all possible bias and eliminate all possible noise included in the model. In reality, because of the constraint of input data quantity and quality and of simplistic assumptions that may be inherent in the model, care should be taken to achieve the proper balance between the calibration objectives and goodness-of-fit statistics. Generally, there are three main objectives when calibrating conceptual hydrologic models vis-à-vis an entire river basin for river forecasting applications, namely: a good reproduction of the observed hydrograph at each individual key forecast point on the river system should be produced. The parameters of the models should function as they are intended. There should be a realistic variation in parameter values from one area to another within the river basin (headwater, mainstream or tributary) and with areas just across the divide in adjacent river basins.

In general, this means that the chosen model parameters need to be adjusted in order to make the model predicted values resemble the observed values. It is important to recognise that the model parameters may not fully incorporate a physical meaning but are mostly uncertain quantities that reflect all of the error sources. There are two basic methods used for calibrating hydrologic models: i) trial and error calibration and ii) automated (parameter) optimisation calibration.

When calibrating any hydrologic models, there are five steps that should be followed:

1. Gather information and data.
2. Assess the spatial variability of hydrologic factors.
3. Analyse historical data and prepare them for use in hydrological models.
4. Select flow-points and the period of record for calibration.
5. Implement calibration results for operational use.

Data requirement: vin terms of data types, basic climatological information, spatial (geographical) and physical information on the nature of the river system, vegetation cover, land-use, soil classification and geology are essential. Commonly, meteorological, and hydrological services consider the data over 30 years as the standard period.

Other requirements: some of the most important requirements are knowledge, experience, teamwork, leadership, and computerised tools along with proven procedures and strategies. Innovation may be required during the calibration process. Using tested procedures and strategies for model development will make model procedures efficient and give consistently good quality results. Thus, a number of standards internationally available models are used as the basis for most flood forecasting systems.

3.1.4.3 Model Verification/Validation

A fundamental rule of model verification is to use data which were not a part of the process of calibration. The validation period used for verification should be long enough to incorporate several observed flood events so it may need to cover two or more years. A number of statistical methods are available for evaluating the success of verification. In flood forecasting applications, comparisons should focus on alarm levels and forecast lead time, etc. An accurate representation of flood volume is critically

important as it demonstrates how effective the model is in relating rainfall and runoff responses. The shape characteristics of the modelled and observed floods can be statistically tested according to three parameters:

- Peak percentage difference between observed and simulated floods.
- Phase-difference of the peak flow.
- Volumetric difference.

3.2 EU Commitments

The European Union's main commitment with respect to flood modelling is the EU Flood Directive (Directive 2007/60/EC on the assessment and management of flood risks 2007, EUFD). The main goals of the European Union Floods Directive (EUFD) are the management of flooding events at an integrated scale and the reduction and the assessment of risks that floods pose to human health, the environment, cultural heritage, and economic activities while emphasising the frequency and the magnitude of such events in addition to their consequences. The EUFD required member states to approach flood risk management in a three-stage process:

- Member states will undertake a preliminary flood risk assessment of their river basins and associated coastal zones by 2011 in order to identify areas where potential significant flood risk (PFRA) exists.
- Where real risks of flood damage exist, they must develop flood hazard maps and flood risk maps for such areas by 2013. These maps will identify areas with a medium likelihood of flooding (at least a 1:100-year event) and extreme events or low likelihood events in which expected water depths should be indicated. In the areas identified as being at risk, the number of inhabitants potentially at risk, the economic activity and the environmental damage potential must be indicated.
- Finally, flood risk management plans must be drawn up for these zones by 2015. These plans are to include measures to reduce the probability of flooding and its potential consequences. They will address all phases of the flood risk management cycle but focus particularly on prevention (i.e., preventing damage caused by floods by avoiding the construction of houses and industries in present and future flood-prone areas or by adapting future developments to the risk of flooding), protection (by taking measures to reduce the likelihood of floods and/or the impact of floods in a specific location such as restoring flood plains and wetlands) and preparedness (e.g., providing instructions to the public on what to do in the event of flooding). Due to the nature of flooding, much flexibility on objectives and measures are left to the member states in view of subsidiarity.

These steps need to be reviewed every six years in a cycle coordinated and synchronised with the Water Framework Directive (WFD). The Directive applies to inland waters as well as all coastal waters across the whole territory of the EU and all types of flooding have to be considered within the assessment.

From a modelling point of view, the EUFD does not require any approach to be followed and actually gives every member the possibility of developing its own methodologies. It should be noted, however, that after the submission of the results per every stage, the EU provides comments and recommendations to the approach followed, highlighting gaps and areas for improvement. The main recommendations provided to member states after the first cycle of the EUFD were:

- Lack of climate change considerations.
- Lack of comprehensive assessment of all types of flooding. In particular, there is a lack of urban and pluvial flood assessments by some members.
- Lack of flood map dissemination or availability.
- Lack of appropriate scale for mapping.

Therefore, although no major issues have been found regarding the modelling component of the flood risk assessments, this is something that is analysed by the EU when the results are reported. In the following sections, a brief summary of the methodologies followed by some members is outlined. It should be noted that this is a summary of the approach from a hydraulic modelling point of view for the first and second stages of the EUFD.

It should be added that even if no modelling requirements are set by the EUFD, a *Handbook on Good practices for Flood Mapping in Europe* was published in 2007 by the EU. Additionally, there are requirements for reporting and for risk modelling. The former will be outlined within this report while the latter is out of the scope of this project.

3.2.1. 1.2 Flood Risk Profile and Types of Flooding

The European Floods Directive requires that all significant sources of flooding be considered in the methodology for the preliminary flood risk assessment and for the flood hazard and risk mapping. The sources of flooding that are considered by the EUFD are:

- Fluvial flooding (including flash-flooding)
- Groundwater flooding
- Pluvial flooding
- Artificial water-bearing infrastructure flooding
- Sea-water flooding

There are also other classifications of sources of flooding with alternative types of flooding following the tentative list of sources of flooding that was considered within the framework of this project:

- Fluvial/river, lake flooding
- Pluvial/flash/urban flooding
- Groundwater flooding
- Snow-melt flooding
- Coastal flooding
- Dam break/infrastructure failure flooding

The main difference between these two lists is the inclusion of a snow-melt flood and the association of flash-flooding and pluvial flooding. In this respect, it should be noted that snow-melt flooding will be considered within fluvial flooding (as it is not expected to cause flooding by itself but only to exacerbate fluvial flooding) and that flash-flooding will be considered as a fluvial flood. There is some controversy in this respect and some authors may find relationships between pluvial and flash-flooding. For instance, the Georgian Methodology for the Preliminary Risk Assessment (discussed below in section 2.2.1) even treats both types of flooding as the same one. However, this is not the case in any of the EU member states. In the consultant's opinion, even if they both are events resulting from extreme rainfall, flash-flooding usually arises from a watercourse whereas pluvial flooding arises from rainfall runoff before it reaches a watercourse or a drainage system. Pluvial floods are usually associated with a short duration (up to 3 hours) high intensity rainfall (exceeding 20 mm/h), although they can also occur with a lower intensity rainfall (~ 10 mm/hr) over longer periods and can be exacerbated when the ground is saturated, frozen, developed or otherwise has a low permeability (SEPA, *Improved Understanding of Pluvial Flood Risk in Scotland*', June 2009). Therefore, pluvial flooding will be treated separately from flash-flooding. The former will be included in fluvial flooding, considering the peculiarities of flash floods if compared to fluvial floods (shorter lead time).

It should be noted that the possibility of two (or more) of the above noted types of flooding will also be considered (if relevant and possible). Therefore, the sources of flooding as indicated by the EUFD will be used.

The definition for each source of flooding is:

- Fluvial: Flooding of land by waters originating from part of a natural drainage system, including natural or modified drainage channels. This source could include flooding from rivers, streams, drainage channels, mountain torrents and ephemeral watercourses, lakes and floods arising from snowmelt.
- Pluvial: Flooding of land directly from rainfall water falling on or flowing over the land. This source could include urban stormwater, rural overland flow, or excess water.
- Groundwater: Flooding of land by underground waters rising to above the land surface. This source could include rising groundwater and underground flow from elevated surface waters.
- Seawater: Flooding of land by water from the sea, estuaries, or coastal lakes. This source could include flooding from the sea (e.g., extreme tidal level and/or storm-surges) or arising from wave action or coastal tsunamis.
- Artificial Water-bearing Infrastructure: Flooding of land by water arising from artificial water-bearing infrastructure or the failure of such infrastructure. This source could include flooding arising from sewerage systems (including stormwater, combined and foul sewers), water supply and wastewater treatment systems, artificial navigation canals and impoundments (e.g., dams and reservoirs).

It should be noted that the type of flooding can also be established depending on the mechanism of the flooding:

- Natural Exceedance: Flooding of land by waters exceeding the capacity of their carrying channel or the level of adjacent lands.
- Defence Exceedance: Flooding of land due to floodwaters overtopping flood defences.
- Defence or Infrastructural Failure: Flooding of land due to the failure of natural or artificial defences or infrastructure. This mechanism of flooding could include the breaching or collapse of a flood defence or retention structure or the failure in the operation of pumping equipment or gates.
- Blockage/Restriction: Flooding of land due to a natural or an artificial blockage or a restriction of a conveyance channel or system. This mechanism of flooding could include the blockage of sewerage systems or be the result of restrictive channel structures such as bridges or culverts or arising from ice jams or landslides.

3.2.2 WISE Reporting Requirements

The reporting to the EC is guided by several documents elaborated to support this process and are listed below:

- Floods Directive GIS Guidance, Guidance on the Reporting of Spatial Data to the Water Information System for Europe, Version 1.4, Date 2020-03-03[3] - Guide for development of spatial data sets.
- Floods Directive Reporting Guidance 2018, Version 4.0, Date 2020-07-11[4] - Guide for Development of Access Database.
- Annex 1: Reporting on the Floods Directive - A User Manual, Version 1.4, Date 2019-03-06[5] - Guide for conducting the reporting process.

The data are reported to the EC using two types of files:

- Access Database (Microsoft Access 2010) or Extensible Markup Language (XML) file.
- Shapefiles to report spatial data or Geography Markup Language (GML) file.

3.2.3 Flood Hazard Mapping – Recommendation

The EUFD does not set up the probability of the events to be considered within the flood hazard analysis, but it does specify that: “Flood hazard maps shall cover the geographical areas which could be flooded according to the following scenarios:

- floods with a low probability, or extreme event scenarios.
- floods with a medium probability (likely return period ≥ 100 years).
- floods with a high probability, where appropriate.

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3. https://svn.eionet.europa.eu/repositories/Reportnet/Dataflows/FloodsDirective/Floods%20Directive%202018/FD%20Spatial%20data%20reporting/Spatial%20Reporting%20Guidance/Floods_GISGuidance.pdf
4. https://svn.eionet.europa.eu/repositories/Reportnet/Dataflows/FloodsDirective/Floods%20Directive%202018/FD%20Descriptive%20data%20reporting/Reporting%20guidance/FD_ReportingGuidance.pdf
5. http://cdr.eionet.europa.eu/help/Floods/Floods_2018/documents/ReportingWorkflowGuide

For each scenario referred to in paragraph 3 the following elements shall be shown:

- the flood extent.
- water depths or water level, as appropriate.
- where appropriate, the flow velocity or the relevant water flow.

The following types of flooding are initially considered within the EUFD (Table 2). It is the responsibility of each member state to analyse flood risk for the type of flooding that is relevant on its territory.

Table 2. Types of Flooding

Type of Flooding	Causes of Flooding	Effect of Flooding	Relevant Parameters
River flooding in flood plains	- Intensive rainfall and/or snowmelt - Ice jam, clogging - Collapse of dikes or other protective structures	- Stagnant or flowing water outside the channel	- Extent (according to probability) - Water depth - Water velocity - Propagation of flood
Urban (pluvial) flooding	- Intensive rainfall	- Stagnant or flowing water in urban areas	- Extent (according to probability) - Water depth - Water velocity
Sea water flooding	- Storm-surge - Tsunami - High tide	- Stagnant or flowing water behind the shoreline - Salinisation of agricultural land	- Extent (according to probability) - Water depth - Water velocity - Propagation of flood
Mountain torrent activity or rapid runoff from hills	- Cloud burst - Lake outburst - Slope instability in watershed - Debris flow	- Water and sediments outside the channel on alluvial fan - Erosion along channel	- Extent (according to probability) - Sediment deposition - Water depth - Water velocity - Propagation of flood
Flash floods in Mediterranean ephemeral water courses	- Cloud burst	- Water and sediments outside the channel on alluvial fan - Erosion along channel	- Extent (according to probability) - Sediment deposition - Water depth - Water velocity - Propagation of flood
Ground-water flooding	- High water level in adjacent water bodies	- Stagnant water in flood plain (long period of flooding)	- Extent (according to probability) - Water depth
Lake flooding	- Water level rise through inflow or wind induced set up	- Stagnant water behind the shoreline	- Extent (according to probability) - Water depth
Artificial water bearing infrastructure (AWBI)	- Failure of infrastructure	- Water and sediments outside the channel on alluvial fan - Erosion along channel	- Extent (according to probability) - Sediment deposition - Water depth - Water velocity - Propagation of flood

3.2.4 Approach by Member States to the EUFD

3.2.4.1 Mapping Flood Hazard and Flood Risk in Areas of Potential Significant Flood Risk

The main output of the Preliminary Flood Risk Assessment is the Areas of Potential Significant Flood Risk (APSFR) which will be analysed in more detail during the Flood Hazard and Risk Mapping (FHRM) stage. As noted, the EUFD (in its article 6) requires member states to prepare flood hazard and flood risk maps at the most appropriate scale for areas identified as being at risk of flooding. The standard approach of the Directive is for member states to undertake a preliminary assessment of the flood risk across their territories and use the results to identify APSFRs based on available or readily derivable information. Member states are also able to use existing flood risk assessments if they are suitable for identifying the APSFRs from all potential sources and in all parts of their territory. If existing risk assessments do not cover all potential significant sources of flooding or the whole country, then a new preliminary flood risk assessment is required for those specific flood sources and/or for areas/river basins not previously assessed.

3.2.4.2 Sources of Floods Mapped

Member states are expected to prepare flood hazard and flood risk maps for all sources of flooding that have been assessed as being significant within their Units of Management. The most commonly mapped source is fluvial flooding with 25 of the 27 member states reporting information vis-à-vis preparing such maps. The table below shows the types of flooding mapped by each of the member states.

Table 3. Summary of Sources of Flooding for Which Flood Maps Have Been Prepared by Member States (Source: EU, 2015)

MS	Source not reported	Fluvial			Piuvial			Groundwater			Seawater			AWBI			Main rivers and sea
	FHRM (UoM)	FHRM (UoM)	Specific map	Combined map	FHRM (UoM)	Specific map	Combined map	FHRM (UoM)	Specific map	Combined map	FHRM (UoM)	Specific map	Combined map	FHRM (UoM)	Specific map	Combined map	FHRM/ Combine
AT		2	Yes			Yes											
BE	2	5	Yes		1	Yes		1	Yes				Yes	1	Yes		
BG	Not reported to WISE																
CY		1	Yes														
CZ		3	Yes														
DE		10	Yes								7	Yes					
DK				Yes							2	Yes					
EE		1		Yes	1		Yes				1		Yes				
EL		1	Yes								1	Yes					
ES		21	Yes		1		Yes			Yes	22	Yes					
FI		6	Yes								2	Yes			Yes		
FR		12	Yes		3		Yes				9	yes					
HR		2		yes							1		Yes			Yes	
HU		1	Yes					1	Yes								
IE		10		Yes							5		Yes				
IT		47	Yes		1	Yes					26	Yes		1	Yes		
LT		4	Yes				Yes				2	Yes			Yes		
LU					1	Yes											
LV		1	Yes								1		Yes				
MT					1	Yes											
NL		4		Yes			Yes						Yes			Yes	
PL		3	Yes								2	Yes					
PT		8	Yes														
RO		12		Yes	3		Yes										
SE	6		Yes												Yes		
SI		2		Yes			Yes				1	Yes				Yes	
SK		2		Yes	1		Yes			Yes							
UK		5	Yes	Yes	12	Yes					5	Yes	Yes	11	Yes		11

3.2.4.3 Flooding Scenarios

The Directive stipulates that as a minimum the hazards from low probability and medium probability flooding scenarios have to be mapped: a return period of 100 years or more is given for the medium probability scenario. Where thought appropriate by member states, the hazards from a high probability flooding scenario should also be mapped. All 25 member states that prepared and reported medium probability fluvial floods used a 100-year return period (as suggested by the Directive) or a 1% annual exceedance probability for the expression of the probability of flooding. It should be noted that the definition of low, medium, and high in terms of corresponding return periods varies widely from country to country and also by flood source.

3.2.3.4 Mapping of Hazard Elements

For each flooding scenario, as a minimum the flood extent and the water depth or level have to be mapped. Where appropriate, flow velocity or water flow may also be mapped. Most of the 25 member states that prepared fluvial flooding hazard maps during the first cycle of the EUFD show flood extents and water depths/levels for all three probability scenarios. Twelve member states also mapped flow velocity or relevant water flow for all three probability scenarios. Thirteen of the 17 member states preparing sea water flood maps produced hazard maps covering the two required probability scenarios and included the two required hazard elements.

3.2.4.5 Scale of Maps

Member states will determine the most appropriate scale of flood hazard maps and flood risk maps, and different scales can be chosen depending, for example, on the area covered and the type and purpose of the map. Maps intended to raise public awareness may require a larger scale than those used by national authorities for strategic planning. Twenty-six member states produced maps that had a scale of 1:25,000 or larger.

3.2.4.6 Modelling Approach

The approach for the preliminary flood risk assessment varies significantly in the member states and even among them. In some cases, just historical information was used whereas in other cases, either GIS or simplified modelling approaches were used for the identification of the APSFR.

The modelling approach followed by member states for the FRHM in the first cycle of the EUFD is similar from a hydraulic modelling point of view. While the hydrological assessment (or the determination of the return period values) differ per country (with ten member states using a hydrological modelling approach), hydraulic models were used for the calculation of the water depth and water extent in all of the cases during the FHRM stage. The approach followed in terms of dimensionality varies depending on the country and even within the same country. Thus, 1D, 2D or 1D-2D modelling approaches were followed depending on the nature of the rivers. It should be noted that while all the sections described above (sources, flooding scenarios, scale of maps, mapping elements) were thoroughly assessed by the European Commission, the hydraulic modelling approach has not been assessed in detail, there are no formal requirements for this, and each member state is at a liberty to define the approach. In all of the cases, however, there are

methodologies for the preliminary flood risk assessment and for the FHRM where each member state defines the approach to be followed depending on the type of flooding.

3.2.5 Flood Risk Assessment Recommendations (JRC)

In addition to the EUFD requirements by the EU, the JRC recently published its *Recommendations for National Risk Assessment for Disaster Risk Management in the EU - Approaches for Identifying, Analysing and Evaluating Risks*. EU member states are required to use these recommendations for undertaking national risk assessment practices. The flood risk recommendations are mainly based on the EUFD, adding information based on global international best practices and the state of the art.

Within these recommendations, five different types of flooding are defined:

1. Fluvial floods occur when river levels rise and burst or overflow their banks, inundating the surrounding land. This can occur in response to storms with higher-than-normal rainfall totals and/or intensities to seasonal strong weather systems, such as monsoons or winter storm tracks, or to the sudden melting of the snow in spring.
2. Flash floods can develop when heavy rainfall occurs suddenly; particularly, in mountainous river catchments, although they can occur anywhere. Strong localised rainfall, rapid flood formation and high-water velocities can be particularly threatening to the population at risk and are highly destructive.
3. Heavy rainfall may cause surface water flooding, also known as pluvial flooding; particularly, in cities where urban drainage systems become overwhelmed.
4. Floods can also be generated by infrastructure failure (e.g., dam breaks), obstructions caused by avalanches, landslides or debris, glacial/lake outbursts and groundwater rising under prolonged very wet conditions which cause waterlogging.
5. Coastal flooding is caused by a combination of high tide, storm-surge, and wave conditions.

In terms of recommendations from a flood hazard point of view, the JRC recommends the use of hydrological and hydraulic models to derive flood inundation maps for a range of probability events and combining this information with GIS and DEM resources.

3.3 Summary of Requirements and Commitments

Section 3 above has described in detail the requirements and commitments from both the WMO and the EU with respect to hydraulic modelling for flood mapping and hazard purposes.

The WMO provides recommendations from a flood mapping and flood forecasting point of view, giving information about the recommended approach for both mapping and forecasting. The flood mapping approach outlined by the WMO is in agreement with international best practices. It should be noted that the WMO recommendations also propose alternative approaches to flood mapping, although the hydrological-hydraulic modelling approach is favoured. From a flood forecasting point of view, the WMO recommendations are also in line with international best practices.

The EUFD is the main policy providing commitments to member states regarding flood hazard and risk assessments. It requires all of the member states to undertake a (1) preliminary flood risk assessment to determine areas at potential risk of flooding that will be analysed in more detail in the (2) flood hazard and risk mapping and subsequently in the (3) flood risk management plans. It is required that all member states consider all of the types of flooding that are relevant on their territory and produce flood hazard and risk information for low and medium-probability events, although high-risk probability results are also suggested. The methodology to be followed in order to undertake both the preliminary and the FHRM is not described, and each member adapts its own methodology for these assessments. There is a requirement for the provision of extent and depth information for the flood mapping, although flood velocity is recommended when appropriate. The EUFD requirements are organised in cycles and member states have to review the results from the previous cycle every six years. There are reporting commitments for the assessment's submission and the European Commission reviews the results of the EUFD on a periodic basis. It is recommended that climate change is also fully considered in the analyses. In the previous EUFD cycle, it was found that pluvial flooding was not fully considered by most member states.

04

Comparative Analysis of International and National Best Practices in Flood Hydraulic Hazard Modelling, Mapping and Assessment

4.1 International Best Practices

A summary of international best practices in hydraulic modelling for floods will be outlined. Flood mapping projects encompass several activities and while hydraulic modelling is a stage within flood project activities, it is difficult to explain these hydraulic modelling practices without going through all of the activities. The main activities within a flood study are outlined in Figure 4.

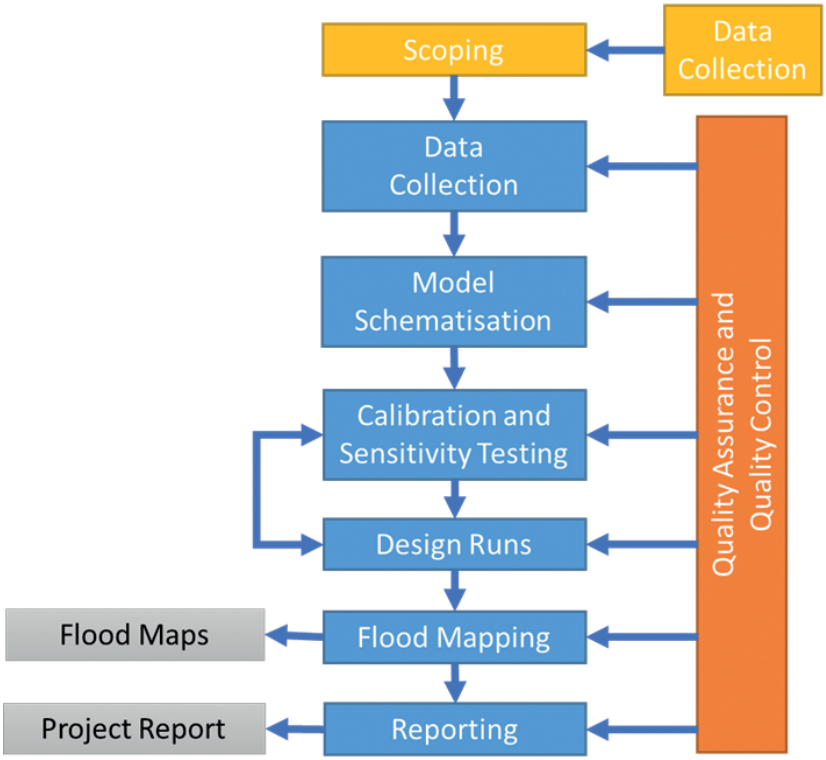


Figure 4. Flood Modelling Study Methodology

Each of the activities and tasks will be briefly outlined. It should be noted that this is not intended as an exhaustive methodology for flood modelling but just as a summary of the required activities and the international best practices.

4.1.1 Scoping Stage

The first task within a flood study is to define the scope of the study. This will establish the purpose of the assessment, the level of the assessment and the data requirements to make informed decisions.

Before starting a flood study, it is important to understand flooding mechanisms at the study location as well as the scale of the study. It is important to note that modelling should ideally consider the catchment scale processes in order to properly represent all flooding mechanisms instead of isolated locations within a catchment. The approach to this differs depending on the country and on the requirements. For instance, for European Union member states, the three stages of the EUFD imply that a catchment approach is followed for the preliminary flood risk assessment while the flood hazard and risk mapping is in most cases undertaken considering the identified areas at risk of potential significant flooding. Therefore, while a catchment approach is considered for the initial stage, a more local assessment is considered for the detailed flood hazard mapping. This is the case, for instance, for countries such as Bulgaria where the detailed flood hazard mapping is only undertaken for local areas at potential flood risk. In some other countries, such as Spain, Portugal and the UK, the competent authorities undertake flood hazard mapping in a catchment scale approach while the EUFD is implemented in order to consider all flood sources and flood mechanisms.

A good understanding of the links between the sources and the impacts of flooding can help identify the most appropriate modelling approach. To help understand the interaction of different actions across catchments and coastlines, it is advisable to use the source–pathway–receptor–impact approach to build a conceptual model of the key processes which need to be considered in the study (Figure 5). This approach is a well-established framework in flood risk management, and it provides a basis for understanding the causal links between the source of flooding, the route by which it is transmitted and the receptor which suffers some impact:

- Sources are the weather events or the conditions that result in flooding (e.g., heavy rainfall, rising sea-level, waves, etc.).
- Pathways are routes between the source of flood waters and the receptor. These include surface and sub-surface flow across the landscape, urban drainage systems and wave overtopping.
- Receptors are the people, industries and built and natural environments that can be impacted by flooding.
- Impacts are the effects on exposed receptors. The severity of any impact will vary depending on the vulnerability of the receptor.

For any area, there may be multiple sources, pathways and receptors which interact with each other.

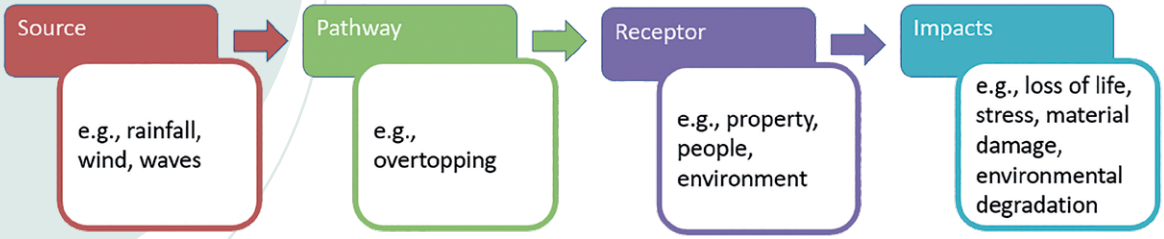


Figure 5: The Source-Pathway-Receptor-Impacts Model (Source: DEFRA/Environment Agency R&D Technical Report FD2302/TR1; Sayers, Gouldby, Simm, Meadowcroft, & Hall, 2003)

Available data should be assessed during the development of this conceptual model in order to determine the need for any additional data collection. A list of available data, with a brief description, should be compiled together with any survey requirements. Knowledge of the catchment should be summarised, including any key areas, and known flooding mechanisms which need to be considered.

4.1.2 Data Collection

4.1.2.1 Data

At the early stages of any flood study, it is paramount to identify the sources of data sets in order to ensure that data are available and to determine the quality and usability of the data sets. Such preliminary analyses will inform the modelling and mapping methods that can be implemented. This analysis will be undertaken for the whole area considered within the flood study in order to ensure that data sets are fully analysed and appropriate gap filling, or remedial actions are identified where there are gaps or issues.

4.1.2.2 Topographical Survey

The implementation of hydraulic models should be undertaken using both remote derived digital elevation data and data from topographic surveys of the watercourse. Regarding cross section surveys, a full scoping assessment of the survey should be carried out beforehand and consider the model extent. The cross sections surveyed should be representative of the channel and floodplain and the spacing between the cross sections and the orientation should be determined.

The lateral extent of the survey should be sufficient to include the full extent of flooding. Guidance on this extent may come from flooding records, geological maps (fluvial deposits) or site visits. During the survey, information on structures, flood routes, potential blockages/obstructions to the channel and channel roughness should also be gathered.

Regarding remote-sensing data, different sources of data are available but the accuracy of this should be assessed before being used in the model. Additionally, the extent of these digital data should be fully determined before acquiring them.

4.1.2.3 Historical Information

Information on historical flooding (e.g., newspaper articles, photos, flood marks) should be collected and utilised in order to guide the survey extent and aid the modelling process. Such data are particularly valuable as they can provide information on historical flooding prior to the periods covered by

hydrometric data. An internet search can also often provide useful information. However, the effect of any alterations and additions to the watercourse and associated structures since the date of the recorded event need to be considered.

4.1.2.4 Management of Data

Most modelling projects utilise significant amounts of data and it is important that these data are managed properly.

It is recommended that a data register is used on all projects for recording when information is received and where it is located. On receiving the data set, it should be checked in order to ensure it is complete and of sufficient quality for the project. The data should then be stored in a central location on a file server, preferably using a file structure format common across projects. It is also important to assess and record the quality of collected data.

4.1.3 Model Schematisation

4.1.3.1 Choice of Model

The modelling software chosen should be capable of producing the required output. The choice of model will firstly be defined by the modelling approach to follow regarding dimensionality. The choice between a 1D or 2D (or 1D+2D) model is relevant primarily in the context of river floodplain modelling. One-dimensional models are appropriate for narrow floodplains, typically where their width is not larger than three times the width of the main river channel. The underlying assumption should be that the contribution of the floodplains to conveyance can be quantified using recent advances in the estimation of compound channel conveyance. An additional condition for such models to be valid is that the floodplains should not be separated from the main channel by embankments, levees, or any raised ground where the channel floodplain unit effectively behaves as a single channel.

One-dimensional river models have limitations that can become significant in many practical applications. The flow is assumed to be unidirectional (generally happening in the direction parallel to the main channel flow) and where this is not true (recirculation areas), conveyance predictions can be severely overestimated. Situations where floodplain flow “makes its own way” are frequent but perhaps an even more significant issue is the fact that 1D cross sections will offer a rather crude representation of floodplain storage capacity in the case of large floodplains.

2D modelling of river floodplains can itself be divided into two important classes of approaches; namely, the one where only floodplain is modelled in 2D (as part of a combined 1D+2D model) and the one where floodplain flow and channel flow are modelled as part of the same 2D grid. The main advantage of 2D modelling (over any other approach for floodplain modelling) is that local variations of velocity and water levels and local changes in flow direction can be represented. The approach does not suffer from the limitations of 1D. In principle, it allows a better representation of floodplain conveyance but a major limitation of combined 1D+2D models for river and floodplain systems is that the exchange processes between the river and the floodplains are still modelled crudely (momentum transfer is not modelled). A major drawback of 2D models is their computational cost. Thus, the approach where the whole river and

floodplain system is represented as part of a 2D unstructured grid deserves special attention.

Once the modelling approach (regarding dimensionality) has been decided, the software to be used for the modelling study should be selected. There are several things to consider when selecting a hydraulic modelling software package:

- Does the software meet the project's objectives?
- Are there existing technical capabilities/skills to implement this software?
- Are there enough resources to acquire this software?
- Is this software widely used/recognised?

Sometimes, a benchmarking study can be required in order to select the most appropriate software or to select multiple items of software that will be acceptable for a particular country's use. In most countries, several software packages are acceptable for flood hydraulic modelling studies. This is because different software packages have different features, and a single model cannot usually be used to represent all of the flood mechanism accurately. Additionally, in some cases there is legacy software, but the most appropriate software may have become available only recently.

Benchmarking studies can also be used to compare the performance of software for modelling specific processes that are important to represent. Therefore, the fact that a software package has been selected should not limit the use of some other packages if required, although it could be more advantageous to use existing resources (in terms of technical or financial issues).

As previously described, the software modelling choice has to consider the different flooding mechanisms in a country. The technical representation of specific flooding mechanisms is not the same for different available software packages and the performance may vary depending on the model used. Thus, the criteria for selecting a specific modelling software package would also include the possibility of accurately representing different flooding mechanisms and different software may be used for different flood sources or flooding mechanisms.

4.1.3.2 Model Domain

One of the first tasks to accomplish would be the definition of the model domain. This should ideally take place after a site visit in order to become familiar with the area, with the problems and project's objectives and with the possible limits of the model. The upstream and downstream limits should be defined by the objectives of the flood study rather than to the limits of the project/study area. The model should extend far enough so that uncertainty in the boundary conditions does not significantly influence the estimated flood levels in the area of interest. There are some key locations that can help in the definition of those boundaries such as natural downstream boundaries (lakes or the sea). In some other cases, the downstream boundary condition can be selected at places where there is a change in flow regime (a hydraulic jump), at hydrological station locations, at dams or downstream of significant constrictions (bridges) and significantly downstream of the area of interest. Regarding the upstream extent of the model, this should also be placed sufficiently far away from the area of interest and the same applies.

The selection of the model's extent is critical at this stage because it sets up the extent of the survey data. It is always recommended to be conservative and try to extend the model as much as possible. However, time and financial constraint may prevent this. It is better to extend the model further than necessary than to have to revisit the survey at later stages. Nevertheless, it is recommended to do so if it is identified in further stages of the modelling process that boundaries have to be extended. It is recommended to undertake some "dummy-runs" to increase the confidence in the definition of the model boundaries.

A brief description of approaches depending on the flood source is provided below. It should be added that the definition of the domain will be undertaken mainly considering the area of interest but also considering the location of the upstream and downstream boundary conditions.

4.1.3.3 Fluvial Flooding

As noted, fluvial boundaries, both upstream and downstream ones, should be located at a sufficient distance from the area of interest so that any errors in the boundary will not significantly affect the predicted water levels at the study area. There are different rules of thumb for the location of downstream boundary conditions (such as L=0.7D/S [D=bank-full depth and S=river slope]). Nonetheless, sensitivity assessments should be undertaken to ensure that the location of the selected boundaries do not affect the results. Furthermore, the location of other hydraulic features should be considered such as the location of the downstream boundary condition where the relationships between level and flow are well defined like, for example, weirs or dams. Additionally, if the downstream boundary is tidal, the downstream boundary should be located where a tidal curve can be defined.

4.1.3.4 Pluvial Flooding

In pluvial flooding, in most cases a precipitation grid or value would be applied directly on the elevation grid and, therefore, an upstream boundary condition is not usually required. In these cases, the model domain should be set so they are sufficiently far away from the area of interest so as not to have an impact on results. This should be ascertained through sensitivity tests.

4.1.3.5 Ground-water Flooding

The ground-water modelling domain should consider the layout and location of the different aquifers involved in the flood study area. It should be noted that in some cases, even if it is not apparent, several aquifers may be inter-connected forming an aquifer system in which case all of the system should be considered. Additionally, interactions with the surface drainage system should be taken into account for the definition of the modelling domain, especially if an integrated modelling approach is going to be followed.

4.1.3.6 Coastal Flooding

For coastal inundation models, a level boundary is typically defined along the coast for sea-water flooding. The inland boundary should be sufficiently far inland to be beyond the coastal flood extents. Therefore, the extent of the domain should consider the coastline and the possible extent of the flood.

4.1.3.7 Artificial Water-bearing Structure (AWBS)

An AWBS flood source could include flooding arising from sewerage systems (including storm water, combined and foul sewers), water supply and wastewater treatment systems, artificial navigation canals and impoundments (e.g., dams and reservoirs). For an AWBS source of flooding, the hydrodynamic domain should be extended in order to account for the resulting flood wave to be sufficiently covered, especially when considering dams and reservoirs. This is usually attained by extending the downstream boundary of the model to a point where the impact from the flood wave is negligible through trial and error and considering infrastructure further downstream that may have an effect on the flow dynamics. Regarding the latter, for instance, downstream infrastructure can cause a build-up of water behind the structure and a secondary failure of an AWBS may occur.

4.1.3.8 Model Boundary Conditions

Upstream Boundaries

Upstream boundary conditions for a river system always have to be specified at every upstream location. This is usually specified as hydrology inflows or by precipitation inputs (if a direct-rainfall modelling approach is followed). This information comes from the hydrological modelling or hydrological statistical assessment.

Lateral Inflows

Sometimes, there is a need to include further inflows in order to represent the increase in the drainage area and additional flows to a river system. The lateral inflow allows for the distribution and apportioning of the inflow from a QT-type boundary or a rainfall/evaporation boundary to avoid applying a point inflow from a boundary to a single node. This is important, for example, when considering the snow melt contribution at an appropriate location within the model. For urban modelling, this means when considering storm-water sewer inflows where it is important to have the correct location rather than a lumped contribution in a single upstream boundary node.

Downstream Boundaries

Downstream boundary conditions are needed in order to give the model information about the conditions at the end of the model domain. These conditions are usually unknown and, therefore, and as previously noted, it is important that the downstream boundary is far enough away from the area of interest so as not to affect the results. Downstream boundary conditions can be represented as a water level boundary, Qh relations or slope values (among others).

4.1.3.9 Simulation, Calibration and Validation

Run Parameters

Run parameters are used in most modelling packages to define the properties of the simulation (such as time-step, tolerances for the model or hydrodynamic settings for the numerical solver). If these values are changed from the standard default values, the potential impact of this on the model results

should be considered. The default values are not always the most appropriate and should be reviewed as part of the model implementation. Guidance can be sought about the ideal values for every model and modeller expertise should also be used here.

Regarding time-steps, a balance between run time durations and model stability has to be found. This is not usually an issue for 1D models, but it is something that has to be considered carefully with 2D models as previously stated. If very low time-step values have to be used, this could indicate that some problems exist with the implemented model.

Some of the hydrodynamic parameters in most hydraulic modelling software can be altered in order to increase the stability of the model such as, for example, tolerances. Increasing these values can decrease the accuracy of the results and, therefore, a balance between accuracy and stability has to be found. It is not recommended to increase these tolerances to a point where the model is working without assessing the impact on the results.

Model Run Log

A model run log should be kept for all model runs (even failed runs) so that an audit trail can be maintained, and simulations rerun later, if necessary. This will also help the modeller when multiple runs for different options or with different values have been carried out. Additionally, it is advisable to use logical nomenclature for different modelling runs in order to help other users and even the existing user in identifying the characteristics of every run.

4.1.4 Calibration and Sensitivity Testing

Calibration and sensitivity testing should be undertaken on every model (calibration data permitting) and the process should start early in the model process. A model that does not perform as intended or required is not 'fit for purpose.'

4.1.4.1 Model Calibration

Calibration of the model is important in order to ensure that the model schematisation accurately represents the system being modelled. Calibration data are not always available, and, in such circumstances, greater emphasis should be put on understanding the model sensitivity and model uncertainties.

The calibration process should include both the hydrological and hydraulic processes and a number of different events. When selecting calibration events, it is useful if they are for a range of flows in order to understand the behaviour of the model to different conditions. In addition to the peak water level, the rising and falling tails of the hydrograph in unsteady models should be similar to those observed and their timing should be as accurate as possible.

It is also useful, as a further check, to ensure that the model results reproduce the observed flood extent. A check on the number of properties that are flooded can also be beneficial.

If calibration is unsuccessful, a number of potential sources of error can be considered. These include:

- Hydrometric data errors in stage datum, timing, and rating curves.
- Hydrological modelling.
- Channel survey.
- Changes in channel geometry.
- Data handling errors.
- Inappropriate schematisation.
- Event specific interventions (for example, structure operations and structure blockages).
- Software limitations.
- Quality of the calibration data.

4.1.4.2 Sensitivity

A sensitivity analysis should be undertaken on the model in order to develop an understanding of the relationship between key input factors. This appreciation is fundamental for ensuring the correct use of the model. Good modelling practice requires the modeller to provide an evaluation of the confidence in the model which assesses the uncertainties associated with the modelling process and with the outcome of the model itself.

A sensitivity analysis could be undertaken on the following areas of the model:

- Roughness (Manning's n).
- Coefficients in structures – bridges, weirs, spills, and orifices.
- Boundaries.
- Structure blockage.
- Model run parameters.

A sensitivity analysis reveals those parameters upon which the model most depends for its accuracy. For example, if the sensitivity tests show that water level prediction varies significantly for relatively small changes in Manning's n, then the modeller needs to take real care in the estimation of channel roughness. This information also helps the modeller to be aware of the risks associated with model uncertainties.

4.1.5 Design Runs

Once a model is calibrated and found 'fit for purpose,' it can be used for design and extreme simulations. The same calibrated and tested model can be used with design events (derived through the hydrological modelling) to assess the response of the system to extreme events. Events of different probability are used at this stage, including an allowance for climate change impacts in most cases.

The relationship between flow and probability is known as the flood frequency curve. There are two common approaches for estimating the flood frequency curve: (i) statistical analysis of flood peak data (single site or pooled analysis) and (ii) the design event method using a rainfall-runoff model. For many catchments, either approach can be applied; however, they can produce very different results.

For catchment or local scale model flow estimates, both approaches should be compared, and the adopted method justified.

Design flow estimates are required at the upstream boundary of any modelled watercourses and at reconciliation points where it is important for the flow in a model to match the hydrological estimates.

The use of design events is critical for the assessment of the flood hydraulic hazard results. As noted, a calibrated flood hydraulic model is used to simulate a range of design scenarios at different extreme probabilities and the resulting information is used for flood mapping purposes, considering all of the purposes outlined above in the flood mapping section.

In most cases, and especially for fluvial flood mapping, design events are derived using a hydrological analysis (either by a statistical analysis of recorded flows or by hydrological modelling or a combination of both methods). More information about this is provided in the hydrological report.

It should be added that the range and number of scenarios run through a model will depend on the use of a flood study. For example, for a flood risk assessment, the 0.5% annual exceedance probability (1 in 200 years) event may be required but for a detailed risk modelling assessment, for instance, a range of flood events (spanning a range from high to low probability) may be required. Flood management techniques are expected to be the most effective for frequent flood events and so a flood mitigation study may require the consideration of more frequent flood events.

The inclusion of running additional scenarios is likely to increase the time required for a flood study but the future use of the model and the results should be considered when specifying the required scenarios as it would be costlier to add this once the project has been finalised. Therefore, it is recommended that as many flood design events as required should be added while implementing a study because the additional effort required during the study implementation would be less than the additional effort once the study has been finalised..

Additionally, extending the range of scenarios to cover more frequent events may improve confidence in the modelling as there is more likely to be data available for validation including anecdotal evidence on the frequency of flooding.

In most European countries, even if just three events are required by the EUFD, national hazard maps use a consistent set range of scenarios across each source of flooding, providing a suitable spread for flood risk modelling purposes. In the following sections, commonly used design scenarios for each of the flood sources are provided.

4.1.5.1 Fluvial Flooding

The scenarios recommended and widely used for fluvial flood hazard maps are given in Table 4.

Table 4. Fluvial Flood Hazard Mapping Scenarios

Annual Exceedance Probability (%)	Return Period (1: years)
50	2
20	5
10	10
4	25
2	50
1	100
0.5	200
0.1	1,000

4.1.5.2 Pluvial Flooding

The scenarios recommended and widely used for fluvial flood hazard maps are given in Table 5. The range of design events is shorter than in fluvial flooding due to the expected impact of pluvial flooding for lower events.

Table 5. Pluvial Flood Hazard Mapping Scenarios

Annual Exceedance Probability (%)	Return Period (1: years)
50	2
20	5
10	10
4	25
2	50
1	100
0.5	200

4.1.5.3 Ground-water Flooding

The surface expression of ground-water flooding may only occur during extreme weather events and at relatively long recurrence intervals. Thus, the flood frequencies traditionally used in flood risk assessment (as shown in the tables above) may be undefinable for groundwater and karst flooding. These inherent difficulties are explicitly acknowledged within the European Union Floods Directive whereby member states are permitted to limit ground-water flood hazard maps to extreme event scenarios only. Therefore, the following is recommended for ground-water flooding.

Table 6. Ground-water Flood Hazard Mapping Scenarios

Annual Exceedance Probability (%)	Return Period (1: years)
0.5	200
0.1	1,000
0.01	10,000

4.1.5.4 Coastal Flooding

Coastal flooding results as a combination of several processes previously noted. To combine wave overtopping, tide and storm surges processes, a joint probability analysis of waves, and the extreme still water level (storm surge and tide) should be undertaken as there will be multiple combinations of wave and extreme still water levels which could constitute, for example, a 0.5% AEP event. This may mean that a range of combinations of extreme water levels and waves need to be run for each flood probability.

Table 7. Coastal Flooding Hazard Mapping Scenarios

Annual Exceedance Probability (%)	Return Period (1: years)
10	10
4	25
2	50
1	100
0.5	200
0.1	1,000
0.01	10,000

4.1.5.5 Artificial Water-bearing Structure

The definition of probability events for AWBS flood hazard mapping is more challenging than for other flood sources. This is because the flood mapping of an AWBS is based on the assumption that a particular AWBS has failed. The triggering mechanism for the failure of the AWBS has to be considered in terms of probability, if possible. For instance, if a dam breaching is caused by extreme water levels behind the dam (overtopping), then the probability of that specific event can be used for the design events of the AWBS. However, this is not always the case, and a dam breaching may be caused by a landslide or a rock-fall with no direct associated probability. Therefore, the events associated with this source of flooding will have to be assessed on a case-by-case basis and the triggering will have to be fully explored. As an initial guideline, the following events can be considered.

Table 8. AWBS Flood Hazard Mapping Scenarios

Annual Exceedance Probability (%)	Return Period (1: years)
1	100
0.5	200
0.1	1,000

4.1.6 Flood Mapping

The results from the design run stage will be used for flood hazard mapping purposes. In previous hydraulic modelling software packages, the flood mapping stage required some additional modelling or GIS effort. Most present hydraulic software packages, however, include flood mapping capabilities. Additionally, the advancement in 2D models where the modelling results can be easily exported to GIS resources, should be noted.

4.1.7 Quality Control and Revisions

To increase the confidence in a hydraulic model implemented for flood hazard purposes and to limit issues and problems in the applicability of any model for other purpose or by other modellers, it is important to undertake quality control and revisions of the model on a periodic basis. During a hydraulic model revision, the following should be checked:

- Model strategy
- Model domain
- Collected data
- Hydrology inputs
- Boundary conditions
- Parameters
- Results

It is recommended that these revisions are undertaken periodically during model implementation and a more thorough revision is made at the end of the modelling exercise.

It should be noted that the EUFD requires that each member state update the three stages of the directive every six years in what is called EUFD cycles. During each of the cycles, the member states are required to address comments from the European Commission regarding previous cycle implementation and update the methodologies if necessary.

There are also several things to consider for the benefit of revisiting and maintaining existing models:

- Data availability: more data may become available due to the deployment of new stations, allowing the possibility of model recalibration.
- Significant events: extreme events may occur in the catchment, allowing for a new recalibration of models and even the derivation of new design events.
- New software: hydraulic modelling software is advancing continuously, and new software features may allow for the representation of flood mechanisms that previously could not be taken into account. For instance, new versions of HEC-RAS allow for the inclusion of gridded precipitation and the inclusion of infiltration processes. In pluvial models, this is an added feature that may allow for a better representation of flood processes.
- New features: new infrastructure, new river structures or new dams can be located in previously implemented model domains leading to the necessity of updating and reviewing models to include these new features in order to properly represent the new conditions.

4.1.8 Reporting

The reporting of any flood modelling study is one of the key activities. The resulting report will help any user to understand how the hydraulic model was implemented, the limitations and applicability of this model and also the results from the study.

The key items to be included in a flood modelling report are:

4.1.8.1 Statement of Objectives

The report should provide an explanation of the reasons leading to the modelling exercise and the planned objectives. It should indicate any deviations from the original objectives or the planned project outputs and outline the reasons why these occurred.

4.1.8.2 Method Statement and Justification

The report should include a clear method statement which makes it clear how the modelling has been carried out in order to fulfil the objectives.

A justification of the methodology should also explain why the model has been used for this application, giving detailed reasons why the modelling tool is applicable/appropriate to the situation.

4.1.8.3 Technical Description

A brief technical description of the modelling software should be given. The schematic showing how individual parts of the model are connected should be provided.

4.1.8.4 Data Sources

All data used in the model must be listed in the report. Additionally, details about any significant change or error in the data or any data handling procedure should be detailed. The ownership of the data collected, and the format of the data should be stated. Uncertainty in data sources should be referenced.

4.1.8.5 Parameters

The derivation of the parameters (roughness, hydrodynamic parameters…) used within the hydraulic model should be stated.

4.1.8.6 Calibration/Verification

Where calibration has been undertaken, the method used must be clearly illustrated and the number of independent data sets used for verification must be explained. The model results must be presented against the observed values for the key locations for each verification data set.

4.1.8.7 Sensitivity Analysis

The results of the sensitivity testing should be described and the potential effect these could have on the model's output should also be discussed.

4.1.8.8 Limitations

Any limitations of the model or modelling technique should be highlighted. The impact of such limitations on the present or future use should be clearly stated.

4.1.8.9 Conclusions

The report should include concluding remarks which highlight key issues from other sections and draw attention to the critical locations and/or structures within the model.

4.2 Comparison of International Best Practices

The section above presented the main methodological international approach for the implementation of fluvial flood hydraulic models. There are obviously several different approaches as to how international best practices are implemented in different countries and for different purposes. Within this section, a brief summary on the main differences in the fluvial modelling approach will be outlined, specifically regarding how this would affect the fluvial methodology for Georgian flood hazard mapping. It should be noted that the detailed methodology will include this information in more detail.

There are several approaches to fluvial flood hazard mapping, and these have been structured in several sections. It should be noted that while the EUFD instructs member states to undertake a preliminary flood risk assessment, flood hazard and risk mapping and flood risk management plan stages, the flood hazard mapping stage will be analysed in this section from a hydraulic modelling point of view:

- Main approach: as outlined in section 3, there are several approaches for the implementation of flood hazard mapping. It should be noted that some countries (including EU member states) have a preference for applying either historical or geomorphological approaches such as Spain or France. For instance, in Spain a geomorphological approach is initially adapted in all the catchments in order to define the hydrological and hydraulic modelling approach and then the hydrological assessment is undertaken in areas where the geomorphological approach has identified areas at potential hazard. It should be noted that while there is merit in implementing the historical or geomorphological methods for fluvial flood hazards, this is not considered appropriate in the Georgian case. There are several reasons behind this, but because all basins in Georgia are going to be analysed, a hydrological-hydraulic modelling methodology in a catchment scale is highly recommended. Additionally, the resulting models will be applied in a forecasting mode, and this is something that cannot occur if a historical or geomorphological approach is followed. Nonetheless, geomorphological, and historical information will be included in the calibration and validation of the models to be implemented in order to enhance their robustness.
- Data: as will be discussed below, data availability is one of the major issues regarding the implementation of a fluvial flood methodology. The implementation of any flood hydraulic hazard model can only be as good as the data used. Data availability varies depending on the country and, unfortunately (in most cases), the availability is more limited in developing countries. It should be noted that while the lack of data does not usually prevent a model from being implemented, the confidence vis-à-vis the results and the robustness of the model is very limited if the required data are not available. From a hydraulic modelling point of view, there are two sets of data that are critical:
    - Topography: the data requirements from a topographical point of view will be outlined below. However, at this stage it should be noted that there are requirements for depicting the channel and the floodplain topography in addition to the inclusion of river structures that will have a significant impact on the flow dynamics. Unfortunately, there are numer-

ous models worldwide that have been implemented just using global DEM resources with no information from the channel topography or from river structures. It should be noted that while the global DEM resources vary in the accuracy of their elevation data, this is always over 4 metres and cannot accurately depict the channel topography. The implementation of these models, while it can provide a very rough idea of the flood hazard, is not recommended. Fortunately, a survey campaign in Georgia has been organised in order to collect the necessary information for the proper implementation of models. In EU member states, models are implemented using both surveyed topographical data for a river channel and also using DEM resources that are local and, therefore, of a better quality and accuracy than global ones.

- Calibration data: as per the topography, there are several flood hazards models worldwide that are implemented without the proper data required for the calibration and the validation of the model. Although in some of these cases a sensitivity analysis is carried out (in some, they are not), an uncalibrated hydraulic model does not merit the same confidence as a calibrated one. A mathematical model is a representation and a simplification of natural processes, and the correct parametrisation is required. The data required for calibration purposes are usually measured water levels although this can be supplemented by other historical information such as flood outlines. In practical applications, however, the availability of spatial flood outlines is very limited, and this actually just provides a snapshot of the resulting flood impact. However, the data availability for calibration does not prevent the models from being implemented and it should not in the Georgian case. Thorough sensitivity tests will be undertaken and revisiting the models will be recommended once the data are available in all of the Georgian basins which will be addressed by this study.

- Hydrological input: the hydrological methodologies for obtaining the necessary boundary conditions for the hydraulic models is the purpose of another deliverable but it should nonetheless be noted that there are several methods available for the definition of the hydrological inputs (as shown in section 3.1.2.6) and this would depend on the data availability and the study requirements.

- Flow regime: 1D hydrodynamic models can be implemented in a steady or an unsteady mode. While in most countries there is no methodological approach to this, steady approaches alone are sometimes used in some old models, especially due to software limitations or to resource availability. The implementation of an unsteady model is more demanding than a steady one, but it should be noted that these are highly recommended, especially in catchment approaches. Unsteady modelling can more accurately represent back-up issues, storage and tidal influences and the inclusion of several watercourses. The use of steady models for local implementations should not be discarded as it provides for an easy and fast way of deriving flood hazard maps, but it should not be considered for catchment scale studies. Obviously, steady models are not available for 2D or 1D-2D modelling implementation.

- Dimensionality: one of the key differences of the modelling approaches resides in the dimensionality of the models to be implemented. As can be observed in Figure 6, there are four common types of numerical models, namely: (i) 1D modes, (ii) Quasi-2D models, (iii) 2D models and (iv) 1D-2D coupling models. The use of Quasi-2D models is not recommended as it not believed that they can accurately represent the flow dynamics. This type of models was developed when 2D models were in their infancy and they required a significant computational effort for implementation. Nowadays, while 2D models are becoming more popular (and faster), the use of either 1D or 1D-2D models should not be discarded. There are several limitations on the implementation of 1D models, especially the fact that the flow path has to be pre-defined and the limited output from a 1D model, with results being produced just at cross-section locations. It should be noted that all the structures are modelled in 1D (even if embedded within a 2D model). As will be described in the methodology, a 1D-2D approach is recommended in Georgian flood mapping for several reasons such as the proper definition of channel dynamics, the information required in the floodplains for flood risk purposes and the use of the models in a forecasting mode.

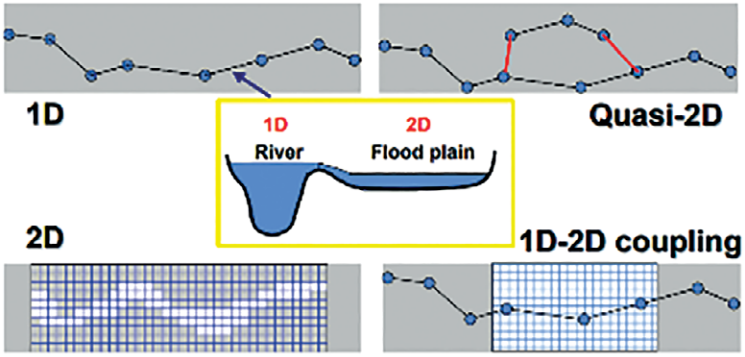


Figure 6. Types of Numerical Models Used for Inundation Modelling[6]

- Calibration, sensitivity testing and validation: in some methodologies explored, there are guidelines for the calibration process, specifying the level of accuracy that the models have to achieve before they can be considered 'fit-for-purpose.' Although this is not a common approach, this would be highly recommended as (if data are available) this increases the confidence in the model. In some other cases, a visual examination and assessment of the validity of the calibration results is used but this approach should not be encouraged. The level of accuracy will be defined in the methodology to be implemented within the framework of this project.

6. Flood Inundation Modelling. Floodsite. https://www.floodsite.net/html/partner_area/project_docs/T08_08_01_inundation_modelling_ExecSum_v2_4_p01.pdf

4.3 Other Sources of Flooding

The previous section 4.1 outlined the main methodological approach for fluvial flooding. Fluvial flooding is the main source of flood hazard in Georgia. Additionally, as noted above (Table 3), fluvial flooding is the most widely considered by member states within the European Union. The main hydraulic modelling methodology is similar for all flood sources in terms of the stages that have to be undertaken within a flood modelling study. It is evident that the data requirements (in sections 5 and 6) and the actual hydrodynamic approach would differ. In the section below, a brief methodological approach for other flood sources will be outlined highlighting the differences in the approach with the hydrodynamic fluvial flood modelling methodology.

4.3.1 Pluvial Flooding

The implementation of pluvial flooding models is more recent than the implementation of other sources of flooding. One of the first instances where pluvial flooding was noted was in the summer 2007 floods in England (UK). After a review of the flooding mechanisms and the actions taken by Sir Michael Pitt, it could be summarised that pluvial flooding was the main source of flooding during that event in some locations. After that event and some other similar instances in Europe, pluvial modelling started to become more 'popular' in EU member states.

Pluvial flooding modelling methodologies are usually based on the implementation of 2D 'rain-on-grid' models. In these models, the terrain is represented by a 2D grid (either structured or unstructured), and rainfall is directly applied to the terrain and routed. There are several different approaches to this:

- Precipitation losses: there are several approaches to precipitation losses in pluvial models. In pluvial modelling methodologies, losses may be associated with precipitation, especially regarding interception, infiltration or to the urban drainage network. There are several studies related to the representativeness of the different losses in urban catchments but in most cases the results from these studies show that the losses are not significant on extreme storm events in urban areas.

  Some 'rain-on-grid' software packages do not have the possibility of including losses in the modelling process and, in some cases, the losses are applied before the modelling process (using effective precipitation). In some other cases, the urban drainage models are also included in the modelling framework, being dynamically coupled to the pluvial models. It should be noted that in the case of Georgia, it is not recommended to include direct precipitation losses at this stage due to data availability and the uncertainty of the results.

- Buildings: the inclusion of buildings on pluvial models is critical because they can determine the flow path and also because they represent one of the key locations where the flood depth needs to be estimated (from a flood risk point of view). There are two different approaches:
  - Raising the elevation to account for the location of the buildings.
  - Raising the roughness coefficient to account for the location of the buildings.

While both methods are valid and would effectively have a similar impact from a flow dynamics point of view, the roughness approach is recommended from a practical point of view (the same DEM file can be used for other flood sources). It should be noted that both cases rely on the availability of building footprint outline polygons in urban areas.

- Surface drainage: natural surface drainage running through a pluvial modelling domain may also have an influence on the pluvial modelling methodology. In the first case, the possible relationship between a fluvial and pluvial event can be considered from a joint probability point of view. Additionally, the natural drainage network may help to alleviate the pluvial flooding through an urban area vis-à-vis losses in a pluvial model. There are two approaches for including the natural surface drainage in the geometry:
  - Use a 1D-2D modelling approach with the urban pluvial area defined in the 2D domain and the 1D domain including the natural watercourses.
  - Use a 2D domain approach, 'burning' the information of the watercourses (channel depth) into the elevation grid used in the pluvial flooding.

  While the results from both exercises should be similar, the second approach would be more feasible for the implementation of flood hazard maps in Georgia. The implementation of a 1D-2D model for this could lead to additional instability issues. Nonetheless, the use of the previously implemented models should also be explored. Fluvial models may be implemented in a 1D-2D approach and, therefore, it would be advisable to re-use these models for pluvial assessment when possible.

  The boundary conditions in the natural drainage network should also be defined and several approaches have been implemented for this. In some cases, a minor base-flow is included in the channels (for stability purposes) while a bank-full approach can also be used as a more conservative approach. If there is no joint-probability assessment, the bank-full approach would be recommended.

4.3.2 Ground-water Flooding

Groundwater has not traditionally been recognised as posing a significant risk and thus remains relatively less understood than other forms of flooding. This type of flooding occurs when the natural underground drainage system cannot drain rainfall away quickly enough, thereby causing the water table to rise above the ground surface. In recent years, ground-water flooding is becoming the object of several research studies, especially after the requirements by the EUFD to assess all sources of flooding, including ground-water sources. Ground-water flooding differs from other types of flooding in terms of the data requirements and on the modelling process.

Because the presence of karst systems is the most significant ground-water flood hazard in Georgia, the methodological approach has focused on this. There are two fundamental approaches to the mathematical modelling of karst systems: distributive models and global models. Distributive models use theoretical concepts such as simplified aquifer geometry and hydrodynamic flow equations to simulate the hydraulic behaviour of karst aquifers. Global models concentrate on mathematically deriving a relationship between input and output where the input is usually a precipitation event, and the output is the spring discharge time series.

The decision on the implementation of each of the models would depend on data availability. It should be noted that the implementation of a distributive model may seem more appropriate, however, data requirements are higher, and the modelling skills requirements are also more intensive. The implementation of a global (or box) model seems more appropriate for the scenario in Georgia where data and ground-water modelling skills are scarce.

If other ground-water types are considered, the methodological approach may differ, and it would depend mainly on the modelling approach and on the interaction with the surface drainage. In some cases, integrated models are implemented in order to represent the interaction between the surface drainage and the groundwater, including the unsaturated zone and the fluxes among all the different layers present and all the different processes. Such models (like MIKE SHE) are very data demanding and while the implementation of such an approach is supposed to yield the most accurate results when data are available (as it considers all the processes), it is not believed that it can be properly implemented in Georgia due to data scarcity issues. Additionally, while models like MIKE SHE represents all the processes, there are some limitations and for instance, surface flooding modelling scheme does not use a full 2D model routing model, just an approximation. Other ground-water models, such as MODFLOW, are not specifically focused on inundation and, therefore, the surface flooding component may not be appropriately represented.

In some other cases, a combination of models is used with pure ground-water models dynamically linked to surface drainage models.

4.3.3 Coastal Flooding

Coastal flooding is due to a combination of astronomical tides, surge, and waves. There are different approaches to coastal flooding which are determined by data availability or by the processes involved. It should be noted that there are several types of processes and modelling methodologies to consider for coastal flooding.

- Tides: the astronomical tides are known in a specific area providing that sufficient information is available for the correct derivation of tide harmonics. The implementation of coastal models is sometimes undertaken in order to assess how the tidal wave propagates in the coastal area.
- Storm-surge: the sea-level is a combination of the astronomical tide and the meteorological tide (or storm-surge). Storm-surge modelling techniques calculate the impact of the present meteorological conditions caused by the wind but mainly by the atmospheric pressure. Low pressure systems can increase the sea-level significantly and this is more significant in locations where the astronomical tide range is not very acute such as in the Black Sea. The propagation of the storm-surge in coastal areas can also be the objective of modelling implementations.
- Waves: two different types of waves can be considered; namely, swell and wind-waves. While swell (waves formed far from a specific location and with a higher period and lower significant wave height) are not supposed to be significant in the Black Sea due to the low availability of wind-fetch area, wind-waves created on the Georgian coast can be significant. There are several methodologies for calculating the expected significant wave height and period of waves in coastal areas. In most cases, this is undertaken through the implementation of a series of nested

models to propagate the waves through the continental shelf and assess the impact of the waves in coastal areas.

- Inundation coastal models: this will be the main type of models to be addressed in this section. Providing that the right information is available from the tide, storm-surge and wave assessments, an inundation model is implemented in coastal areas to assess the flood impact on these areas.

Three approaches to inundation modelling of a coastal hazard are widely used: namely, the rapid flood spreading method, the water-level projection method or the 2D hydrodynamic approach.

4.3.3.1 Rapid Flood Spreading Model

The rapid flood spreading methodology addresses coastal flooding through the division of the pre-identified potential areas at risk of flooding into a series of interconnected basins (or reservoirs) with spill crests identified between each basin. The main concept behind this methodology relies on the use of several interconnected basins and when one basin is filled, water spills into the next basin until the coastal flood volume has been accounted for. In this methodology, the boundary conditions are split depending on the basins or units with consistent overtopping conditions. A tide, storm-surge, and wave levels in metres over a tidal cycle or the duration of a storm-surge will be the base level for any wave overtopping volume in m^3/s per metre of length of the coastline. The input volume is a total m^3 per metre length of coastline for the flood event, storm, or tidal cycle. This method does not allow for any interactions with other flood sources such as fluvial or pluvial. However, the rapid-spreading method can be modified to take the form of a 1D hydrodynamic model with weir equations applied to the overtopped shoreline. This alternative method requires a time series input of overtopping and tidal/surge/wave levels in m^3/s per metre length of coastline. Fluvial and pluvial sources can be integrated in this modified approach.

4.3.3.2 . 2D Hydrodynamic Model

The 2D hydrodynamic inundation model approach would be similar to the modelling process for the 2D component of fluvial flooding or for the pluvial methodology, although obviously different boundary conditions would be used. In this case, model boundary conditions would be obtained from the other set of assessments or models described above and they would be a time series input of tide and storm-surge levels in metres and m^3/s per metre length of coastline for wave overtopping. With this approach, pluvial and fluvial models and boundary conditions can be readily incorporated into the model where coincident flooding from different sources needs to be considered (after a careful assessment of the joint probability of those sources).

4.3.3.3 Water-Level Projection Method

This is the most basic of the methods outlined. In this case, no formal modelling is undertaken, and this method relies on GIS resources. This method can only be used for storm-surge and tide events, and it implies the use of a constant water-level against the existing DEM information. This assessment will assume that anything below the estimated sea-water level will be flooded. This method is not recommended in extensive coastal areas (such as in the Rioni basin) and it does not account for flood defence infrastructure.

In the case of Georgia, the implementation of a 2D inundation hydrodynamic model will be recommended. Although this could be the most time-consuming methodology, it is considered that it is also the most accurate in terms of the inclusion of different flood mechanisms. It should be noted that while there are several 2D hydrodynamic models available, the use of a coastal model will be recommended. For instance, while HEC-RAS has 2D modelling capabilities, this modelling software is not conceived for coastal applications. On the other hand, MIKE 21 (as part of MIKE FLOOD) was actually conceived as a coastal model (that is now being used in inland applications). This is because a coastal model can consider marine processes such as viscosity or wind impact.

4.3.4 Artificial Water-bearing Structures

Flooding of land by water arising from artificial water-bearing structures (AWBS) or the failure of such infrastructure is also considered in the European Union Flood Directive. This source could include flooding arising from sewerage systems (including storm water, combined and foul sewers), water supply and wastewater treatment systems, artificial navigation canals and impoundments (e.g., dams and reservoirs).

These human-made systems for containing water have the potential to fail and the resulting escape of water may cause flooding. Examples of this include burst water mains or drainage pipes as well as failures of pumping systems, dams, or breaches in flood defences. This type of flooding is not only confined to locations usually considered at risk of flooding, although low-lying areas and areas behind engineered defences are at a greater risk. Often, the onset will be rapid as the failure of a system will lead to an escape of water at high pressure and velocity: a dam failure, for example, may be devastating as the volume and speed of the water is typically large. The failure of embankments, levees or dikes also has the potential to cause devastating floods which may persist for a long time where the water has few escape routes.

The modelling implementation of the flood source varies depending on the data, the methodology followed or the study's expected outputs. There are several differences:

- Data availability: as per all the flood sources modelling and the associated methodology, the data availability is critical for the implementation of AWBS modelling. It should be noted that few EU member states implemented this methodology or developed flood hazard maps associated with this flood source. The reasons for this are not clearly understood as it is expected that all member states have infrastructures that could fail and cause a significant flood hazard. In this respect, it should be noted that damns are not considered within the EUFR methodology in some member states (such as Bulgaria) because they are considered to be critical infrastructure and no data can be disseminated regarding this type of infrastructure. In some other countries, such as the United Kingdom, dams and reservoirs fall under the Reservoirs Act which has its own requirements for dam breach modelling and inundation mapping with stricter requirements than the EUFD.
- Additionally, they fall under the Civil Protection Act as they are objects of critical infrastructure and so detailed modelling and mapping as well as contingency plans are likely to be subject to restrictions.

Nonetheless, one of the main data requirements for AWBS modelling would be information about the actual infrastructure that may fail. As will be detailed in the methodological document, the main objects of infrastructure to consider will be flood defences and dams/reservoirs. The availability of data will determine the methodological approach as the availability of detailed information will allow the implementation of detailed modelling. It should be noted that data are not available in some cases and so very basic methodologies are implemented using only information from global resources and satellite images. This approach is not recommended and as will be detailed in the methodology, it is not suggested that the modelling of these structures is undertaken unless suitable data are available.

- Modelling methodology: there are several aspects to consider within the AWBS modelling methodology from a failure point of view and from an inundation point of view:
  - Failure: as noted above, flood defences (such as flood walls or levees) and dams/reservoirs will be addressed in the AWBS modelling in this assessment (and in the methodology). The purpose of the AWBR modelling would be to assess the flood hazard were a specific structure to fail fully or partially. Therefore, breach hydrographs are developed within the failure assessment for further analysis in the inundation modelling.

There are several approaches for the definition of the breaching hydrographs such as empirical approaches, hydrodynamic approaches, or analytical approaches.

Empirical models are derived from test case studies or observed dam failures but are not process-based. They are only able to provide the user with an estimated peak breach discharge and a time to peak discharge and require prior knowledge of the structure geometry (e.g., its height, width, length) and/or the reservoir (e.g., its volume, depth, and surface area) which can be used in a simple equation. Analytical or parametric models are slightly more advanced in that they may be semi-physically based but typically assume that the time taken for the breach to reach its maximum size is known. This information might be available but is often not.

There are a number of fully physically numerical models which can produce reasonably accurate results for dams and flood defences. These models are usually based on the 1-D Saint-Venant equations using implicit finite difference models in order to determine the discharge and depth variation at different sections with time.

It should be noted that the approach for flood defences and for dams/reservoirs will be similar as they will behave similarly.

  - Inundation: the inundation modelling will have the purpose of routing the breach hydrographs through the terrain in order to obtain flood hazard mapping. There are several approaches for inundation modelling, and this will vary depending on the dimensionality and also on the approach used for sediment input. Therefore, the following approaches are mainly used for the inundation mapping of AWBS failures:
    - 1D models
    - 2D models
    - Debris-flow models

While 1D models were mainly used historically, nowadays most AWBS studies and flood hazard assessments are undertaken using 2D modelling approaches. There are several reasons for this. The main issue with 1D models is that they will only determine the water-level and the discharge at pre-defined locations which means that the flow path has to be known and defined in advance. This may not be a problem with low-medium flows in areas where the topography information is accurate, and the flow path is known. However, in most dam or flood defences breach scenarios, the amount of flow being released usually exceeds previous records and the water may not follow a pre-defined path. In addition to that, the advantages of using 2D numerical models for a hydrodynamic simulation of AWBS include their ability to simulate multi-directional and multi-channel flow, the super-elevation of flow around channel bends, hydraulic jumps, trans-critical flow regimes and flow recirculation. It should be added that 2D hydraulic modelling results will provide more information than results from a 1D model such as detailed information about the water depth, velocity, and water surface elevation across the whole floodplain (for flood risk purposes) whereas a 1D model would provide this information just as pre-defined cross sections. Therefore, the consultant's opinion is that the use of a 2D approach in this case is much more beneficial.

There are some other things to consider, especially in light of the joint probability of an AWBS flood event occurring simultaneously as a fluvial or pluvial event. For instance, the natural surface drainage network is included in AWBS models in some cases and discharges for a pre-defined extreme event are also included. In some other cases, the natural drainage is not considered. In the Georgian case, and after a careful joint-probability assessment, this will be considered.

4.4 National Experience

The National Environment Agency (NEA) is the main stakeholder with experience in hydraulic modelling for flood mapping and assessment purposes. However, there are also other stakeholders with experience in this field, especially NGOs (CENN) and academic institutions (Institute of Earth Sciences within the Ilia State University).

The experience of the NEA in flood modelling is mainly related to the implementation of funded international projects such as the Adaptation Fund Rioni project, the CTC-N Assessment of Suitable Flood Mitigation Measures in Tbilisi project, the Polish Centre for International Aid (PCPM) supported Study of Hydraulic Modelling against Floods/Support to the Competence and Readiness of Georgian Institutions project or the UNDP Georgia Strengthening Urban Risk Management of Tbilisi project. Within all of these projects, flood studies and hydraulic models have been implemented following international best practices. In these studies, a similar approach to the FHRM stage of the EUFD was implemented. The involvement of the NEA's hydraulic modellers in the implementation of those projects, however, is unclear. Capacity building activities have been identified in these four projects and while hydrological and hydraulic modelling activities were implemented by the NEA's team for the UNDP Georgia Strengthening Urban Risk Management of

Tbilisi project with the support of international experts, the Rioni and the CTC-N projects were mainly implemented by international experts. The level of involvement of the NEA's modellers in the Polish project's activities is unclear.

4.5 Comparison of International and National Experience

To compare international and the national experience, a brief assessment of the capacities and number of models implemented by the NEA has been undertaken. At this stage, no other implementations undertaken by other institutions have been considered. The hydraulic model implementations by other organisations in Georgia are limited and the NEA has the main responsibilities for hazard mapping and assessment.

Table 9. NEA's Hydraulic Modelling Experience

Model Experience	Total Number	Number with International Support	Software Packages used
Number of Flood Modelling Studies Undertaken	15	15	MIKE 11; MIKE 21 - MIKE FLOOD. HEC-RAS
Number of Flood Models Implemented in 1D Steady	-	-	-
Number of Flood Models Implemented in 1D Unsteady	11	11	MIKE 11
Number of Flood Models Implemented in 1D-2D	3	3	MIKE 11; MIKE 21 - MIKE FLOOD; HEC-RAS
Number of Flood Models Implemented in 2D	1	1	MIKE 21
Number of Model Revisited for Improvement	0	.	

The NEA has implemented a total of 15 models (Table 9) for flood hazard assessment purposes, all of them with international support and using MIKE suite products or HEC-RAS. Of these, 11 models in 1D, one model in 2D and the remaining three models using a 1D-2D approach.

International best practices were followed during model implementation in light of the fact that the NEA mainly followed the guidance of international experts.

Nonetheless, the following can be said about these international projects:

- Adaptation Fund-UNDP: Climate Resilient Flood Management Practices in Georgia project: a hydrological and hydraulic model was implemented in the Rioni basin within this project. This model was also implemented in a forecasting mode as part of the flood forecasting system in the Rioni basin. Several training activities were associated with these implementations and NEA staff collaborated actively in some of the stages of this implementation. Unfortunately, the main

modelling work for both hazard modelling and mapping, and for forecasting and early warning was undertaken by international consultants despite the extensive training that was provided to the NEA. It can be concluded that the capacities built did not translate into lasting capabilities in the implementation of hazard or forecasting models.

- UNDP: Strengthening National DRR Capacities in Georgia project: flood hydraulic models were implemented in the Gldanistkali and Vere Rivers in Tbilisi within this project. Both rivers are tributaries of the Mtkvari River. Hydrological and hydraulic modelling was undertaken for these two rivers by NEA staff with the support of an international expert within this project. Training on modelling was also received by NEA personnel. The involvement of NEA personnel within the key modelling sections is described below:
- CTC-N: Assessment of Suitable Flood Mitigation Measures (based on a Dukniskhevi River Extreme Flood Analysis) in Tbilisi, Georgia project: an international team undertook climate change downscaling, hydrological modelling, hydraulic modelling, and flood mitigation modelling for the Leghvtakhevi River in Tbilisi within this project. NEA staff was trained in hydrological modelling and in hydraulic modelling (including mitigation modelling), but NEA staff was not involved in the actual modelling work, although they provided data (including the cross section and hydraulic structure survey) and also the approval of the modelling methods.
- PCPM - Didkhevi, Stori and Lagodekhiskhevi: The Polish Centre for International Aid implemented the Study of Hydraulic Modelling against Floods - 1st Stage – Preparation for the Implementation of EU Directive No 2007/60EC project. Flood hazard maps were produced using hydrological (HEC-HMS) and hydraulic (MIKE 11) modelling for three river basins: namely, the Didkhevi, Stori and Lagodekhiskhevi Rivers within this project. Several capacity building activities were implemented throughout the project's implementation period.
- SDC – Mestia: The Swiss Agency for Development and Cooperation (SDC) implemented the Disaster Risk Reduction for the Mestia Municipality project. Within this project, flood hazard maps were produced for five river basins – the Mulkhura, Mestiachala, Dolra, Nakra and Nenskra Rivers (tributaries of the Enguri River). It should be noted that no formal hydrological or hydraulic modelling was undertaken within the framework of this project and peak flows were estimated using empirical equations developed by Rostomov approach (technical instructions of maximum river flow calculation in the conditions of the Caucasus for rivers with catchment areas less than 400 km^2) and velocity values for each surveyed cross section were calculated based on Chezy-Manning's equation. Maximum depth values were interpolated between cross sections and flood inundation zones were depicted using GIS resources.
- PCPM - Avaniskhevi, Chelti, Intsoba, Lopota, Shromiskhevi and Aragvi: The Polish Centre for International Aid implemented the Study of Hydraulic Modelling Against Floods – 2nd stage – Support to the Competence and Readiness of Georgian Institutions. Flood hazard maps were produced using hydrological (HEC-HMS) and hydraulic (MIKE 11, 21 and Flood) modelling for six river basins: the Avaniskhevi, Chelti, Intsoba, Lopota, Shromiskhevi and Aragvi, including one example of a dam breach modelling implementation. As per the other PCPM project, capacity building activities were undertaken.

Table 10. Involvement of NEA Staff in International Projects. (0=no, 1=limited, 2=medium and 3=high involvement)

Flood Modelling Stage	UNDP Rioni Basin	UNDP Vere-Gldanistkali Rivers	CTC-N Leghvtakhevi River	PCPM - Did-khevi, Stori and Lagodekhiskhevi Rivers	SADC - Mestia	PCPM - Avani-skhevi, Chelti, Intsoba, Lopota, Shromiskhevi and Aragvi Rivers
Flood Studies Scoping	1	2	0	0	1	0
Data Collection	2	3	1	2	2	2
Model Schematisation and Implementation	1	3	0	1	1	1
Calibration and Sensitivity Testing	0	3	0	1	NA	2
Design Runs	0	3	0	1	NA	2
Flood Mapping	0	3	0	1	1	2
Quality Control and Revisions	0	3	0	1	NA	2
Reporting	0	3	0	2	1	2

The capacities of the NEA at different stages of hydraulic model implementation within flood risk projects have also been assessed. This has been undertaken considering the number of NEA staff (modellers) with capacities for each of these stages (Table 11). The number of staff for each of these stages varies from two to four. It should be added that the information within this table has been completed by the NEA.

Table 11. Number of NEA Staff with Modelling Experience

Flood Modelling Stage	Number of NEA Staff with Experience
Flood Studies Scoping	4
Data Collection	4
Model Schematisation and Implementation	4
Calibration and Sensitivity Testing	2
Design Runs	2
Flood Mapping	4
Quality Control and Revisions	2
Reporting	2

It should be added that there is currently no formal methodology for undertaking hydraulic modelling studies within the NEA.

In summary, all of the projects implemented by the NEA followed international best practices to some extent, although different methodologies were followed depending on the particular international support. While there is some experience within the NEA for implementing hydraulic modelling projects following these practices, there is limited experience in all the stages but more significantly for flood studies scoping, modelling implementation and calibration and sensitivity testing. The initial implementation of two hydraulic models undertaken by NEA staff were analysed, and it can be added that there is limited experience in the initial model build stages of a model implementation.

The previous experience analysis was focused on fluvial flooding. It should be added that the experience of the NEA on other flood sources is very limited or altogether non-existent.

05

Data Requirements and availability analysis for Flood Hydraulic Hazard Modelling and Mapping

The data requirements for flood hydraulic modelling will depend on the flood source to be considered. As noted above, these can be fluvial, pluvial, groundwater, coastal and AWBS. All of the five sources of flooding are relevant in Georgia as there have been events related to each of these types of flooding and even a combination of them.

It should be noted, however, that Georgian stakeholders have more experience vis-à-vis fluvial flooding as the most relevant source of flooding and, therefore, the data availability is higher for this type of flooding.

5.1 Fluvial Flooding

In order to undertake fluvial flood hydraulic modelling, the data requirements and data availability in Georgia is considered. It should be noted that an assessment of the data availability has been undertaken by NEA staff under the supervision of the international expert for the three catchments (Natanebi, Kintrisi and Supsa, included in Annex I) and that some of the information collected through that process has been included in this section apart from information from other sources:

5.1.2 Topographic Data and Base Mapping

An assessment of the following data sets was undertaken:

- Digital Elevation Model (DEM): the DEM is one of the key parameters for the modelling of all the flood sources, including the fluvial one. An assessment has been undertaken regarding the quality of all of the different sources already available and the following can be outlined:
  - LiDAR: A 1 m DEM is adequate for the areas where data have been acquired.

    The LiDAR data area of interest (AoI) was defined using an indicative modelling and very high flows in all the basins within the framework. However, due to restriction issues, LiDAR data could not be acquired in some of these pre-identified areas and there are, therefore, some limitations in the future implementation of the models in these locations.

There are some other LiDAR data sources available as previously described. The consultant only had access to LiDAR data in the urban Tbilisi area. These LiDAR data were assessed and found to be of an adequate accuracy for modelling purposes. Although some minor deviations from the collected topographic survey data were found, these are not believed to pose an issue for modelling purposes. The other LiDAR data sources could not be assessed.

- Orthophoto and global DEMs: the main issue to be considered at this stage is to complement the LiDAR DEM in areas where this is not available with other DEMs. The first 'candidate' for this would be the orthophoto DEM. This DEM was derived from orthophoto images, and it is managed by the Public Registry Office of Georgia. The DEM for the first three catchments (Supsa, Natanebi and Kintrisi) has been analysed in the section above and while it was supposed to have an accuracy of less than 4 metres when comparing this DEM with actual topographic survey data, the differences in excess of 10 metres have been found on the floodplains. In some cases, global DEM data sources have performed better than the orthophoto DEM. This issue was raised by the consultant at the very beginning of the project implementation period and is being investigated. It may be the case that the final (or more accurate) version of the orthophoto DEM has not been provided as of yet. Nonetheless, this is a matter of concern and would limit the accuracy of fluvial models. If the accuracy of this DEM is questionable, pluvial models that rely on these data sources are not recommended to be implemented. A full assessment of the DEMs is proposed within the flood methodology with several options depending on the results from the accuracy assessment. Because of its importance, more information about the importance of the resolution and the accuracy of the DEM is provided in the pluvial modelling section.

  It should be noted that there are commercial global DEM resources, such as DEMs from Airbus and JAXA, that could be considered if the final resulting orthophoto DEM accuracy is not satisfactory. This information has been collected and it can be considered if needed.

- Cross sections: as noted, the cross-section scoping has been undertaken by the NEA in close communication with the hydraulic modelling expert. The cross-section information has been collected in most cases in locations where the consultant has provided his input and the scope of the survey is assumed to be of sufficient coverage and quality. There are concerns, however, regarding the quality of the survey information from hydraulic structures. No information from these is available to the consultant as of yet but previous modelling experiences in Georgia show that there is a lack of capacities for surveying hydraulic structures. In order to overcome this, the consultant has prepared a document detailing the modelling data needs for these structures.
- Base mapping: global resources for base mapping can be used for hydraulic modelling. While old Soviet digitised base mapping is also available, these resources are just digitised images, and the use of global resources is considered adequate for the modelling purposes.
- Aerial imagery (aerial photos and satellite imagery): there are both global and national resources for aerial imagery. The use of the national resources relies on the acquisition and processing of orthophotos. The global resources are satellite imagery from either Google Satellite or Bing. Both data sources are adequate, and the existing resources are adequate for flood hydraulic modelling.

It should be noted that LiDAR data are being procured for the floodplains of Georgia, hence all other data sets should be reviewed for catchment topographic data requirements and assessed including the quality and the cost of acquiring such data sets for the whole of Georgia.

- Digital Elevation Model (DEM): it should be noted that while the requirements for DEM availability and accuracy may vary depending on the flood source, this will only be analysed in the fluvial section and differences will be provided within the specific flood sources if required. Additionally, it should be added that the DEM is one of the key data sources to be considered for flood modelling and special attention will be paid to this in the data requirements and in the data availability sections. There are different DEM sources to be considered in Georgia.
    - LIDAR data: The extent of the LiDAR procured under the UNDP project is shown in Figure 7.

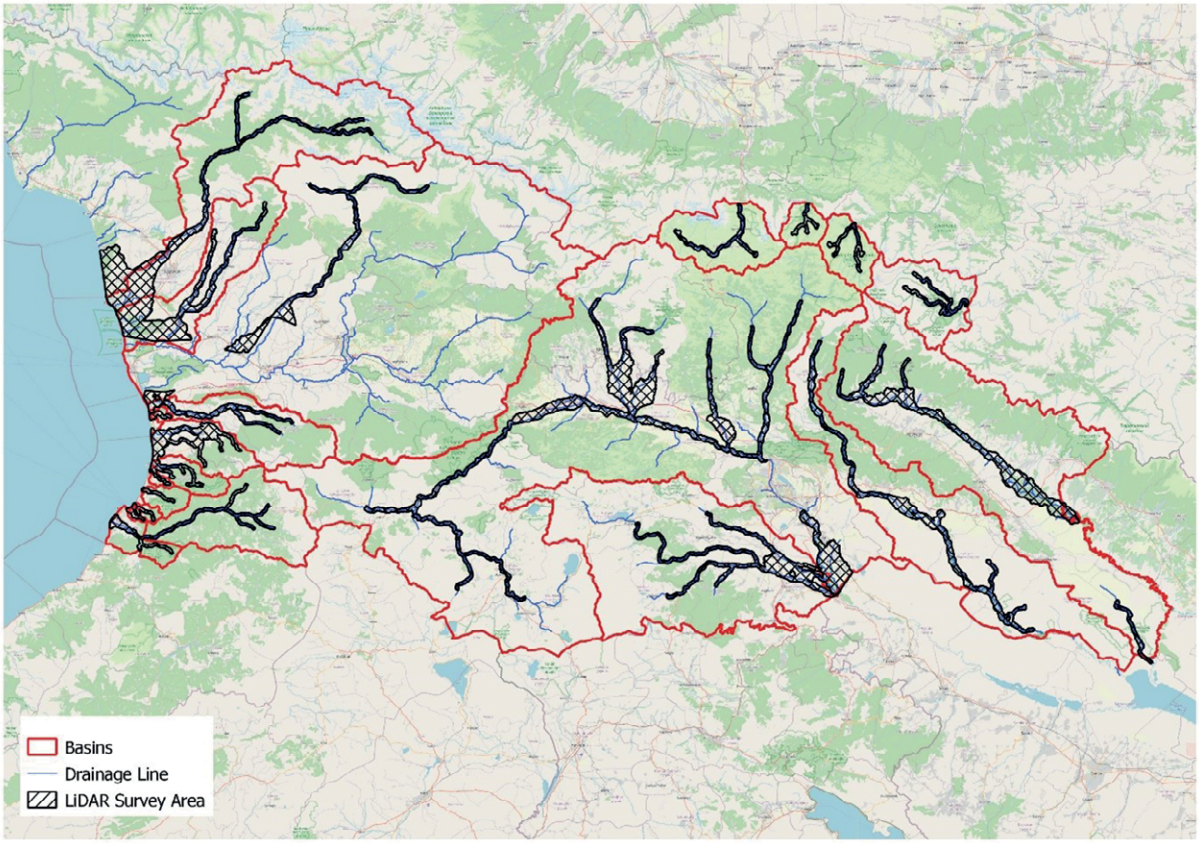


Figure 7. LiDAR Survey Extent

There are more LiDAR data available in Georgia such as in the urban Tbilisi area, in some areas in Kakheti in the Alazani catchment and north of Tbilisi (Figure 8). The accuracy of some of the old LiDAR data will be reviewed when available. The data that are not available at the moment will be acquired and fully assessed before they are included in the modelling framework.

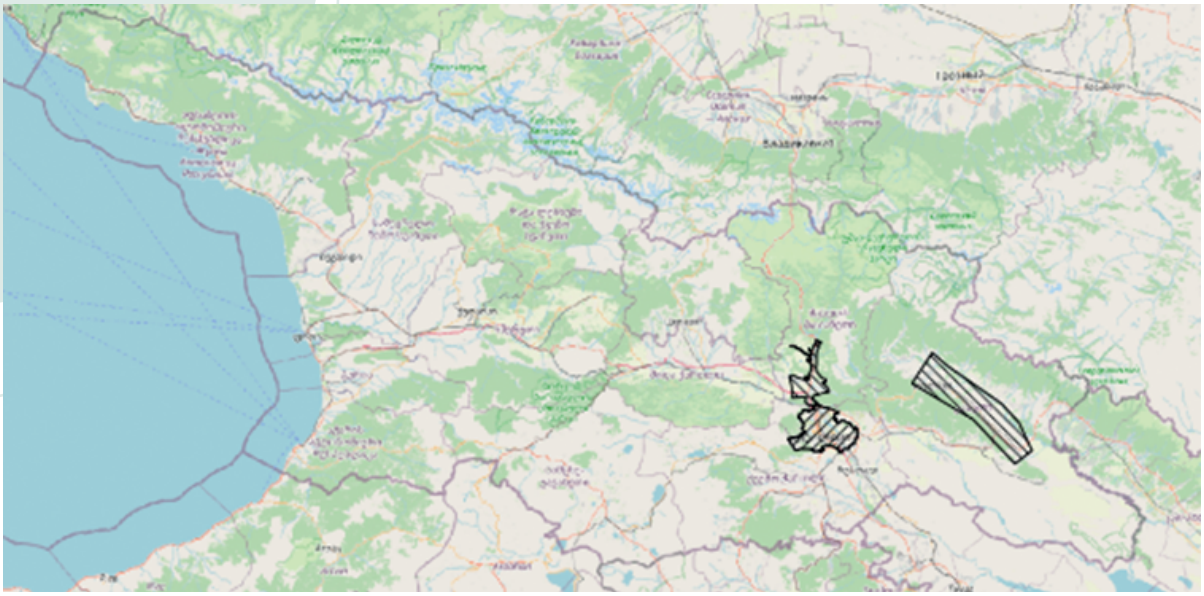


Figure 8. Other LiDAR in Georgia

- Orthophoto DEM: the Georgian Public Registry has a DEM that was derived from orthophotos.

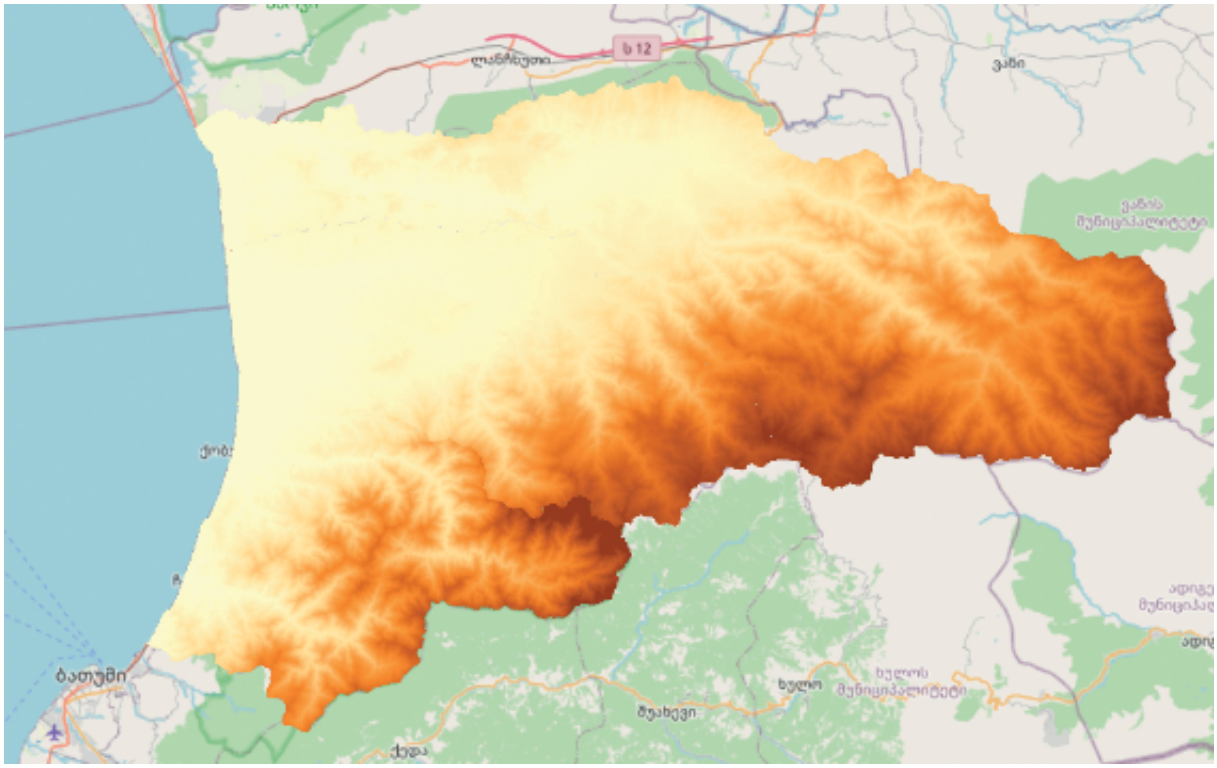


Figure 9. Orthophoto DEM for the Kintrisi, Supsa and Natanebi Catchments

- Global wide DEM. There are several sources of global DEMs.

Figure 10. MERIT DEM for Georgia

The existing Georgian national DEM spatial resolution, vertical accuracy and source availability are presented in Table 12.

Table 12. High Resolution DEMs in Georgia with a National Coverage

DEM Type	Spatial Resolution	Vertical Accuracy	Source
LiDAR Data	1 m	~0.15 m (technical specification)	UNDP – GCF-SDC programme
Orthophoto DEM Data	15 m	~4.0 m	Public Registry Office
SRTM Global DEM	30 m	~15 m	Global Sources
MERIT DEM	90 m	~4.0-5.0 m	Global Sources

Some comparisons and data accuracy checks have been undertaken with the existing data. In the first place, the Tbilisi LiDAR data have been compared against actual cross section data in several sections for the Leghvtakhevi catchment in Tbilisi (Figure 11). This comparison has been undertaken for all the available cross sections while only four of them are being shown for illustration purposes. As can be observed, this comparison is moderately satisfactory and in most cases the difference between the LiDAR and the survey data is in the order of centimetres. LiDAR data are supposed to be slightly more accurate than what the analysis has shown, although the LiDAR quality would be sufficient for modelling purposes. Nonetheless, the accuracy of the cross-section survey should also be considered.

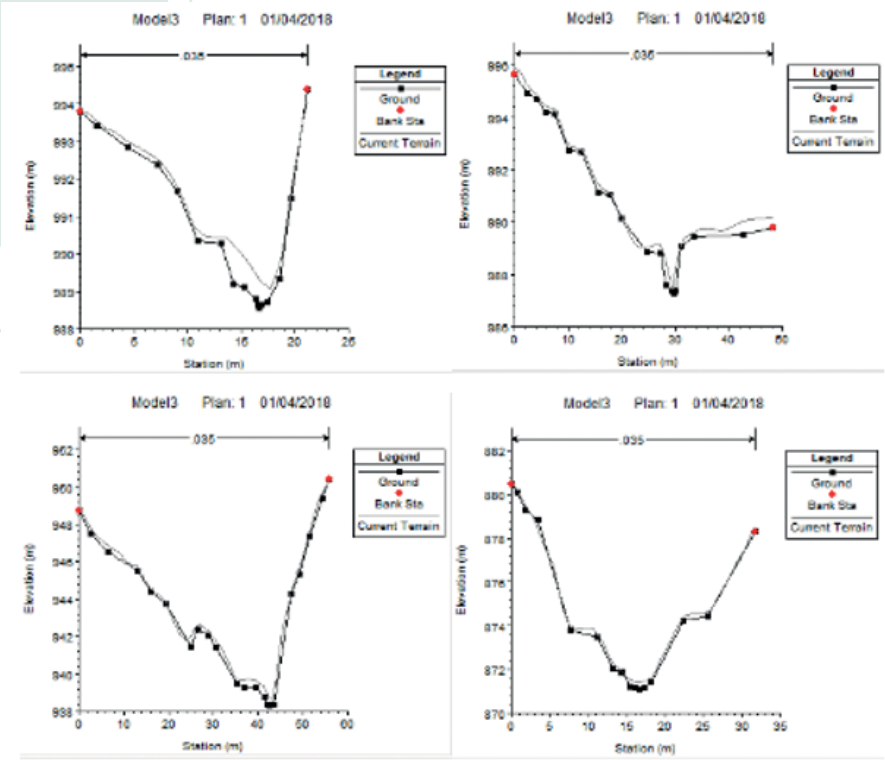


Figure 11. Comparison of Cross Section Data with Tbilisi LiDAR

A further comparison has been undertaken for a global DEM (MERIT) and for the orthophoto DEM in the three first catchments (Figure 12 and Figure 13). The MERIT DEM has been selected because even if the spatial resolution is 90 m (there are global DEMs with higher spatial resolution), it is believed that it provides the best elevation accuracy based on previous assessments and uses. As can be noted, the two DEMs are comparable from a catchment point of view, although there are locations where the orthophoto DEM shows spurious values (zero values) across the catchments.

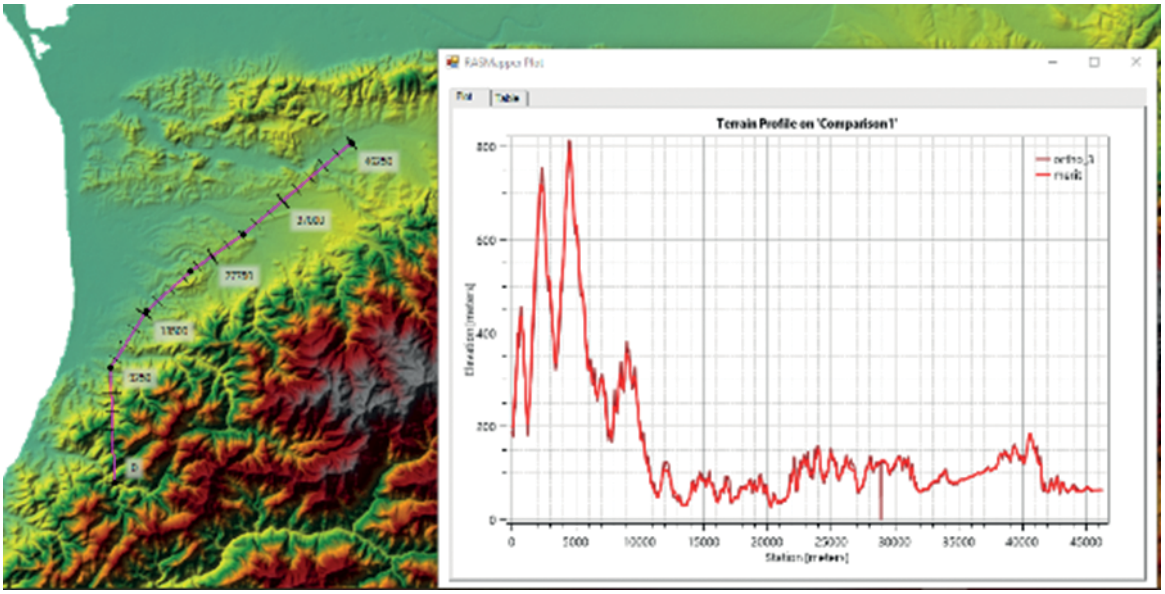


Figure 12. Comparison of Orthophoto DEM (Brown) and MERIT DEM (Red)

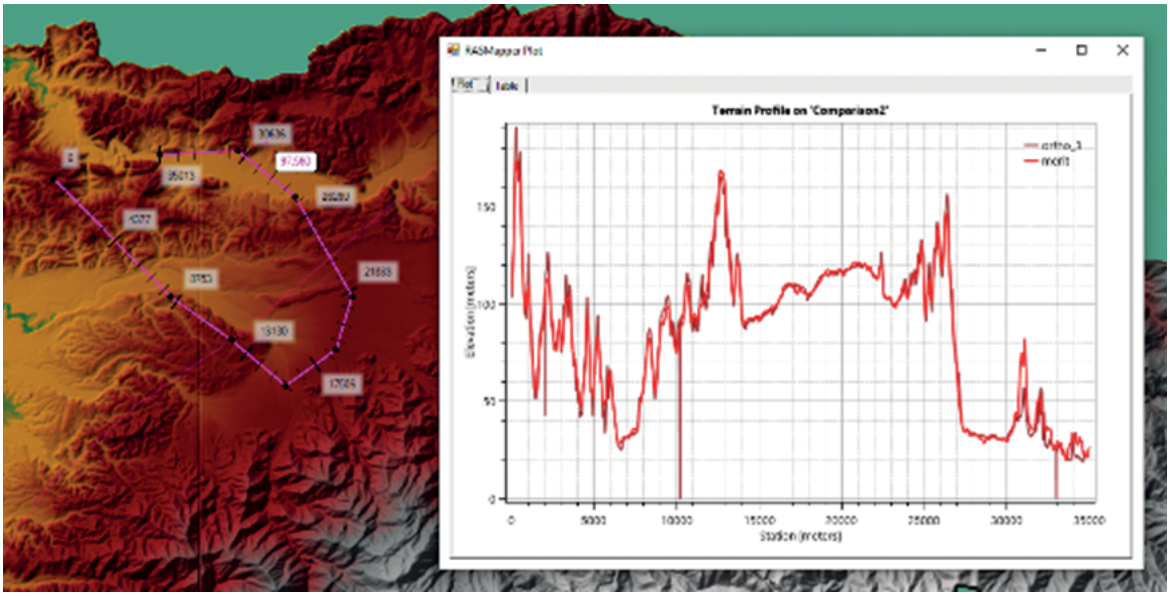
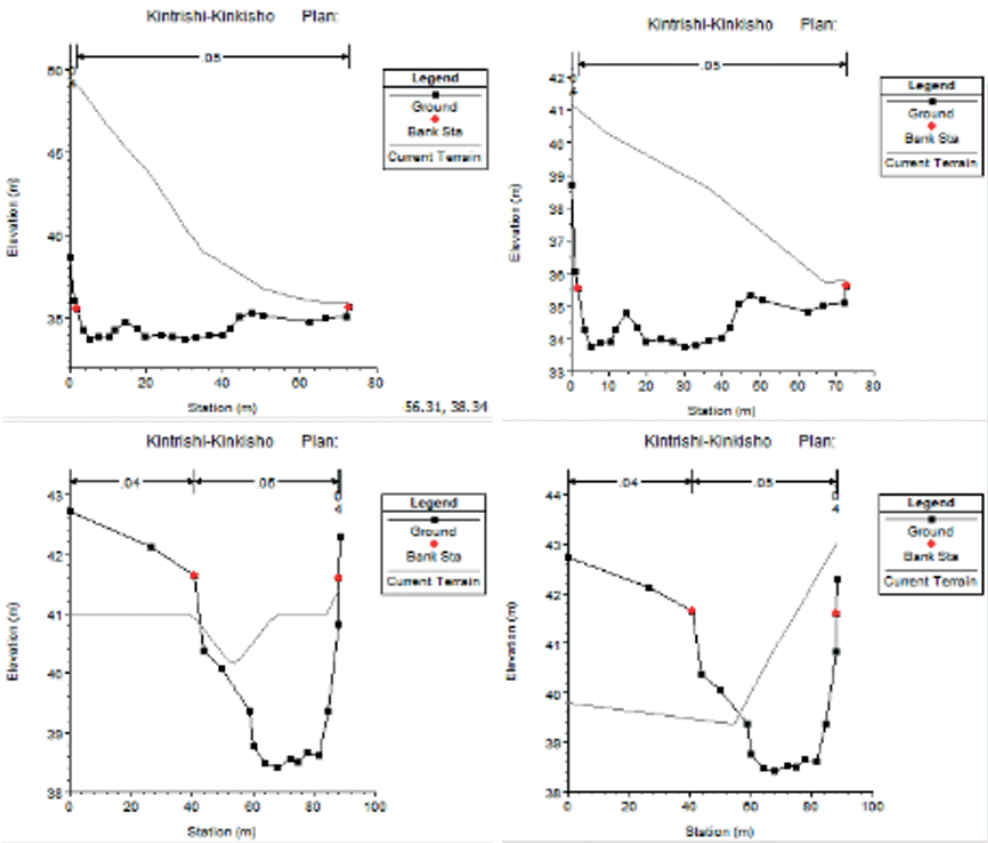


Figure 13. Comparison of Orthophoto DEM (Brown) and MERIT DEM (Red)

In a further comparison, the two DEMs have been compared against cross section data in the Kintisi River (Figure 14).



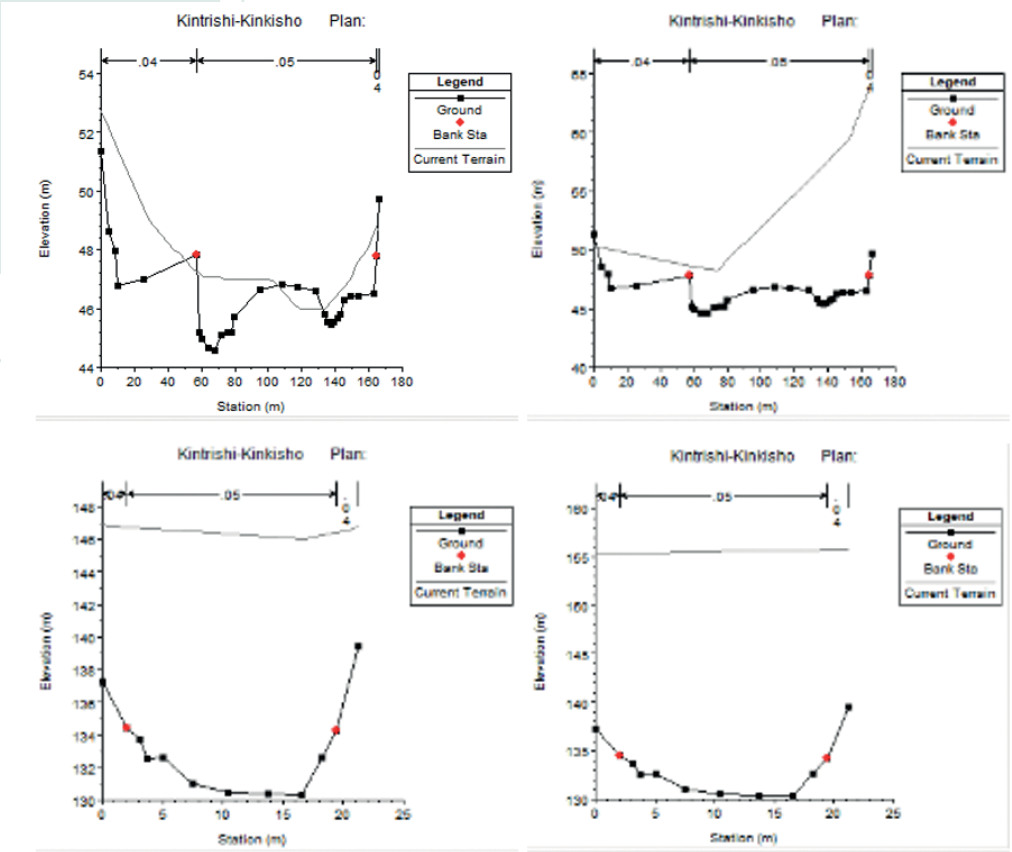


Figure 14. Comparison of Cross Section Data with Orthophoto DEM (Left) and MERIT DEM (Right)

As can be observed, the results are not satisfactory. While the MERIT DEM does not represent the channel properly (and it is not expected with a 90 m resolution grid), the orthophoto DEM does not represent the channel or floodplain topography properly either. In some locations, a difference of more than ten metres between the orthophoto DEM and the cross-section survey data can be observed. A comparison between all the survey points and the orthophoto DEM has been undertaken and the results are also not satisfactory. However, it should be considered that the DEM is not expected to capture the channel itself. On the banks, however the DEM should be more accurate and hence, the reason for the cross-section approach to assess this.

Cross sections: as noted above, a topographical cross section survey and hydraulic structure survey is being undertaken in all the basins. This topographic survey has been completed for six basins and some other watercourses and basins will be addressed later. The cross-section survey obtained for the first three catchments is shown in Figure 15.

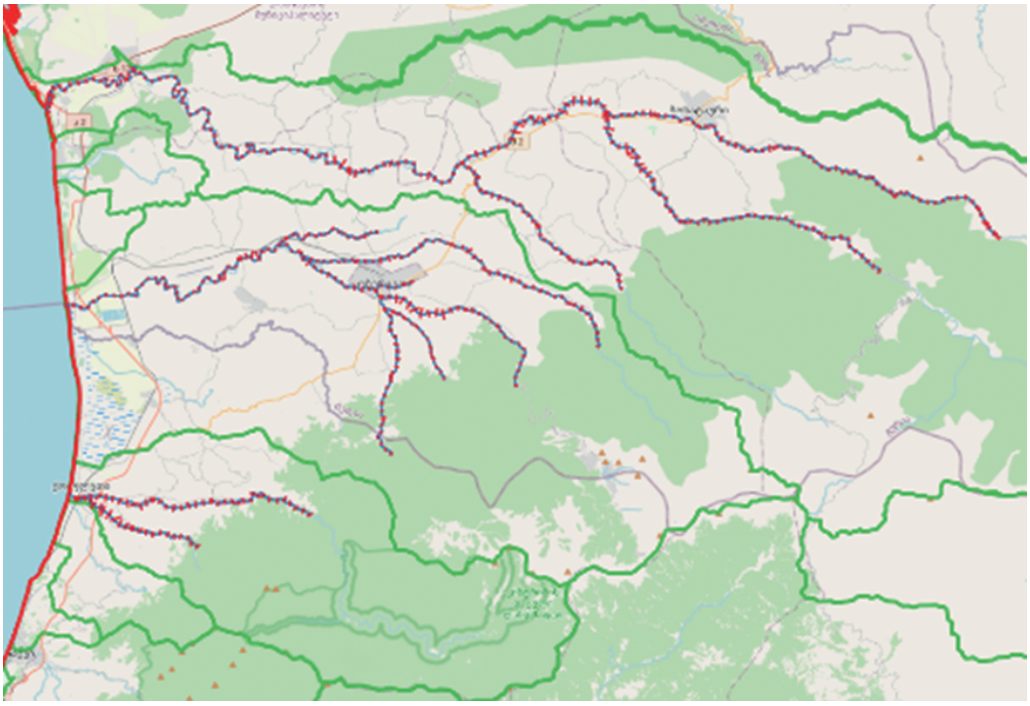


Figure 15. Cross Section Survey for the Natanebi, Kintrisi and Supsa Catchments

- Base Mapping: apart from global sources (OpenStreetMaps), there is no digital base mapping in Georgia for the implementation of flood models. There are also old Soviet digitised images for background purposes.
- Aerial imagery (aerial photos and satellite imagery): there are orthophotos available for the whole territory of Georgia from the Public Registry.

5.1.3 Hydrometric Data Sets

- Rainfall data: as noted, rainfall data are not a direct input to fluvial hydraulic models (unless the direct rainfall method is used). The quality, availability and spatial and temporal coverage of the rainfall data is assessed. From a hydraulic modelling point of view, however, there are concerns about the temporal resolution of rainfall data from the data coverage point of view. There are alternative sources of data to overcome these issues such as satellite precipitation estimates, meteorological reanalysis data and weather radar data. Weather radar data are addressed in the pluvial modelling section owing to its relevance in urban areas.

  The rainfall data availability in the three first catchments (Supsa, Natanebi and Kintrisi) has been analysed. In this section, the data for Supsa will be shown. In the appendix, information about the other two catchments is available.

  The Figure 16 shows the location of both the hydrological and the meteorological station in the Supsa catchment. Figure 17 shows the Voronoi (or Thiessen) polygons for the Supsa catchment. As can be observed, the density of the precipitation stations in the upper catchment is not very high while it is slightly better in other parts of the catchment.

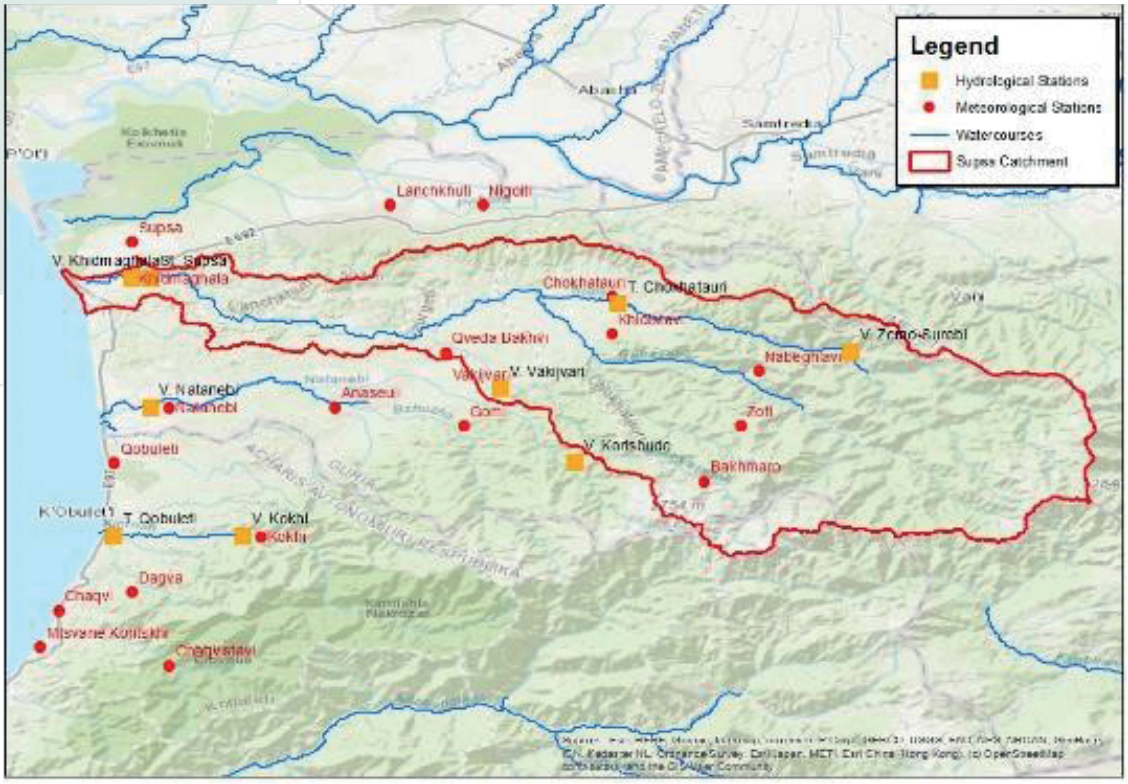


Figure 16. Meteorological and Hydrological Stations in the Supsa Catchment

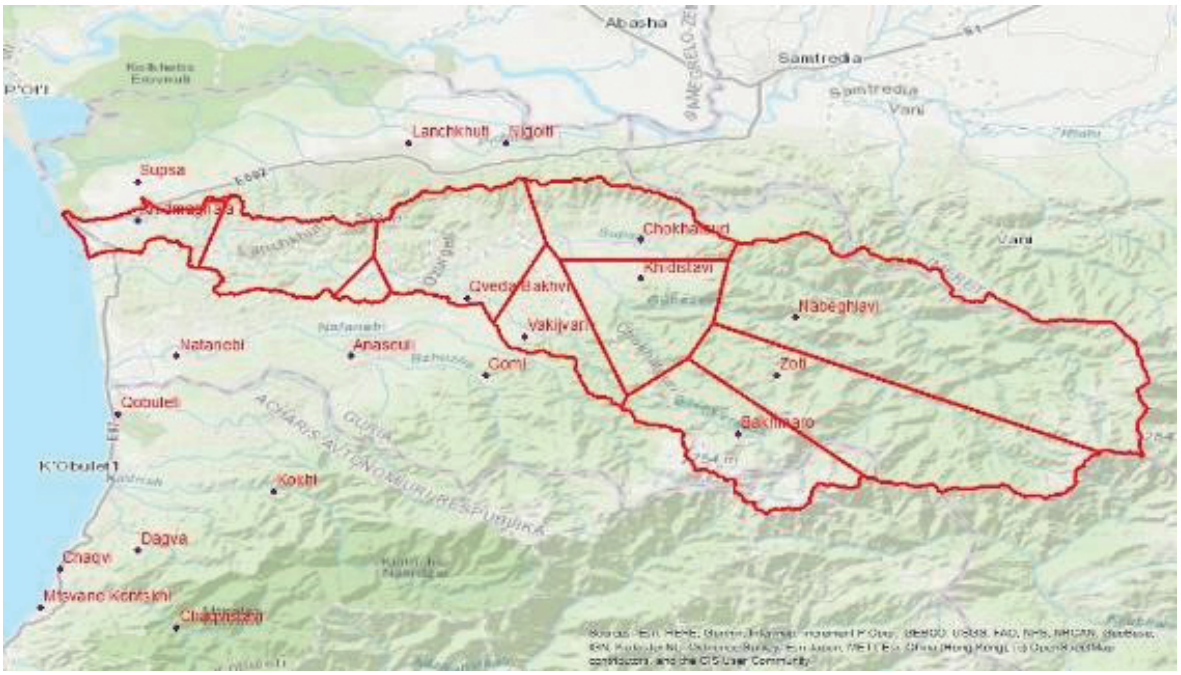


Figure 17. Voronoi Polygons for the Supsa Catchment

Figure 18 below shows the time availability for these stations where some of them show a long availability while others have been deployed for a short period of time.

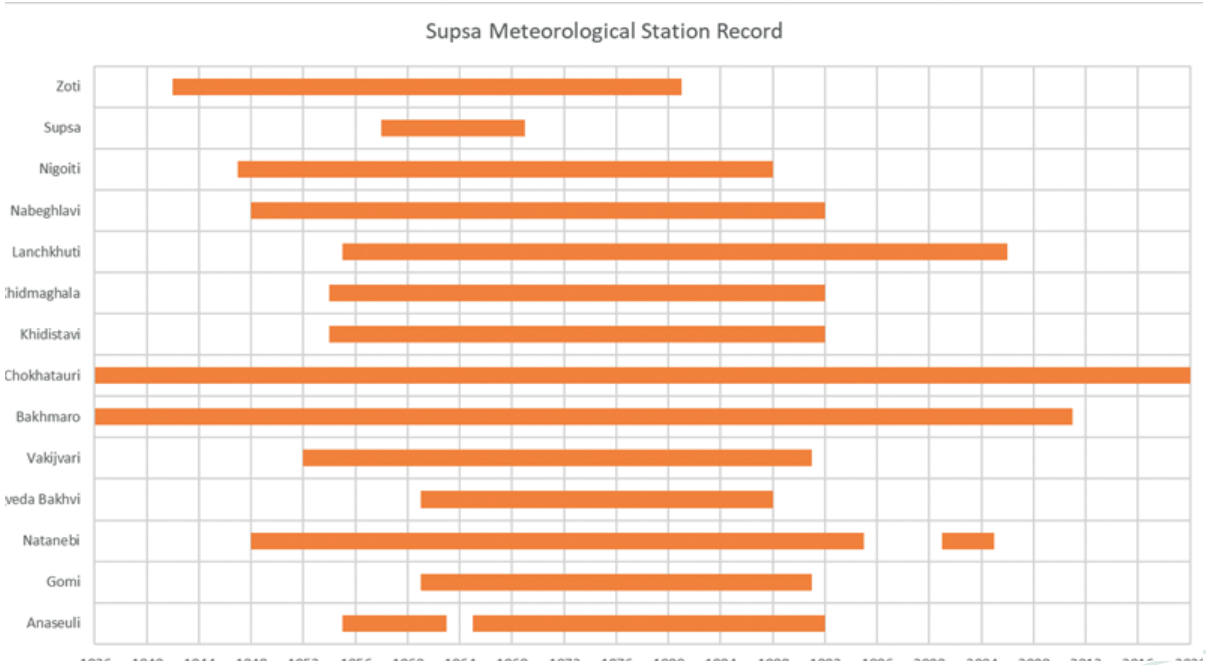


Figure 18. Rainfall Data Availability in the Supsa Catchment

As noted, a detailed analysis per catchment will be undertaken by NEA modellers before the implementation of the flood modelling framework in any catchment and an analysis of the precipitation (and other) data availability will be undertaken.

The collection of rainfall data per catchment is undertaken using existing stations and decommissioned ones while bearing in mind that the network coverage was higher in Georgia during Soviet times. All of the old stations and most of the existing ones, however, record data on a daily basis which will pose issues from a hydrological and hydraulic modelling point of view, especially in small catchments. Stations recording sub-daily data (hourly) are located in the Rioni basin and around Tbilisi. Figure 19 below shows the location of all of the existing precipitation observational points in Georgia, including meteorological posts and meteorological stations.

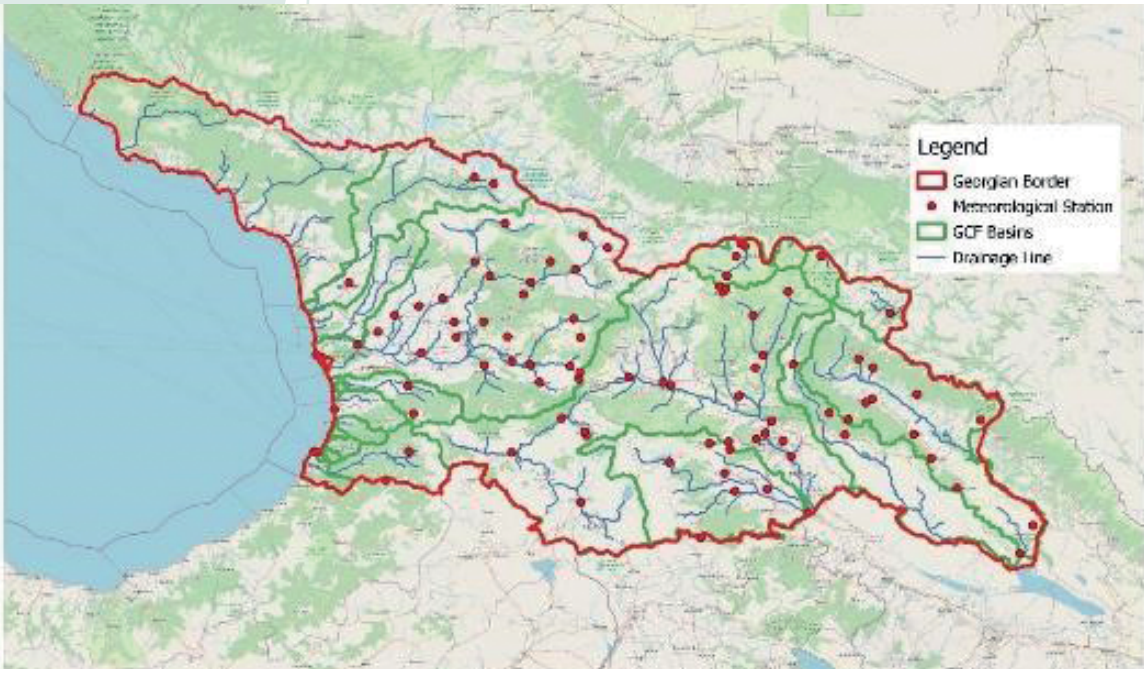


Figure 19. Existing Meteorological Stations and Posts in Georgia

The monitoring network in Georgia is expected to be expanded. Figure 20 shows the location of the proposed additional meteorological posts and stations. While these observational points will be deployed in the near future, and it is unlikely that they will provide relevant information for the direct implementation of models, the information coming from these stations could be useful for sub-daily purposes and, therefore, their locations should be considered for modelling purposes.

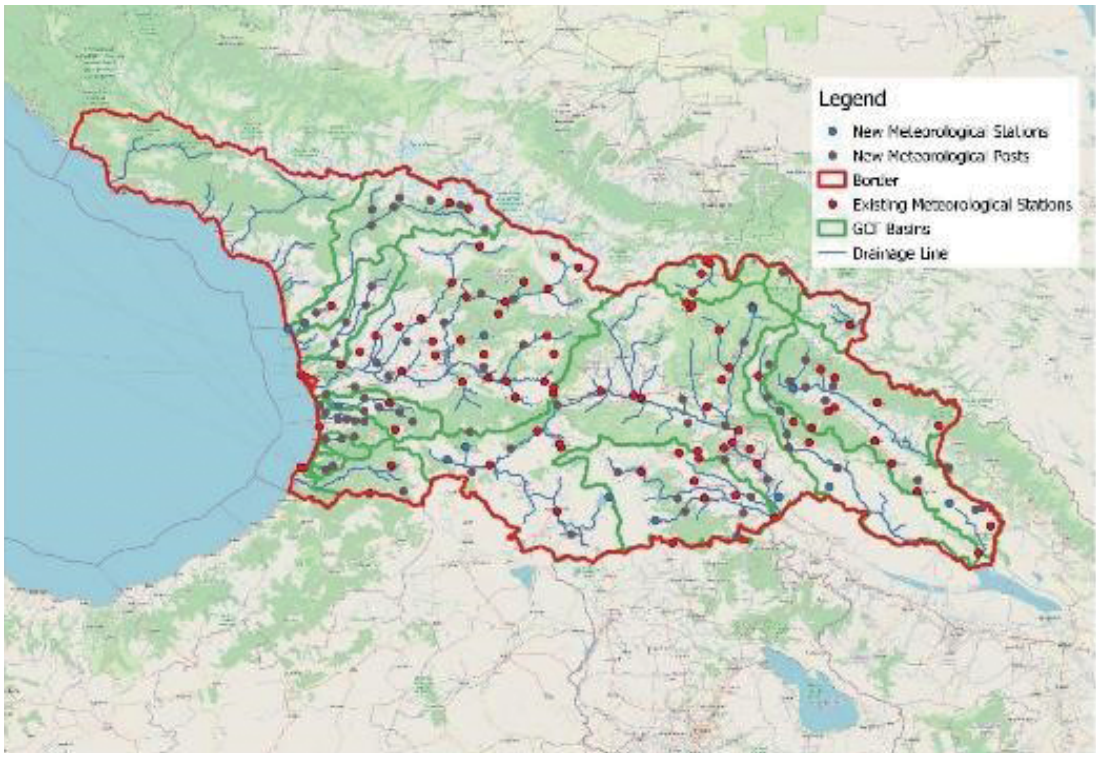


Figure 20. Proposed New Meteorological Stations and Posts

A further quick assessment has been undertaken with the information of the existing and proposed meteorological stations. Sub-catchments have been derived using the MERIT DEM for the whole territory of Georgia and this has been compared with the location of the existing and proposed stations (Figure 21). As can be observed, most sub-catchments are covered by stations. There are some areas in the south-west and north of Tbilisi where the coverage may be limited but in general the whole territory is covered. It should be noted that the derivation of the sub-catchments was undertaken using default values from the ArcHydro and, therefore, a more detailed assessment will be necessary per catchment while also considering the location of significant decommissioned stations.

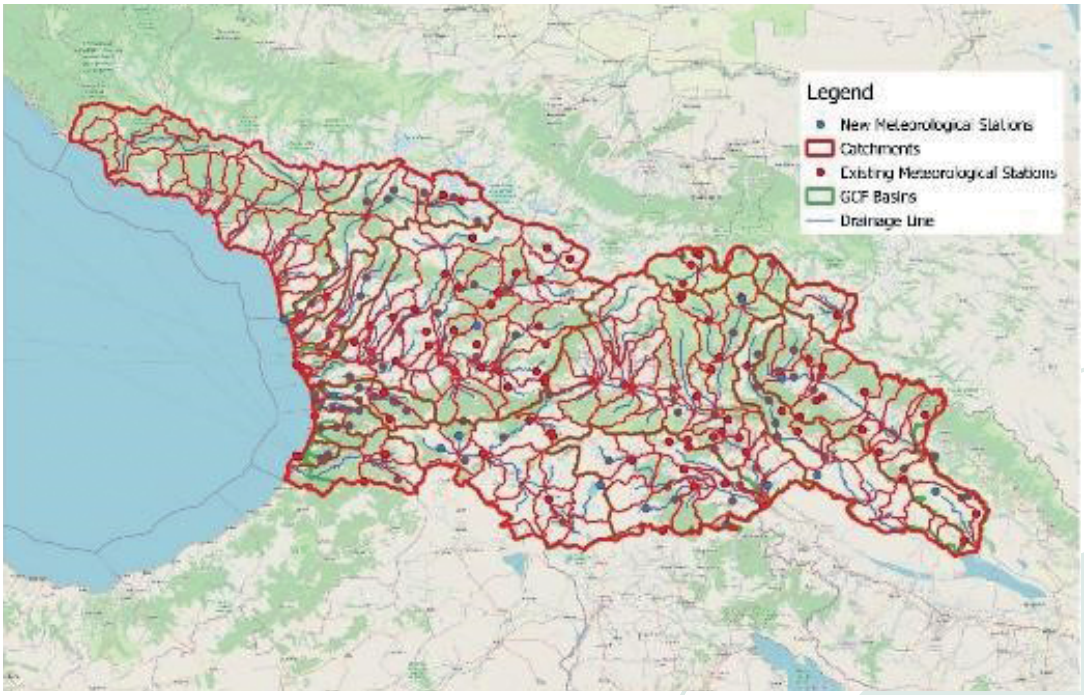


Figure 21. Sub-catchments, Existing and Proposed Meteorological Stations

- Flow and level data: flow and level data will be used for calibration purposes in the hydraulic modelling implementation. The location of the hydrological stations is shown in Figure 16 with four stations on the main Supsa River and one station on one tributary, although the records for the latter are only available for a short range of time. This can be observed in Figure 22 below where the actual availability of records for this catchment is shown. There is also no information regarding the type of hydrological station or the rating curves for these stations.

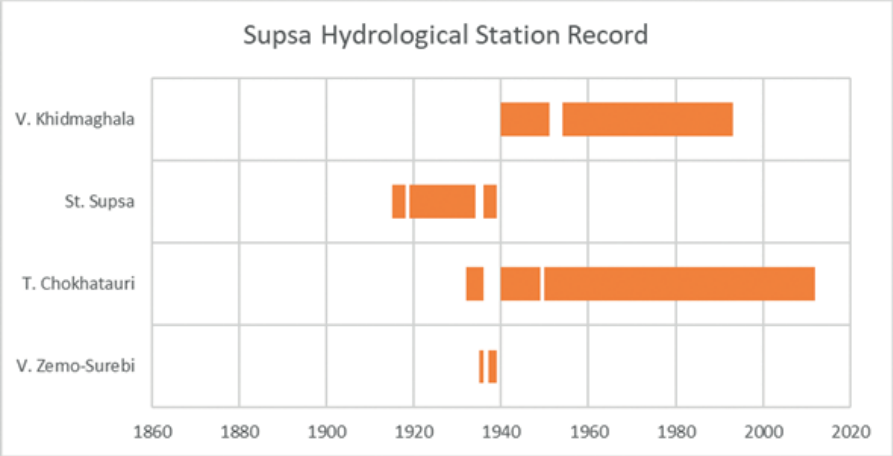


Figure 22. Flow Data Availability in the Supsa Catchment

The situation with the hydrological stations is very similar to the one of the meteorological ones. Data are recorded on a daily basis in most cases but only in stations deployed in the Rioni basin and in the Tbilisi urban area. It should be noted that as per the precipitation gauges, information about the location of the existing stations (not including decommissioned ones, see Figure 23) and the proposed ones (Figure 24) has been obtained and processed.

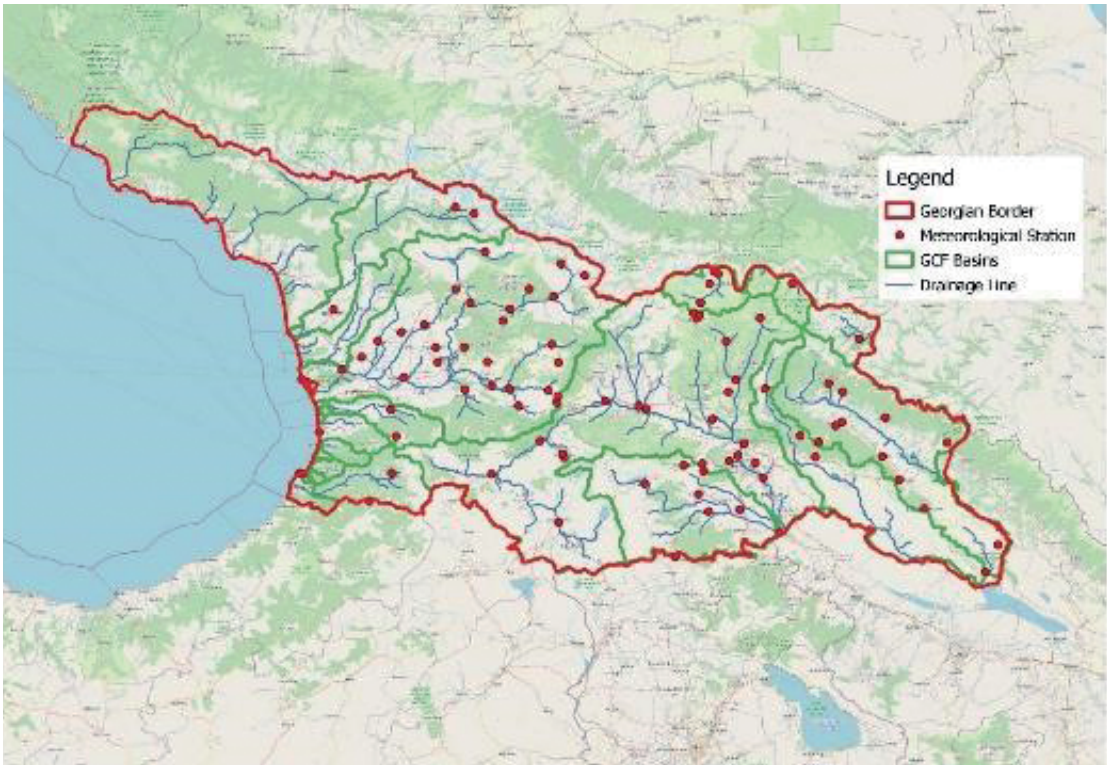


Figure 23. Existing Hydrological Stations

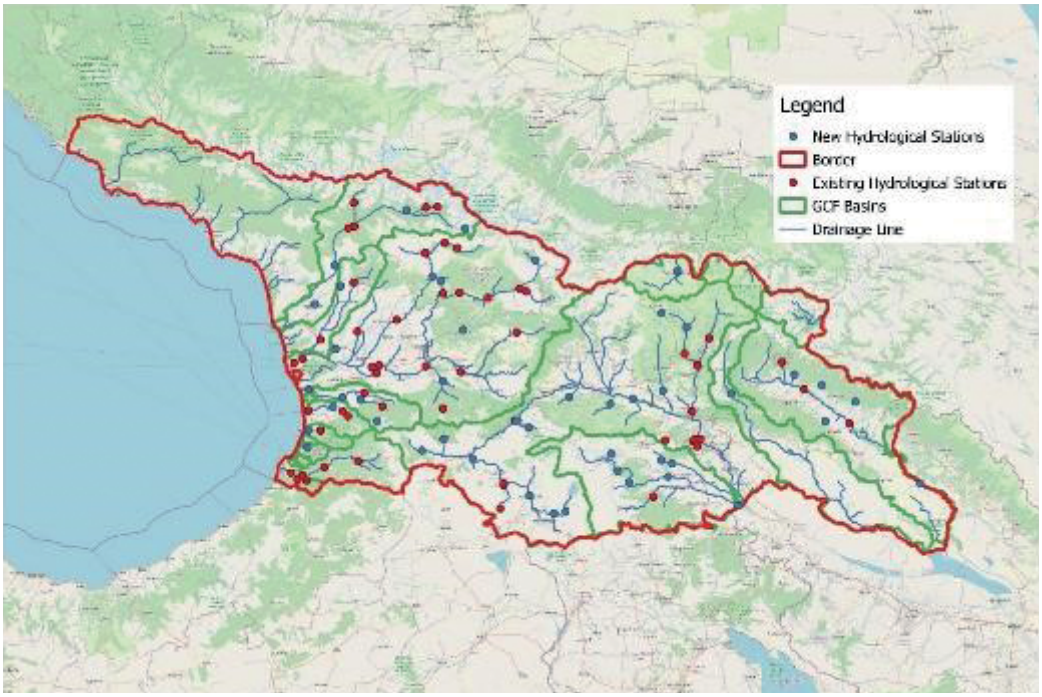


Figure 24. Proposed Hydrological Stations

- Records of past flooding: as noted, all of the possible calibration sources have been investigated from maps of observed events, indicative flood maps and satellite imagery. No significant success has been obtained in this task and there is limited information available to supplement the calibration process. This will be a matter of continuous research and more efforts will be paid to try to identify as many calibration sources as possible for every basin. Again, the sensitivity tests will play a major role in increasing the robustness of implemented hydraulic flood models.

  No maps of observed flooding events have been found apart from the Vere impact assessment report and flood outlines as developed by the NEA (Figure 25).

Figure 25. Observed Flood Mapping for the Vere River for the June 2015 Event

- No indicative flood extent maps of previous events have been found.
- Satellite imagery: different satellite imagery providers have been assessed in terms of finding suitable flood outlines. Copernicus, the International Charter for Space and Disasters, the Darmouth Flood Observatory, Landsat and MERIS data sources have been assessed. Unfortunately, no suitable satellite images have been found for calibration purposes. The only information found was broad and unrealistic shape polygons in the Darmouth Flood Observatory repository.

5.1.4 Physical Catchment Data Sets

- Land-use maps: several data sources have been considered for the definition of land-use. The Copernicus land-use data (100 m grid and updated yearly) have been found to be of sufficient accuracy and their use is recommended for roughness definition purposes.
- Map of existing flood defences: no information is available regarding the location of flood defences. It should be noted that 'as-built' drawings are not generally available in Georgia and, therefore, the expected success of this activity is limited. When a list of flood defences become available, additional survey efforts should be dedicated to collect data from these structures vis-à-vis the available data per defence and their significance. The use of orthophotos and LiDAR sources for flood defence data should also be noted. Of further note is that while flood defence structures will be included in the fluvial modelling, they will be analysed from a failure point of view in the AWBS section.

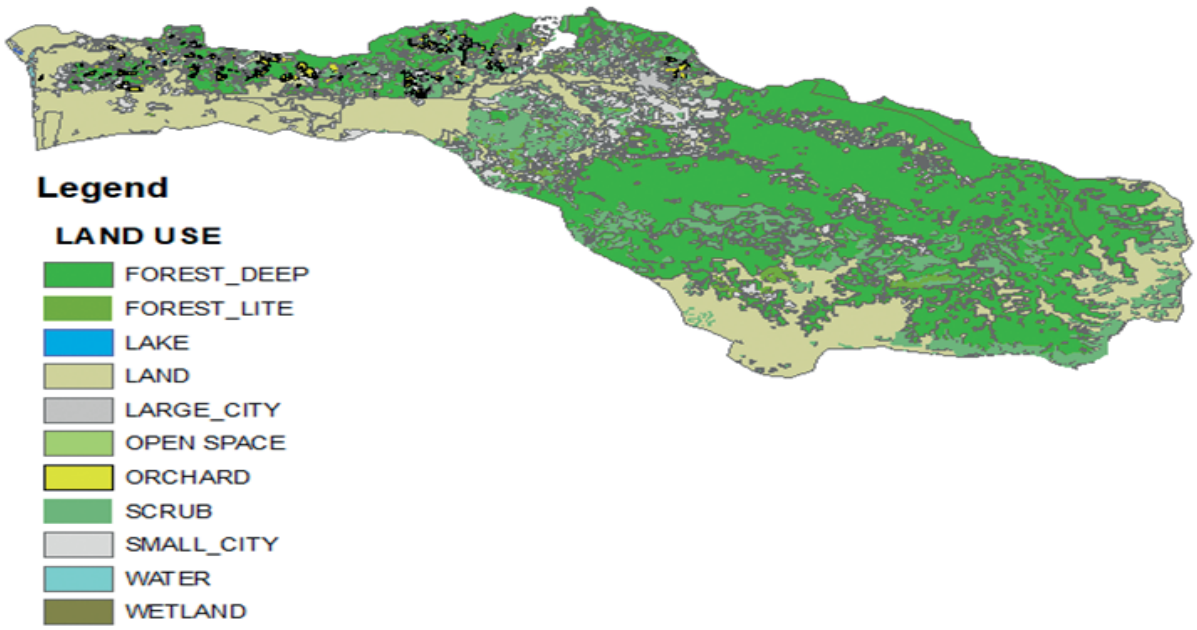


Figure 26. Land-use Map of the River Supsa Basin

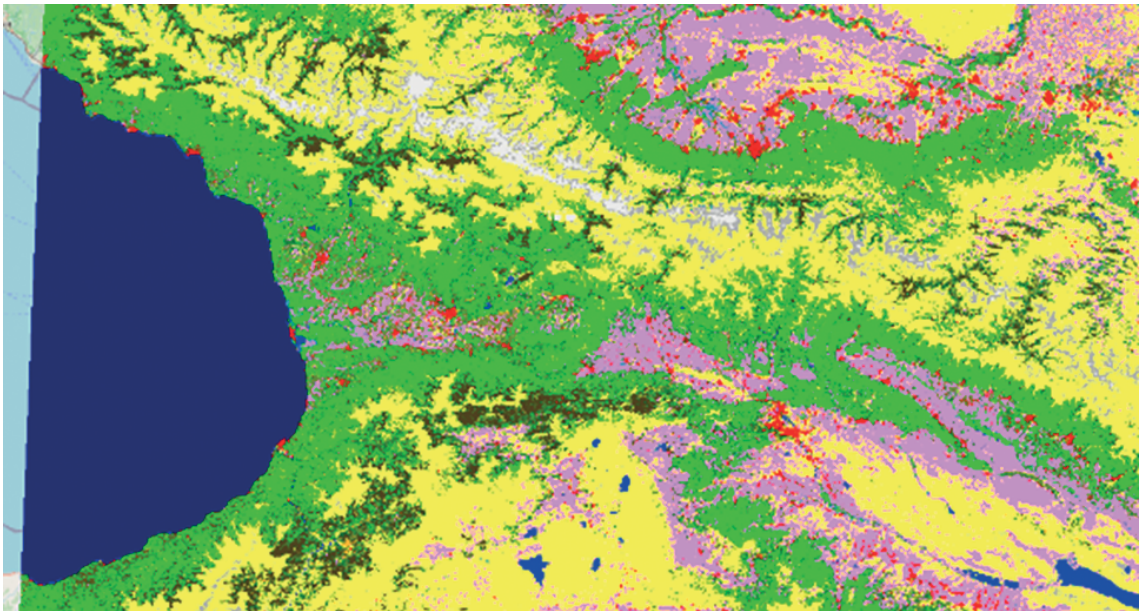


Figure 27. Copernicus Land-use.[7] Legend Available in the Publication Below

5.2 Pluvial Flooding

Due to the nature of pluvial flooding and its impact on urban areas, topographical information is one of the main data requirements. One special characteristic to be considered at this stage is spatial recurrence. Pluvial flooding may occur anywhere. From a historical point of view, there are locations that are statistically more prone to pluvial flooding, but this type of flooding can occur anywhere. The impact and the severity of the flooding will be determined by the topography and the urbanisation of a particular location.

A data requirement exercise was undertaken for pluvial flooding and additional data sets, or differences vis-à-vis fluvial flooding will be outlined in this section (as will be done for the other sources of flooding). The following data requirements and data availability in Georgia will be considered:

- Details of historical and recorded pluvial flooding in Georgia: there are no specific records of a pluvial flooding source in Georgia at the moment.
- DEM data: as will be detailed below, DEM data for pluvial modelling is one of the most critical input data to be considered. There are several data sources to be considered at this stage. As noted above, the main one is the LiDAR data (Figure 7). More details on the topographical and spatial resolution will be outlined below.
- Land cover and use data: land cover and land-use data will provide information for pluvial modelling regarding roughness (or resistance). This is an important factor in deter-

7. M. Buchhorn, B. Smets, L. Bertels, B. De Roo, M. Lesiv, N.E. Tsendbazar, L. Linlin, A. Tarko. (2020): Copernicus Global Land Service: Land Cover 100m: Version 3 Globe 2015-2019: Product User Manual; Zenodo, Geneva, Switzerland, September 2020; doi: 10.5281/zenodo.3938963

mining how the water will flow in a particular area. Due to the relevance of the permeability on pluvial modelling results, special attention will be paid to this data source. It should be noted that the land-cover data will be combined with the building's footprint data for roughness purposes. The same sources as described for fluvial flooding will be considered here.

- Building footprint data: building footprint data are relevant in pluvial flooding because they provide information and data for the flow routing within the modelling implementation. Cadastre data will be used to provide a building footprint across Georgian urban areas. These data have not been acquired as of yet, but they appear to be available. In the absence of cadastre data, other sources of information will be used such as building polygon information from OpenStreetMaps (Figure 28). The methodology for the inclusion of building footprint data into the pluvial models will be described in detail in the methodology report.

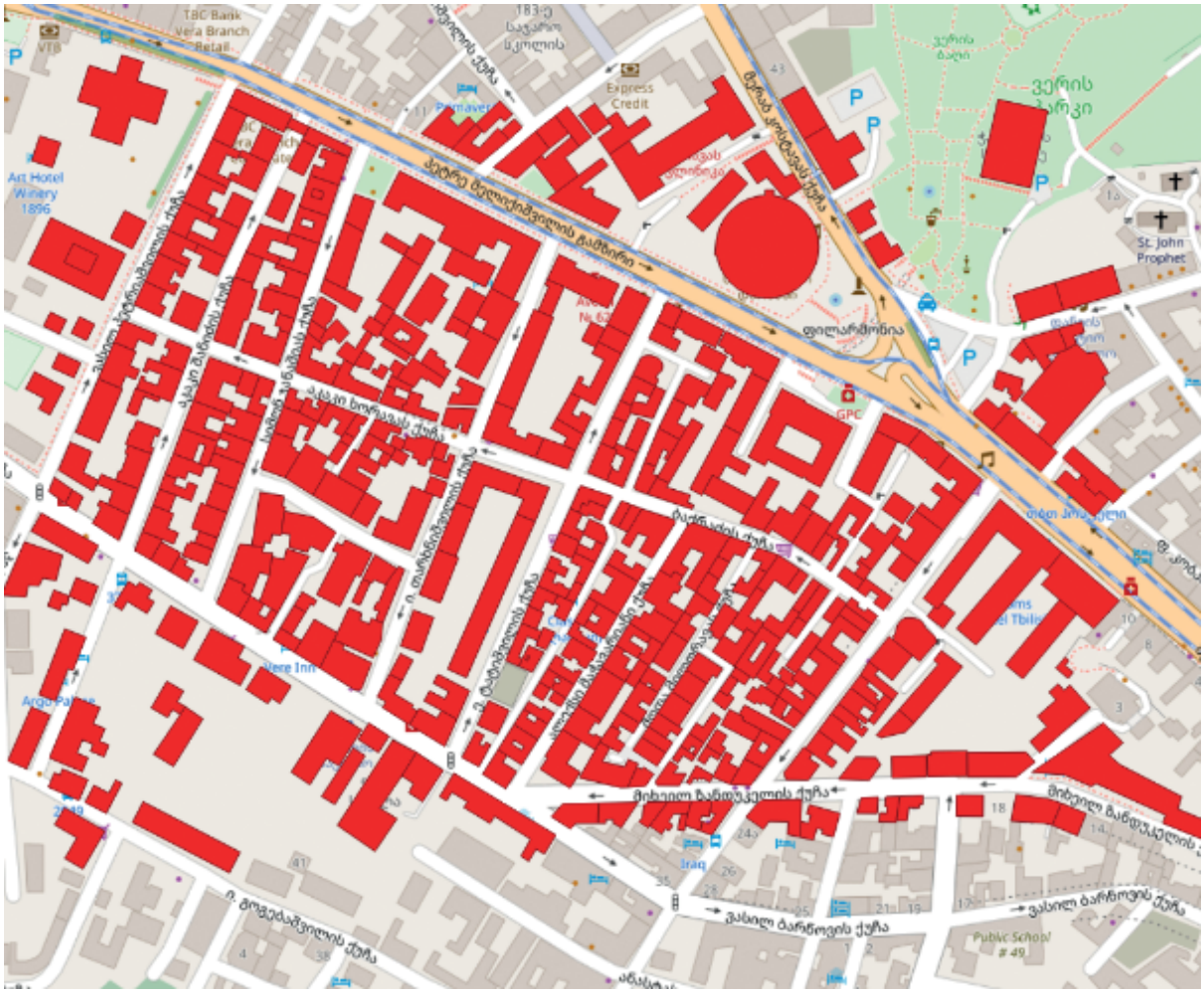


Figure 28. OpenStreetMaps Buildings (in Red) in Tbilisi

- Road and rail infrastructure data: road and rain infrastructure data will be needed as well for pluvial modelling. These data will be either collected from cadastre sources or from OpenStreetMaps (available) as per the building layouts.
- Flood defence data (e.g., levees and embankments): flood defence infrastructure is critical for all flood modelling sources. This is especially the case for pluvial flooding because these objects of infrastructures may affect the water flow and direction. Details from flood defence data need to be collected and included into the model when available. At the moment, no success has been obtained in collecting these data in Georgia.
- Sewerage network data: the influence of the sewerage network on pluvial flooding is a matter of research. Nonetheless, based on previous studies it can be considered that the sewerage or surface drainage network system does not play a major role from a pluvial point of view. Nonetheless, the availability of high-quality information and data on the sewerage network determines whether integrating underground sewer and pipe networks into pluvial flood models can improve the uncertainty in the resulting flood hazard and risk maps. This will be discussed below in the urban drainage section.

  Some of the data sources required for pluvial flooding were analysed in detail in the fluvial section. Some more information regarding the DEM impact on the results are shown below, including information about additional sources required for pluvial modelling:

- Details of historical and recorded pluvial flooding in Georgia: no records of historical pluvial flooding are available in Georgia. This is a matter of concern, although it is believed that more information can be gathered in the future. The list of flood events at the NEA should be detailed further and more work should be undertaken in terms of categorising each of the events depending on the flood source.
- DEM data: topography plays a major role in determining the accuracy of flood inundation areas for pluvial flooding. This is the case for all sources of flooding but the impact on pluvial flooding may be more relevant. The type, accuracy and resolution of the elevation data are extremely important in developing flood maps with these factors widely believed to have a direct impact on the resulting flood mapping extents and depths (Figure 29. Flood Mapping Difference Depending on the Resolution, 5 m Versus 30 m, Saksena & Merwade, 2015[8]). Flooding may be greatly over- or underestimated if poor quality elevation data are used. The resolution, or horizontal resolution, of elevation data is the size of each cell which is given the same height value, generally in metres. The smaller the cell size, the higher the resolution of the data.

8. Saksena, Siddharth & Merwade, Venkatesh. (2015): "Incorporating the Effect of DEM Resolution and Accuracy for Improved Flood Inundation Mapping." *Journal of Hydrology*. 530. 10.1016/j.jhydrol.2015.09.069.

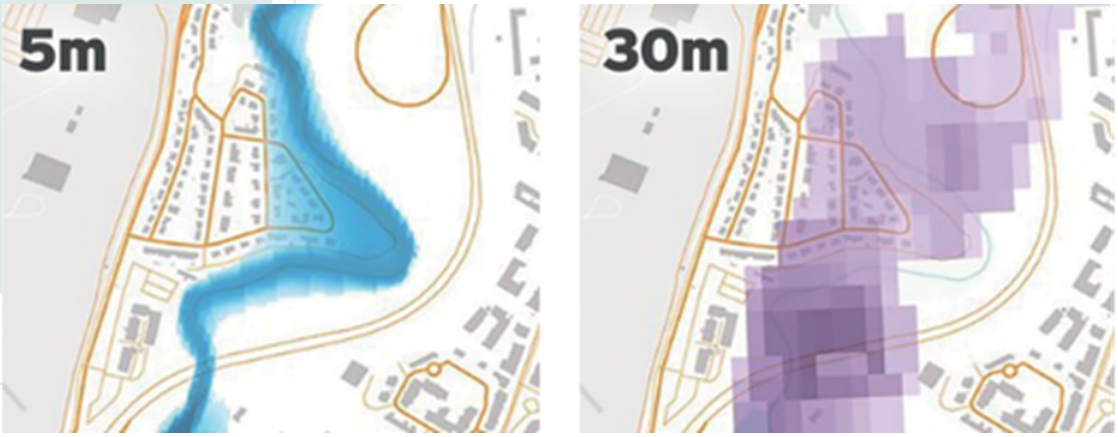


Figure 29. Flood Mapping Difference Depending on the Resolution, 5 m Versus 30 m

Therefore, the use of a sufficient spatial resolution is required in the pluvial modelling. This will be an issue if only the LiDAR data are available. It is only recommended to implement pluvial models at this stage where LiDAR data are available unless a more accurate orthophoto DEM becomes available.

- Building footprint data: the building footprint data are relevant in pluvial flooding because they provide information and data for the flow routing within the modelling implementation. The data available from the cadastre appear to be of sufficient quality. Even if they were not available, the OpenStreetMaps resources were analysed and found to be of sufficient quality and density.
- Road and rail infrastructure data: the same can be said for road and rail infrastructure data as per building data.
- Flood defence data: no flood defence data are available as yet. While this would not prevent the implementation of models, the accuracy of the results may be highly compromised. It is recommended that further efforts are taken to collect these data.

5.2.1 Urban Drainage Flooding

A specific section has been included for urban drainage flooding within the issue of pluvial flooding. While there is no direct equivalence between urban drainage flooding and pluvial flooding, the latter does usually occur in urban areas (and elsewhere but the risk is more significant in urban areas due to the high number of elements at risk) and the impact of pluvial flooding may be exacerbated by the lack of an appropriate urban drainage system. There are several studies about this and in most cases it has been determined that the impact of the drainage network on pluvial flooding is very limited (at least from a modelling point of view). Additionally, it should be added that urban drainage systems are usually designed to withstand a limited return period event (for example, 30 years in the UK and ten years in Spain) and, therefore, any precipitation event with a higher probability is going to act as pluvial flooding. Further additionally, this is considering that the system was designed accurately, and that the system is working at 100% which is rarely the case.

Nonetheless, it was considered important to include a section regarding data requirements for urban drainage flooding. While data are critical for al flood source modelling, this is especially the case for urban drainage system flood hazard modelling. The following is required:

- Network data: there are several requirements for the network data:
  - Manhole covers and depth.
  - Pipe invert levels and diameters.
  - Ancillaries: pumping stations and combined sewer overflows (CSO) are two of the most significant ancillaries in an urban drainage network. Very detailed information about the CSO and pumping stations is required to successfully implement a network model.
- CCTV surveys (to assess the state of the network, illegal connections, and infiltration).
- Runoff contribution surveys to assess the runoff contribution of specific areas to either the combined or the separate system when both are present.
- Flow-rainfall surveys: urban drainage network models have to be calibrated and validated against information from flow survey campaigns in order to assess the accuracy of the models. The calibration of network models is undertaken in most cases following a dry-weather and wet-weather calibration process, mainly with combined systems, and, therefore, the flow survey duration should consider that at least two dry-weather events (with no rainfall for 48 hours in advance) and three rainfall events (with sufficient precipitation, depending on the location) are recorded by the flow survey.

  no urban drainage network data could be collected. It is not recommended that this is pursued at this stage.

5.3 Ground-water Flooding

The implementation of any ground-water model requires significant data input. This is especially the case for ground-water flood modelling projects where an understanding of groundwater and surface water interactions during extreme conditions is a prerequisite for the characterisation of a groundwater flood hazard. This will include information on surface and subsurface geology, water tables, precipitation, evapotranspiration, pumped abstractions, stream flows, soils, land-use, vegetation, irrigation and aquifer characteristics and boundaries.

As per any other flood source modelling, the modelling implementation is highly dependent on the information available, and a ground-water model will not represent the existing conditions from a hydrological point of view if it is not based on a rational hydrogeological conception of the basin. The following data needs are considered:

- DEM: sufficiently detailed and accurate topographic data are required. The DEM should be of sufficient quality to show all surface water bodies and divides. The expected LiDAR data in combination with existing DEM resources are considered adequate for these purposes.

- Information about the location of surface drainage systems, springs, wetlands, and swamps. There is some information about the existence of wetlands and swamps (Table 13) but no specific information about their location.

Table 13. List of Marshes and Wetlands in Georgia

Name	Location	Metres a.s.l.	Area, km²	Average depth, m
Pichori-Paliastomi	Pichori River floodplain	0.5-1.8	191	8
Chaladidi-Poti	Between the Rioni and Khobi Rivers	12.5	144	1.5
Eristskali II	Between the Okumi and Gagida Rivers	0.5-1.8	117	1
Churia	Between the Enguri and Khobi Rivers	3	90	0.8
Nakargali	At the confluence of the Enguri River	4	21	1.5
Ispani I and Ispani II	Chorokhi and Ochkhamuri River basin	1.5	19	2
Eristskali I	Between the riverbank and the dunes	1.5	15	1
Natanebi-Supsa	Between the Natanebi and Supsa Rivers	0.5-1.5	15	7
Pichori-Kvishona	Between the Isareta and Gagida Rivers	4	13.2	2
Torsa	River floodplain	80.5	9	1

- Geological data and cross sections showing the areal and vertical extent and boundaries of the system.
- Aquifer data, including information about the aquifer thickness and lateral extent, aquifer boundaries, lithological variations within the aquifer and aquifer characteristics.
- Land-use or land-cover data: the same as those used for fluvial flood modelling.
- Contour maps showing the elevation of the base of the aquifers and confining beds.
- Maps showing the extent and thickness of stream and lake sediments.

All the data above are required for the definition of the geometry of the ground-water domain under investigation, including the thickness and areal extent of each unit. In addition to that, the following information is required:

- Water table and potentiometric data for all aquifers to be included in the modelling domain.
- Hydrographs of ground-water head and surface water levels and discharge rates.
- Data and cross sections showing the hydraulic conductivity and/or transmissivity distribution.
- Data and cross sections showing the storage properties of the aquifers and confining beds.
- Hydraulic conductivity values and their distribution for stream and lake sediments.
- Spatial and temporal distribution of rates of evaporation, ground-water recharge, surface water, ground-water interaction, groundwater pumping and natural ground-water discharge.

As per any other flood source, the data collection and analysis stage of the modelling process involves the confirmation of the availability of the required data, an assessment of the spatial distribution, the

richness and validity of the data, an analysis of the data and the level of confidence vis-à-vis the information. A detailed assessment could include a complex statistical analysis together with an analysis of errors that can be used in a later uncertainty analysis.

One of the key aspects in the implementation of any flood ground-water modelling project is to understand and assess the parameter distributions for modelling implementation and the result from this analysis should yield:

- Initial parameter value estimates for all hydrogeological units.
- Quantification of any flow processes or stresses (e.g., recharge, abstraction).

The latter as aforementioned is critical for understanding the flooding mechanism and the hydro-geological behaviour of any particular basin. It should be noted that a groundwater 'basin' does not necessarily correspond (from a geographical point of view) to a fluvial basin and, therefore, this should also be considered in the modelling implementation and in the data collection.

It should be added that some of the data outlined above may be used only during the modelling conceptualisation, but some other data will also be used during the design and calibration of the model. This includes data about the model layers and hydraulic parameters as well as observations of the hydraulic head, the water table elevation, and fluxes.

An analysis has been undertaken regarding the availability of these data in Georgia. There are 56 groundwater monitoring stations in Georgia (Figure 30) with most of these stations having been recently deployed (from 2015) and with the main purpose of the network being water resources.

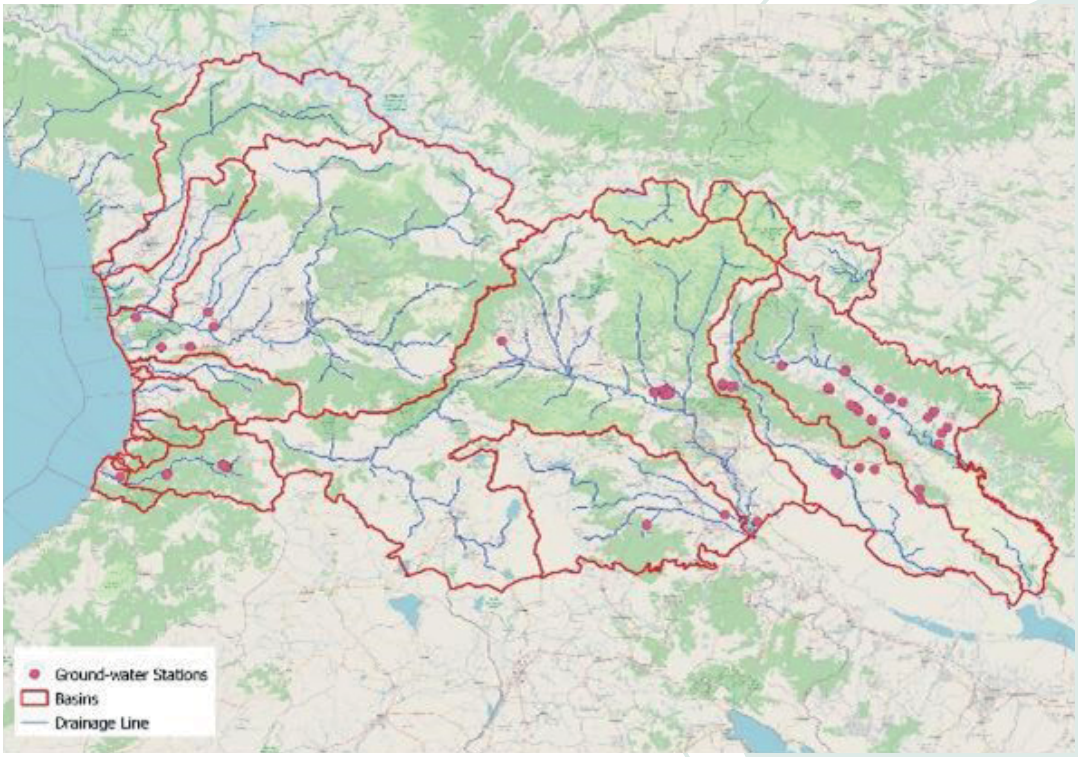


Figure 30. Ground-water Monitoring Network in Georgia

Monitoring devices have been deployed in both artesian (Figure 31) and sub-artesian wells (Figure 32), resulting in discharge and water data (respectively) on a daily basis.

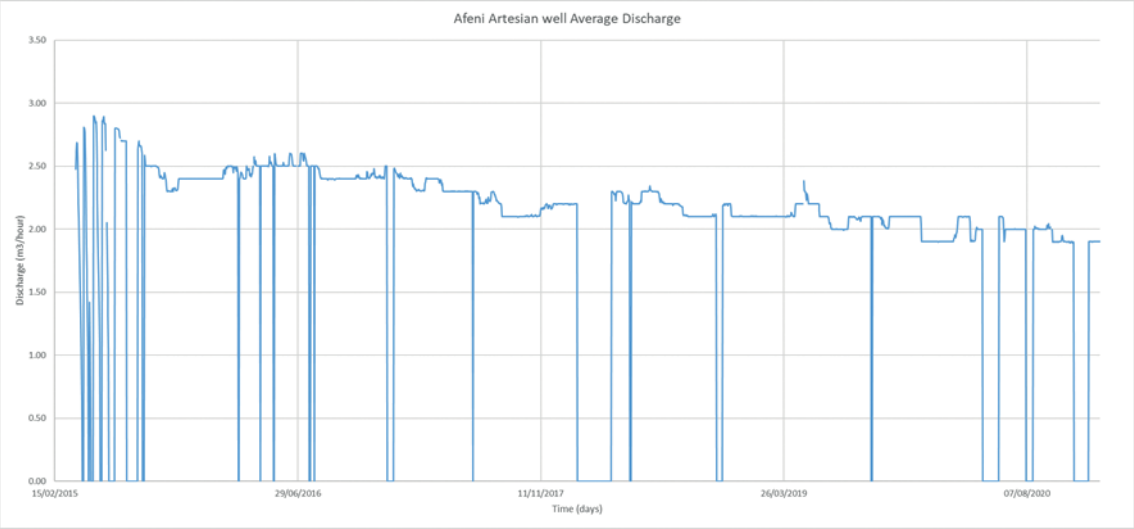


Figure 31. Afeni Well Average Discharge

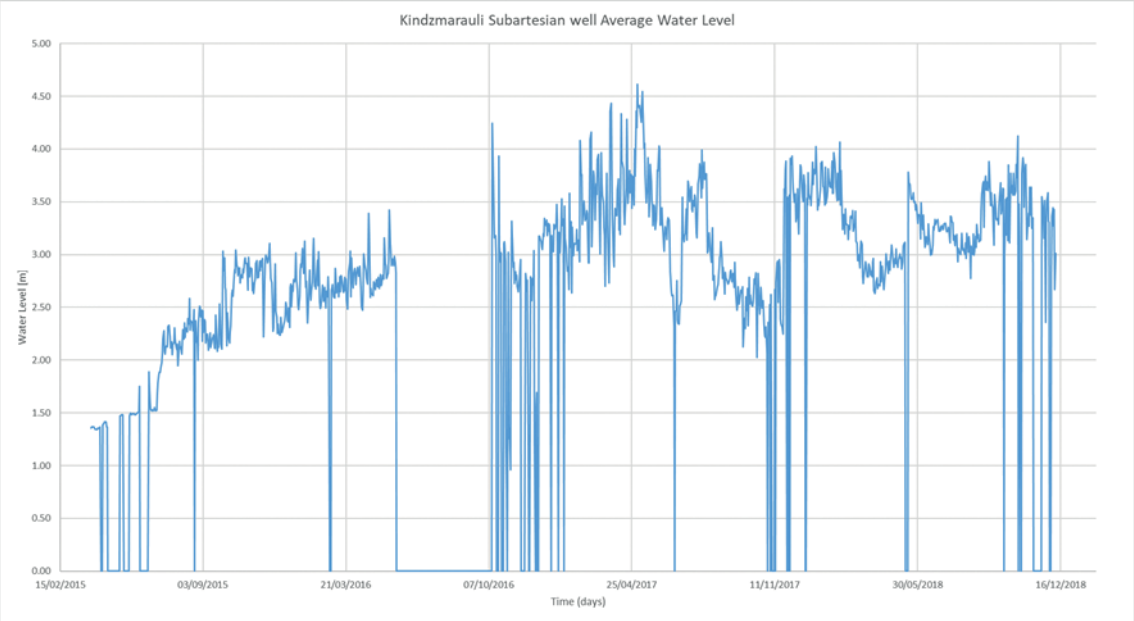


Figure 32. Kindzmarauli Well Average Water Level

There is limited information about ground-water flooding data. The location of the groundwater monitoring network has been obtained, along with two examples of data collected. The network focuses on water resources and so it is not believed that it can serve flood modelling purposes. There are no capacities regarding ground-water flood modelling in Georgia and it has not been the focus of monitoring network activities. While a methodology will be proposed for this modelling, only the implementation of global (conceptual) models may be possible considering the present constraints.

5.4 Coastal Flooding

There are several data requirements for coastal flood modelling purposes:

- Topographical-bathymetrical information: the topographical and bathymetrical information would determine the approach to follow for coastal flood modelling. The availability of elevation data for coastal and floodplain features and structures which can influence coastal processes and overland flow paths and ponding is critical for this assessment. If these data are not available or are not of sufficient quality, it would not be recommended to undertake a coastal flood assessment. If these data are available, a 2D hydrodynamic model approach would be recommended. There are several sources of information for bathymetrical data that should be considered:
  - GEBCO: The General bathymetric Chart of the Oceans (GEBCO) consists of an international group of experts in ocean mapping with the aim to provide the most authoritative publicly available bathymetry of the world's oceans. The GEBCO bathymetry for the Georgia Black Sea coast was collected (Figure 33). The information is available in a 1/8 arc minute resolution (around 350 m x 490 m) grid format from the GEBCO database. It should be noted that a quick assessment of the data has outlined that the values are scarce and constant vis-à-vis the coastal area.

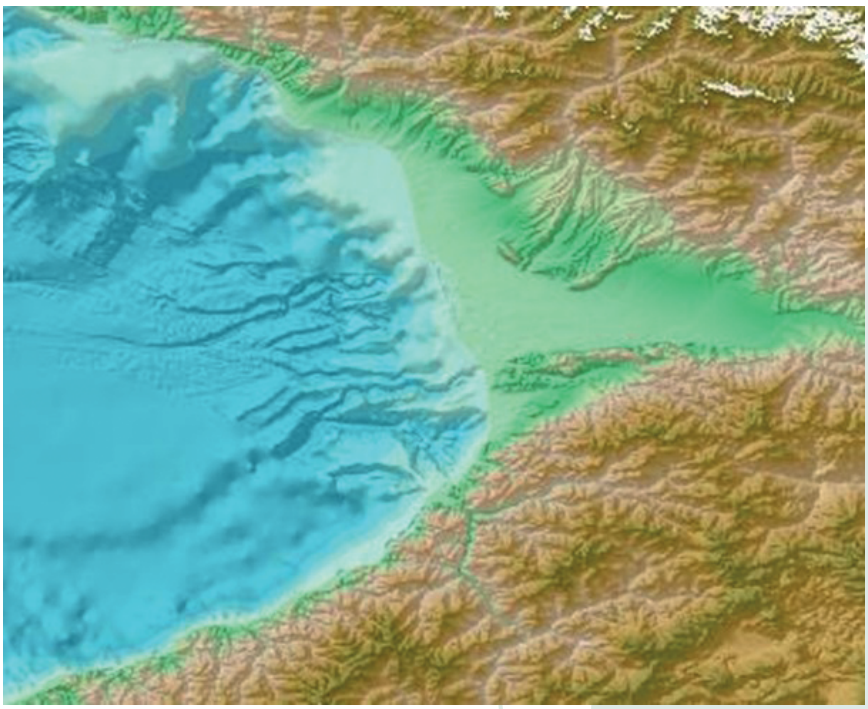


Figure 33. GEBCO Bathymetrical Information in Georgia

  - The European Marine Observation and Data Network EMODnet was also explored. While providing a finer resolution (1/4 of an arc minute, around a 90 m x 190 m grid), the information provided by the EMODnet does not provide further details vis-à-vis the coastal area (Figure 34).

Figure 34. EMODnet Bathymetrical Information in Georgia

- Information from nautical charts: bathymetrical information from nautical charts (Figure 35) can also help to complement other sources of information, especially if this information is in a digital format. Nautical charts, however, are commercial and will need to be acquired in order to assess their validity.

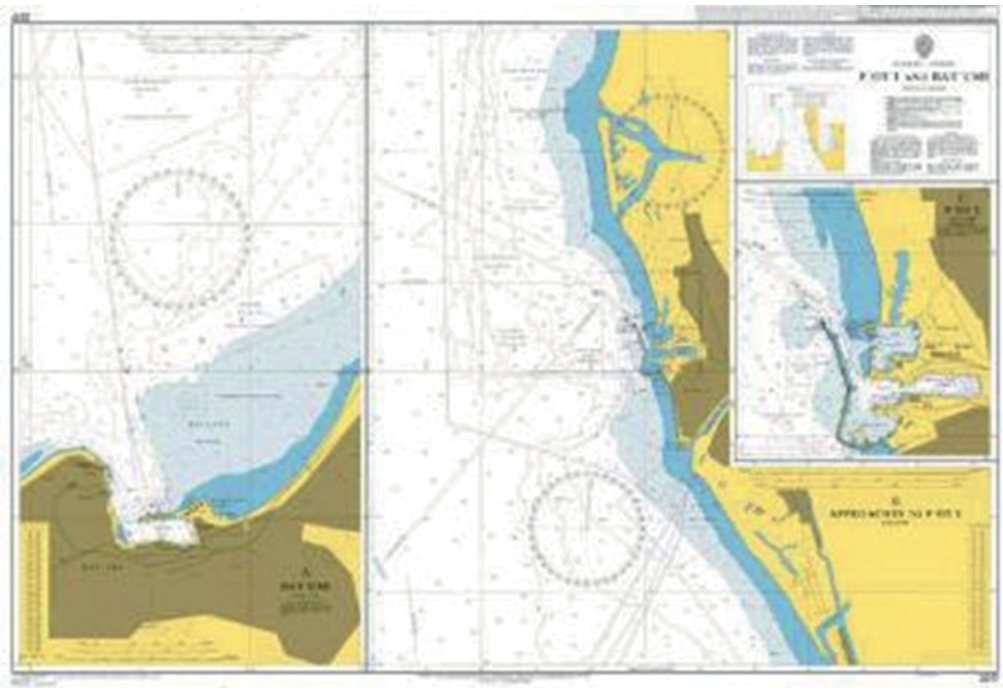


Figure 35. Nautical Chart of the Georgian Coast

This preliminary assessment indicates that while there are some bathymetrical data available, they may not be of the necessary accuracy for coastal flood modelling but, more specifically, they may not be accurate enough for wave and storm-surge modelling. It should be noted that the bathymetry has a major influence on the results from wave and storm-surge modelling.

- Coastal data: information about waves and the sea-level will be critical for the implementation of any coastal model (waves, storm-surge, or coastal flooding) as it will determine the possibility of calibrating such models. There are two tide gauges on the coast of Georgia, in Poti (Figure 36) and Batumi, and there is information about a wave buoy having been deployed in Batumi until 1991,[9] although it has not been possible to collect the data from this wave buoy.

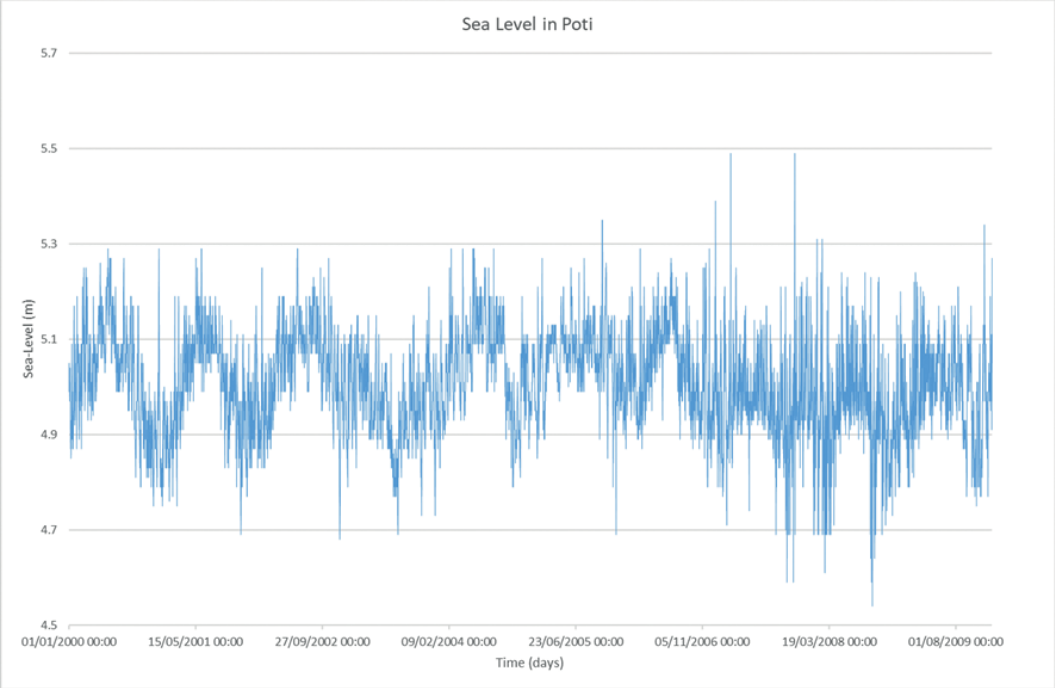


Figure 36. Sea-level in Poti

- Flood and coastal defences: the location and details of flood barriers, seawalls and levees located on the coast. It should be noted that it is expected that several coastal defences will be present on the Georgian coast such as groynes and breakwaters for erosion/sedimentation purposes. Although in the long term these structures will benefit the coastal flood magnitude, it should be noted that they are not relevant from a coastal modelling point of view.
- There is no information about coastal flood defences available. This is a major issue and while more efforts will be paid to the collection of these data, the acquisition of this information is not expected. This could have a significant influence on the results. In order to overcome this, the commissioning of a survey to collect these data would be recommended if a list of flood coastal defences becomes available.

9. S. Khorava, A. Kikava. (2015): "Protection of Ajara Coast Zone by an Artificial Beach." Proceedings of International Conference Applied Ecology: Problems, Innovations. Ltd Kalmosani Publishing Georgia, pp. 192-197

5.5 Artificial Water-bearing Structures

As per other flood sources, the specific requirements for AWBS flooding will be detailed in this section. Additionally, only the additional data sources will be detailed as the other ones (such as land-cover or topographical information) have been discussed in detail in previous sections. The main data source to consider for AWBS flood modelling is information about the structures themselves.

- Details of dams and flood defences: these, as noted, are the most relevant data needed for AWBS flood modelling (apart from the DEM). In section 5.5.1 below, the data details needed for dam breach modelling are outlined. It is important to consider that these data details assume that the locations and basic characteristics of every single infrastructure to consider are already collected.

The only information available at this stage is a list of reservoirs (Table 14).

Table 14. List of Reservoirs in Georgia

Reservoir	River	Volume, mln m³		S, surface area, km²	Depth, m		Function
		T, total	P, power storage		T / S	P / S	
Jvari	Enguri	1,092	662	13.5	80.9	49	Power generation
Shaori	Shaora	71	68	13.2	5.4	5.2	
Tkibuli	Tkibuli	84	62	11.5	7.3	5.4	
Gali	Eristskali	145	26	8	18.1	3.3	
Lajanuri	Lajanuri, Tskhenistskali	12	16	1.6	7.5	10	
Gumati	Rioni	39	13	2.4	16.3	5.4	
Vartsikhe	Rioni, Kvirila	14.6	2.4	5.1	2.9	0.5	
Zhinvali	Aragvi	520	370	11.5	45.2	32.2	Multipurpose
Sioni	Iori	325	300	14.4	22.6	20.8	
Tsalka	Ktsia-Khrami	312	292	34	9.2	8.6	
Tbilisi	Iori	308	155	11.8	26.1	13.1	
Dalismta	Iori	140	120				
Algeti	Algeti	65	60	2.3	28.3	26.1	Irrigation
Zonkari	Patara Liakhvi	40	39	1.4	28.6	27.9	
Jandari	Mtkvari	52	23	12.5	4.2	1.8	
Nadarbazevi	Didi Liakhvi	8.2	7.2	2	4.1	3.6	
Narekvavi	Narekvavi	6.8	5.6	0.56	12.1	10	
Pantiani	Mashavera	5.4	5.3	0.6	8.6	8.5	
Kumisi	Mtkvari	11	4	5.4	2	0.7	
Kudigori	Duruji	3.5	3.5	3	1.2	1.2	
Zahesi	Mtkvari	12	3	2	6	1.5	Power generation

Therefore, more detailed information of each of the reservoirs or dams is not available at the moment. It is paramount that details of critical dam and flood defence infrastructure are collected as soon as possible and analysed.

- Details of historical and recorded AWBS flooding in Georgia: the records of previous historical AWBS flooding would need to be collected and analysed. Any collected data will be analysed in detail at this stage and will be used for calibration and validation purposes. It should be noted that AWBS flooding is usually not recurrent (dams or structures are usually destroyed or decommissioned after failure) and, therefore, calibration may not be possible with the collected data. No data have been obtained at the moment.
- DEM data: the DEM input for AWBS modelling should consider the area immediately downstream of each of the structures. It should be noted that at this stage the derivation of the dam breach flows (hydrographs) is not expected to be implemented using physical modelling and that an empirical approach is suggested. Therefore, the DEM information in the exact location of the structure (or upstream of them) is not a significant requirement. The implementation of the hydrodynamic model will be undertaken with special care vis-à-vis the area immediately downstream from the structure. Due to the expected and sudden release of significant discharge quantities, the hydrodynamic model will be further refined in this location, defining a finer grid size through the inclusion of break-lines in the model domain grid. Therefore, a good quality DEM is required at this location in order to properly represent the flow dynamics immediately downstream from the structure. The main input for this would be the recently acquired LiDAR data (Figure 7). Other sources of DEM data can be considered as was outlined above in the fluvial flooding section.

5.5.1 Dam and Flood Defence Details

In order to implement both the empirical and the physical dam break models, the following information will be needed.

Table 15. Data Needs

Dam or Flood Defence Data
Maximum height of the dam
Maximum depth of water stored behind the dam
Volume of water behind the dam
Reservoir surface area
Dam crest top width
Dam bottom width
Average dam width
Side slope of dam
Slope of downstream dam face
Slope of upstream dam face
Dam length
Properties of Dam Material
Earth fill type
Porosity (if required)

As noted above, it is recommended that an empirical approach is used to calculate the dam/flood-defence flow hydrograph as a result of the breach of the structure. Structure breach modelling involves the study of dam or flood defence breach parameters and using them to predict reservoir or river outflow hydrographs which are then routed downstream of a river reach.

Empirical models are derived from test case studies or observed dam failures but are not process-based. They are only able to provide the user with an estimated peak breach discharge and a time to peak discharge and require a prior knowledge of the structure geometry (e.g.. its height, width, length) and/or the reservoir (e.g., its volume, depth, and surface area) which can be used in a simple equation.

Several empirical models have been developed in order to define the breach outflow hydrograph in a dam or flood defence failure event. These models estimate the peak outflow discharge and the time required for the flow rate to rise to the peak as a function of dam and/or reservoir properties. Most of the formulas were developed by a regression analysis of case study data from real dam failures. These formulas offer a means for estimating the complete breach hydrograph if one assumes a hydrograph shape and knows the volume of the water to be released through the breach. The most commonly assumed hydrograph shape is triangular. The most widely applied peak-flow prediction equations have been those of MacDonald & Langridge-Monopolis[10] (1984), Costa[11] (1985) and Froehlich[12,13] (1995 and 2004). An analysis by Wahl[14] (2004) found the Froehlich (1995) equation to have the lowest uncertainty of the peak flow prediction equations available at that time.

The advantages of this approach are its simplicity and quickness which makes it useful as a screening tool for analysing large dam and flood defence inventories and it offers a quick way to check the reasonability of the results from other methods. The disadvantages of this approach are the fact that none of the equations includes factors related to material erodibility and the time parameters predicted by these equations help define the shape of the hydrograph but do not fully answer the question of how much warning time is available prior to the release of peak outflow. The issue of the warning time, however, is not significant for hazard mapping. The time parameter predicted by these methods is the rise time of the hydrograph from the end of the breach initia-

10. T.C. MacDonald, J. Langridge-Monopolis. (1984): "Breaching Characteristics of Dam Failures." *Journal of Hydraulic Engineering*, 110,5, pp. 567–586.

11. J.E. Costa, R.L. Schuster. "The Formation and Failure of Natural Dams." *Geological Society of America Bulletin*, vol. 100, pp. 1054-1068.

12. D.C. Froehlich. (1995): "Embankment Dam Breach Parameters Revisited." Proceedings of the 1st International Conference on Water Resources Engineering, American Society of Civil Engineers, New York, pp. 887–891.

13. D.C. Froehlich. (2004): "Two-dimensional Model for Embankment Dam Breach Formation and Flood Wave Generation." Proc Dam Safety 2004, 21st Annual Conference of the Association of State Dam Safety Officials, Association of State Dam Safety Officials, Lexington, Ky.

14. T. Wahl. Dam Breach Modelling – An Overview of Analysis Methods. Joint Federal Interagency Conference on Sedimentation and Hydrologic Modelling. June 27 - July 1, 2010.

tion to the time of the peak outflow. The end of the breach initiation is the time at which erosion through the embankment has progressed to the upstream side of the crest. Prior to this, the time from first overtopping or the first observable seepage flow of concern to the end of the breach initiation can be lengthy, especially if the embankment is erosion resistant.

A more detailed assessment of recent empirical methods should be undertaken within the framework of the FHRM and their applicability to Georgia depending on data availability.

As stated above, the Froehlich approach was determined to be the most accurate in terms of peak flow predictions and this is the recommended approach considering the information available at this stage. The following data would be needed for the implementation of this method (Figure 37):

- Failure mode: either piping or overtopping.
- Height of water over base elevation of breach (H_w).
- Volume of water in the reservoir at the time of failure (V_w).
- Reservoir surface area at H_w (A_s).
- Height of breach (H_b).
- Breach side-slope ratio (Z_b).

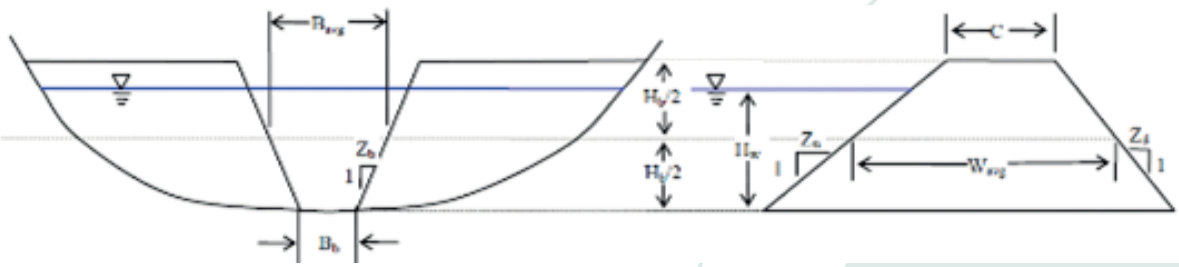


Figure 37. Dam Breach Parameters

In the case that some of the parameters above are not obtained, they could be derived from the available DEM (or from LiDAR sources). The implementation of the empirical modelling will yield:

- Average breach width (B_{avg}).
- Bottom width of breach (B_b).
- Breach formation time (T_f).
- Storage intensity (SI).
- Predicted peak flow (Q_p).

In terms of the approach and data requirements for flood defences, this would depend on the design of the actual flood defence. In the case of levees and walls, the main information requirement would be similar to that of dams, and they will be treated as such from a breach flow point of view. In this case, it would be important to get detailed information about the crest of the flood defence, preferably a longitudinal profile along the full length of the structure with data at small intervals. Other structure data requirements will have to be evaluated on a case-by-case basis. It should be added that the flood defence structures will form part of other sources of flooding modelling and that their details will be included in the modelling framework. The same modelling framework should be used for AWBS modelling, although the failure of each particular structure will be explored in this case.

Preliminary Flood Risk Assessment

1 INTRODUCTION

The aim of the preliminary flood risk assessment is to identify areas at potential risk of significant flooding (APRSFs) and is based on available or readily derivable information which includes:

- Hydrography, topography, and land-use.
- Description of floods that have occurred in the past and have had significant adverse impacts on human health and life, the environment, cultural heritage, and economic activity.
- Assessment of the potential adverse consequences of floods that can occur in the future.
- Forecast of long-term developments; particularly, impacts of climate change on the occurrence of floods.

The APSFRs identified in the PFRA do not provide the basis for spatial planning. The aim of a PFRA is not to define and assess flood risk areas precisely but to make a preliminary identification of them. Due to the nature of this assessment, two different stages can be established: namely, historically significant flooding and future (potential) significant flooding.

2 HISTORICALLY SIGNIFICANT FLOODS

The assessment of historically significant floods will be mainly based on the collection of information through a questionnaire. There are different stages that are foreseen within this assessment. It should be noted that in the case of historically significant floods, the assessment would be the same for all sources of flooding and that the collection of information will be undertaken using a questionnaire prepared for this purpose (Annex I).

2.1 Preparatory Stage

Information about past floods will be collected during the preparatory stage. This information will be collected considering Article 4.2 (c) of the EUFD. Significant past floods under Article 4.2 (c) are part of the past floods for which information from stakeholders, surveys and other sources has already been collected and systematised.

The reliability of past flood data is of great importance for meeting the requirements of the EUFD. Identifying past floods with significant adverse consequences requires a national database containing detailed information on all past events and the damage they have caused.

The EUFD explicitly states that this information should be available or easily accessible.

It should be added that while the questionnaire included in Annex I just deals with the hazard side of the past floods, the collection of information from a risk/damage point of view should also be considered. This information should be collected and organised using a database maintained by several stakeholders. From a hazard point of view, it is expected that the National Environmental Agency (NEA) will be the main stakeholder collecting these data in consideration of the nature of the questionnaire, although other stakeholders may also be relevant.

It is recommended that a database of historical floods be developed and updated periodically, at least considering the six-year period for each EUFD cycle. In this respect, it should be added that a vulnerability database will be implemented for socio-economic modelling purposes within the framework of this project.

2.2 Classification of Past Floods According to Criteria for Significant Adverse Consequences

After the collected data have been compiled, it is necessary to ascertain if a particular past flood is significant or not. The methodology for determining past floods with significant adverse consequences has several requirements regarding the input data for past floods. On the one hand, the data must present single events of a known source (fluvial, pluvial, etc.) as well as the place and time of occurrence. On the other hand, comprehensive information is needed vis-à-vis the damage caused and this must be addressed in various aspects such as the consequences for human health, economic activity, the environment, and cultural heritage (as required by the EUFD). In addition to this, a unified approach for measuring damage would also be needed in order to standardise the methodology for measuring damage and the assignation to assets, people, economic activity, and any other receptor. The damage data and assessment will not be covered within this deliverable.

Thus, the first step in the classification of past floods would be to filter them according to their extent, number and the size of the settlements that have been affected as well as their recurrence. The aim of this exercise is to identify flood events that have affected large areas and have occurred several times (significant floods). The following approach is suggested:

- Flood location criteria:
  - Number of communities affected by the same flood:
    - Criterion threshold: 3 communities.
  - Size of the affected communities expressed as the total population:
    - Criterion threshold: 500 people.

- Criteria related to the flood's characteristics:
  - Size of the flooded area within each of the affected community:
    - Criterion threshold: 100 km^2.
  - Percentage of the community that is affected:
  - Criterion thresholds: 20%.
  - Time characteristic of the flood (at least one of the specified criteria must be met).
- Recurrence of the flood
  - Criterion threshold: 3 times.
- Flood duration
  - Criterion threshold: 1 day.

As noted above, the data collected by the questionnaires must contain information regarding the flood's events, its duration, its extent, and the communities affected in order to undertake this stage of the research on past floods,. Based on previous communications with the NEA, this information is available, and it will be organised in a database in order to determine the significance of each of the past floods. The following is proposed for the determination of the flood's significance:

- Floods that meet at least three of the criteria should be considered as significant.
- Floods that meet less than three of the criteria should be excluded from consideration for past floods which could lead to significant adverse consequences in the future.

2.3 Probability of Recurrence of the Event

The EUFD treats those floods that are unlikely to recur as irrelevant. For this reason, all past floods should be checked for the possibility to happen now or again in the future. This analysis is undertaken considering the following:

- Flood mechanism: the flood occurred in a way that is impossible for it to be repeated. An example would be if a dam-breach led to flooding in a community and, subsequently, it was decided to decommission that particular dam. It can be concluded that this exact same flood cannot happen again in the future, it is not recurrent and, therefore, it is not considered further in this analysis.
- Protective measures: a check must be made to show whether structural or other measures have been taken to prevent a flood after its recurrence. Detailed information on the measures must be used for this analysis in order to demonstrate that any particular event cannot be repeated in the future.

In order to undertake this analysis, additional information is needed for the flood mechanism and protective measures considerations. For the former, as much information as possible should be collected from every source available. All of the information regarding implemented flood schemes should be collected and assessed in detail vis-à-vis a protective measures assessment. The cooperation between

the NEA and the Ministry of Regional Development and Infrastructure would be paramount at this stage. If no comprehensive information about flood protection measures is obtained, a particular flood should not be excluded from consideration.

As a result of this analysis, all of the floods that are still likely to recur in the future move on to the next step of the analysis. All of the other floods are not reported under the PFRA and are not taken into account in determining the APSFR.

2.4 Current Condition of the Flooded Area

To determine floods under Article 4.2 (c), the EUFD also requires an approach for determining any significant adverse consequences if any particular flood recurred now or in the future and in the same extent and intensity. Due to the fact that there is very often no information about the exact flood extent, the application of this criteria for determining any significant adverse consequences for past floods cannot be considered as accurate. Nonetheless, a verification of the change in the risk elements is proposed to be undertaken in order to ascertain if any potential significant adverse consequences vis-à-vis human health, economic activity and the environment will result from a flood.

In summary, the approach for historically significant floods can be summarised in the following diagram.

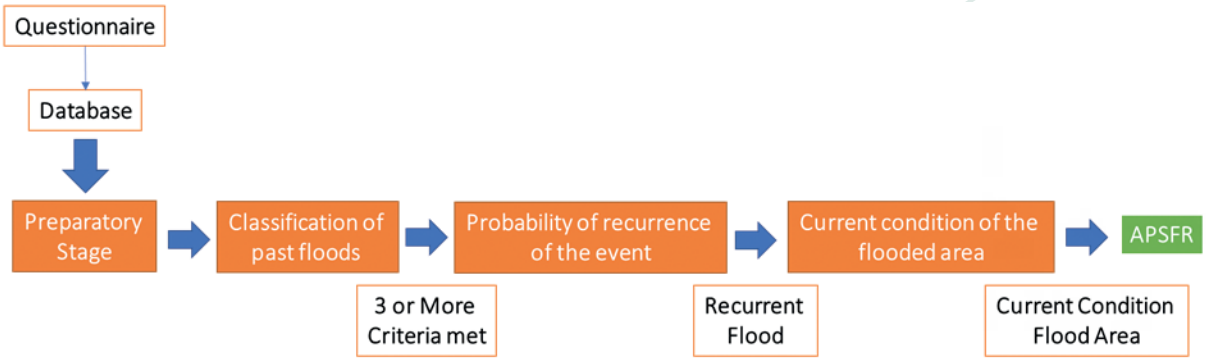


Figure 1-1. Past-flood Assessment Approach

3 Future Potential Significant Floods

The analysis of potential significant floods, in general, can be undertaken using different methods such as, for example, simplified or numerical methods in consideration of the source of flooding and the information available. The methodology for the assessment of future significant floods will be undertaken in terms of the source of flooding. As previously noted, the narrative for the methodology for this assessment will be limited because all of the river basins in Georgia will be analysed from a FHRM point of view and this entails a whole-basin approach.

3.1 Fluvial Flooding

The definition of areas with a potential fluvial flood hazard can be made by the application of:

(1) Simplified approximate methods with a limited claim to accuracy (for example, based on specific criteria such as the "horizontal distance" or the "vertical distance" of a particular area relative to the riverbed) or others.

(2) Numerical methods (hydraulic calculations and modelling).

It should be noted that a methodology for a preliminary flood risk assessment for fluvial flooding was developed[15] within the framework of the PPRD East 2 Programme.

This methodology can be summarised as follows:

- The methodology is based on the implementation of GISRAH-PFRA, a tool designed with the idea of optimising the processing chain of the PFRA and reducing the elaboration time and the overall risk assessment methodology with a semi-automatised tool that works in open-source GIS environments, i.e., QGIS.
- However, a certain degree of supervision is left to the operator to supervise the elaborations and adapt the methodology to the different catchments.
- This method is designed to produce risk maps oriented toward civil protection purposes.
- It is also important to note that the GISRAH-PFRA method is based on five categories of hazard, vulnerability, and risk: Very Low (VL), Low (L), Medium (M), Very High (VH) and High (H).
- The GISRAH-PFRA method is based on topographic data, population data, land-use data, building footprint data, the road network, and a selection of points of interest. An analysis of the hydrological and climatic characteristics of the area is also recommended.
- The preliminary flood hazard assessment of this methodology is based on the Flood Susceptibility Index (FSI), addressing both riverine and flash floods. This method is based on the methodology proposed in Samela et al., 2017[16] for the so-called Geomorphic Flood Index (GFI) which is provided by a combination of different thematic maps that describe the hydraulic, hydrological, geographical, and morphological properties of the territory. The main driver for this methodology is topographic information because the index can be directly extracted from a given DEM. The variables used to produce the GFI are the flow contribution area (A_r), the elevation to the nearest stream (H) and the water depth (h_r, computed as a function of the contributing area).

15. Support to Georgia in Approximation of the EU Directive 2007/60/EC (Floods Directive). Methodology for the Development of a Preliminary Flood Risk Assessment.

16. C. Samela, T.J. Troy, & S. Manfreda. (2017). "Geomorphic Classifiers for Flood-prone Areas Delineation for Data-scarce Environments." *Advances in Water Resources*, *102*,13-28.

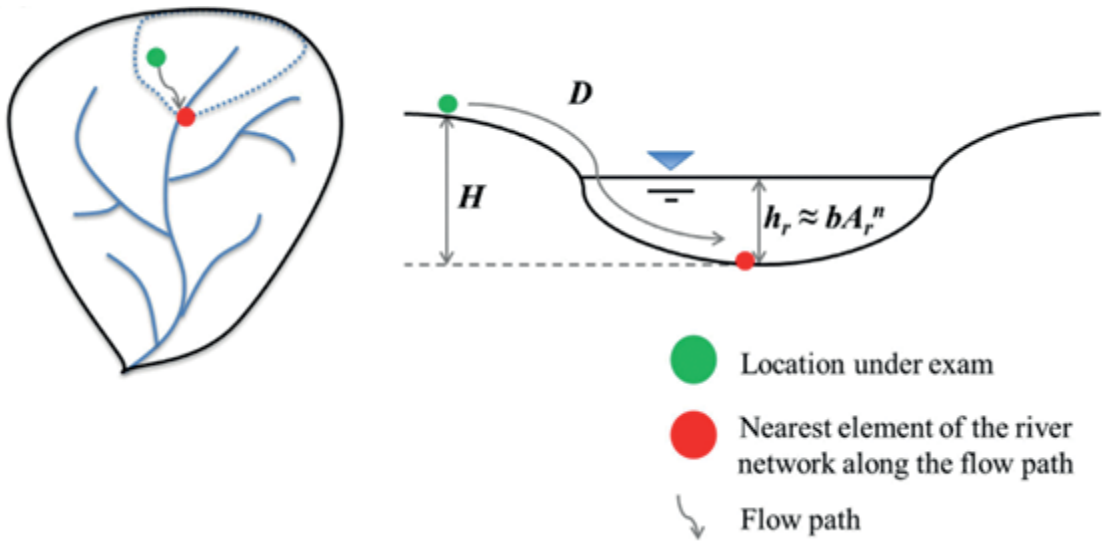


Figure 1-2. Description of the FSI Based on the GFI. Source: Samela et al., 2017

A threshold value of the GFI should be calibrated based on the comparison of the final index map with existing flood or flash-flood hazard maps. If no reference maps are available, the calibration of the threshold can be performed on the basis of simplified morphological considerations. The resulting map is finally classified considering the five abovementioned hazard classes.

- This information is further processed considering the vulnerability and the exposure in order to derive the flood risk in each of the areas. The figure below shows the results from the example in the Tskhenistskali catchment Figure 13.

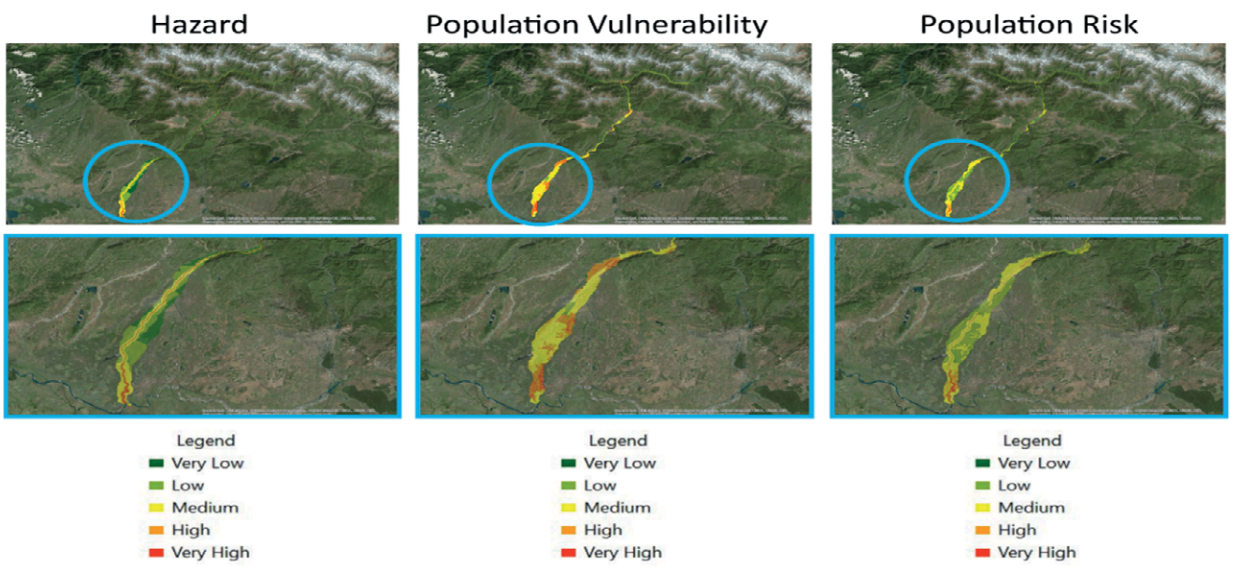


Figure 1-3. Results of the PFRA Using the GISRAH-PFRA Methodology in the Tskhenistskali Catchment

- The risk (exposure and vulnerability) approach of this methodology will not be analysed in this section. The hazard methodology, while it is robust and ensures a rapid implementation for other catchments, relies on the existence of previously derived flood maps or the calibration of results based on morphological considerations. Additionally, the water depth, as one of the main drivers of the index classification and while being calculated based on the contributing area, depends on a scale factor (b) and an exponent (n) that can be adjusted manually and have a significant impact on the results. The results depend on these two values and the topography with no direct hydrological input. A sensitivity test of these two variables would be recommended during implementation and it would be preferable to undertake an assessment in order to ensure the consistency of the results and the applicability of this method for other catchments in Georgia.

Therefore, and as previously noted, it is recommended that this method is used for future preliminary flood risk assessments in Georgia given that it has its benefits and has already been adapted by the NEA.

3.2 Pluvial Flooding

There is no existing pluvial flooding PFRA methodology used by any of the Georgia stakeholders. A brief methodology will be proposed here given that all of the river basins will be included in the flood hazard and risk mapping and that an assessment will not be undertaken at this stage.

The pluvial PFRA methodology will be based on a rain-on-grid approach. A variety of depths and intensities of precipitation over a range of durations will be used to simulate how rainfall would flow over the land and, in particular, pond in low-lying areas.

It should be noted that the PFRA assessment for pluvial flooding will be undertaken in the next cycle of the EUFD and, therefore, an analysis of rainfall events will already have been undertaken within the framework of the FHRM. The information from this analysis will provide data about different rainfall events (depth, duration, and intensity) to be used during this assessment. In addition to this, no rainfall infiltration or interception will be used during this stage. In urban areas, the flow drained by the urban storm-water drainage system will also not be considered, assuming a conservative approach.

The modelling process, therefore, can be summarised as follows:

- Rainfall analysis and preparation: as outlined above, precipitation data from several extreme events will be analysed and processed in order to derive rainfall events with different depths, durations, and intensities.
- Rain-on-grid models will be implemented: this will be undertaken using 2D hydrodynamic models. It is suggested to create a nation-wide model covering the whole territory of Georgia with a coarse grid size (100 m or greater) in order to be able to undertake this assessment within a reasonable time range. The suggested cell size can be adjusted depending on the computing resources available. The input DEM for this assessment will be a national one derived from the

best available sources. However, no modifications will be undertaken at this stage in the DEM in terms of adding bridges, culverts, watercourses and so on. It is advisable to use the most accurate DEM available for the whole country. No upstream boundary condition will be required (this will be the precipitation). Downstream boundary conditions will only be required at the borders of the modelling domain and be located far away from the area of interest. In the coastal area, sea-level boundary conditions will be used. Inland, normal depth boundary conditions will be used. Information on the roughness will be derived from national/global sources for the whole model.

This process will produce maps of areas likely to flood from intense rainfall events for several flood event probabilities. In order to determine the significance of the predicted flooding, a flood depth threshold is suggested (i.e., 200 mm). This suggested depth should consider the floor depth usually present in particular areas. It should be added that a surface area threshold should also be used in order to define areas that are significant (i.e., 100 m^2).

The results from this process should be combined with vulnerability and exposure information to define the preliminary risk assessment for pluvial flooding.

3.3 Groundwater Flooding

The methodology used to map areas potentially prone to groundwater flooding will be based on existing information and local knowledge as compared to other flood sources where a modelling approach may be suggested. There are several reasons behind this but the main one is that implementing a groundwater model and linking this to a surface area model is very demanding (especially from a data point of view) and, therefore, this is not recommended.

The historical information which was collected indicated that the vast majority of extensive and recurring groundwater floods in Georgia originates at karts locations (Figure 14) and, therefore, the focus of the groundwater PFRA assessment will be on those areas.

The following methodology is proposed for the mapping of potential groundwater extents from groundwater areas:

1) To collect and assess information from past groundwater flood events. This is line with the historically significant flood activities as outlined above. However, in this case it is recommended that a more detailed analysis is undertaken, considering ground-based observation, aerial photography, or satellite imagery. These data sources will be used to derive the flood extent and impact.
2) The delineation of flood extents around groundwater springs based on an assumed height of flooding of 4 metres above the base elevation of the spring (and comparing this against the DEM following a water level projection method).
3) The use of records of past groundwater flood events to validate or adjust the flood extents derived using the other approaches.

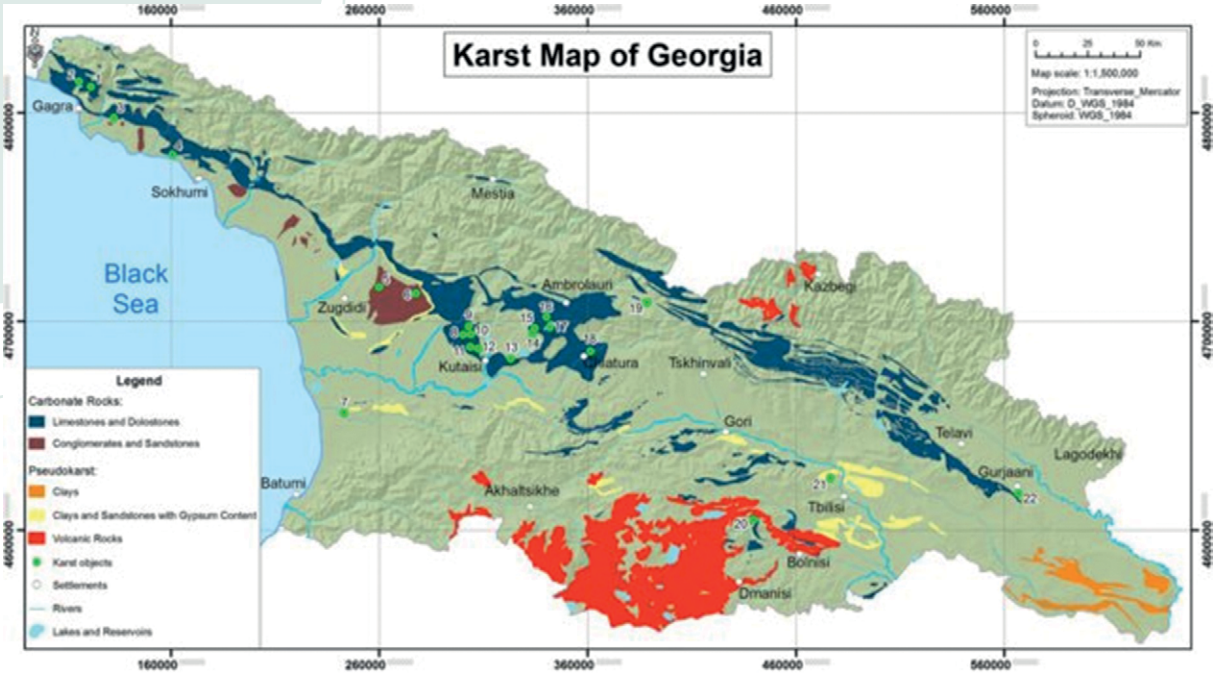


Figure 1-4. Karst Map of Georgia (Source: Asanidze et al., 201917)

The results from this process should be combined with vulnerability and exposure information to define the preliminary risk assessment for groundwater flooding.

3.4 Coastal Flooding

Coastal flooding can be caused by a combination of several processes. Because of the different nature of this source of flooding, these processes and their influence in Georgia will be outlined here. This explanation is valid for both the PFRA and the FHRM phases and, therefore, it will not be reproduced in the section on coastal flooding. The relevant processes are:

- Tide: the astronomical tide varies around the seas and oceans associated with amphidromic points (points with a zero-tide range). Enclosed seas, such as the Black Sea, have special amphidromic points and they can be explained from the direct action of the tidal forces. As a result, these seas have a much smaller tide range with water levels that approximate the "equilibrium tide" and with tidal forces playing a locally subordinate role. As can be observed in Figure 15 below, the amphidromic point for the M2 constituent in the Black Sea is located in the centre of the basin and the tidal range for this is in the order of centimetres.

17. Lasha Asanidze, Zaza Lezhava, Kukuri Tsikarishvili, George Gaprindashvili, Nino Chikhradze and Jason Polk. (2019). "Karst Map of Georgia (Caucasus Region) scale: 1:1,500,000." *Carbonates and Evaporites* 34:1205-1212.

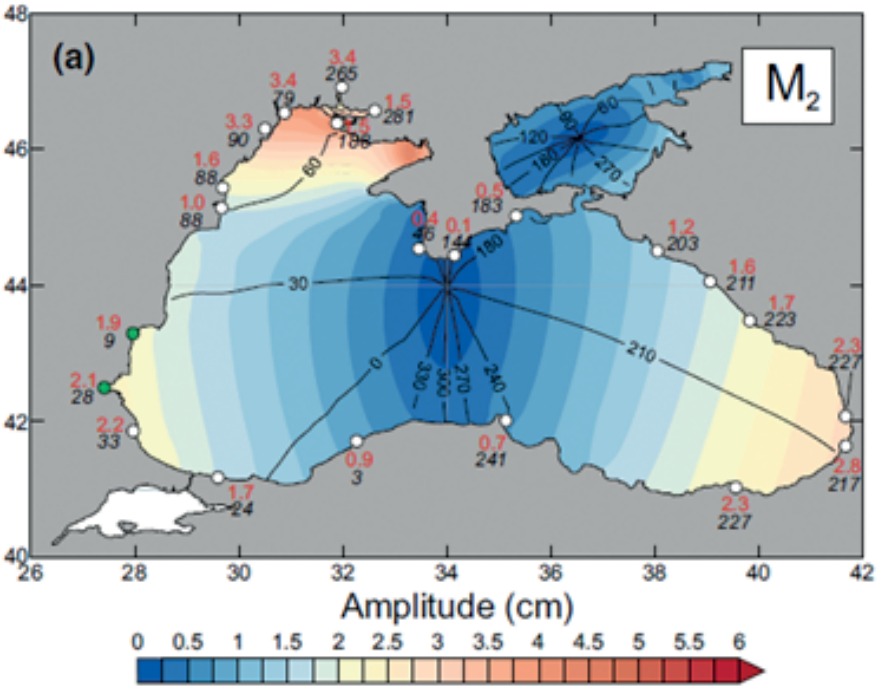


Figure 1-5. Tidal Maps of Amplitudes (Shaded) and Co-tidal Lines (Solid Lines) in Degrees of (a) Semidiurnal Harmonic M218

- Storm-surge: coastal storms create storm-surges or wave set-up along the coast. Its impact on coastal areas can be differentiated into surge dominated coastal areas and wave set-up dominated coastal areas depending on the coastal bathymetry as shown in Figure 16 below.

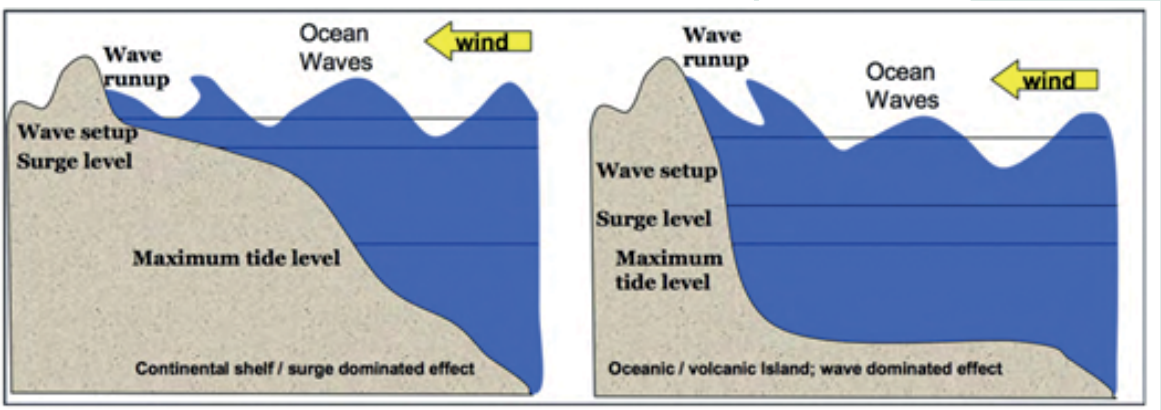


Figure 1-6. Schematic Representation of the Effects of Storms Depending on Coastal Bathymetry19

In shallow waters, wind dominates and sets the water in motion through surface drag. For strong depressions, which are associated with high and sustained winds, the surface wind drags, counter-

18. Igor P. Medvedev. (2018). "Tides in the Black Sea: Observations and Numerical Modelling." *Pure Appl. Geophysics*. 175, 1951–1969.

19. Integrated Flood Management Tools Series: Coastal and Delta Flood Management. WMO, 2013.

acted by bottom friction, leads to a water level rise or surge. The surge propagates in the direction of the wind as well as with a deflection due to the Earth's rotation. In decreasing water depths towards the coast, interactions with the seabed and the tide increase, resulting in a further enhanced wind-induced surge height along the coasts as long as the wind maintains the effect. Depending on the presence of local sea bottom (bathymetric) characteristics plus constrictions such as river inlets and estuaries, severe storms may easily lead to peak surge heights that exceed five metres. When the wind decreases or changes direction, the surge height decreases as the water surface tends to regain its original state such as in the presence of normal tides.

- Waves: storm winds also generate and propagate surface waves referred to as the "sea-state." Waves that have been generated by winds elsewhere are called "swell." For a severe storm in the open sea, significant wave heights (an average of one-third higher than normal height waves) may reach levels of eight to ten metres or more. In shallow water moving to the coast, interactions with other water and land phenomena, breaking and further dissipation takes place which all lead to a decrease of wave height. In coastal areas with a steep bathymetry slope, the waves generated by a storm contribute to a large extent to flooding caused by the piling of water (wave set-up) and by wave overtopping.

The coastal flooding situation in Georgia with respect to the processes outlined above has been studied by several authors. The range of the tide in the Black Sea has been analysed considering all constituents. The maximum tidal range for Poti and Batumi are 12 and 11 centimetres, respectively.

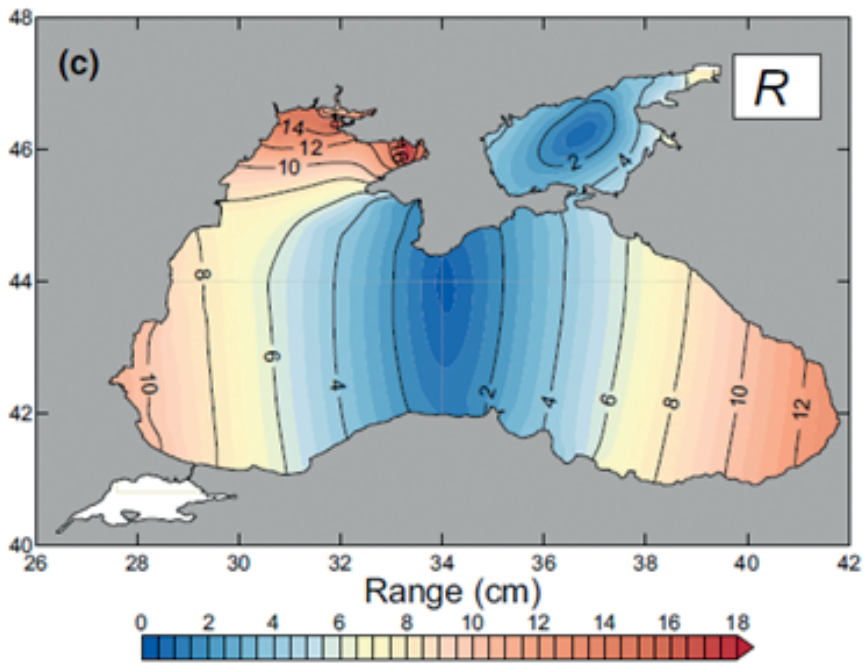


Figure 1-7. Tidal Range for the Black Sea20

20. Igor P. Medvedev. (2018). "Tides in the Black Sea: Observations and Numerical Modelling." *Pure Appl. Geophysics.* 175, 1951-1969.

The storm-surge in the Black Sea has also been studied in detail. As noted above, the decrease in water depth close to the coast showed a continental shelf pattern on the Georgian coast. Figure 18 shows the maximum 90-year storm-surge in the Black Sea with values on the Georgia coast under 0.16 metres. It should be noted that in a mostly enclosed sea and in seas with a limited tidal range (such as the Mediterranean), the storm-surge may play a more important role in coastal flooding. For instance, while the tidal range is in most locations under 0.3 metres in the Mediterranean Sea, the storm-surge may be over a metre. In the Georgian case, however, the maximum tidal range and the maximum storm-surge appear to be in the same order of magnitude (around 15 centimetres).

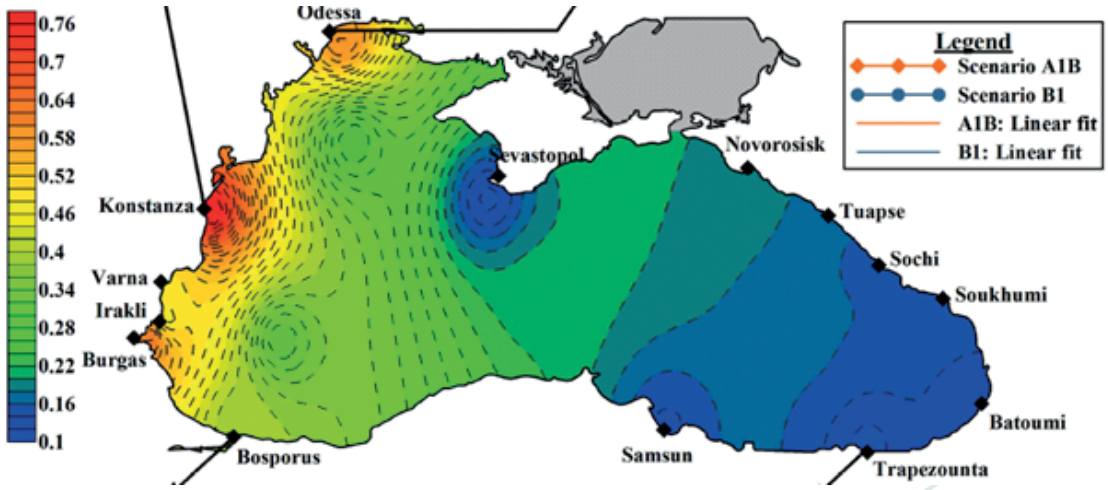


Figure 1-8. Spatial Distribution of Time-averaged (90-year mean) Values of Annual Maximum SLH21

The significant wave heights for the Black Sea were analysed by Divinsky et al. (2020) using a second generation of wave modelling implementation and running different design extreme scenarios in a pre-calibrated model. The significant wave heights for different return periods are shown in Figure 19 below. No detailed information vis-à-vis the Georgian coast is available at this stage but values between three and nine metres are predicted for the 25, 50 and 100-year return period events based on the figures below. These results are for wind-waves (sea-state) while the swell wave heights are neglected if compared to the wind-waves. This is expected considering the small surface fetch area available for long-distance waves.

Therefore, considering all of the information outlined above, it seems that waves may play the most significant role in the coastal flood dynamics in Georgia. This should be further evaluated with local observations and flood records. Additionally, a local wave model should be implemented on the coast of Georgia in order to fully understand the wave regime in this area (providing that wave gauges are not available).

21. Yannis N. Krestenitis, Yannis Androulidakis and Katerina Kombiadou. (2014). "Storm-surge Modelling in the Black Sea." Proceedings - Protection and Restoration of Coastal Zone and Open Sea Waters.

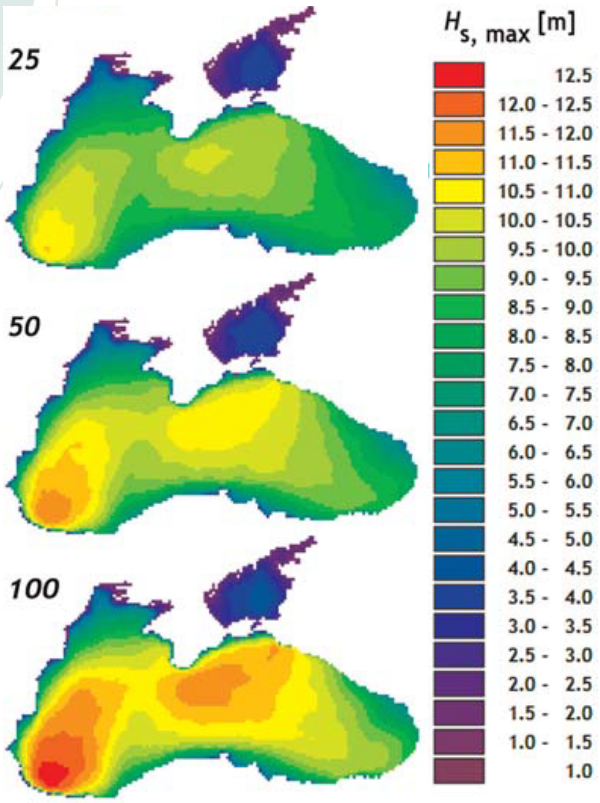


Figure 1-9. Significant Wave Height Probability Assessment (Source: Divinsky et al., 202022)

The following will be assessed during the PFRA stage of the coastal (or seawater) source of flooding:

- Analysis of historical recorded sea-levels and waves and a collection of astronomical tide predictions and harmonics.
- Statistical analysis of combined tide levels, storm-surges, and significant wave heights to estimate extreme water levels along the national coastline for defined probabilities.
- Calculation of the extent of the predictive flooding by comparing the calculated extreme levels along the coast to the ground level based on a DEM.
- This exercise will produce maps at a strategic level to provide an overview of coastal flood hazard and risk in Georgia.

This preliminary analysis has several limitations which are inherent of a preliminary flood hazard assessment:

- The flood extents and the ASPRFs will be determined by horizontal projection in-land of the extreme sea-levels. This approach may overestimate the extent of flooding in large flat areas as the method does not account for the inland propagation and then the recession of the flooding following the rise and fall of the water levels.

22. Boris V. Divinsky, Vladimir V. Fomin, Ruben D. Kosyan and Yuri D. Ratner. (2020). "Extreme Wind Waves in the Black Sea." *Oceanologia* 62, 23-30.

- Flood defences, structures in or around river channels and other minor or local features will not be considered at this stage of a preliminary hazard identification.
- This method does not consider possible interactions between currents and waves.

This process will produce maps of areas likely to flood from different extreme sea-level event probabilities. In order to determine the significance of the predicted flooding, a flood depth threshold is suggested (i.e., 200 millimetres). This suggested depth should consider the floor depth usually present in particular areas. It should be added that a threshold of surface area should also be used in order to define areas that are significant (i.e., 100 m^2).

The results from this process should be combined with vulnerability and exposure information to define the preliminary risk assessment for coastal (seawater) flooding.

3.5 Artificial Water-bearing Infrastructure Flooding

Flooding of land by water arising from artificial water-bearing structures (AWBS) or the failure of such infrastructure is also considered in the European Union Floods Directive. This source could include flooding arising from sewerage systems (including stormwater, combined and foul sewers), water supply and wastewater treatment systems, artificial navigation canals and impoundments (e.g., dams and reservoirs).

These human-made systems contain water and has the potential to fail with the resulting escape of water able to cause flooding. Examples of this include burst water mains or drainage pipes as well as failures of pumping systems, dams, or breaches in flood defences. This type of flooding is not only confined to locations usually considered at risk of flooding, although low-lying areas and areas behind engineered defences are at a greater risk. Often the onset will be rapid as the failure of a system will lead to an escape of water at a high pressure and velocity: dam failure, for example, may be devastating as the volume and speed of the water is typically large. The failure of embankments, levees or dikes also has the potential to cause devastating floods which may persist for a long time where the water has few escape routes.

In order to determine the type of infrastructure that should be covered within this analysis, the following should be noted.

- Canals will be covered in the fluvial flooding methodology. These structures are being surveyed and included in the fluvial assessment as 'river reaches.'
- Sewerage systems will not be considered within the implementation of the Floods Directive due to data constraints. Nonetheless, a brief summary of a suggested approach for the sewerage system flood source will be proposed in the FHRM methodology.
- No significant impact is expected from water supply and wastewater treatment systems in Georgia and, therefore, these will not be considered.
- Dams (including water supply reservoirs) and flood defences will be considered in detail. The main constraint for these structures at the moment is the lack of information.

The proposed methodology for the assessment of dams and flood defences is briefly outlined below:

- Data collection and analysis: information about the locations and characteristics of flood defences and dams will be collected and analysed.
- Hydrological assessment: a brief assessment will be undertaken in this PFRA in order to derive plausible and realistic breaching flows for both dams and flood defences. This assessment will not be as detailed as the one that will be carried out within the FHRM, and it will be based on preliminary information.
- Basic hydraulic routing: a basic hydraulic model will be used to route the preliminary hydrological assessment flows. This basic hydraulic routing model will be implemented in a course scale and use the best available DEM information.
- Assessment of areas at potential significant flood risk: the basic hydraulic implementation will produce preliminary flood maps. It should be noted that the main driver vis-à-vis these maps will be the hydrological assessment. To determine the significance of the identified areas, a threshold will be applied for the predicted water depth (i.e., 200 millimetres) and for the flood extent (i.e., 100 m^2).

The results from this process should be combined with vulnerability and exposure information to define the preliminary risk assessment for AWBS flooding.

Flood Hazard and Risk Modelling and Mapping

1 INTRODUCTION

The provisions of the EUFD relating to flood hazard maps are contained in Article 6(3) and (4) of the Directive:

- Flood hazard maps must cover the geographical areas which could be flooded according to the following scenarios (paragraph 3):
  - Floods with a low probability or extreme event scenarios.
  - Floods with a medium probability (likely return period ≥ 100 years).
  - Floods with a high probability, where appropriate.
- For each scenario, the following elements must be shown on the flood hazard maps (paragraph 4):
  - Flood extent (area).
  - Water depths or water level, as appropriate.
  - Flow velocity or the relevant water flow, where appropriate.

For coastal areas where an adequate level of protection is in place (paragraph 6) and for areas where flooding is from groundwater sources (paragraph 7), the preparation of flood hazard maps should be limited to the scenario with a low probability or extreme event scenarios.

Flood events with a low probability are defined as events with a statistical return period much lower than one in 100 years. Examples of extreme event scenarios include:

- Failure of flood protection infrastructure.
- Joint occurrence of a flood event with a low probability of return in a coastal region (storm-surge) and a fluvial flood event with a low probability of return.
- Unfavourable combination of a flood event with a low probability of return in conjunction with a structural or other form of interference in the discharge, e.g., construction faults, bridge, or outlet blockage scenarios, etc.

In coastal areas where adequate protection is in place, potentially adverse consequences are only to be anticipated in extreme event scenarios.

As frequent flood events can also have significant impacts, it is recommended that a ten-year flood event (or similar event as agreed within the NEA and the project implementation unit) should be

depicted for inland waters, excluding extreme flood scenarios and flood events with a return period of 100 years. For each of these three scenarios, the flood hazard maps should show the water depth (or water level), the flow velocity where appropriate, and based on the calculation procedure selected and the information yielded. These pre-requisites will be agreed with the risk side of the implementation.

In areas of overlap between potential hazards from storm-surge events and/or fluvial flood events (or any other combination of sources of flooding), a separate identification and a joint depiction of the inundation areas are recommended for all scenarios. This will be addressed in more detail in the methodology.

2 Principles of Flood Hydraulic Modelling

2.1 The Need for Flood Hydraulic Modelling

Flood hydraulic models are implemented to obtain predictions of quantities useful for the management of floodplain systems such as discharge, water surface elevation, inundation extent and flow velocity.

A flood hydraulic model is an estimate of the processes that are perceived to be relevant to the application and may be tested by comparison to analytical solutions, scale models or field data.

Compound channel flows are fully turbulent over a wide range of space scales. They are also unsteady (non-constant) in time, but it is computationally impossible to simulate flows with this level of complexity. Fortunately, the processes perceived by modellers to be relevant to the accurate simulation of floodplain flow for a particular purpose are typically a small sub-set of known physical mechanisms. Therefore, one of the critical steps in selecting an appropriate numerical modelling framework for floodplain flows is to identify those processes that are relevant to a particular modelling problem and decide how these can be discretised and parameterised in the most computationally efficient manner.

Floods are one of the most destructive and recurring natural disasters all over the world. This is also the case in Georgia where floods from different sources have caused several disasters in recent years. One of the crucial tasks in quantifying the damage estimation of flood events is determining the reliable prediction of the potential extent and water depth of a flood inundation. Thus, flood inundation modelling results are used to provide detailed information for decision-making vis-à-vis future urban planning design.

One of the key objectives of flood inundation studies is to provide information for minimising the susceptibility and the vulnerability to loss in both the economy and in terms of human lives within a floodplain and, therefore, it is necessary to use flood hydraulic models to simulate and predict the flood hazard.

The principle of flood hydraulic models is to allow the upstream flood flow to discharge directly to the

downstream flood extent. These models become valuable and helpful flood predictive tools which are able to be applied in different real and virtual scenarios for analysis.

2.2 Hydraulics Theoretical Background

A brief discussion of the hydraulics theoretical background will be provided in this section. This will not be a comprehensive theoretical review as this would be outside of the scope of this methodology document. Rather, it will provide some insight vis-à-vis the main assumptions and equations used in flood hydraulic modelling.

2.2.1 Some Basic Concepts and Equations in Hydrodynamics

The following equations and concepts will be introduced; namely, the continuity equation, the Euler equations, and the Navier-Stokes equation. Hydraulic models use these equations in order to route the flow as defined in the boundary conditions. The way these equations are solved depends on the software used as well as the available schemes.

2.2.1.1 Continuity Equation

For a cubical element of fluid (control volume) of density ρ and velocities u, v, w along the axes x, y, z, from considerations of mass conservation, the continuity equation can be expressed as:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) + \frac{\partial}{\partial z}(\rho w) = 0 \qquad (1)$$

2.2.1.2 Euler Equations

The differential form of Newton's second law of motion for fluid flow in a pressure field without friction results in:

$$-\frac{\partial \rho}{\partial x} + \rho X = \rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} + \frac{\partial u}{\partial t}\right) \qquad (2)$$

$$-\frac{\partial \rho}{\partial y} + \rho Y = \rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} + \frac{\partial u}{\partial t}\right) \qquad (3)$$

$$-\frac{\partial \rho}{\partial z} + \rho Z = \rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} + \frac{\partial u}{\partial t}\right) \qquad (4)$$

where ρX, ρY and ρZ are body forces/unit volume in the directions x, y, and z.

2.2.1.3 Navier-Stokes Equations

Introducing the definition of dynamic viscosity as the ratio of shear intensity τ in the x–y plane to the rate of angular deformation and by adding the effect of viscosity to account for frictional forces and shear stresses to the Euler equations (2, 3, 4), the Navier–Stokes equations can be obtained:

$$-\frac{\partial \rho}{\partial x} + \rho X + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) = \rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} + \frac{\partial u}{\partial t}\right) \qquad (5)$$

All hydraulic models, independently of the dimensionality, solve the Navier-Stokes (5) equations for calculating the discharge at all pre-defined locations. The only change undertaken vis-à-vis these equations is related to how this equation is integrated depending on the dimensionality.

There are some other equations or numbers worth noting in order to understand some key concepts; namely, the Manning equation and the Manning number, the Reynolds number, the Froude number, and the Courant number.

2.2.1.4 Manning Equation and the Manning Number

The Manning equation is an empirical equation that describes the relationship between the velocity in a conduit and the channel geometry, slope and a friction coefficient expressed as a "Manning n." The Manning equation describes the energy balance between gravity and friction in a conduit. It is an empirical equation because it is not based on first principles formed from theories of science and physics but, rather, it is derived from curve fitting to observed data.

$$Q = \frac{1}{n} R^{2/3} S^{1/2} A \qquad (6)$$

Where Q is the discharge, R is the hydraulic radius, S is the slope, A is the cross-sectional area and n is the Manning's Roughness Coefficient.

The Manning's Roughness Coefficient is of great importance in hydraulic modelling as it is the most common parameter used to define the roughness of a specific stream or floodplain. There are other methods for applying the roughness in a model, but it is recommended that the Manning approach is used in all implementations within this methodology.

It should be noted that the Manning number is an empirically derived coefficient that depends on many factors, including surface roughness and sinuosity. This is estimated from field inspections and photographs of river channels and floodplains, and it is adjusted during the calibrations of models.

In natural streams, the Manning number may vary along its reach and will even vary in a given reach of a channel with different stages of flow. Overbank values for a given reach can also vary depending on the time of year and the velocity of flow because summer vegetation will yield a higher Manning number value due to leaves and seasonal vegetation.

2.2.1.5 Reynolds Number

The Reynolds number (Re) helps predict flow patterns in different fluid flow situations. At low Reynolds numbers, flows tend to be dominated by a laminar flow while at high Reynolds numbers of flows tend to be turbulent. The turbulence results from differences in the fluid's speed and direction which may sometimes intersect or even move counter to the overall direction of the flow (eddy currents). These eddy currents begin to churn the flow, using up energy in the process which increases the chances of cavitation for liquids. Reynolds numbers are an important dimensionless quantity in fluid mechanics.

The Reynolds number is defined with the following equation considering that u is the flow speed (m/s), L is a characteristic linear dimension (m), μ is the dynamic viscosity of the fluid (Pa·s or N·s/m^2 or kg/(m·s)) and ν is the kinematic viscosity of the fluid (m^2/s):

$$Re = \frac{uL}{\nu} = \frac{\rho uL}{\mu} \qquad (7)$$

2.2.1.6 Froude Number

The Froude number (Fr) is a dimensionless number defined as the ratio of the flow inertia to the external field (mainly due to gravity). The Froude number is based on the speed-length ratio where g is the gravity constant:

$$Fr = \frac{u}{\sqrt{gL}} \qquad (8)$$

For Fr < 1 the flow behaves as a sub-critical flow, Fr > 1 the flow is characterised as a supercritical flow. When Fr ≈ 1 the flow is denoted as a critical flow. In flood hydraulic modelling, the calculation of the Froude number is paramount because the computational approach and the modelling requirements for boundary conditions differ.

2.2.1.7 Courant Number

The convergence condition by Courant-Friedrichs-Lewy (widely known as the Courant number) is a necessary condition for convergence while solving certain partial differential equations numerically. It arises in the numerical analysis of explicit time integration schemes when these are used for a numerical solution. As a consequence, the time-step must be less than a certain time in many explicit time-marching computer simulations; otherwise, the simulation produces incorrect results. In hydraulic modelling, a Courant Number limit can be established in order to ensure correct results. It is always recommended that the Courant Number is always under 1 during the computational process.

2.2.2 Types of Flow

The following types of flow should be considered:

- Steady and Unsteady Flow: a steady flow is when the discharge passing a given section is constant with respect to time. When the discharge varies with time, the flow is unsteady. The maintenance of steady flow requires that the rates of inflow and outflow be constant and equal.
- Uniform Flow and Non-uniform Flow: a non-uniform flow is one in which the velocity and depth vary over distance while they remain constant in uniform flow. Uniform flow can occur only in a channel of constant cross-section, roughness, and slope in the flow direction; however, non-uniform flow can occur in such a channel or in a natural channel with variable properties.
- Subcritical Flow: depths of flow greater than critical depths (depth of maximum discharge when the specific energy is held constant) resulting from relatively flat slopes. The Froude number is less than one. A flow of this type is most common in flat streams.
- Supercritical Flow: depths of flow less than critical depths resulting from relatively steep slopes. The Froude number is greater than one. A flow of this type is most common is steep streams.

2.3 Flood Hydraulic Modelling Basics

As noted, a flood hydraulic model is a representation (or simplification) of a natural process with the aim of reproducing and predicting water levels, water depths and water velocities at a specific location. Flood hydraulic models vary depending on the application and the flood source or mechanisms considered. Nonetheless, some common features can be identified and all hydraulic models for flood purposes consist of a geometry, boundary conditions and initial conditions.

2.3.1 Geometry

In order for a flood hydraulic model to simulate the natural environment during flood conditions, geometry information is required. The information contained within the geometry, or the data requirements varies depending on the dimensionality of the model, the modelling approach, the modelling implementation, and the flood processes. Nonetheless, there is some common information required within the geometry of a model such as the topography and relevant structures. The topography can be either cross-sections and/or a DEM. Within the geometry, the modelling domain; that is, the area that will be modelled, has to be defined as does the location of the boundary conditions.

2.3.2 Boundary Conditions

Boundary conditions have to be provided for the model, as a minimum, at the upstream and downstream boundaries of the domain. This is because the conditions at these locations are unknown, and information must be provided for the model.

Boundary condition data require values for each of the model's independent variables at each boundary node and at each time-step for unsteady simulations. The precise data required depend on the model, the flow regime, and the dimensionality. For instance, for a 1D sub-critical flow, the boundary data requirements, as a minimum, will consist of the flux rate across each inflow boundary and the water surface elevation at each outflow boundary. Additionally, boundary conditions can be established within the modelling domain depending on the modelling application, extent, and flow regime.

2.3.3 Initial Conditions

Initial conditions for a hydraulic model require values for each of the model's dependent variable at each computational node at time t=0. In practice, these will be incompletely known, if at all, and some additional assumptions will, therefore, be necessary. For steady state (i.e., non-transient) simulations, any reasonable guess vis-à-vis the initial conditions is usually sufficient as the simulation can be run until the solution is in equilibrium with the boundary conditions and the initial conditions have ceased to have an influence. However, for dynamic simulations this will not be the case and while care can be taken to make the initial conditions as realistic as possible, a 'spin up' period during which model performance is impaired will always exist. For example, initial conditions for a flood simulation in a compound channel are often taken as the water depths and the flow velocities predicted by a steady state simulation with inflow and outflow boundary conditions at the same value as those used to commence the dynamic run. While most natural systems are rarely in a steady state, a careful selection of simulation periods to coincide with their start with near steady state conditions can minimise the impact of this assumption.

01

Fluvial Flood Hazard and Risk Mapping

1.1 Fluvial Flooding Mechanisms

A fluvial flood results when a stream runs out of its confines and submerges surrounding areas. Floods are a natural consequence of stream flow in a continually changing environment. Flood results as the amount of water flowing into one area is greater than the capacity of the system to hold it within natural confines.

There are many influencing factors besides exceptional precipitation that can lead to or exacerbate flooding. Knowing the factors that influence the chances of flooding can help understand potential mitigation opportunities and will also be paramount to define the flood modelling strategy.

1.1.1 Flow Processing in Compound Channels

In fluvial environments, basins normally consist of a main channel and one or two adjacent floodplain areas. When a flood wave exceeds the bank's full height, water will travel rapidly over the low-lying floodplains. During a flood, the floodplain may either act as storage or an additional means of conveyance. In the language of fluid dynamics, a flood is a long and low amplitude wave passing through a compound channel with a complex geometry. Flood waves are routed downstream with speed and attenuated by frictional losses such that the hydrograph is flattened out in downstream sections.

When the bank's full height is exceeded and compound flow ensues, the principal mechanisms are momentum exchange between the fast-moving channel and the slower floodplain flow and the interaction between meandering channel flows and the flow on the floodplain. The channel-floodplain momentum exchange occurs across a shear layer which is manifest as a series of vortices with vertically aligned axes. A further vigorous momentum exchange occurs during out-of-bank flow in meandering compound channels. Here, water spills from the downstream apex of channel bends and flows over meander loops before interacting with channel flow in the next meander. These three-dimensional interactions modify secondary circulations within the channel and represent an additional energy loss in the near channel area. Floodplain flows beyond the meander belt will not be subject to such energy losses and this region may provide a route for more rapid flow conveyance.

Away from the near-channel zone, water movement on the floodplain may be more accurately described as a typical shallow water flow (typically described as one where the width: depth ratio exceeds 10:1) as the horizontal extent may be large (up to several kilometres) as compared to the depth (usually less than 10 metres). Such shallow water flows over low-lying topography are characterised by a rapid extension and retreat of the inundation front over considerable distances, potentially with distinct processes occurring during the wetting and drying phases.

1.1.2 Fluvial Flooding

As noted, fluvial flooding is a natural event that occurs in all rivers. It is usually caused by excess precipitation but can also be exacerbated by other processes/mechanisms (Figure 21).

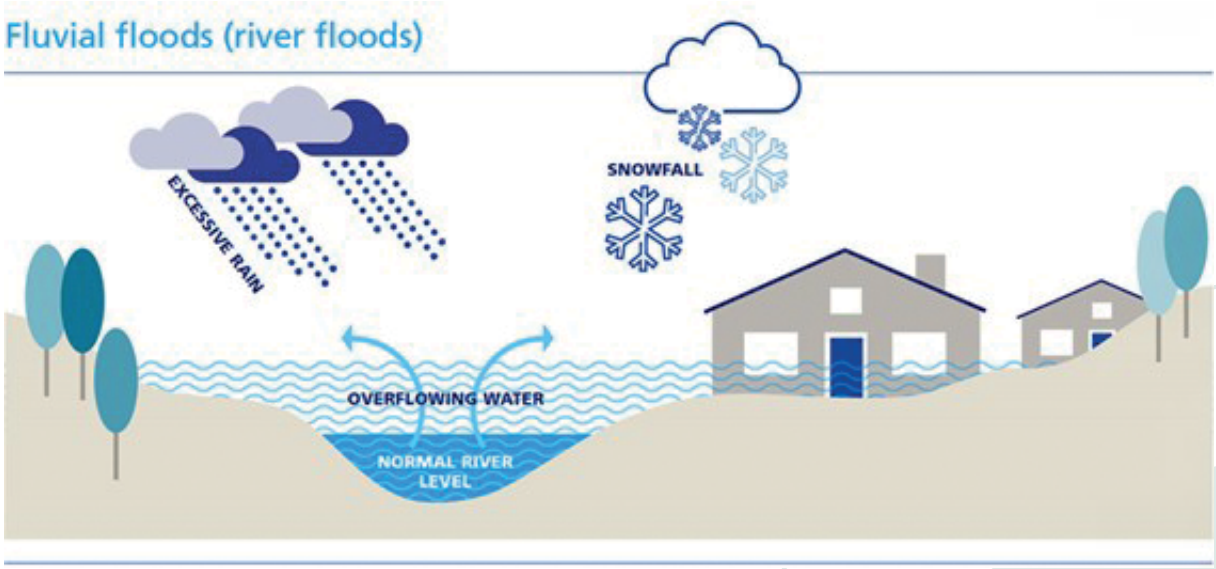


Figure 2-1. Fluvial (River) Flooding (Source: Zurich Insurance)

In terms of the source-pathway-receptor approach,[23] the following main processes can be identified (Table 16).

Table 16. Source-Pathway-Receptor for Fluvial Flooding

Source	Pathway	Receptor
Rainfall	River	Property
Snow melting	Overtopping	Population
Sea-water level	Overflow	Environment
Blockages	River	Infrastructure

23. Sayers, Gouldy, Simm, Meadowcroft and Hall. (2003). DEFRA/Environment Agency R&D Technical Report FD2302/TR1.

Therefore, the process described above should be considered in order to be able to ascertain the flood fluvial hazard in all the basins in Georgia. It should be noted that most of these processes (sources) will be considered from a hydrological modelling point of view. The pathways will be mostly addressed from a hydraulic modelling point of view and the receptors will be addressed in the risk modelling.

The main paths to consider from a fluvial perspective are overtopping, overflowing and the actual river.

There are, however, some other processes that should be considered from a fluvial point of view as will be described below.

1.1.3 Natural Processes

Fluvial flooding results (in most cases) from excessive precipitation but there are some other natural processes and watershed features that impact the intensity, timing, and frequency of riverine flooding.

- Precipitation and snowpack.
- Hydrologic characteristics (watershed slope, land cover, soil types).
- Channel shape, slope, sinuosity, depth vs. width.
- Watershed size, shape, vegetation, and sudden changes (e.g., forest fires and landslides).
- Sediment deposition and erosion.

All of these different processes will be considered during the modelling implementation. While the precipitation, the watershed features and the hydrological characteristics will be accounted for in the hydrological modelling/assessment, the channel characteristics and the possibility of sediment changes will be considered in the hydraulic modelling implementation.

1.1.4 Structural Processes

Human-made structures and development can significantly impact the flow of floodwaters through the hydrologic system. Properly designed systems can significantly reduce flooding while undersized structures can increase flooding risks and frequency. The following is a list of human modifications in natural watercourses that can impact flood risks:

- Levees, dams, and other hydraulic structures.
- Storm-water management systems.
- Channel construction and modification (straightening, smoothing).
- Stream crossings (bridges, culverts), including blockages.
- Designed basin transfers.

The importance of structures in flood hydraulic modelling should be fully considered throughout the implementation. All relevant structures will be identified, surveyed, and included into the pertinent hydraulic models. It should be noted that different blockage percentages should be tested.

1.2 Methodologies and Procedures for Fluvial Flood Hazard Modelling, Mapping and Assessment

Floods from river sources comprise the most common flooding in Georgia. Therefore, most of the monitoring and modelling capacities in Georgia (and within the National Environmental Agency [NEA]) are dedicated to this type of flooding.

1.2.1 Considerations

Some considerations have to be drawn regarding the fluvial flooding methodology:

- The fluvial flooding will address all floods coming from watercourses, independently of the time to the peak of the catchment. Therefore, flash floods will also be covered by this methodology.
- Snow-melting contributions to the flooding will also be considered. While the snow-melting source of flooding is not considered to be 'responsible' for any previous flood events in Georgia as noted above, the contribution of this source of flooding in fluvial cases cannot be neglected and, therefore, snow-melting will be addressed within the fluvial flooding from a hydrological point of view.
- The fluvial methodology will be the most detailed one within this report. There are several reasons for this:
    - As noted above, fluvial flooding is considered to be the most significant one in Georgia and all the river basins will be modelled from a fluvial point of view.
    - Data collection campaigns are already being undertaken for this source of flooding, considering international best practices for the data collection.
    - Existing data, in terms of hydrological data and also topographical data, in Georgia have historically addressed fluvial flooding. Considering the new data to be collected, the database for fluvial flooding is extensive enough to allow for the modelling of all river basins.
    - Some of the data and modelling approaches can also be used for other sources of flooding. For instance, the hydrodynamic implementation procedures for fluvial and AWBS will not differ much. Additionally, the data management procedures for the DEM will not differ much from fluvial flooding to other types of flooding.
    - The experience of national stakeholders in fluvial flooding is much larger than the ones for any other sources of flooding.

Therefore, the fluvial flooding methodology will be as detailed as possible within the context of this report.

- It should be noted that the methodology, however, will be general enough in terms of modelling software. There are also several reasons for this:
    - It is believed that it would be beneficial for a (newly formed) hydraulic modelling team to have experience with more than one software modelling package.
    - In Georgia, there are some capacities regarding the implementation of both MIKE FLOOD and

HEC-RAS. The former it is being used in the Rioni Flood Forecasting System. Recent developments in the 2D module of HEC-RAS mean that there is no need to use commercial software for 2D modelling projects at the moment but there will always be uncertainty about how modelling software is going to evolve in the future.

- Some software will be more appropriate for certain flood mechanisms while different ones will be better others and, therefore, having a plethora of software modelling capabilities is recommended.

Therefore, the methodology will be provided independently of the software to be used, although examples will be provided in order to facilitate the implementation on the most common software packages available. Given that HEC-RAS and MIKE software are the two most common ones worldwide and that these two software modelling packages are available in Georgia, a benchmarking of both modelling packages (mainly from a user point of view) it is also being provided in Annex II.

1.2.2 Fluvial Flood Hydrodynamic Modelling Methodology

The main approach for the fluvial flood hydrodynamic modelling methodology is described in Figure 2-2. This approach is actually for the whole modelling exercise, although only the hydrodynamic side of the implementation will be covered in this section.

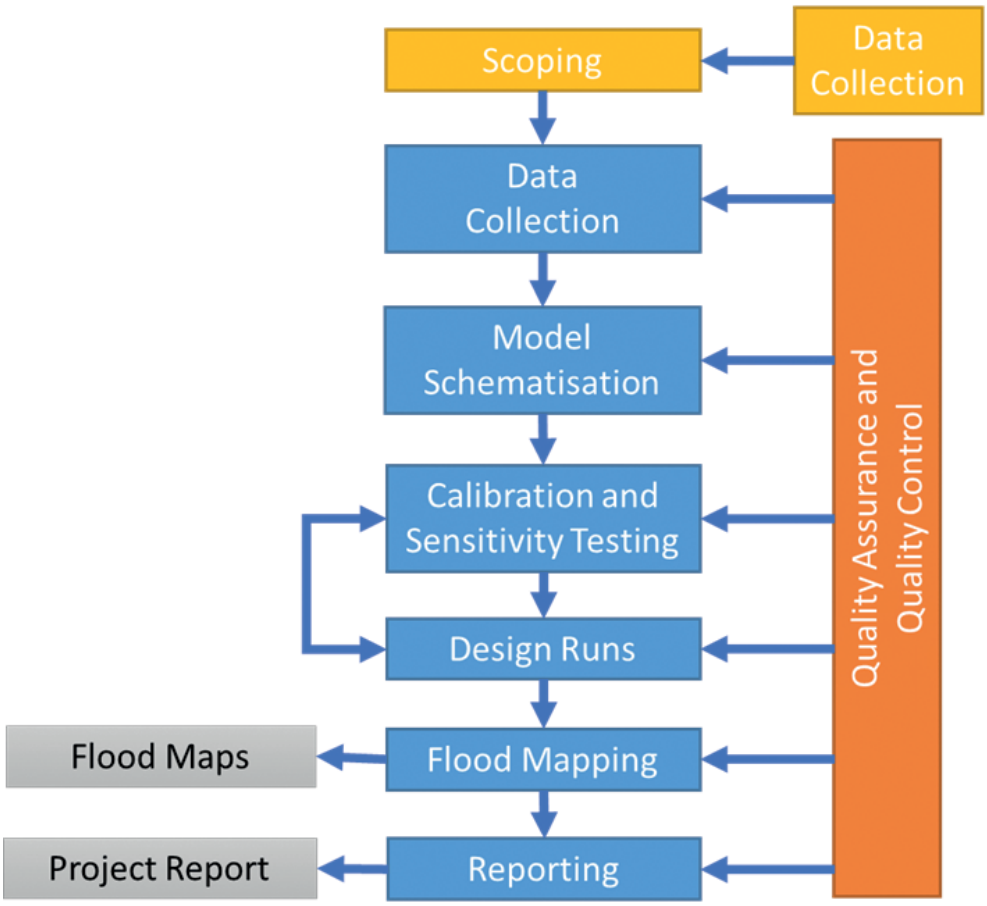


Figure 2-2. Fluvial Flood Modelling Methodology

Each of these activities will be covered in detail in the sections below. As was noted above, this will be especially detailed for the fluvial methodology.

1.2.3 Modelling Scoping

During the scoping phase of a hydrodynamic flood modelling study, different stages and activities need to be carried out such as the definition of the modelling objective, the modelling approach, the software recommendation, and the initial data assessment.

1.2.3.1 Define Modelling Objective

During the early stages of the modelling scoping activity, it is paramount to develop a clear statement of the purpose of the proposed modelling study as this will determine the level of assessment carried out. While the main purpose of the flood hazard and risk mapping is in agreement with the requirements of the European Floods Directive within the framework of this project, the objective of a flood modelling exercise may vary. It is our intention that this methodology can be used for all of the flood modelling activities to be undertaken in Georgia by national and private stakeholders. The purpose may be for flood mapping to support development planning and management or options assessment for a flood prevention scheme or a detailed design. During the scoping activity, consideration should be given to the required accuracy and the level of quality control given the purpose of the model. The required and expected study outputs should be listed as part of the modelling objective. Potential future uses of the model and the outputs should also be considered as this may enable the model to be built in such a way as to maximise reuse and ensure that necessary outputs are supplied.

1.2.3.2 Modelling Approach

The modelling approach should be as clearly defined as possible during the scoping phase. The main drivers of the modelling approach would be the flooding mechanism, the data availability, and the resources available while also considering financial, technical, and human resources. The modelling approach will first identify the flooding mechanism. At this stage, it will be important to analyse the area of interest in detail and collect sufficient information as to define the contribution from different flood sources in the study area while also considering the joint probability of different flood sources occurring simultaneously. Additionally, the probability of a flood event leading to another hazard should be noted during the modelling approach and understood from a multi-hazard point of view. A quick review of the data available should also be undertaken while considering future data sources and data to be collected (survey requirements) as this will determine the modelling approach. An assessment of the financial, time, technical and human resources to undertake the project should also be done at this stage while clearly defining the hydrodynamic modelling capabilities and resources. The modelling approach may be altered at a later stage once all of the data have been collected and a better understanding of the flood mechanism and processes is obtained. The modelling approach will be defined in detail in further sections below.

1.2.3.3 Flood Inundation Models

Different tools and software are available for flood inundation modelling, each with their advantages and disadvantages. At this stage, the different choices of numerical models that can be used have to be analysed and the capabilities of these tools have to be assessed against the different flood sources and flood mechanisms that take place in the catchment alongside describing the applicability of the different types of models to these of the processes. Based on this analysis, a recommendation for the type of model to use for a particular flood modelling study will be undertaken.

1.2.3.3.1 Elements of a Fluvial Flood Hydraulic Model

The main elements of a fluvial flood hydraulic model are described in Figure 2-3.

Figure 2-3. Elements of a Fluvial Flood Hydraulic Model

1.2.3.3.1.1 Geometry

The geometry file contains all of the information related to the topography, the structures, and the river centreline of a fluvial flood hydraulic model, both for 1D and 2D models. Additionally, the geometry specifies how these two models are linked. The approach to the geometry file specification differs greatly depending on the modelling software, although the following has to be specified in all cases:

- River centreline, including information about the coordinates for every river centre-line point. The calculation interval throughout the river centreline can also be defined in some modelling software. The river centreline also defines the modelling domain for the 1D model.
- Cross-sections profiles, including information for the coordinates for every cross-section point and its chainage. The roughness coefficients and the cross-section parametrisation (contraction

and expansion parameters) should also be defined. Additionally, some other information is also needed depending on the type of cross-section.

- Structures: all of the structures within the river will be defined in the geometry file. The approach to defining structures also varies greatly depending on the modelling software.
- Computational grid: a computational modelling grid for the 2D domain should also be defined providing that a 1D-2D modelling approach will be followed. The computational grid also defines the modelling domain for the 2D model.
- Link for the 1D-2D: the linking between the 1D and the 2D models should also be defined with different approaches and options depending on the software.

1.2.3.3.1.2 Boundary Conditions

The boundary conditions for the fluvial hydraulic model should also be defined. The boundary conditions differ depending on the modelling approach, the modelling domain and extent, the fluvial flood processes to be considered and the expected modelling outputs. Nonetheless, it should be noted that the boundary conditions will in most cases be provided by the hydrological modelling in locations previously defined and considering all of the flood processes.

1.2.3.3.1.3 Plans/Simulations

A plan/simulation relates the geometry information and the boundary conditions. Information about the simulation time-step, the simulation period and the parametrisation of the modelling should be included in the plan/simulation file as well as the output options.

1.2.3.3.1.4 Results/Outputs

The main purpose of implementing a flood hydraulic model is to have a tool that can be used to analyse a range of conditions and flood processes in a particular location. The results from the implementation of this tool are flood water extent, water discharge, water velocity and water depth at pre-defined locations within a modelling domain. The results from any modelling implementation should be analysed in detail and then exported when the model has been calibrated and validated so they can be used for flood hazard mapping and for flood risk modelling.

1.2.3.3.2 Dimensionality

Hydrodynamic models can be classified according to their dimensionality. Flood modelling methods currently widely in use can be characterised by their dimensionality or the way they combine approaches of different dimensionalities. The most significant ones are the 1D, 1D+2D and 2D methodologies because this cover most of the modelling applications necessary to support the implementation of flood risk management strategies. Three-dimensional numerical models are also available based on the 3D Reynolds-averaged Navier-Stokes equations, but significant practical challenges need to be overcome before such models can be routinely applied at the scale necessary to support flood risk management decisions.

In fact, all of the numerical model types are based on the same Navier-Stokes equation and the dimensionality varies depending on how that equation is integrated.

1.2.3.3.2.1 1D Numerical Models

One-dimensional models are based on some form of the one-dimensional St-Venant or shallow water equations which can be derived by integrating the Navier-Stokes equations over the cross-sectional surface of the flow. The assumptions used in the derivation of the St-Venant equations limit their use to where the direction of water movement is aligned to the centreline of the river channel. The 1D approach poses two main issues:

1) Floodplain flow is assumed to be in one direction parallel to the main channel, which is often not the case.
2) The cross-sectional averaged velocity predicted by the St-Venant has a less tangible physical meaning in a situation where large variations in velocity magnitude exist across the floodplain.

On the other hand, one of the principal strengths of 1D river models is their capability to simulate flows over and through a large range of hydraulic structures such as weirs, gates, and sluices.

1.2.3.3.2.2 2D Numerical Models

Two-dimensional hydrodynamic numerical models are based on the two-dimensional shallow water equations (SWE). The SWE can be derived by integrating the Reynolds-averaged Navier-Stokes equations over the flow depth. In this integration process, a hydrostatic pressure distribution is assumed. A solution to these equations can be obtained from a variety of numerical methods (such as finite difference, finite element, or finite volume) and use different numerical grids (such as Cartesian or boundary fitted, structured or unstructured), all of which have advantages and disadvantages in the context of floodplain modelling.

1.2.3.3.2.2.1 Computational Grids

The numerical method outlined above is implemented on a discretised representation of space either called a mesh or a grid. There are two types of grids: namely, structured, and unstructured grids. A structured grid is a grid that can be conceptually represented on a rectangular matrix. Any point in the matrix is physically connected to the four points on either side. An unstructured grid is a grid that cannot be represented on a rectangular matrix. The main strength of unstructured grid models lies in the possibility to follow irregular floodplain contours and to apply a non-uniform resolution. It can be refined locally to take into account fine features in the flow while keeping a low resolution in areas where refinement is not needed, thereby ensuring an optimal use of computer power. However, the finer areas usually dictate that a smaller time-step be used which can increase computation time.

Structured square grids have an obvious advantage over unstructured grids in that the construction of the physical geometry of the grid is straightforward and entirely defined by a small number of user-defined parameters such as, for example, resolution, lower left corner coordinates and dimensions (alternatively, an irregular GIS defined outline can also be used). The issue of grid generation for unstructured grids can be more complicated and time-consuming.

1.2.3.3.2.3 1D+2D Numerical Models

A number of commercial software packages include the possibility to link a 1D river model to 2D floodplain grids. This has become popular in recent years because it allows the modeller to take advantage of the established tradition of 1D river modelling while at the same time modelling floodplains in two dimensions. This also results in computational savings over structured fully 2D approaches where a finer grid would be required to correctly represent the river channel geometry.

Several techniques exist to date to link 1D and 2D models. The most widely used technique for 1D river and 2D floodplain linking is the lateral link where the exchange flows are typically modelled using broad crested weir equations or depth-discharge curves based on water level differences. A limitation of the approach is that the complicated momentum exchange processes that characterise the river-floodplain boundary are not modelled (due to the fact that these processes intimately depend on complex 3D flow patterns in the river which by definition are not resolved in a 1D river model).

Other linking approaches include the longitudinal link which one may use to model a watercourse partly in 1D (upstream) and partly in 2D (downstream) or to connect the downstream extremity of a 1D model to a 2D grid. In this approach, the flow from the 1D enters the 2D model as a “source” and the water level in the 2D model at the junction is used as a downstream boundary condition in the 1D model. Some combined 1D+2D models also offer the possibility to use small 1D components to represent pipes or culverts within an otherwise 2D model.

1.2.3.3.2.4 Advantages – Disadvantages of 1D, 2D (or 1D+2D)

The choice between a 1D or 2D (or 1D+2D) model is relevant primarily in the context of river floodplain modelling. One-dimensional models are appropriate for narrow floodplains, typically where their width is not larger than three times the width of the main river channel. The underlying assumption should be that the contribution of the floodplains to conveyance can be quantified using recent advances in the estimation of compound channel conveyance. An additional condition for such models to be valid is that the floodplains should not be separated from the main channel by embankments, levees, or any raised ground where the channel floodplain unit effectively behaves as a single channel.

One-dimensional river models have limitations that can become significant in many practical applications. The flow is assumed to be unidirectional (generally happening in the direction parallel to the main channel flow) and where this is not true (recirculation areas) conveyance predictions can be severely overestimated. Situations where floodplain flow “makes its own way” are frequent but perhaps an even more significant issue is the fact that 1D cross-sections will offer a rather crude representation of floodplain storage capacity in the case of large floodplains.

On the other hand, 2D modelling of river floodplains can itself be divided into two important classes of approaches; namely, the one where only floodplain is modelled in 2D (as part of a combined 1D+2D model) and the one where floodplain flow and channel flow are modelled as part of the same 2D grid. The main advantage of 2D modelling (over any other approach for floodplain modelling) is that local

variations of velocity and water levels and local changes in flow direction can be represented. The approach does not suffer from the limitations of the 1D. It allows in principle a better representation of floodplain conveyance but a major limitation of combined 1D+2D models for river and floodplain systems is that the exchange processes between the river and the floodplains are still modelled crudely (momentum transfer is not modelled). A major drawback of 2D models is their computational cost. Thus, the approach where the whole river and floodplain system is represented as part of a 2D unstructured grid deserves special attention.

The different advantages and disadvantages of every type of model are summarised in Table 17 below

Table 17. Summary of Numerical Model Types - Advantages/Disadvantages

Type of Model	Advantages	Disadvantages
1D	• Accurate hydraulic description in rivers/channels which are one-dimensional flow. • Less computational points relative to 2D model. • Easy to analyse and extract results.	• Flow-paths must be known beforehand. • Substantially more effort required for model schematisation • Depth and width averaged flow; no detailed flow descriptions in floodplains.
2D	• 2D flow simulated dynamically without prescribing flow patterns. • Flexibility for tailoring grid resolution within the model (unstructured grids). • Detailed information on velocity, depths, etc., on floodplains.	• Requires fine grid in rivers/channels in order to define conveyance accurately. • Requires more computational effort than 1D engine.
1D+2D	• Contains the benefits from both 1D and 2D engines. • Integration of floodplains, rivers, and coastal systems. • Visual presentation of flood results. • Allows sub-grid scale features (hydraulic structures) to be accurately represented.	• Two models must be maintained instead of one. • Computational effort.

In order to select the final dimensionality approach, the needs of the flood forecasting platform will also be considered. Flood forecasting models need to be run on a periodic basis and with a relatively high speed. Due to the high number of watercourses and associated models, a 1D approach has to be followed for the forecasting platform.

Therefore, while the modelling approach (in terms of dimensionality) will be decided on a basin-by-basin basis, the following can be summarised:

- In most cases, a 1D-2D approach will be used. While the 1D will define the channel, the 2D will define the floodplain and urban areas. The resulting 1D module will be used in the forecasting platform.
- Urban areas will be modelled in 2D.
- Even if in some areas, due to steep channels and no significant floodplain, a 2D approach will be used to model any floodplain area considering the output data needed for risk modelling (velocity, depth, and water surface elevation).

1.2.3.4 Initial Data Assessment

An initial data assessment will be undertaken during the scoping phase. The initial data available will be collected, including land-use data, hydrometric data, historical flood data and any available topographic data. Any shortcomings or additional data requirements will be flagged at this stage, the topographic survey needs will be carefully analysed, and the survey will be commissioned. More information about the topographic survey requirements and procedures is available in the 'National Guidelines for Survey for Flood Modelling' deliverable and they will not be repeated here.

The data requirements and availability for hydraulic modelling is included in Annex IV of this document.

This data assessment will need to be undertaken before any modelling activity.

1.2.3.5 DEM

The DEM data should be processed and analysed in detail. As will be noted further below, different sources of DEM data exist and the quality and accuracy of each of the available data sources should be ascertained. It is obvious that the most accurate DEM should be selected in every location. In terms of the processing of the DEM and as will be described below in the methodology, it is important to create a 'master' DEM combining all of the DEM sources that can be used for all flood sources and that covers the whole country. This procedure has been described in detail.

Regarding the DEM exporting format for hydraulic modelling, this would depend on the flood modelling software to be used. The recommendation is to work with GeoTIFF formats for HEC-RAS and with an ASC format for MIKE. This has been detailed in the data process section.

1.2.3.6 Cross-section Data

The cross-section data, as from the survey, should be analysed in detail to identify issues and/or spurious data. The following is recommended:

- It is assumed that the cross-section survey data will be available in GIS and spreadsheet format. The cross-section data will be ingested into GIS and also graphical profiles for each cross-section and will be available for each of the surveyed locations.
- Cross-sections should be surveyed from left to right (looking downstream), measuring every change in the topography. The modeller will assess that the cross-section data accurately reflect the data needs as stated in the survey brief. The location of the cross-sections in the survey brief and from the actual survey may differ due to logistic or access reasons and so it should be understood that it is not possible to collect data in the pre-specified locations in some cases. However, if that is the case, this should be justified, and alternative locations should be sought. Therefore, the modeller should flag any lack of data at this stage, especially if this may be an issue during the modelling implementation. This is especially important in Georgia where very steep and fast rivers require a significant density of cross-sections in some cases.
- The modeller will check the consistency of the survey data through the GIS or using spreadsheets. It should be checked that markers are available for each collected point, that the data is consistent and that there are no obvious spurious data.

- Cross-section points will be ordered following this left-right convention. The distance (D) from each point to the next one will be calculated using the following formula:

The distance should be calculated from point to point but the value to be used should be cumulative, considering all of the previously calculated distances.

- Abrupt changes in the profiles should be clarified as well as unrealistic values.
- The data format for cross-section importing has been discussed in other sections.

1.2.3.7 Hydrographic Data

Data from meteorological and hydrological stations are not a direct input for flood hydraulic models and the initial data assessment of these data is part of the hydrological assessments. Nonetheless, there are some recommendations for the initial data assessment.

- Precipitation data should be analysed in order to identify significant events. Additionally, it would be important to understand the influence of direct precipitation and runoff in the particular basin of the study. This information should come from the hydrological analysis, but it is important that the hydraulic modellers become familiar with the main mechanisms driving the fluvial flood.
- Temperature data, if available, should also be analysed in order to identify the possibility of the temperature contribution to snow-melting.
- The discharge from stations will also be used in the modelling. The data should be processed for gaps and for an analysis of specific events in order to understand the mechanisms related to flood events. Most of the data handling and initial assessment, however, will be done from a hydrological analysis point of view. A time-series of the discharge should be produced in a suitable format so this can be considered during the calibration of the models. Some modelling software allows measured discharge data to be ingested in the modelling framework so that comparisons and analysis can be undertaken directly. It is recommended that all of the discharge data is in an HEC-DSS format so it can be used in the HEC-RAS framework.

1.2.3.8 Satellite Data

As will be detailed below, remote sensing data are very useful for flood validation purposes. It is recommended that a database with all of the available satellite data for flood validation is created. An initial assessment of the satellite data should be undertaken at this stage, evaluating cloud cover (for optical data) and the availability of images during flood events.

1.2.4 Hydrodynamic Modelling

This section will detail the proposed hydraulic modelling methodology with the main aim of producing flood maps. From a hydraulic modelling point of view, the main purpose of this activity is obviously to define the strategy to be followed vis-à-vis flood mapping but also that the models will be used for flood mitigation (optioneering) and flood forecasting purposes.

The hydrodynamic modelling methodology can be summarised in the figure below (Figure 2.4).

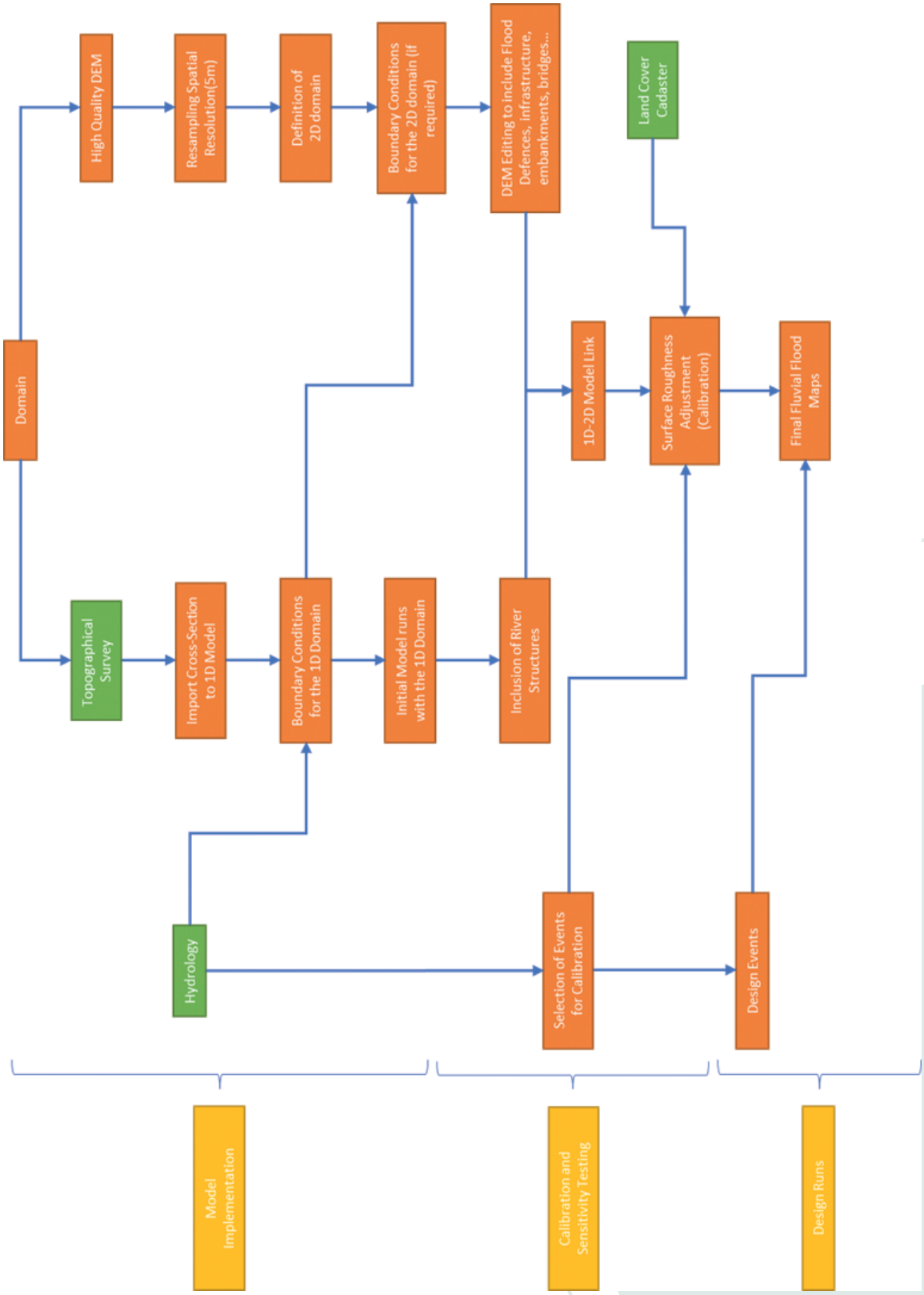


Figure 2-4. Fluvial Modelling Methodology

1.2.4.1 Modelling Domain

The selection of the modelling domain is a very important stage in the modelling process. The study's extent should be sufficient to represent the assumed flooding mechanism and the boundaries of the study area should be sufficiently far away from the area of interest and in consideration of flow controls in order to have no impact on the results. Good places to set study boundaries are areas where the flood extents are relatively constrained for large events or where there is a hydraulic control such as a weir or a tidal boundary.

Data available for calibration should be considered in setting the study's extent as extending the study area to cover calibration data may significantly improve confidence in the study's output. For fluvial studies covering gauged rivers, it is strongly recommended that the study extent covers at least one and preferably two or more gauges in order to assist in calibration. The availability of topographic data should not be used to constrain the study area where other considerations suggest that a larger area would be more appropriate. Instead, it should be the other way around so that the modelling domain determines the topographic data extent (the preference should be for additional data collection rather than a reduced study extent).

It should be noted, however, that the time required for a modelling study will increase with the study's extent. However, potential future uses of the model should be weighed against any increase in cost as a single study covering a larger area is likely to be significantly cheaper than several smaller studies and may also be more accurate and robust.

As inconsistencies between different modelling approaches may be particularly evident in urban

areas, studies should not normally have boundaries within continuous urban areas.

In summary, the following should be considered when selecting the modelling domain:

- As noted, the model domain should encompass all flood mechanisms.
- Where possible, upstream boundaries should be located close to existing or historical flow gauges for model robustness.
- Where possible, the model's extent of adjacent models should be overlapped to ensure confidence in the boundary conditions.
- Where possible, the downstream boundary condition should be placed in a hydraulic control location, a flow gauge location or a break in the floodplain.
- When the area of interest is close to a lake/sea, the model should be extended to these and use the observed water/tide level.
- When the particular watercourse is a tributary of another river, the model should be extended to include the larger watercourse if possible.
- The backwater effect of the downstream boundary condition should be avoided as much as possible, and the model should be extended as much as possible.

In the figures below (Figure 2-5 and Figure 2-6), a practical example is shown for Tbilisi for the topographical survey that will be undertaken in 2021. The cross-sections that will be surveyed are shown in Figure 2-5.

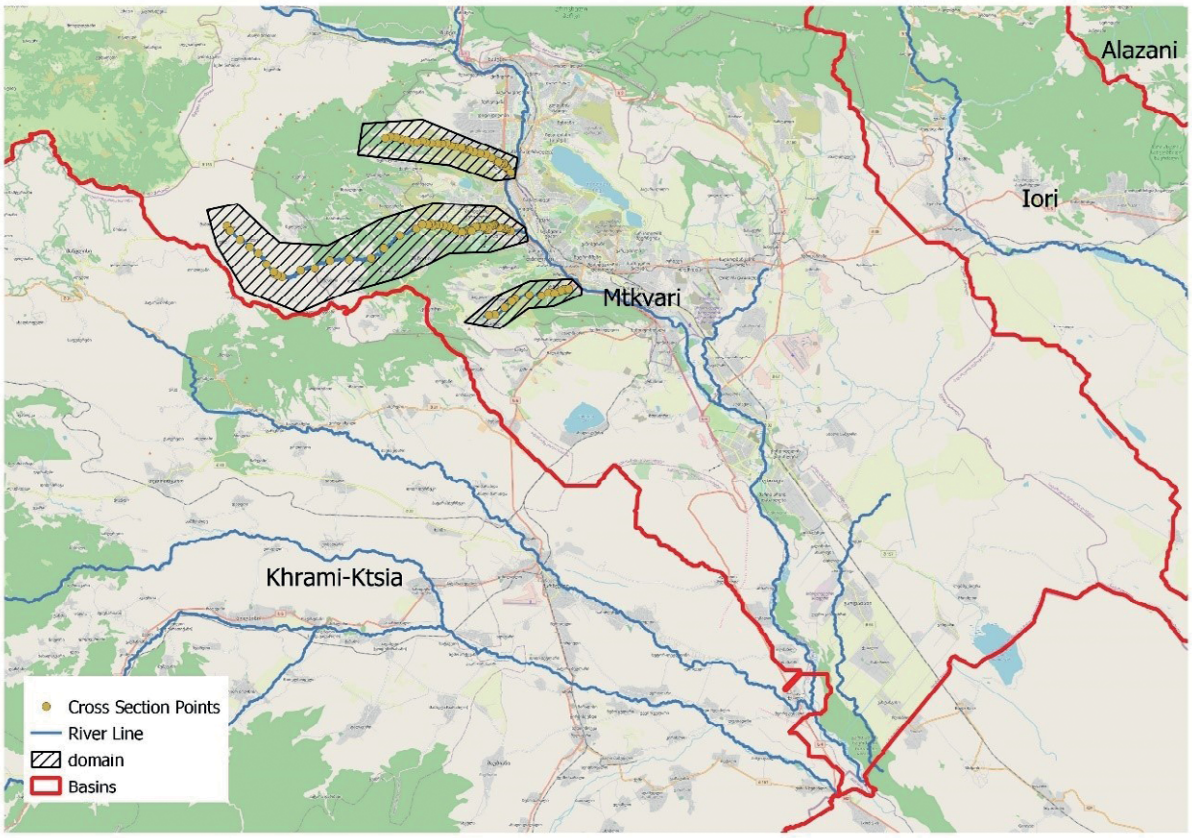


Figure 2-5. Initial Domain

While the modelling domain can be estimated initially as shown, it would be advisable that the modelling domain is extended to cover the Mtkvari River where the three tributaries are discharging in order to get a better representation of the boundary conditions downstream for these three tributaries (as shown in Figure 2-6). Moreover, the Mtkvari River will be modelled in its totality, although there is not sufficient topographic information at the moment. Nonetheless, it will be advisable to model the Mtkvari River to the downstream end even with the cross-section derived from the DEM with a large spacing. This can be further refined in subsequent stages of the project. The inclusion of the Mtkvari River at this stage, however, will increase the robustness of the modelling results for these three tributaries.

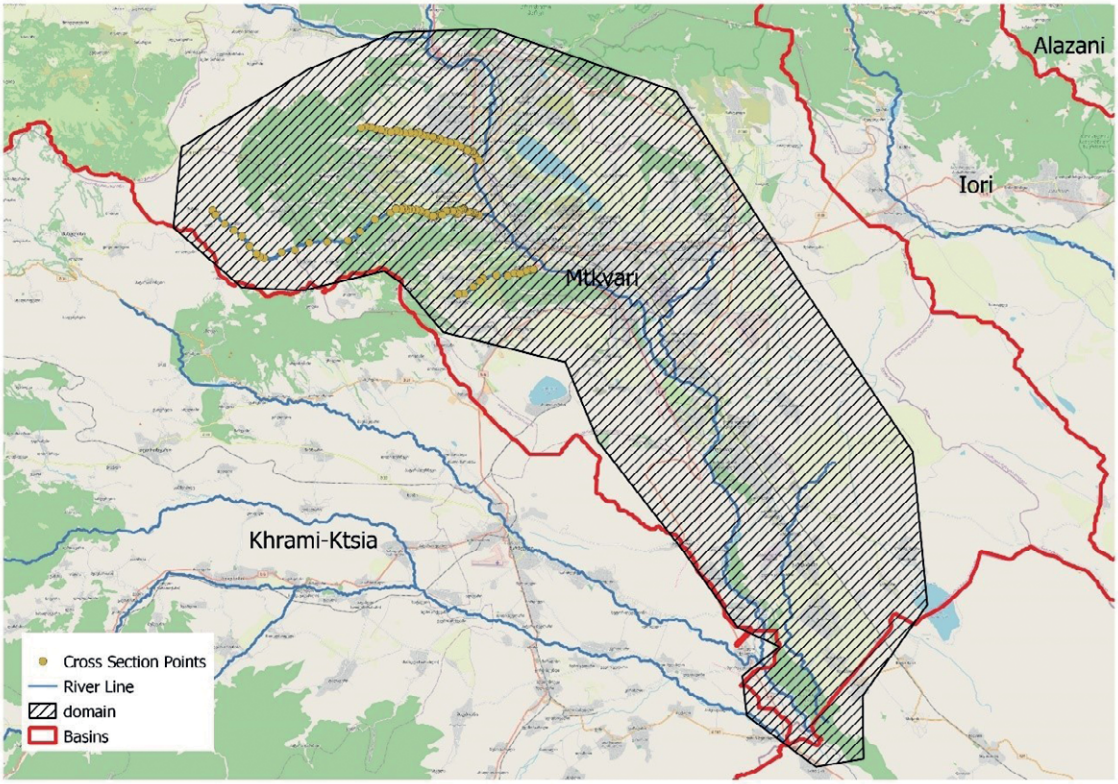


Figure 2-6. Recommended Modelling Domain

All river basins in Georgia will be modelled within this assessment with especial attention to areas with historical flood risk and to the urban and key infrastructure areas. The number of models will be limited as much as possible while trying to extend them in order to minimise their number so as to use a single model to the extent possible. Following with the example above, the full Mtkvari River will be modelled with its numerous tributaries by the end of the modelling implementation.

1.2.4.2 Numerical Model Implementation

The strategy for the model implementation will define the initial steps required for the hydraulic modelling; namely, the management of the topographic data, the definition of the model's extents, the definition of the grid and the required physical parameters such as roughness and viscosity (if required).

The modelling implementation will follow the approach outlined in Figure 2-4 and each of the activities within this methodology will be described in the following sections.

1.2.4.3 Geometry Files - Modelling Approach

The first key input file required in the numerical model will be the geometry file for both the 1D and the 2D engines. A very thorough analysis of the topographic data should be carried out before this stage. In most cases, however, the river channel (up to the top of the banks) should be modelled in 1D, and the floodplain should be modelled in 2D (Figure 2-7). Special attention should be paid to the 1D and the 2D model linking methods and to the crest height of the banks/embankments.

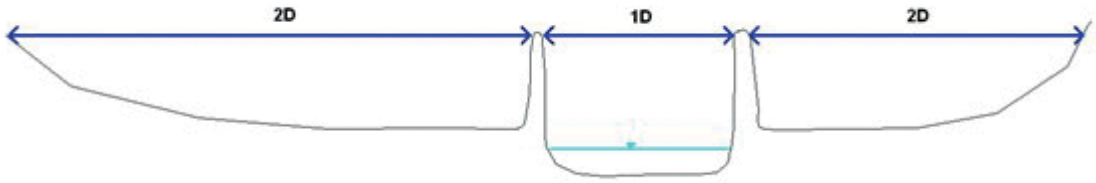


Figure 2-7. Modelling Approach

1D Module Data

In this section, the procedure for the inclusion of the cross-section data which were collected through the topographic survey into the hydrodynamic model will be described. Prior to the importing process, the collected data should be analysed in detail as discussed above.

Due to the large number of rivers and watercourses to be surveyed and modelled, an automatic importing approach should be used. No matter what the software for the hydraulic model is, the importing of the cross-sections into the modelling side of the activities should be undertaken through HEC-RAS. This is because there is a flexibility to import the cross-section to HEC-RAS and then export them to other modelling software.

In order to import the cross-sections, the comma separated value data import option should be used. This process will import cross-section geometry and it does not resolve the river network which should be resolved subsequently.

The data must be in the format of “River Station,” “X,” “Y,” “Z”, or “River Station,” “Station” or “Elevation.” More information about this can be found in the HEC-RAS manual.[24]

The modeller should review all of the information in the geometry file and start the modelling implementation, adding information about river reaches, junctions and roughness (detailed below).

It should be noted that it may be necessary to include additional cross-sections in some locations, especially due to instability issues but also for other reasons as detailed below. All hydraulic modelling software used worldwide has the capabilities for the inclusion of interpolated cross-sections.

These cross-sections should be included after the initial assessments of the model stability and for modelling reasons:

- When there is no upstream and/or downstream cross-section close to structures (due to survey issues).
- When there is a significant river length between the surveyed cross-sections (due to survey issues). The stipulated maximum length between cross-sections varies depending on the model’s

24. https://www.hec.usace.army.mil/confluence/rasdocs/rasum/latest/entering-and-editing-geometric-data/importing-geometric-data#ImportingGeometricData-GISFormat. Last accessed: 09/03/2021.

stability. In high steep sections or close to the boundaries, more cross-sections are usually required.

- In watercourses with high gradients present.

It should be added that interpolated cross-sections should only be added when necessary and that this should be documented and included in the modelling report. Additionally, it is recommended to analyse the option of using LiDAR data for the interpolation process. In most software applications, it is possible to analyse the difference between the cross-section data and the DEM data for any particular location. While it is not expected that the LiDAR data would be able to represent the full channel with a high degree of accuracy, the LiDAR survey was undertaken when the river flow was at its lowest and, therefore, this information would be valuable for cross-section interpolation. An assessment of the LiDAR data and the surveyed data can also be undertaken to ascertain the degree of accuracy of the LiDAR data for these purposes.

It should be noted that adding cross-sections (interpolated) will not always solve all of the issues in a model and that cross-sections which are too close together can also cause problems with numerical stability in some cases and lead to long model run times as the model has to be run with a small time-step.

There are some specific situations worth noting from a 1D geometry point of view. In braided channels or split flow-paths (Figure 2-8), there is a choice for this to be modelled either as a single set of cross-sections covering both flow-paths or as separate cross-sections which can be used for each branch of the channel with some representation of the flow pathway between the cross-sections. The former option would be recommended in most cases, especially if there are no significant elements at risk in that specific location. When a single section is used, the calculated water level in both channels is the same and the flow split between the channels is not calculated but this approximation would be sufficient in most cases.

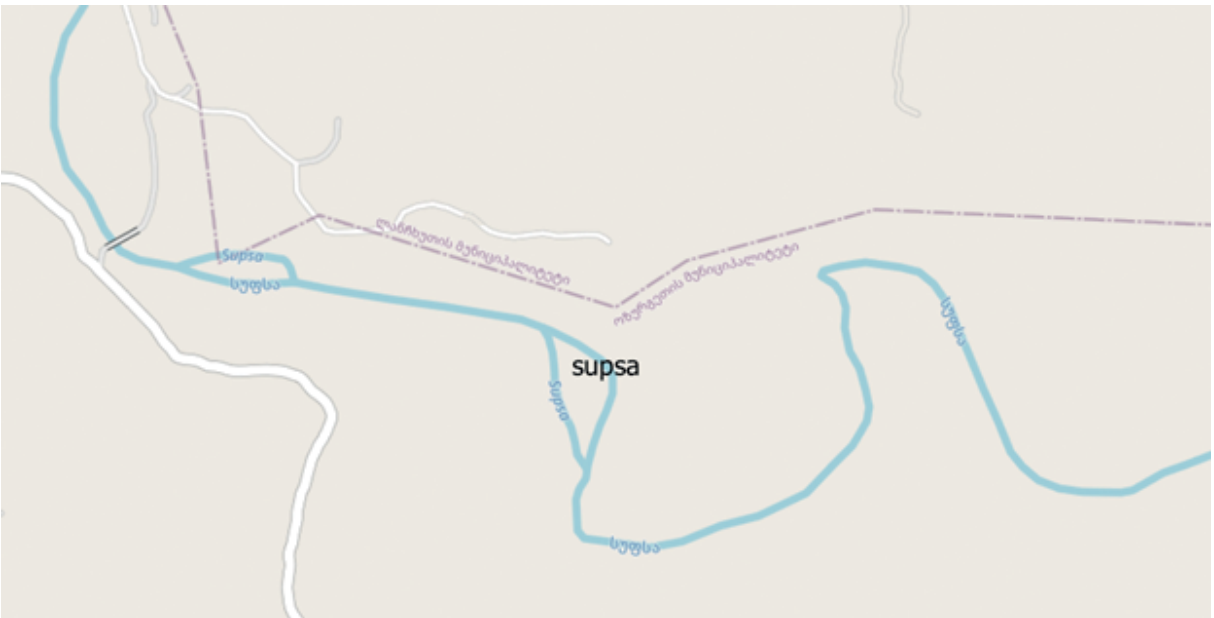


Figure 2-8. Braided Channels for the Supsa River

In some other cases, especially in large sections and close to urban and risk areas, two split channels may be used, although it should be noted that this will lead to a calculation of the flow going down to each of the channels (in an unsteady mode).

It should be added that the nomenclature of the cross-sections will follow the software requirements but that comments will be added in order to facilitate the identification of the cross-sections with the survey data.

2D Module Data

1.2.4.3.2.4.1 DEM Data

The main input for the 2D module would be the DEM. Information about the DEM has been provided above (and also in subsequent sections below). Nonetheless, it would be important to use a 'master' DEM in all fluvial modelling work. The following should be considered:

- A LiDAR has been collected within the framework of this project (Figure 2-19). This data will have preference over any other data. There are more LiDAR data available in Georgia such as in the urban Tbilisi area, in some areas in Kakheti in the Alazani catchment and in the northeast of the country. The accuracy of some of the old LiDAR data will be reviewed. To this end it should be noted that the newly acquired data are overlapping in some areas with old LiDAR data. If the result from this analysis is satisfactory (differences less than 0.1 metre), the old LiDAR data will be used and given the same priority status as for the new LiDAR.
- In the areas where there are no LiDAR data, preference will be given to the orthophoto DEM. As noted below, this DEM is not available to the consultant as of yet. The accuracy of this orthophoto DEM (that supposedly covers the whole territory of Georgia) will also be assessed. Nonetheless, it is believed that the accuracy of this DEM will be better than any global DEM can provide.
- Global DEM resources will be used when there is an area with no orthophoto or LiDAR data. The accuracy of global DEMs, such as ASTER, SRTM or MERIT, will be assessed in different locations against the new LiDAR. The global DEM providing the best accuracy will be selected.
- The LiDAR DEM, the orthophoto DEM and the global DEM (if required) will be merged into a single DEM (master DEM) for all of the fluvial modelling work. Special attention will be paid to the border areas between different DEMs to avoid any elevation data discrepancies that may affect the modelling results.
- In other flood sources, the modelling would depend on the quality of the DEM, and, in some cases, it will not be recommended that the modelling process continue if no quality DEM is available. This will not be the case for fluvial modelling and in all the cases the modelling process will be undertaken.

1.4.4.3.2.4.2 2D Geometry

The master DEM will be imported into the 2D module of the hydrodynamic software. It should be noted that the DEM will be resampled to a 5-metre DEM in order to allow for a proper handling of the DEM considering that this will cover the whole territory of Georgia.

The use of the DEM in the 2D module will differ depending on the software to be used and also depending on the computational grid approach. There are no preferences at this moment regarding the implementation of either structured or unstructured grids nor is there a preference for the grid size. This would depend on the river basin in particular or in the detail required for the flood hazard and risk modelling output. It should be noted that the level of detail will be higher in urban areas and historical flood sites where break-lines or an unstructured mesh will be used if appropriate.

1.4.4.3.2.4.3 1D-2D Linking Geometry

As described in the approach in Figure 2-4, it is suggested that the 1D and the 2D modules are implemented separately. Even if the linking between these two modules is envisaged at a later stage in the modelling process, it would be important to describe the recommended linking processes between the 1D and the 2D model at this stage. As described earlier, it is recommended that the floodplains are modelled in 2D while the channel is modelled in 1D. The linking process in this case would be through a lateral structure (example in Figure 2-9 and in Figure 210).

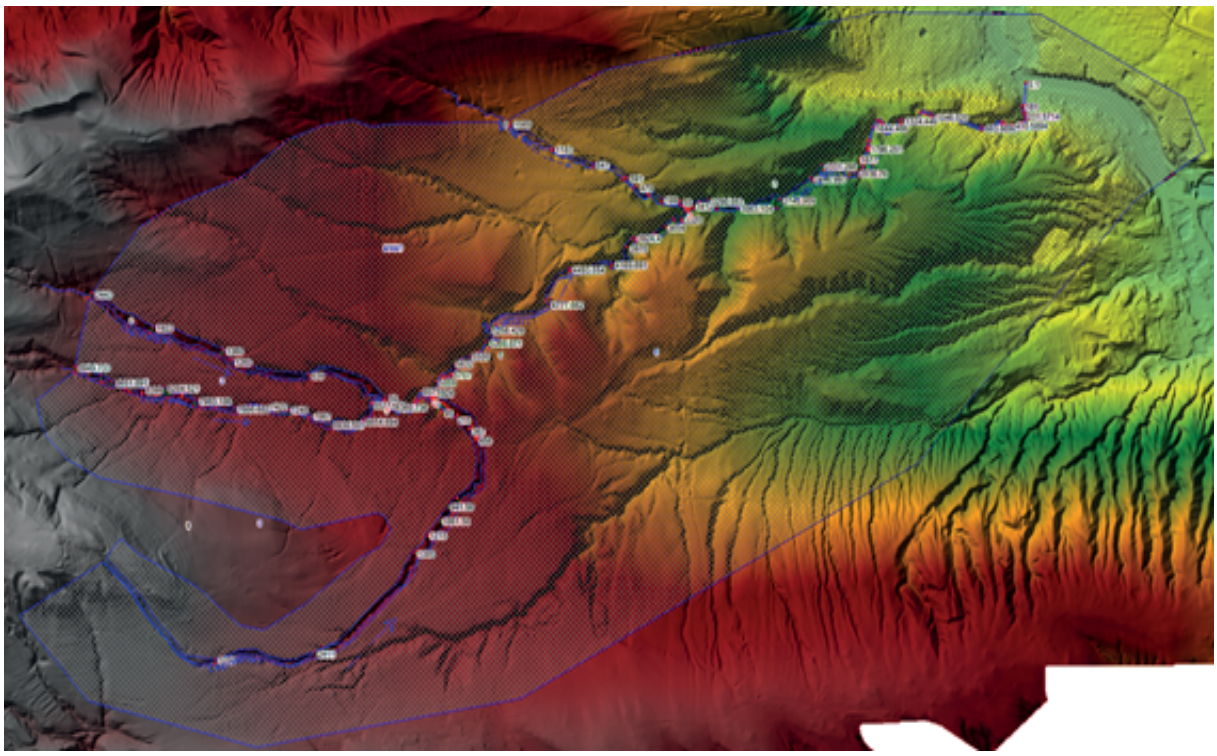


Figure 2-9. Example of 1D-2D for Tbilisi

Different software applications have different approaches for the linking process. Nonetheless, in all the cases special attention would be paid to:

- Domains: as noted above, the 1D domain should cover the channel while the 2D domains will cover the floodplains (Figure 210). This would be the general approach while local adjustments may need to be undertaken during the model implementations. The correct geo-referencing of the cross-section data would be highly important at this stage in order to ascertain that the conveyance is not double accounted for in both the 1D and the 2D domains. The implementation of several 2D domains may be required in order to allow for junctions and other structures.
- Crest level: the level of the lateral link will highly determine the amount of water going from the 1D to the 2D domain and vice versa and, therefore, special attention should be paid to define the elevations in the lateral structure.
- Weir coefficient: while the physics around the transfer from a 1D to a 2D domain are not well understood and this is more of a 3D process, the water exchange in between the two modules will be controlled by the weir computation. The standard weir equation should be used as an initial step using default values. If there is a need to adapt these values during the modelling process, this should be justified and documented.
- Instabilities: lateral links are a significant source of instabilities in 1D-2D models. In order to limit these instabilities, the number of iterations between the 1D and the 2D, and between the flow and water-surface tolerances should be set to limit the instabilities while accurately calculating the water exchange.

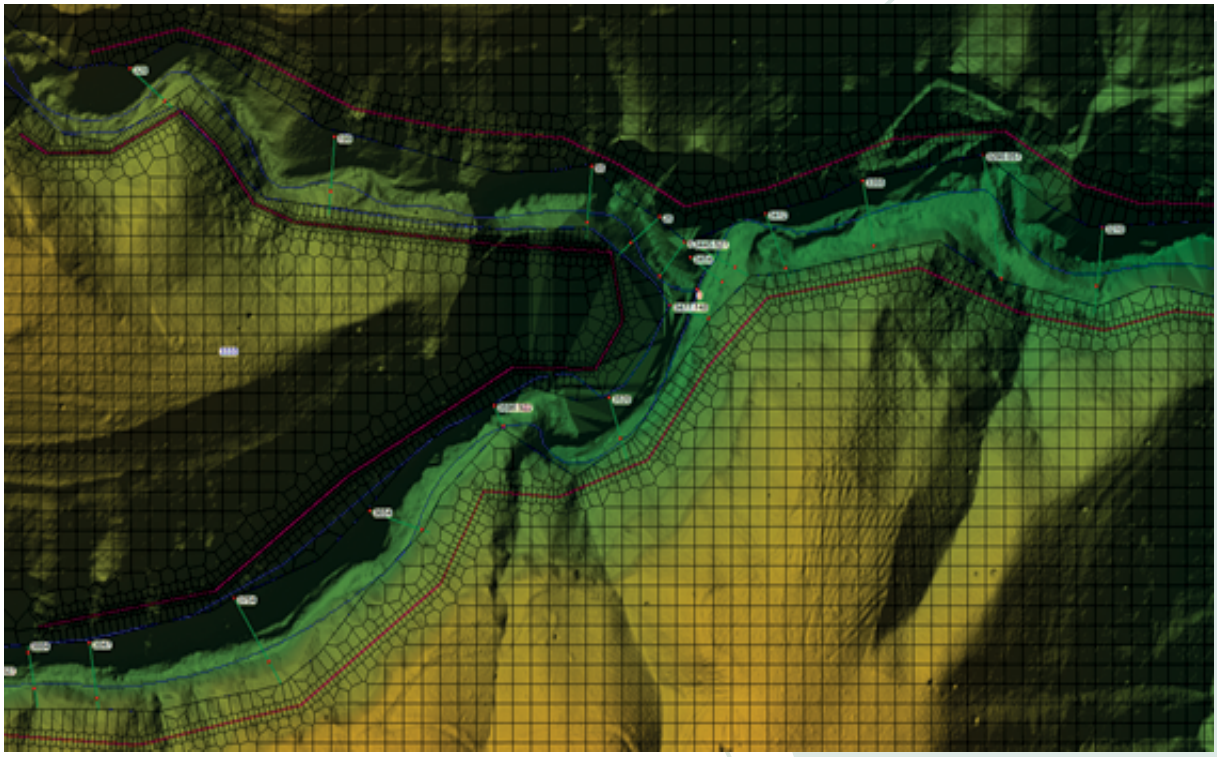


Figure 2-10. Example of 1D-2D for Tbilisi

In other cases, other types of linking processes between the 1D and the 2D domains would be required, especially the normal link where a 1D model feeds into a 2D one (or vice versa). In that case, the standard coupling process should be followed and any changes to the default values should be justified and documented.

1.2.4.3.1 Roughness

The definition of the roughness coefficient is one of the critical steps for the successful implementation of the hydraulic model. This section will cover the roughness recommendations and procedures for both the 1D and the 2D modules. As an initial approach, the Manning's n approach will be used to represent the roughness, using information from land-cover data (from Copernicus). This will be completed with input data from photographs and from the field campaigns. It should be noted that seasonal variations of the roughness may be taken into account, mainly during the calibration process. Initially, the Manning roughness approach will be followed. Literature reviews and software recommendations for Manning´s roughness coefficients will be used. These coefficients may change during the calibration process. The recommended values for the channel and floodplains are included in Annex I.

It should be noted that this is one of the few things that can be modified during the calibration process, although any change should always be supported by evidence in order to avoid force-fitting issues.

The roughness definition will be undertaken per cross-section in the 1D approach, allowing (justified) local changes and variations depending on the information from the survey campaign. The roughness in the 2D domain will be undertaken using grid-based land-cover data, assigning values to each of the land-cover classes as described above.

The roughness in both the channel and in the floodplain should be adjusted during calibration if needed. More information about the calibration is provided below.

1.2.4.3.2 Boundary Conditions

The next step in the model's implementation is the input of boundary conditions. The approach to the boundary conditions will vary depending on the location of the hydrodynamic model and on the flooding mechanism. Nonetheless, some considerations and common procedures can be drawn. In a numerical model, boundary conditions are needed at the upstream and downstream end of a model in order to provide information to the model about what is occurring outside of the model's domain. While the upstream boundary conditions are usually represented by flow hydrographs (as derived by the hydrological model), other options are available such as stage hydrographs or direct precipitation. More options are available for the downstream boundary conditions and the choice of this would highly depend on the model's locations. Preferably, the number of downstream boundary conditions to be specified in the models will be limited if most of the models are connected. More information will be given below.

1.2.4.3.2.1 Hydrological Inputs

Hydrological inputs will be required at the upstream end of the models and also at pre-selected locations (lateral inflows), considering the increase of the contributing area. The hydrological inputs will be

provided by either a hydrological model or by a hydrological/statistical analysis of recorded discharge data. It should be noted that the hydrological inputs will be obtained from the hydrological study for both selected calibration events (to be discussed below) and for a range of design events. Locations for these inputs should be agreed between the hydrological and the hydraulic expert. Hydrological input locations should be selected in the upstream end of all of the modelled watercourses, in key junctions and in pre-defined locations to account for an increase in the contributing area (as previously noted). In the Figure 2-11 below, an example of pre-defined locations for the hydrological input in a tributary of the Mtkvari River in Tbilisi is shown. As can be seen, locations have been selected in this example for the upstream end of all of the modelled watercourses, at major junctions and at the downstream end of the model. The procedures for the derivation of these flows are out of the scope of this methodology and they will be addressed in the hydrological methodology.

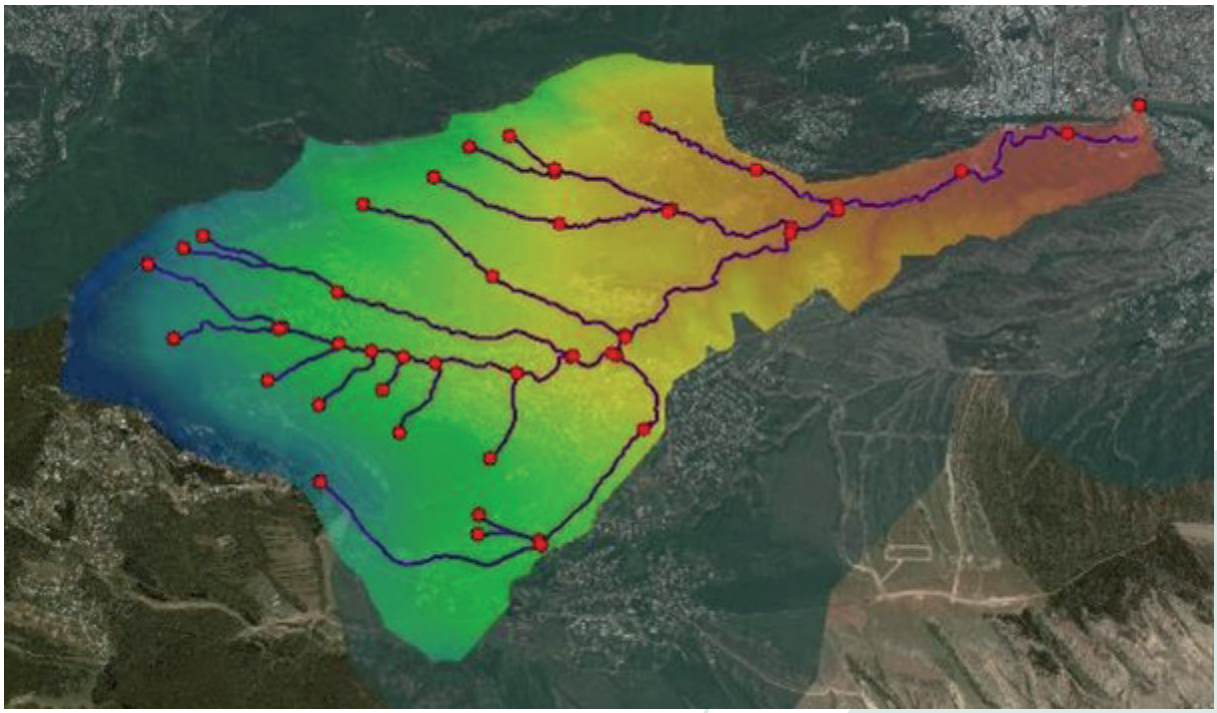


Figure 2-11. Selected Input Hydrological Locations for a Catchment in Tbilisi

It should be noted that the use of precipitation input in the hydrodynamic model can also be considered in some cases. This would be the case for pluvial flooding as it provides a better representation of the flow dynamics in urban areas. The links between the pluvial and fluvial flooding will be discussed below but, nonetheless, the use of precipitation as a boundary condition can be considered in sufficiently large urban areas. The precipitation input should also be provided considering calibration events and design events and this will be addressed by the hydrological methodology. It is paramount that a close working relationship is established between the hydrological modelling team and the hydraulic modelling team in order to ensure that the required modelling inputs for the hydrodynamic modelling are available.

1.2.4.3.2.2 Downstream Boundary

The type of downstream boundary condition will be selected depending on the location of the model. In the case that the hydrodynamic model is close to the Black Sea, it is highly recommended that the downstream boundary is located in the mouth of that particular river and that a stage hydrograph boundary condition is used. This information will also come from the hydrological methodology, but it is recommended that actual sea-level information is used for the calibration runs while a joint probability assessment is undertaken for the design events in order to understand the dependency between fluvial events and coastal events. It should be noted that while the contribution of waves may be considered for coastal flooding, only the sea-level (tides and storm-surge) will be considered for the fluvial-coastal joint probability as it is not expected that waves would cause any back-up problems to the fluvial flow.

In the case that a particular watercourse it is not discharging into the Black Sea, there are several options for the downstream boundary condition that should be considered. In the case of the river discharging into another (larger) one, and if that larger river is not included in the model, it would be recommended to also use a stage hydrograph boundary condition. If there is no information about this, a constant stage hydrograph can be used considering bank-full conditions in the larger river at the discharge location. In open downstream boundaries (the watercourse is not discharging into any other body of water at the location of the boundary), it is recommended that a normal depth boundary condition (using the river slope at that location) is used. This is because the normal depth type boundary condition is the most stable one and it does represent the actual geometry of the river system.

1.2.4.3.2.3 2D Boundaries

It should be noted that it is not envisaged that the 2D domain would require upstream or lateral boundary conditions (apart from the direct precipitation cases as previously noted) as the 2D domain will obtain the water inflow through the lateral or direct link with the 1D domain. In most cases, however, downstream boundary conditions will be required. The approach would be similar as per the 1D domain with stage hydrograph boundary conditions for the 2D domains close to the sea and with normal depth boundary conditions in open boundaries. It should be added that in the case of coastal 2D models, it is paramount that the same stage hydrograph information is used for both the 1D and the 2D domain in order to avoid inconsistencies in the modelling results in the coastal boundary.

1.2.4.3.3 Initial Runs

The implemented models, with the geometry (only cross-sections and the river geometry) and the boundary conditions already included, are frequently run-in order to identify issues and mistakes as soon as possible. Nonetheless, once the geometry and the boundary conditions are fully included in the model, it is recommended to run the models and improve the results while checking for inconsistencies, places with errors in the calculations, unexpected hydraulic jumps, and locations with a high Froude number. The initial runs should be undertaken separately for the 1D and the 2D domains before they are linked. The initial runs with the 1D model should also be carried out with no structure information and in the steady mode at first. Once no problems have been identified with the steady mode, the 1D model should be run in the unsteady mode. It should be added that all of the fluvial models will

be run in the unsteady mode, especially considering the high number of tributaries to be considered, the tidal influence and the possible water storage to occur in some locations.

1.2.4.3.4 River Structures

Once the results and the output from the initial run stage are satisfactory, the inclusion of structures can be started. It should be noted that within the modelling process, the model will be run to assess its stability and results every time a structure is included in the model. This is because the inclusion of structures can lead to several issues from a modelling point of view, and it is important to identify these problems as soon as possible within the modelling process.

The process for including structures is out of the scope of this methodology and it varies largely depending on the software to be used. Most modelling software has built-in representations for a range of structure types with options to switch between different equivalent representations of some structures. The precise details of how a structure is represented in a hydraulic model will depend on the software and on the structure. Nonetheless some general principles can be outlined:

- Structure coefficients or parameter values: the representation of a structure in a 1D model involves the estimation of parameter values by the modeller. This estimation is usually based on user experience, site visits, photographs, and survey drawings. This estimation introduces uncertainty into the model and sensitivity testing should be carried out for structure coefficients especially where there is high uncertainty in the value to be used or the output of the modelling is expected to be sensitive to the parameter value.
- Inclusion of all flow-paths: there may be multiple flow-paths around a structure, particularly during flood events. For instance, there may be flow over a bridge deck or out of a bank around the side of a weir. All relevant flow-paths should be represented. The approach for including all of the relevant flow-paths differs greatly depending on the modelling software and, therefore, special attention should be given to this in order to properly represent the actual conditions in that structure for a range of flows.
- Level of detail: as noted, the input of structures into a model increases the uncertainty of the results and also increases the instability of the modelling simulation.
- Blockages: where structures have been identified as being at risk of blocking, the effect of blockages should be investigated through sensitivity testing. This is especially important for some rivers in Georgia, and this should be analysed in detail if a multi-hazard point of view it is going to be considered. As a brief example, after the clean-up following the Vere River flood in Tbilisi in 2015, the issue of a culvert (Figure 212) was identified. In particular, a landslide at the upper side of the catchment led to a high number of debris and material being present in the Vere River and this led to the blockage of several culverts and subsequently high-water levels (in the excess of 15 metres) and wide-spread flooding. Therefore, blockages in key culverts should be especially considered and analysed. This will be undertaken using different percentages of blockage (25, 50 and 75%) and analysing the resulting impact of these blockages. Special coordination should be undertaken with other hazards (especially landslides and mudflows) to identify key structures where this may happen and where this may result in a significant flood risk.

Figure 2-12. Upstream Face of a Culvert in Tbilisi After the 2015 Event[25]

The following structures will be considered in the modelling implementation. It should be added that the survey information required for each of these structures has been outlined in previous reports.

1.2.4.3.4.1 Bridges

Flow in the vicinity of bridges may be a combination of free surface flow where flow is below the bridge deck, pressurised or surcharged flow where the flow is in contact with the deck and weir flow which occurs over the bridge deck. The bridge schematisation should be sufficient to represent all of the modes of flow which can occur. This may involve the use of multiple model units to represent the bridge (for example, a bridge unit and a weir or spill unit to represent flow over the bridge depending on the hydraulic modelling software). Most of the widely used software has several bridge representations available for each mode of flow. It should be noted that there will not be suitable calibration data available around bridges in most cases and, therefore, the choice of representation to be used will be largely based on user experience. If necessary, sensitivity tests can be carried out for different bridge representations.

The process for including a bridge in the fluvial hydraulic model varies greatly depending on the modelling software. These differences are even related to the file system approach. For example,

25. Tbilisi Disaster Needs Assessment 2015. Georgia/Tbilisi Flood Assessment Mission. Technical Assessment Report of Events. World Bank. 20 July 2015.

HEC-RAS bridge information is contained within the geometry file. In MIKE, the bridges and structures are included within the network file with no relation to the cross-sections. Regarding the latter, a simulation file needs to be opened while undertaking the bridge modelling, otherwise the modeller will not know where the bridge is located and/or the upstream and the downstream cross-sections of the bridge.

Some guidelines will be provided within this methodology considering the HEC-RAS approach. Based on the consultant's experience, the bridge modelling approach in HEC-RAS is more user friendly, models are more stable once structures have been included and the results are more accurate. MIKE models tend to be more unstable when bridges are included, and they sometimes produce spurious or unrealistic results.

HEC-RAS computes energy losses (Figure 2-13) caused by bridges by first calculating the losses in the reach in the downstream side of the structure (expansion of flow), then in the structure itself and finally in the upstream side of the bridge (contraction of flow). While there are different approaches for the modelling of structures, the upstream and the downstream losses are related to the coefficients used.

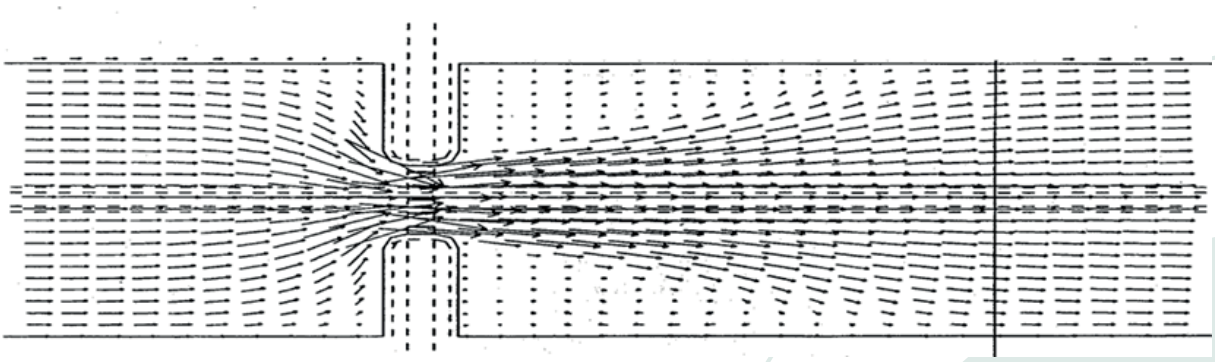


Figure 2-13. Energy Losses Around a Structure

Some general guidelines will be provided for the inclusion of bridges in HEC-RAS and most of these recommendations are applicable to other modelling software. As noted, however, there are significant peculiarities pertinent to different modelling software.

Cross-section locations: as specified in the National Guidelines for Flood Modelling Surveys, at least four cross-sections are required for the modelling of bridges (and other structures) in all hydraulic modelling implementations. While the flood modelling software automatically selects the immediate upstream and downstream cross-sections for the visual representation of the structure, the energy losses are calculated using four cross-sections as depicted in Figure 2-14. It should be added that the modelling software automatically creates two additional cross-sections inside the structure.

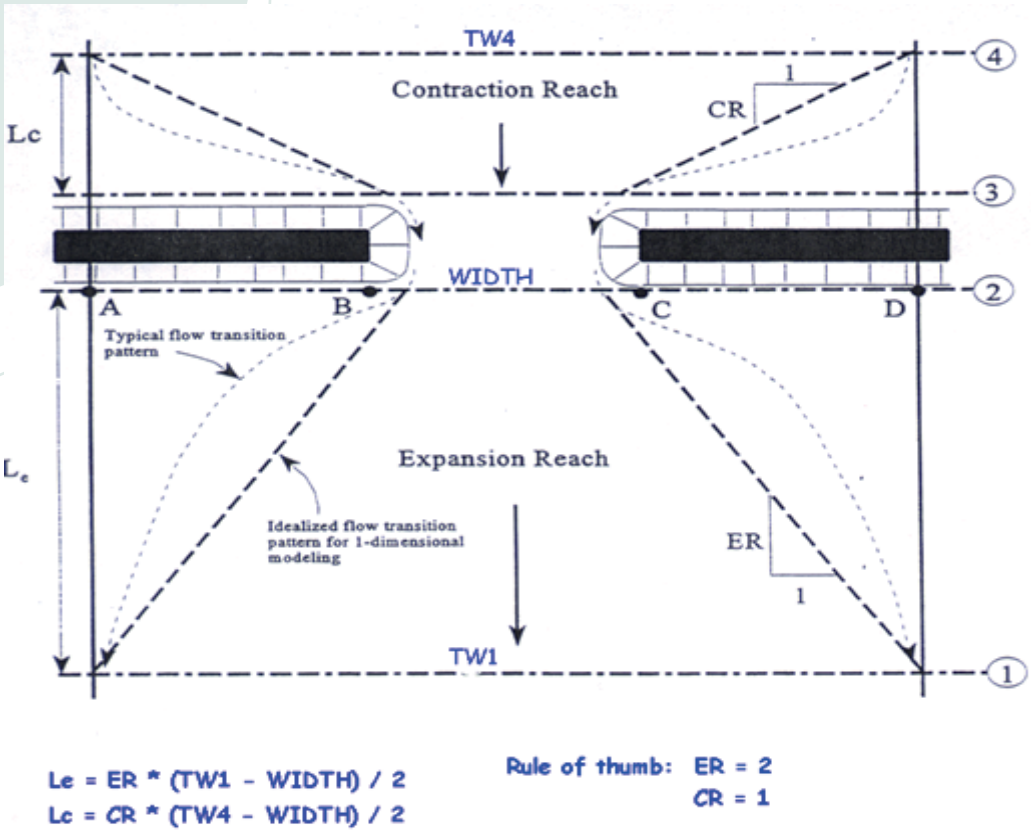


Figure 2-14. Locations of Cross-sections in Bridges

Therefore, the first step during the modelling implementation of bridges should be to define the chainage (river station) of the structure. In this case, it would be very important to accurately define the chainage because the cross-sections are assigned to the bridge depending on this chainage.

The locations of the cross-sections should follow the diagram outlined above in order to facilitate the modelling implementation.

Definition of ineffective flow areas: special attention should be paid to the definition of ineffective flow areas near bridge structures (Figure 2-15), especially for low flow conditions. These ineffective flow areas should be defined following the approach given in the figure below and also considering that these areas will no longer be ineffective during high flow conditions and, therefore, the level of the ineffective flow area should be defined accordingly. The ineffective flow areas should be set at elevations (x) and stations (y) that will adequately describe the active flow at the immediate upstream and downstream cross-sections outside of the edges of the bridge's opening to allow for the contraction and expansion flow that occurs in the vicinity of the structure. The elevations to be specified for the ineffective flow areas should correspond to elevations where significant weir flow passes over the bridge. This will be unknown for the downstream cross-section and, therefore, this will be estimated in initial runs.

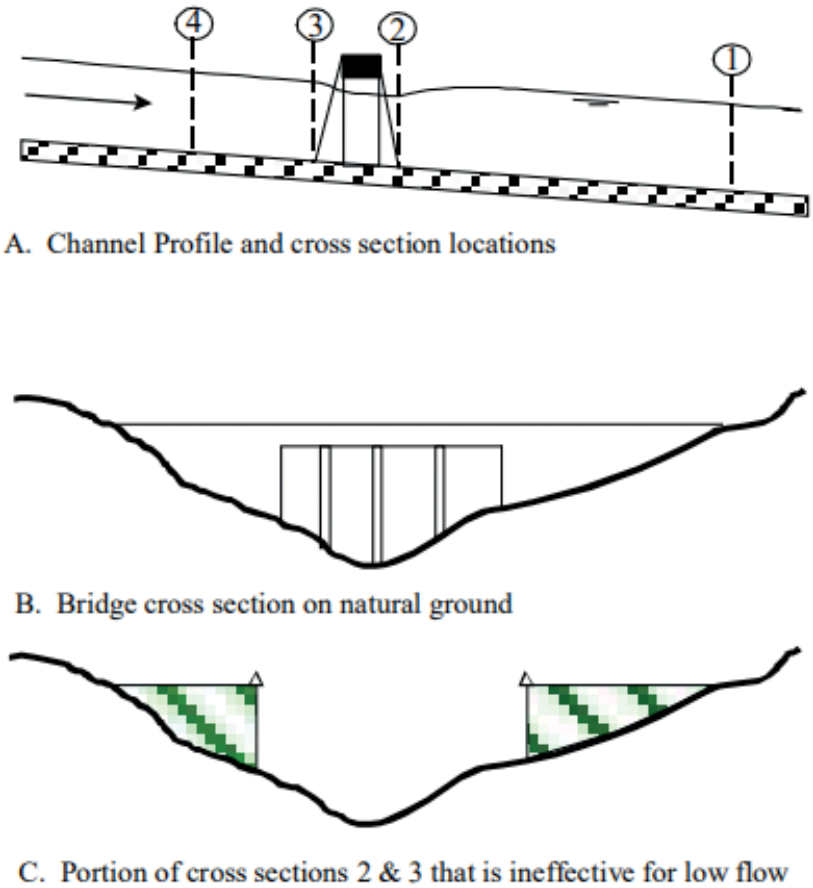


Figure 2-15. Ineffective Flow Areas Near Bridges[26]

- Contraction and expansion coefficients: the Manning's equation is used during the calculation to compute friction losses while contraction and expansion losses are generated during the standard step profile calculations. When the velocity head increases in the downstream direction, the contraction coefficient is used; the expansion coefficient used is used when it decreases. It is obvious that contraction occurs in the upstream cross-sections while expansion occurs in the two cross-sections located downstream of the bridge or structure. The contraction and expansion coefficients are used to compute energy losses associated with changes in the shape of the cross-sections. The recommended values for these coefficients are shown below in Table 18.

Table 18. Contraction and Expansion Coefficients

Transition	Contraction	Expansion
No transition loss computed	0.0	0.0
Gradual transitions	0.1	0.3
Typical bridge transition	0.3	0.5
Abrupt transition	0.6	0.8

26. HEC-RAS Reference Manual (2021).

- Hydraulic computations: as noted, there are several options for undertaking hydraulic computations within a bridge. These vary depending on the modelling software and also on the flow conditions. The choice of methods available in HEC-RAS will be briefly described here while providing recommendations for the modelling approach. First, it would be important to determine what flow conditions are available:

1. A low flow condition exists when the flow going through the bridge opening behaves as open channel flow (water surface elevation is below the upstream soffit). In this case, the following methods are available for hydraulic computation:

   - Energy Equation (standard step method): this method treats the bridge in the same manner as a natural cross-section (subtracting the area of the bridge below the water surface) and extending the wetted perimeter to the area in contact with the bridge structure.
   - Momentum Balance: this method is based on using the momentum balance equation in between the upstream and the downstream cross-sections of the bridge (the two ones closer to the structure). For this method, a drag coefficient has to be defined with the following typical values (Table 19):

Table 19. Typical Drag Coefficients for Various Pier Shapes

Pier Shape	Drag Coefficient CD
Circular pier	1.20
Elongated piers with semi-circular ends	1.33
Elliptical piers with 2:1 length to width	0.60
Elliptical piers with 4:1 length to width	0.32
Elliptical piers with 8:1 length to width	0.29
Square nose piers	2.00
Triangular nose with 30-degree angle	1.00
Triangular nose with 60-degree angle	1.39
Triangular nose with 90-degree angle	1.60
Triangular nose with 120-degree angle	1.72

   - Yarnell Equation: an empirical equation (based on laboratory experiments) that can only predict the change in the water surface downstream and upstream of the bridge. In this case, the Yarnell's Coefficient also has to be specified with the recommended values below (Table 20):

Table 20. Yarnell's Coefficient K

Pier Shape	Yarnell K Coefficient
Semi-circular nose and tail	0.90
Twin-cylinder piers with connecting diaphragm	0.95
Twin-cylinder piers without diaphragm	1.05
90-degree triangular nose and tail	1.05
Square nose and tail	1.25
Ten pile trestles bent	2.50

- FHWA WSPRO Method: the WSPRO method computes the water surface profile through a bridge by solving the energy equation. The method is an iterative solution performed from the most downstream cross-section to the most upstream one (considering the four cross-sections included in Figure 2-14).

Any of these methods are available to the modeller. A modelling test should be undertaken in order to compare the results from each of these methods in the case of any doubt about the modelling approach. More information about the equations and the rationale behind each of these methods is available in the HEC-RAS reference manual (https://www.hec.usace.army.mil/software/hec-ras/documentation/HEC-RAS_6.0_Reference_Manual.pdf).

The following recommendations are available for selecting a low flow method:

a) In cases where the bridge piers are a small obstruction to the flow and friction losses are the predominate consideration, the energy-based method, the momentum method and the WSPRO method should give the best answers.

b) In cases where pier losses and friction losses are both predominant, the momentum method should be the most applicable.

c) Whenever the flow passes through a critical depth within the vicinity of the bridge, either the momentum or the energy methods should be used.

d) The Yarnell and WSPRO methods are only for sub-critical flow.

e) Both the energy and the momentum methods can be used for supercritical flow.

f) The momentum-based method may be better at locations that have a substantial amount of pier impact and drag losses.

g) For bridges in which the piers are the dominant contributor to energy losses and the change in the water surface, either the momentum method or the Yarnell equation would be most applicable, although the momentum method is recommended.

2. High flow conditions exist when the water surface elevation gets in contact with the soffit of the upstream side of the structure. Two different methods are available for this:

- Energy Equation (standard step method): following the same procedure as for low flows.
- Pressure and Weir Flow Method: a second approach for the computation of high flows is to use separate hydraulic equations to compute the flow as pressure and/or weir flow. These two different methods will be briefly described below:
  - Pressure flow: pressure flow occurs when the flow comes into contact with the low chord (soffit) of the bridge, backwater occurs, and an orifice flow is established. Two different orifice flow cases should be distinguished; the first is when only the upstream side of the bridge is in contact with the water and the second is when the bridge's opening is full of flowing water. In the case of HEC-RAS, the software will automatically select the appropriate equation depending upon the flow situation.

    In the first orifice flow case described, the sluice gate equation is used where the drag coeffi-

cient should be specified with values ranging from 0.27 to 0.5 with 0.5 as the value typically used.

In the second orifice flow described (the upstream and the downstream side of the bridge are submerged), the standard full flowing orifice equation is used and the coefficient of discharge for fully submerged pressure flow should be defined with typical values of 0.8.

- Weir flow: flow over a bridge is calculated using the standard weir equation:

$$Q = CLH^{3/2}$$

Where:

Q = Total flow over the weir

C = Coefficients of discharge for weir flow

L = Effective length of the weir

H = Difference between energy upstream and road crest

The weir equation will be used throughout the modelling implementation and methodology for several reasons, including internal structures in 2D domains, 1D-2D links and culverts. Therefore, it has been included here for reference.

The following coefficient of discharge for weir flow is recommended (Table 21):

Table 21. Recommended Coefficient of Discharge (m) for Weir Flow

Type of Weir	Coefficient of Discharge (m)
Rectangular Bridge Deck	1.44
Roadway	1.66
Bridge and Roadway	1.55
Trapezoidal Bridge	1.70

When the weir becomes highly submerged, the modelling software will automatically switch to calculating the upstream water surface by the energy equation (standard step backwater) instead of using the pressure and weir flow equations. The criteria for when the programme switches to the energy calculations can be controlled by the modeller with the default value being 98 percent.

The following recommendations are available for selecting a low flow method:

a) When the bridge deck is a small obstruction to the flow and the bridge opening is not acting like a pressurised orifice, the energy equation should be used.

b) When the bridge deck and road embankment are a large obstruction to the flow and backwater is created due to the constriction of the flow, the pressure and weir method should be used.

- Implementation procedure: the following procedure should be followed for the inclusion of bridges in flood hydraulic models:
  1. As noted, the first step would be to review the survey information and load all of the possible information in GIS and/or the hydraulic model interface. All of the required information must be available, including the location of the bridge as related to the cross-sections in the vicinity.
  2. As discussed above, the definition of the chainage (or river station) associated to the bridge is very important in order to establish the upstream and the downstream cross-sections for the bridge definition. If there are no cross-sections from the survey sufficiently close to the bridge, the modeller will include cross-sections using interpolation or from LiDAR/DEM sources.
  3. As noted in the main approach for the methodology, it is recommended that a stable model with all of the cross-sections and boundary conditions is implemented before the inclusion of any structure. Additionally, it is recommended that structures are included one by one, and that the model's performance is assessed after the inclusion of each structure.
  4. Within the implemented hydraulic model, the first step in the structure modelling should be the definition of the deck-roadway. This is an important step in the definition of the bridge opening and also in the definition of the flow constraint. This will be defined for the upstream and the downstream faces of the bridge considering the information from the survey. The deck definition should be sufficient to represent the bridge's opening and provide information about the high and low cord.
  5. The hydraulic modelling approach for the bridge should also be defined considering all of the information outlined above.
  6. For unsteady modelling implementations, it is important to define the high and the low maximum expected tailwater as well as the maximum discharge allowed through the structure. The definition of these values comes from hydraulic modelling experience, but maximum values should be defined with an ample range considering that these values are used to calculate the pre-defined hydraulic curves within the structure.

1.2.4.3.4.2 Culverts

All culvert models should contain a representation of inlet losses, outlet losses and losses due to friction along the culvert barrel and where a culvert changes shape, bends or is obstructed due to service crossings and so additional losses should be included to account for these variables. Losses due to the presence of screens should be included in the representation of the culvert inlet.

Culverts can be particularly prone to blockage; therefore, detailed local studies or sensitivity testing of a culvert barrel's sedimentation due to inlet blockage should be carried out.

It should be noted that there is no clear distinction about when to use a culvert or a bridge from a modelling point of view and this will highly depend on the modelling software. For instance, culverts are more stable than bridges in HEC-RAS and the use of the former in HEC-RAS would be preferable in most cases if they can properly be represented in the model. A rule of thumb would be to model anything

that is shorter than 10 metres in width as bridges and anything greater than 10 metres as culverts. Nonetheless, this should be analysed on a case-by-case basis and always in consideration that either the culvert or the bridge modelling unit has to represent the actual available conveyance.

Within HEC-RAS, culvert routines are similar to those of bridge except that the Federal Highway Administration's (FHWA, 1985) standard equations for culvert hydraulics are used to compute inlet control losses at the structure.

The definition of the hydraulic modelling approach for culverts should follow the same guidelines as the ones described for bridges. Nonetheless, it should be considered that the energy based standard step method is the most suitable approach for long culverts under low flow conditions. Additionally, several sections can be taken in the case of long culverts to model changes in grade or shape or to model a very long culvert. This approach also has the benefit of providing detailed information at several locations within the culvert which is not possible with culvert routines in HEC-RAS. However, if the culvert flows full or if it is controlled by inlet conditions, culvert routines would then be the best approach.

The following culvert shapes are available in HEC-RAS (Figure 2-16).

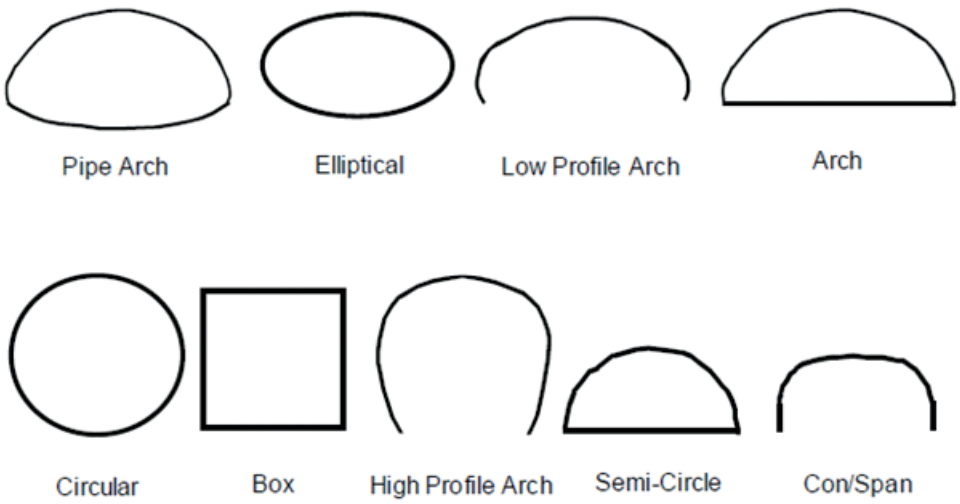


Figure 2-16. Available Culvert Shapes (Source: HEC-RAS Reference Manual)

The approach for determining cross-section locations as well as those used within the modelling framework is the same as for bridge modelling.

In terms of the required modelling information, the use of culverts involves the definition of some extra parameters; namely, the entrance and the exit loss coefficients.

The entrance losses are computed as a function of the velocity head inside the culvert at the upstream end. The velocity head is multiplied by the entrance loss coefficient to estimate the amount of energy lost as flow enters the culvert. A higher value for the coefficient gives a higher head loss. Recommended values depending on the type of culvert and the entrance and the exit type are available in the HEC-RAS Reference Manual (2021). It would be recommended that a value of 0.5 (for the entrance) and

1.0 (for the exit) are initially used in any hydraulic implementation and that these values are adjusted depending on the results and the particular culvert.

The modelling implementation for culverts should follow the same steps as the ones described for bridges. Of note, however, that the deck/roadway should be defined with no opening area, because the culvert opening will be defined in the culvert section.

Additionally, it should be noted that roughness values have to be defined for the top and the bottom of the culvert (the recommended values are in the HEC-RAS Reference Manual).

1.2.4.3.4.3 Weirs and Gates

The modelling of weirs and gates will be considered in cases where this is necessary and where they actually represent a change in flow dynamics. In some cases, weirs can be represented by cross-sections, and it may not be necessary to include a structure to represent the dynamics. It should be noted that there are numerous Soviet-period check dams in small watercourses in Georgia, especially in the Tbilisi area (Figure 217). While these small dams will have an impact on flow dynamics, most of them (if not all) have been earth-filled and act as a 'waterfall' in most cases. These check dams pose several issues from a modelling point of view. Nonetheless, it is recommended to only represent them in the cross-sections and not to initially include them as structures. The hydraulic dynamics in these locations should be thoroughly analysed, including the presence of hydraulic jumps and errors in hydraulic calculations. The inclusion of a weir (or inline structure) in these locations may increase the stability of the models and may better represent the flow (applying the weir equation) but this is to be analysed on a case-by-case basis.

Figure 2-17. Check Dams in Urban Areas in Tbilisi

The modelling approach, the hydraulic background and the modelling implementation that should be followed for inline structures and weirs is the same as the one described for the deck/roadway modelling for bridges, including the definition of the weir coefficient.

1.2.4.3.5 Linking Process

Although the linking possibilities between a 1D and a 2D model have been outlined in previous sections, the 1D and the 2D models will not be linked until both models are fully implemented and working satisfactorily in a separate mode. This is because the linking of the two models will increase the instability of the models and, therefore, it is important to establish that both models are separately working perfectly before linking them. The process and the options for linking the 1D and the 2D models have been described in the sections above. Nonetheless, some common issues to consider when linking these models should be considered at this stage:

- Elevation of links: as noted previously, it is paramount that the link (lateral structure) elevation is properly defined. If the wrong link elevation is set for lateral links between 1D and 2D models, this may lead to flow across the link before (or after) the bank is overtopped.
- Numerical stability can be a problem for 1D-2D models, particularly if there is a frequent exchange of water across the link. This can show up as oscillations in velocity and water level in both the 1D and 2D components. The model log file should be examined for any reports or numerical instability and the results animated and examined for spurious flow patterns and results.
- Mass balance errors can be a particular problem for 1D-2D models. The mass balance files for the 1D component, the 2D component and the combined model should be checked to ensure the mass balance is within the acceptable limits, usually within a 1% cumulative error. The mass balance should be given in the modelling report.

1.2.5 Calibration and Sensitivity

While the model calibration and validation stages are important for determining the degree of confidence which can be placed on the model's results, the sensitivity analysis is important for understanding the level of uncertainty in the modelling. The sensitivity analysis affects the model's potential practical use and the confidence in decisions which are based on the modelling.

It is important to define the meaning of the calibration and validation activities of a model as this usually leads to confusion. Calibration is the process of adjusting model parameters such as roughness or other parameters within plausibly physical ranges until the resulting predictions give the best possible fit for a selected observed event. A model is said to be validated if it is able to provide accurate predictions against other observed events (non-calibration events) within acceptable limits. Model calibration and validation provides an understanding of the appropriateness of the model considering observed flow/stage data. The main objective of model calibration and validation is to provide a demonstration of the quality of model predictions. If calibration is not carried out, confidence in the model's application will be significantly reduced.

The model will be calibrated against recorded events when data are available. The information from the hydro-meteorological stations in every single basin will be analysed for this purpose as well as taking into account historically reported flooding events.

Where stage and flow calibration data are not available, a reality check vis-à-vis the predicted outlines and levels for an event should be carried out using other historical flooding information such as satellite spatial flood outlines, photographs, or anecdotal descriptions of flooding. It is important that the reliability of the data is checked prior to use.

It should be noted that the selection of the calibration event will be undertaken per basin and in close collaboration with the hydrological and the hydraulic modelling teams. While the existence of data is critical for the selection of the events, the selection of events will be based on the impact caused by these storms and the hydraulic dynamics observed.

During the calibration process special attention will be paid to:

- Roughness: the roughness coefficient will be adjusted depending on the season and based on local experience. An analysis will be carried out in order to decide roughness coefficients for design events.
- Land-use and geometry: depending on when the selected events took place, the river geometry or the land-use in a catchment may have changed considerably. This will be taken into account during the calibration process.

The following calibration issues should be considered:

- Calibration should mainly be undertaken against the water level as discharge data are derived from the stage data. An analysis of the rating curves will also be undertaken while considering that discharge should be derived in most cases by using several rating curves. The use of reliable rating curves for discharge calibration can also be considered.
- Force-fitting should be avoided. This is a very significant issue during calibration. The calibration should not be forced to fit with unrealistic roughness values or storage. A single event may be calibrated successfully with parameters that are outside of the range that would be considered normal for that stream, although other events have to be considered and the previously established values may not work for these other events. Therefore, it is recommended that the roughness and storage values are within a realistic range for the model's parameters. If using a realistic range of values, the model is not representing the recorded values accordingly, other reasons should be investigated. As noted above, the reliability of the stage and the discharge data should be established beforehand.
- The influence of the downstream boundary condition on the calibration locations should be established.
- Discrepancies may arise from a lack of quality cross-section data. A model can only be as good as the input data it has.
- The off-channel storage should be considered during the calibration as was previously noted as a force-fitting issue. The volume of off-channel storage areas can be under-estimated, resulting in a flood wave that travels faster than it would in reality and leading to an overestimation of peaks downstream. Therefore, the off-channel storage should be carefully evaluated. The use of the 1D-2D approach should limit these issues but it would depend on the quality of the linking process and the available data.

- As will be discussed below, the calibration should be based on floods that encompass a wide range of flows from low to high. Unsteady 1D hydraulic models may become instable during low-flow conditions.
- Even if the tide range in Georgia is limited, the influence of the sea-level (astronomical and meteorological tide [storm-surge]) should be considered in the results. An assessment of the influence of the sea-level should be undertaken.
- In tidally influenced rivers and flows into lakes/reservoirs, the inertial terms in the momentum equation are important; an adjustment of the roughness may not enhance the calibration in these cases. The use of appropriate geometric information and storage values would be critical here.
- Changes in the geometry of the river between the occurrence of the event and the survey data should be considered. Additionally, the occurrence of breaches and overtopping of flood defences should also be taken into account.

1.2.5.1 Calibration Guidelines

In order to facilitate the implementation of this methodology, some general guidelines will be proposed regarding the calibration procedure. As discussed above, the flow resistance coefficients are the main calibration parameters of fluvial flood hydraulics models, although the discharge coefficients of weirs or other structures may also be considered in this process of calibration.

The main approach of a calibration process is related to the comparison of modelling outputs to actual recorded water elevation and/or discharge data at locations where these data are available. In order to enhance the modelling results, flow resistance coefficient estimates may then be refined to better match the observed data. The general process would be:

1. All the data available for the calibration of a hydraulic model should be collected and analysed. As noted previously, these data include:
   i. Water level and discharge data at hydrological stations, including rating curves.
   ii. High-water marks in buildings and structures.
   iii. Historical records from newspapers or local accounts.
   iv. Flood extents from remote sensing sources.
2. The calibration data should be assessed for their accuracy and suitability for the calibration of models. It should be noted that in some cases local records are not entirely accurate and remote sensing data do not always correspond to the highest water level experienced in a particular location.
3. During the calibration, it is very important to ascertain that all of the processes are accounted for, including the tide, the snow-melting contribution, the groundwater influence, blockages in culverts and bridges, additional influences due to solid-content and so on as noted above.
4. The accuracy of the discharge data from the hydrological assessment should also be established. This is especially important because adjustments from a hydraulic modelling point of view can have a limited impact and, therefore, no unrealistic values should be used for the roughness or other hydraulic parameters as noted above.

5. Once the initial results from the modelling exercise are available, these should be compared with the observed data. The main data to be considered are data from stations as they will be the most reliable. Nonetheless, these data will be of a limited range because stations are not located in flood areas in most cases. The process for calibration would depend on the results and the location of the stations:
   i. The calibration strategy may differ depending on the software used. While there is some software that includes the possibility of optimisation, this is not the case for most modelling software. Therefore, a manual approach should be followed in most cases.
   ii. The modelling results and the measured data should be compared to each other, either through the same modelling framework or using external software (such as spreadsheets and plots).
   iii. At this stage, it is very important to understand the level of adjustments/calibration required. For instance, if the model is producing similar or comparable results, an assessment of the roughness can be undertaken, and this should be able to improve the results. However, if the results are very different, with missing peaks (either in the measured or modelling data) or differences of an order of magnitude or higher, then it is highly recommended to inspect the hydrological input.
   iv. The roughness coefficients impact the water depth and the water velocity. The higher the roughness coefficient, the lower the velocity and the higher the water depth. Obviously, the lower the roughness coefficient, the lower the water depth and the higher the velocity. Therefore, if a model is slightly over-predicting the water depth in a particular location, it is recommended that the roughness coefficients are lowered (slightly).
   v. If there is a difference in the peak arrival between the measured data and the simulated data, the roughness coefficients could also be adjusted. For instance, if the peak occurs in the modelling results earlier than in the measured data, then the roughness coefficients may be raised and, therefore, the velocities would be lower, and the peak will be delayed in the modelling results.
   vi. In both cases it is important to consider several events and that the calibrated results for one event do not make the results worse for the other event.
   vii. It is very important to keep a calibration log with all of the different tests and all of the different results so this can be analysed by other modellers and included in the modelling report.
6. In order to calibrate a high-water mark, the only value which can be used is the peak water level for specific events and the approach thereto should be the same as the one outlined above.
7. In order to calibrate the model for the flood extent, several points should also be considered:
   i. Flood extent from aerial photographs or remote sensing provide only a snapshot of an event.
   ii. The calibration will have to be undertaken using spatial results from the modelling output. While this approach is slightly more complicated, the approach will be the same. It is important at this stage to assess the weir coefficients and the weir levels for out-of-bank flow in addition to the roughness coefficients. The flood extent will cover areas that are outside of the

main channel and, therefore, the flow would have escaped the 1D model into the 2D model. In this case, the level of flooding can be affected by the incorrect representation of the lateral links between the 1D and the 2D domains and, therefore, this should be ascertained in detail.

iii. Similarly, the presence of different structures may have an impact on the modelling results from a spatial point of view. Therefore, the flood extent may be affected by the modelling approach of culverts and bridges and/or by the coefficients used.

1.2.5.2 Calibration Strategy

The calibration strategy to be defined would be the same for all of the flood sources. Nonetheless, it is envisaged that this calibration strategy will only be able to be followed for fluvial flooding based on an assessment of the data availability. It is recommended that a minimum of three calibration events and one validation event are used during this assessment. If data for this number of events are not available, other means can be used to increase model confidence (sensitivity testing).

Even if calibration data are only available for a short period of time and with no significant events in some cases, the calibration, and the validation of models under these circumstances can still be useful, especially for checking the performance of a wave transformation model or flows predicted by the hydrological model.

The calibration process should be fully documented in a report and should include calibration event dates and measurements as well as locations of historical floods. Changes to parameters and the rationale for any revision must be clearly documented.

River models should be calibrated for levels at stations, although the discharge should also be considered if the ratings curves are reliable. It is strongly recommended that the study's extent covers at least one and preferably two or more gauges where possible in order to assist in the calibration.

The hydraulic parameters which are usually varied during model calibration are the surface roughness, storage, and structure coefficients. Model boundaries, including parameters in hydrological models, may also be varied, considering the hydrological model calibration. A combined approach to hydraulic-hydrological model calibration should be undertaken where possible.

The calibration events should cover both in-bank and out-of-bank scenarios to ensure that both the channel and the floodplain are modelled correctly. Although the inclusion of larger events is important, not all of the events have caused extensive flooding, and it is also valid to show the model correctly predicting water not reaching particular locations. Utilising recent events may minimise the impact of recent changes in hydraulic structures or catchment characteristics.

The data requirements for each calibration event should consider the existing data availability. Existing water level records from most hydrological stations in Georgia have daily records while some stations in the Rioni catchment and in Tbilisi have hourly data. In both cases, the available data only date back to 2015 and, therefore, there are only five-six years (at most) with hourly data in a limited number of hydrological stations. In most cases, it would be important to calibrate against sub-daily data (preferably under one hour) and this would especially be the case in watercourses with a time to peak which is

less than one day. Data limitations have to be considered but this will not prevent a model from being calibrated or used for flood mapping purposes. Ideally, the following information should be gathered for all of the gauged catchments:

- Flow and level time series for any gauges within the study reach, including tributaries, at the lowest time interval possible.
- Rain gauge data for any gauges within or surrounding the catchment.
- Tide gauge data (if the specific watercourses are discharging into the Black Sea).

The calibration criteria should consider:

- Peak water level.
- Overall hydrograph shape.
- Timing of the peak level.

The accuracy of the calibration should be set using tolerances of both peak water level and in the timing of the peak level. The proposed tolerances are +/-300 mm or less for water level, one hour or less for the timing and +/-15% for the volume of discharge. The hydrograph shape, as noted above, will also be considered from a qualitative point of view.

Nonetheless, the accuracy in the timing of the peak would depend on the hydrograph duration. In the case that there are several peaks in a single event, the accuracy should be maintained in all of the peaks (both for the timing and for the water level). Obviously, the data interval availability should be considered in this target of accuracy. Additionally, calibration plots can be produced for an event by comparing modelled flows with those recorded at the gauging station. Tables can also be used to present a comparison of the observed and the modelled peak flow, the time to peak and the peak stage at particular locations.

In addition to this, there are several model performance indicators that can be used, especially the goodness-of-fit of any simulated hydrograph. In order to use this indicator, the hydrograph results have to be transformed and normalised into a measure of the overall root mean square error (RMSE) which is based on the coefficient of determination (R^2). R^2 values equal to 1 indicate a perfect accuracy performance of the model. The R^2 can be calculated using:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(O_i - S_i)^2}{\sum_{i=1}^{N}(O_i - \overline{O})^2}$$

Where:

O_i : measured value.

S_i : simulated value.

$\overline{O}$: mean of measured value.

1.2.5.3 Sensitivity Analysis

Several sensitivity analyses will be carried out in order to ascertain the impact that the roughness, the boundary conditions, and other hydraulic modelling parameters may have on the modelling results. This is especially important in ungauged catchments where the model's suitability should be established based on these assessments.

Model sensitivity tests should be undertaken in order to give the modeller, the reviewer, and the users an understanding of what parameters affect the model and in what ways. Sensitivity testing involves varying an element of the modelling and then assessing how this alters the model's results. This helps develop an understanding of the confidence in the model and its outputs.

Sensitivity to the following parameters should be undertaken within the framework of flood hazard mapping:

- Boundary conditions (15% decrease and increase in flows).
- Surface roughness (15% decrease and increase of the Manning's n used in the model).
- Location and type of the upstream and the downstream boundary conditions to ensure there is no impact on the results within the area of interest.
- Blockage of critical structures such as culverts and other hydraulic structures which may be prone to blockage during flood events. The blockage percentages outlined above (25, 50 and 75%) should be tested.

Additional sensitivity testing of the following may be required depending on the specifics of the model:

- 2D model resolution, increasing or decreasing the cell size.
- Spill coefficients (weir equation).
- Initial conditions/initial water levels in storage areas such as ponds and flood storage reservoirs.

Results from the sensitivity analyses should be presented in the modelling report. The results of the sensitivity tests should be plausible and realistic. For instance, an increase in the roughness (Manning's n) should yield an increase in water depth. Any discrepancies in the results of the sensitivity tests should be analysed and assessed carefully by the modeller.

1.2.6 Design Events

Design events are used in order to derive the required flood hazard maps. The input from the design events should come from the hydrological analysis. Therefore, a design event will be run using the same model yielded by the calibration, the validation and the sensitivity test activity but changing the boundary conditions, especially regarding the hydrological input (but also considering coastal water levels or any other boundary).

The European Union Floods Directive requires that flood mapping is undertaken for three design event probabilities: namely, low, medium, and high. Nonetheless, more design events will be used within the

framework of this project and for risk modelling purposes. Fluvial hydraulic models will be run for the annual, 1:5, 1:25, 1:50, 1:100 and 1:500-year events.

It should be noted that stability issues may arise during this process because the hydraulic models will not have been run for such extreme events in most cases (especially the 1:500-year event) during the calibration and validation process. Therefore, it would be important that the model is run again for the calibration, the validation, and the sensitivity test scenarios if any changes are undertaken to the model's implementation due to stability issues in order to ascertain that the modelling implementation is still valid.

1.2.7 Flood Mapping

The procedures for fluvial flood mapping depend on the hydraulic modelling package to be used during the modelling implementation. Many hydraulic modelling packages include functionality to produce flood maps from 1D results while others contain add-ons to GIS packages. Flood maps can also be produced solely in GIS. Nonetheless, the two most probable software packages for use during this assessment (MIKE FLOOD and HEC-RAS) have in-built flood mapping capabilities.

The basic data requirements to create a flood extent map include maximum water levels, a DEM and cross-section locations. If the model includes a reservoir or storage units, then these will need to be represented separately in order to show the water level within the reservoir unit as opposed to the cross-section at this location. In this case, a plan showing the reservoir locations is also required.

The resolution of the DEM used determines the resolution of the flood maps. As such, it should be appropriate for the level of detail in the model and should not lead to excessively large file sizes for the depth grids. It is recommended that flood maps have a maximum resolution of 5 metres.

Due to the interpolation of level results between model cross-sections, several issues may occur in 1D flood maps and a careful check against the 1D model results is required. The maps should be examined for the following features and, if necessary, the model should be amended accordingly.

- Isolated patches of flooding which are not well connected to the river.
- Flood extents which appear constrained by cross-section extents or reservoir extents (glass walling).
- Flood extents which are greater than the area covered by the cross-section extents or reservoir extents.

Of note is that 1D flood models do not have the functionality to produce floodplain velocity. Because this is a requirement for the flood risk model, the floodplains in all of the cases will be modelled in 2D (as outlined above).

The production of flood maps from 2D models is simpler than from 1D models as water levels, depth and velocity can be a direct output from 2D models. Flood extents are then produced by contouring the processed depth grid.

Fluvial flood depth should be colour coded as follows:

Depth [m]	R	G	B	Colour
0.05 < 0.5	204	255	255	
0.5 < 1.0	153	255	255	
1.0 < 1.5	102	255	255	
1.5 < 2.0	51	255	255	
2.0 < 2.5	153	204	255	
2.5 < 3.0	102	178	255	
3.0 < 4.0	0	128	255	
> 4	63	0	125	

Flood depths of less than 0.05 metre should not be mapped.

1.2.8 General Steps in Developing a Hydraulic Model with HEC-RAS

A brief description of the required process to implement a hydraulic model in HEC-RAS will be outlined in this section. HEC-RAS is believed to be the most suitable software package at the moment in order to undertake flood hazard mapping. As previously stated, the idea of using some other software should not be discarded and even encouraged (noting the MIKE FLOOD license at the NEA and the previously noted analysis of HEC-RAS and MIKE FLOOD capabilities and the user approach in Annex II).

There are five main steps in creating a hydraulic model with HEC-RAS:

- Starting a new project.
- Entering geometric data.
- Entering flow data and boundary conditions.
- Performing the hydraulic calculations.
- Viewing and producing results.

1.2.8.1 Starting a New Project

The first step in developing a hydraulic model with HEC-RAS is to establish the directory in which you wish to work and to define a new project.

1.2.8.2 Entering Geometric Data

The next step is to enter the necessary geometric data which consist of a background map layer (optional), connectivity information for the stream system (river system schematic), cross-section data and hydraulic structure data (bridges, culverts, weirs, etc.).

The modeller can develop the geometric data in HEC-RAS by first drawing the river system schematic.

After the river system schematic is drawn, the modeller can start entering cross-section and hydraulic structure data. The River, Reach and River Station identifiers are used to describe where the cross-section is located in the river system. HEC-RAS requires cross sections to be ordered within a reach from the highest river station upstream to the lowest river station downstream.

The required data for any cross-section consist of station-elevation data (cross-section point coordinates), downstream reach lengths (distances from the current cross-section to the next cross-section downstream), Manning's n values (at a minimum you must have a left overbank, main channel, and a right overbank Manning's n value.

Once the cross-section data are entered, the modeller can then add any hydraulic structures such as bridges, culverts, dams, weirs, and spillways.

It should be added that some of this information can be prepared using external resources such as the HEC-GeoRAS module within ArcGIS. Using this module, the modeller can prepare the river network and the cross-section information and then export that to HEC-RAS.

1.2.8.3 Entering Flow Data and Boundary Conditions

Once the geometric data are entered, the modeller can then enter either steady flow or unsteady flow data. The type of flow data entered depends upon the type of analyses to be performed. Boundary conditions are required in order to perform the calculations.

1.2.8.4 Performing the Hydraulic Computations

Once all of the geometric data and flow data are entered, the modeller can begin to perform the hydraulic calculations. There are five types of calculations that can be performed in HEC-RAS: steady flow analysis, unsteady flow analysis, sediment transport/mobile boundary modelling, water quality analyses and hydraulic design functions.

1.2.8.5 Viewing and Printing Results

Once the model has finished all of the computations, the modeller can begin viewing the results.

1.3 Data Requirements and Data Availability for Fluvial Flood Modelling

In order to undertake fluvial flood hydraulic modelling, the data requirements and data availability in Georgia will be considered. It should be noted that an assessment of the data availability has been undertaken by NEA staff under the supervision of the international expert for three catchments (Natanebi, Kintrisi and Supsa included in Annex I) and that some of the information collected through that process has been included in this section apart from information from other sources.

The data requirements and data availability for fluvial flood hazard modelling have been the target of specific deliverables. Within this section, a review and assessment of the data requirements and data availability from a hydraulic modelling point of view will be done.

In order to undertake fluvial flood hydraulic modelling, the following data requirements and data availability in Georgia will be considered:

1.3.1 Topographic Data and Base Mapping

It should be noted that LiDAR data are being procured for the floodplains of Georgia, hence all other data sets should be reviewed for catchment topographic data requirements and assessed including the quality and the cost of acquiring such data sets for the whole of Georgia.

There are several topographical products available. In order to gain a better understanding of each of these products, a brief description of them is necessary.

- LiDAR (Light Detection and Ranging): is a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth. These light pulses generate precise three-dimensional information about the shape of the Earth and its surface characteristics.
- DEM (Digital Elevation Model): represents the bare-Earth surface, removing all natural and built features.
- DSM (Digital Surface Model): captures both the natural and built/artificial features of the environment, as shown below.
- DTM (Digital Terrain Model): typically augments a DEM by including vector features of the natural terrain such as rivers and ridges. A DTM may be interpolated to generate a DEM. It should be noted that there are different definitions of DTM depending on the country and the term DTM and DEM are sometimes used indistinctively.

Figure 2-18 shows the difference between DSM (top) and DTM (bottom).

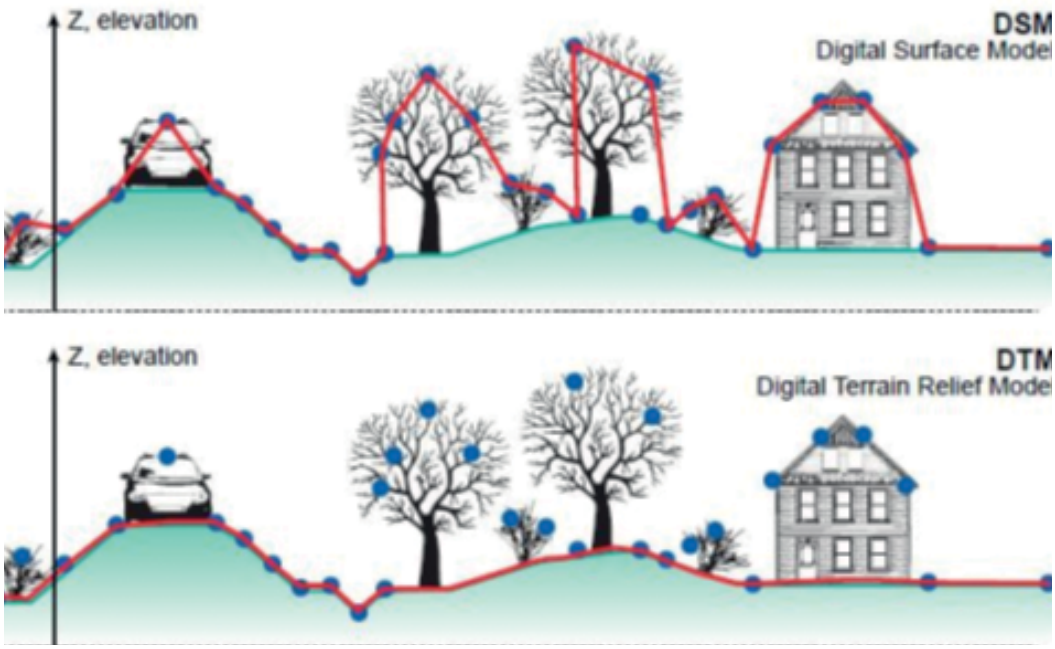


Figure 2-18. Difference Between DSM and DTM

Topographical information is very important for flood hydraulic mapping because it determines the areas that will be flooded, the extent of the flooding and also the water depth or the water surface elevation of the flooding. Topographical information should also be used during the 1D modelling as it will be helpful in providing further cross-section data, analysing possible spurious data and to enlarge cross-sections if needed.

The following topographic data requirements are identified:

- Digital Elevation Model (DEM): it should be noted that while the requirements for DEM availability and accuracy may vary depending on the flood source, this will only be analysed in the fluvial section and differences will be provided within the specific flood sources if required. Additionally, the DEM is one of the key data sources to be considered for flood modelling and special attention will be paid to this in the data requirements and in the data availability sections. There are different DEM sources to be considered in Georgia.
    - LIDAR data: as noted, a LiDAR survey is being commissioned within the framework of this project. The extent of the LiDAR survey is shown in Figure 2-19.

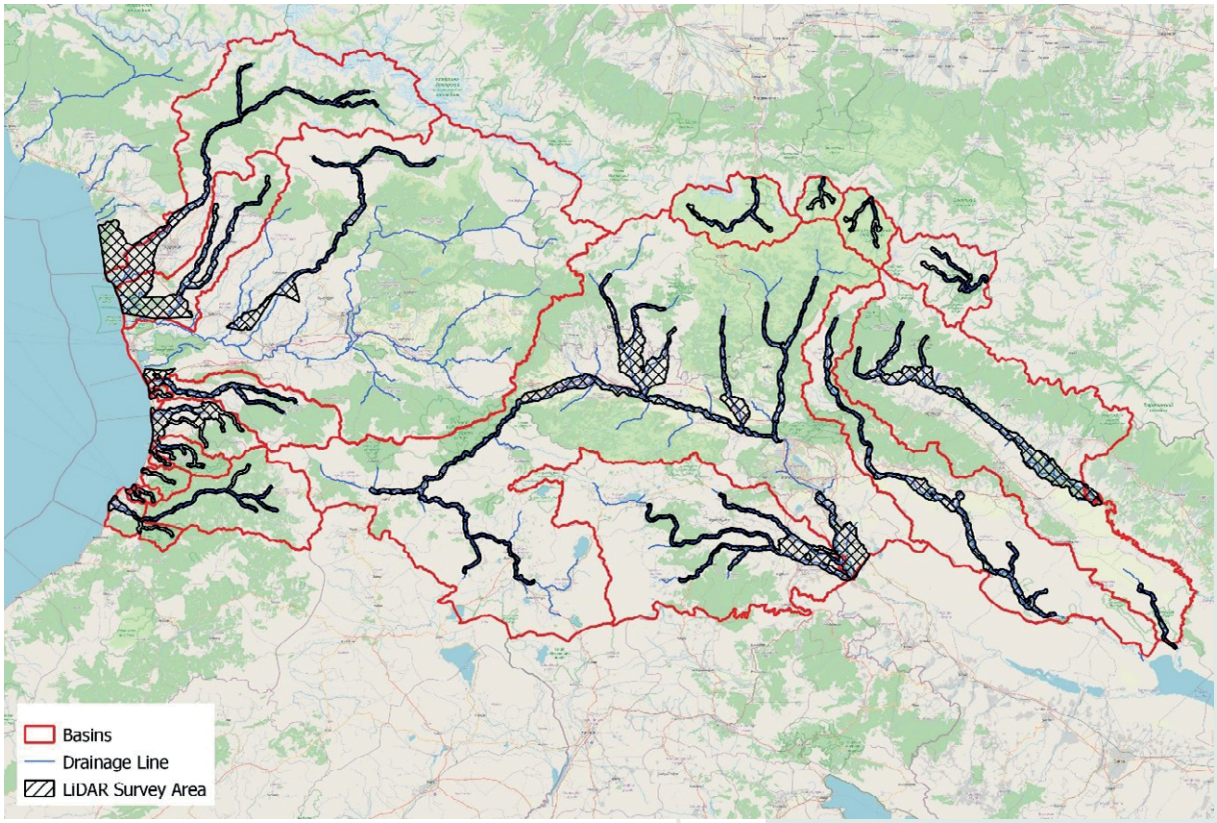


Figure 2-19. LiDAR Survey Extent

The proposed LiDAR survey data (Figure 2-19) will have a horizontal resolution of 1 metre with more than eight points collected per square metre and with an expected vertical accuracy better than 0.015 metre.

There are more LiDAR data available in Georgia such as in the urban Tbilisi area, in some areas in Kakheti in the Alazani catchment and north of Tbilisi (Figure 220). The accuracy of some of the old LiDAR

data will be reviewed when available. The data that are not available at the moment will be acquired and fully assessed before they are included in the modelling framework.

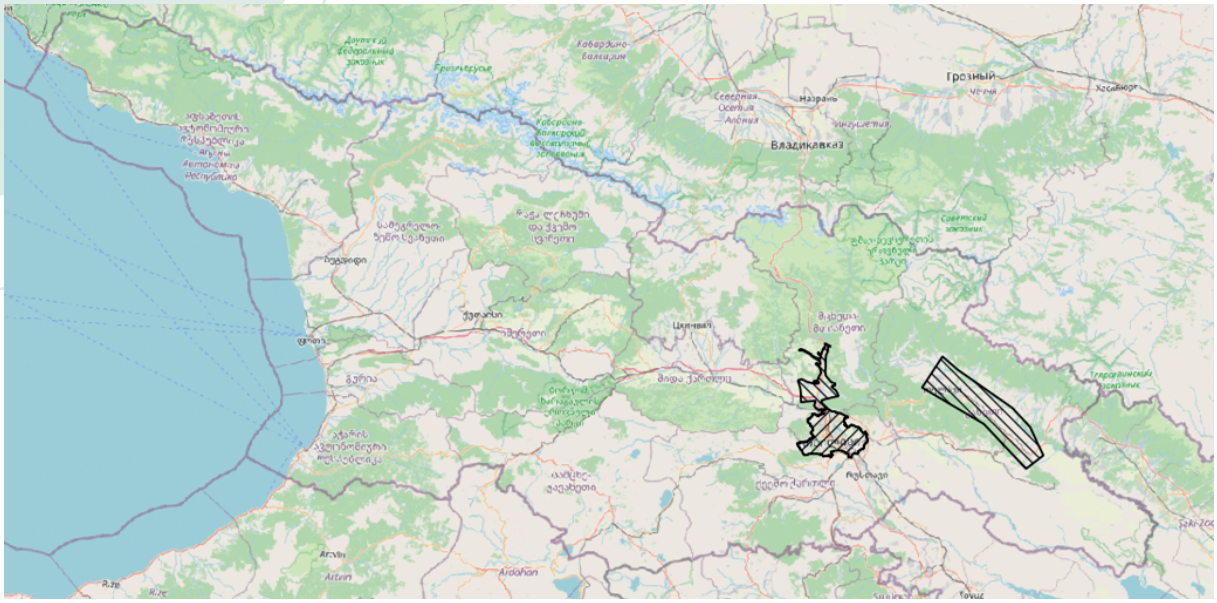


Figure 2-20. Other LiDAR in Georgia

- Orthophoto DEM: the Georgian Public Registry has a DEM that was derived from orthophotos. This DEM is not yet available to the consultant for the whole territory of Georgia as the existing data are only for the first three catchments (Figure 221) and their accuracy has been estimated at 4 metres.

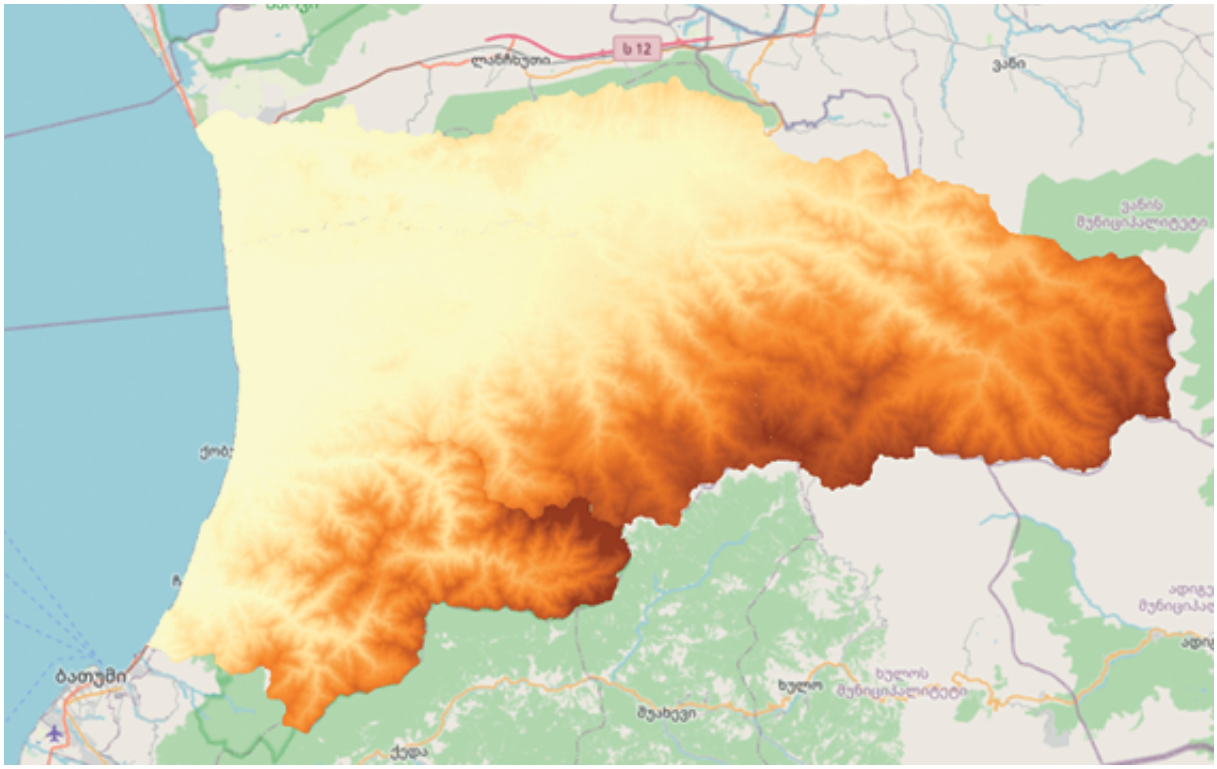


Figure 2-21. Orthophoto DEM for the Kintrisi, Supsa and Natanebi Catchments

- Global wide DEM: there are several sources of global DEMs.
  - STRM NASA V3: high-resolution topographic data generated from NASA's Shuttle Radar Topography Mission (SRTM) combined with further processing by the Jet Propulsion Laboratory (JPL) which is available through multiple repositories. It was released with a 1 arc-second, or 30 metres, sampling that reveals the full resolution of the original measurements. NASA's mission made use of dual radar antennas to acquire interferometric radar data. In 2019, NASA released a void-filled version of the Shuttle Radar Topography Mission digital elevation model, known as "SRTM Plus" or SRTM NASA Version 3. SRTM Plus uses the previous version of SRTM (Version 2) where the radar interferometric method was successful (not void). Most voids are filled with elevation data from the ASTER GDEM2 (Global Digital Elevation Model Version 2). Additional void filling of small areas used the GMTED2010 elevation model compiled by the US Geological Survey. It has to be noted that the SRTM radars are not able to sense the surface beneath vegetation canopies and thus the elevation measurements which are produced reflect the top of the canopies. The evaluation of the quality of the cartographic products derived from the SRTM show global linear vertical absolute height error values of less than 16 metres, an average linear vertical relative height error of less than 10 metres, a circular absolute geolocation error of less than 20 metres and a circular relative geolocation error of less than 15 metres. It should be noted that the accuracy of this product varies from place to place, and an assessment has not been undertaken for Georgia.
  - ASTER GDEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer-Global DEM) developed by the Ministry of Economy, Trade, and Industry (METI) of Japan and NASA was first released in June 2009 and generated data using stereo-pair images collected by the ASTER instrument on-board NASA's Terra spacecraft. ASTER is a sensor on NASA's Terra satellite that uses stereoscopic imaging to measure elevations via optical parallax where not obscured by clouds. The spatial resolution (horizontal) is 30x30 metres. A joint US-Japan validation team conducted a high-level review of the accuracy of the first dataset, and versions of the GDEM derived from the processing of the raw data. This review shows global elevations are on average within three metres of highly edited altimeter measurements with standard deviations and root mean square errors under 12 metres.
  - AW3D-DEM (ALOS: Advanced Land Observing Satellite, World 3D-DEM). The Advanced Land Observing Satellite (ALOS) initiative belongs to the Japan Aerospace Exploration Agency (JAXA), and it has been running a project to develop the precise AW3D global digital 3D map since 2014. ALOS World 3D-30m (AW3D30) is a free global DSM data set with a horizontal resolution of an approximately 30 metre mesh (1 arc-second in latitude and longitude) converted from the AW3D DSM data set (a five-metre mesh). The high-level assessment of the vertical accuracy of the product, as shown in the product's description issued in April 2019 by the JAXA itself, shows an absolute difference from existing global topographic data such as SRTM-3, ASTER GDEM and ICESat of less than five metres. ALOS World 3D-30m (AW3D30) is derived directly from the AW3D DSM dataset (a five-metre mesh) which is not available for free but must be purchased if required.

- PALSAR Radiometric Terrain Corrected (RTC) High Resolution DEM: this topographic information is the result of processing (amending or correcting) the raw data collected by the aforementioned ALOS initiative by means of using other DEM available. For Georgia, such auxiliary information is provided by the Shuttle Radar Topography Mission (SRTM) GL1 data at a 30-metre resolution. This product has been elaborated by the Alaska Satellite Facility (ASF) and presents the data in GeoTIFF format, i.e., in raster files with a horizontal resolution of 12.5 x 12.5 metres. Actual elevations as read directly from the tiles and downloaded for free from the web may show different values from those shown by the rest of the source material explained in this section since these DEMS are geoid-based and the ASF radiometrically terrain-corrected (RTC) product file shows ellipsoid height. Care must be taken when making any comparison between the different models vis-à-vis the topographic information while also being careful not to mix sources of information when assembling the final DEM to be used in any assessment. Therefore, the accuracy of this product varies greatly from place to place, and its assessment is difficult to be do at this stage.
- MERIT (Multi-Error-Removed Improved-Terrain): the MERIT DEM was developed by removing multiple error components (absolute bias, stripe noise, speckle noise and tree height bias) from the existing space-borne DEMs (SRTM3 v2.1 and AW3D-30m v1). It represents the terrain elevations at a three second resolution (90 metres at the equator) and covers land areas between 90N-60S, referenced to EGM96 geoid.

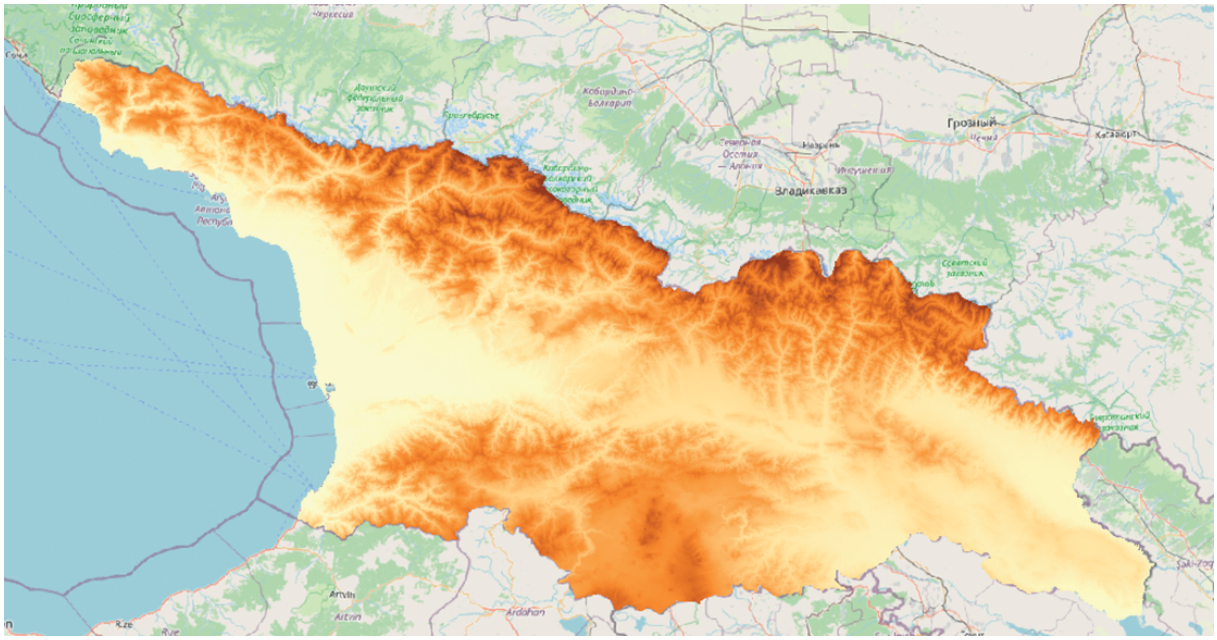


Figure 2-22. MERIT DEM for Georgia

The existing Georgian National DEMs spatial resolution, vertical accuracy and source availability are presented in Table 22.

Table 22. High Resolution DEMs in Georgia with a National Coverage

DEM Type	Spatial Resolution	Vertical Accuracy	Source
LiDAR Data	1 m	~0.15 m (technical specification)	UNDP – GCF-SDC programme
Orthophoto DEM Data	15 m	~4.0 m	Public Registry Office
SRTM Global DEM	30 m	~15 m	Global Sources
MERIT DEM	90 m	~4.0-5.0 m	Global Sources
ALOS	30	4.4	Global Sources
ASTER	30	17	Global Sources
PALSAR	12.5	5.5	Global Sources

At this stage, it is not possible to properly assess the quality of the LiDAR data collected within this project and the other available orthophoto data, but procedures have been defined in the methodology for this assessment, including the different options to follow depending on the analysis results.

Nonetheless, some comparisons and data accuracy checks have been undertaken with the existing data. In the first place, the Tbilisi LiDAR data have been compared against actual cross-section data in several sections for the Leghvtakhevi catchment in Tbilisi (Figure 223). This comparison has been undertaken for all of the available cross-sections, although only four of them are shown for illustration purposes. As can be observed, this comparison is moderately satisfactory and the difference between the LiDAR and the survey data is in the order of centimetres in most cases. LiDAR data are supposed to be slightly more accurate than what the analysis has shown, although the quality of these LiDAR data would be sufficient for modelling purposes. Nonetheless, the accuracy of the cross-section survey should also be considered.

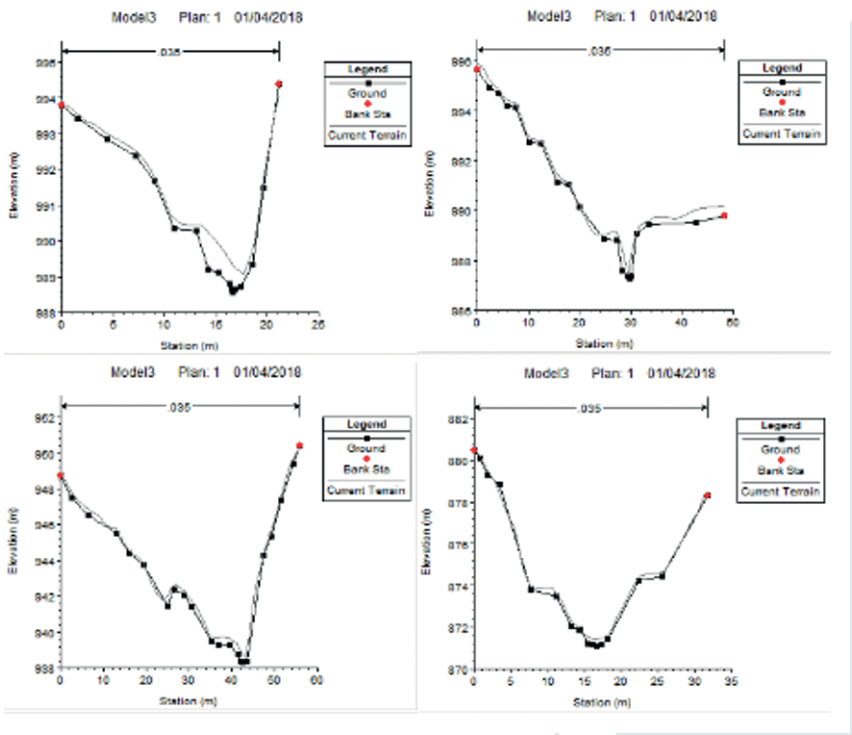


Figure 2-23. Comparison of Cross-section Data with Tbilisi LiDAR

A further comparison has been undertaken for a global DEM (MERIT) and for the orthophoto DEM in the three first catchments (Figure 224 and Figure 225). The MERIT DEM has been selected because it is believed that it provides the best elevation accuracy based on previous assessments and uses even if the spatial resolution is 90 metres (there are global DEMs with a higher spatial resolution). As can be noted, the two DEMs are comparable from a catchment point of view, although there are locations where the orthophoto DEM shows spurious values (zero values) across the catchments.

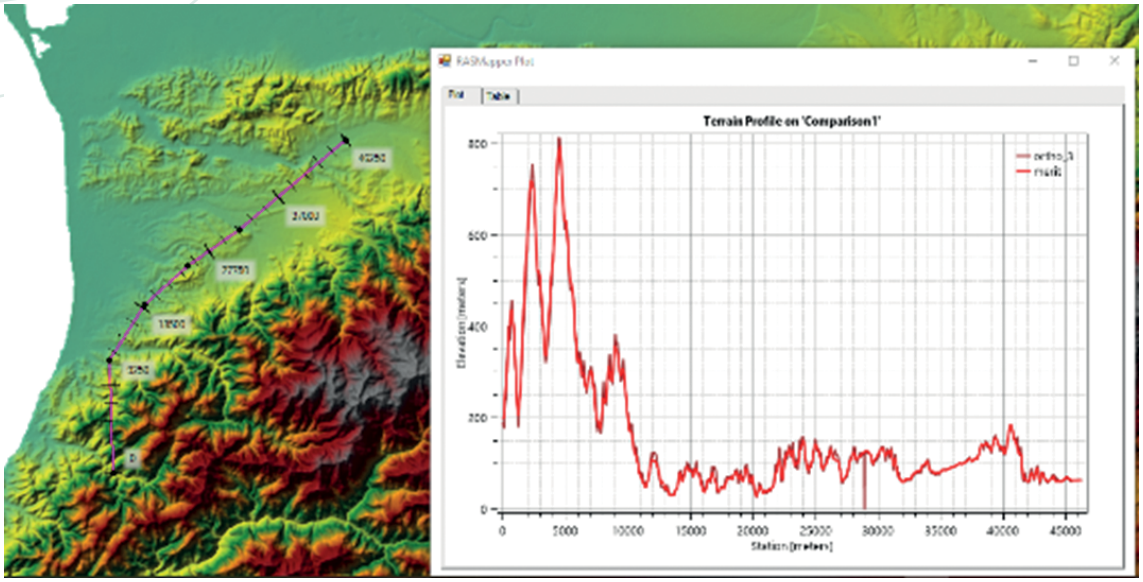


Figure 2-24. Comparison of Orthophoto DEM (Brown) and MERIT DEM (Red)

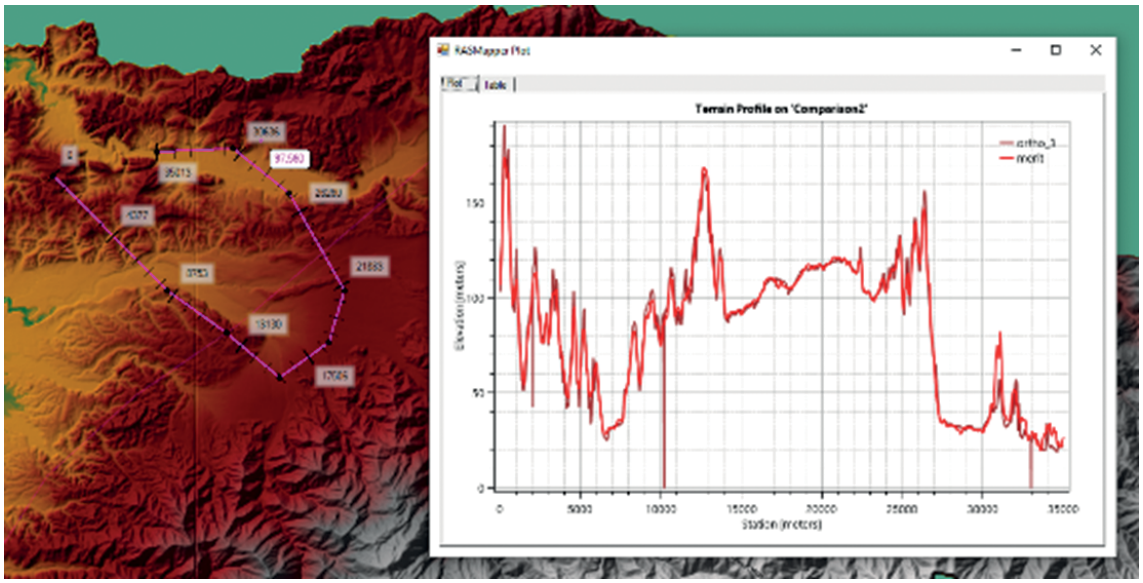


Figure 2-25. Comparison of Orthophoto DEM (Brown) and MERIT DEM (Red)

Further, the two DEMs have been compared against cross-section data in the Kintrisi River (Figure 226).

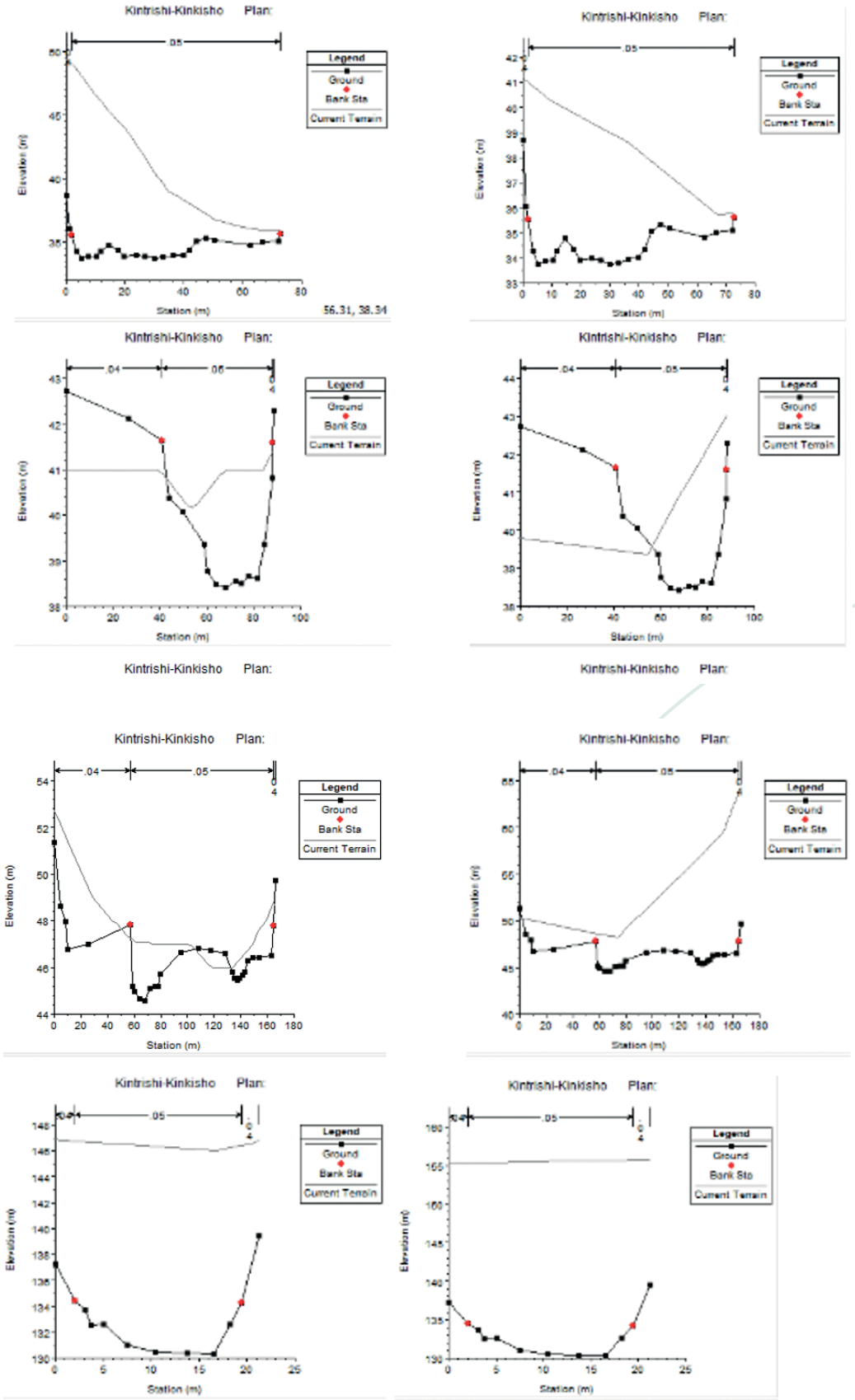


Figure 2-26. Comparison of Cross-section Data with Orthophoto DEM (Left) and MERIT DEM (Right)

As can be observed, the results are not satisfactory. While the MERIT DEM does not properly represent the channel (and it is not expected with a 90-metre resolution grid), the orthophoto DEM also does not properly represent the channel or floodplain topography. In some locations, a difference of more than ten metres between the orthophoto DEM and the cross-section survey data can be observed. A comparison between all of the survey points and the orthophoto DEM has been completed. This has been undertaken even though the DEM is not expected to capture the channel itself and therefore the results are unsatisfactory. The DEM should be more accurate in the banks, however, which explains the reason for the cross-section approach to assess this. This issue has been raised to the NEA and it is being investigated in order to ascertain if this version of the orthophoto is the most accurate and reliable one.

- Cross-sections: cross-section data is required for hydraulic modelling, especially for 1D modelling implementations. DEM data are based on several sources (LiDAR, Orthophoto, Satellite Radar, etc.) that measure the terrain. Those sources, however, cannot penetrate the water surface and, therefore, no 'bathymetry' information is available from DEM resources (unless incorporated later). Due to the lack of resources as well as the only recent availability of several open-source global DEM data, it is currently common to implement hydraulic models for fluvial purposes without any actual cross-section data. These models, however, tend to over-estimate water depths and flood extent due to the lack of channel data. This may lead to erroneous risk assessment and mitigation measures.

  Cross-section data is the main input required in a 1D hydraulic model. These data are used for the calculation of all of the equations described in the previous sections such as, for example, the continuity equation and the Navier-Stokes equation. Even if a hydraulic model is implemented only in a 2D mode, it is important to burn the cross-section data into the DEM in order to have a proper representation of the channel topography (bathymetry).

  The cross-section data come from topographical survey campaigns. As noted, these data can be directly extracted from DEMs, but the main channel topography is lost in the process and, therefore, it is not recommended. As mentioned above, the cross-section guidelines are provided in the Appendix IV with detailed specifications for topographical surveys.

  The appropriate cross-section spacing depends on the physical characteristics of the channel and the scale and purpose of the study; for instance, cross-sections may be further apart for a channel with a uniform cross-section and slope and more frequent cross-sections may be required for the design of flood defences. It is difficult, therefore, to provide general guidance on cross-section spacing, however it can be said generally:

  - For large rural rivers on low slopes, the maximum cross-section spacing should be around 200 metres.
  - For smaller streams, sleeper slopes or within urban areas, the maximum cross-section spacing should be around 50 metres.

Cross-section data are also generally required at the following points:

- All major obstructions to flow such as bridges and culverts as well as road and rail.
- Embankments across the floodplain.
- Points of significant changes in the shape of the channel and/or changes in the floodplain width.

- Significant changes in stream slope or near control sections (e.g., rapid drops at weirs and dams).
- Areas where there is a significant change in channel or bank roughness.
- At existing flood protection structures.
- Upstream and downstream of confluences with significant tributaries.
- At gauging stations or other locations where information is available for calibration.
- Other key areas of interest such as places adjacent to proposed development sites.

As an illustration, Figure 227 shows some of the factors that should be considered in specifying cross-sections for a model. The floodplain width and the availability and appropriateness of other data for representing out-of-bank flow-paths should be considered in establishing the required cross-section width.

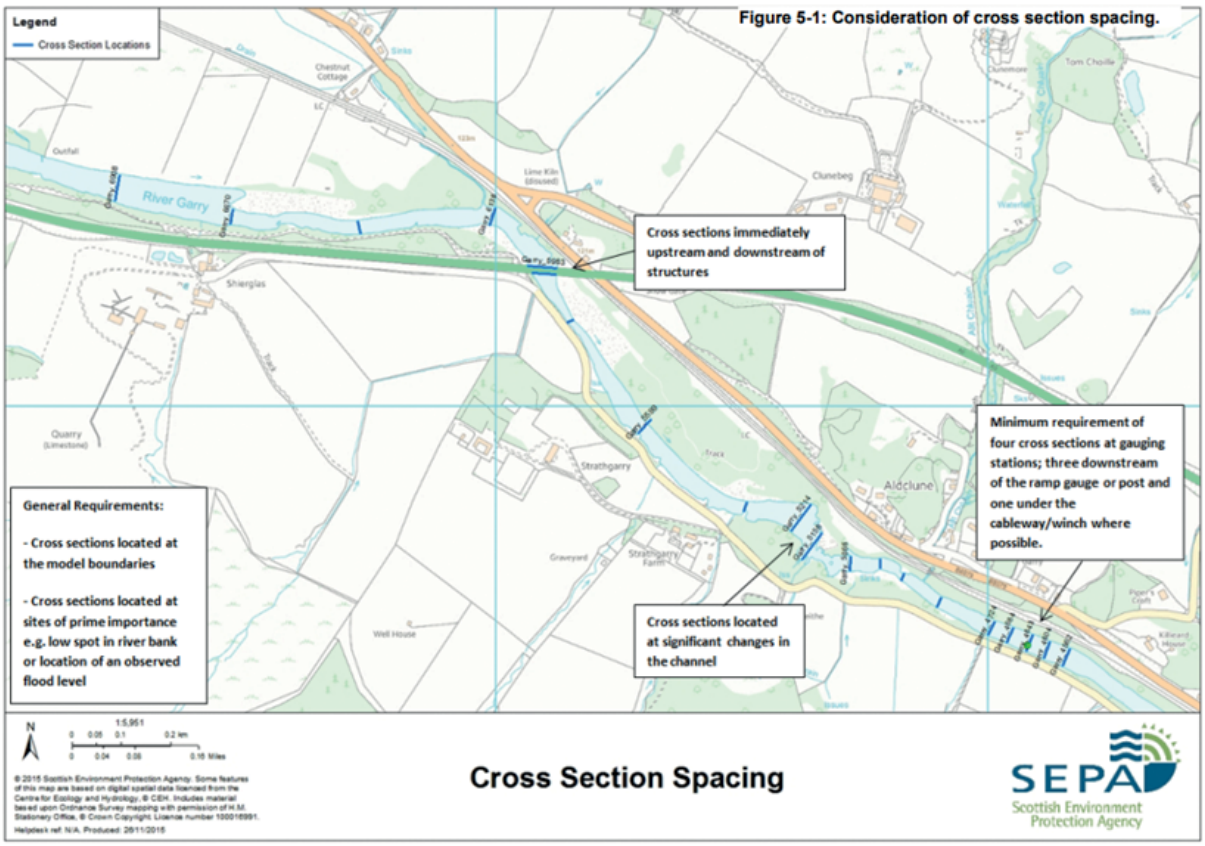


Figure 2-27. Cross-section Spacing (Source: Scottish Environment Protection Agency)

In addition to cross-section surveys during topographic campaigns, it is paramount that data for all of the different structures are present for the particular catchment. More information is included in the above-mentioned guidelines, including details about the four cross-sections required and the information needed depending on the type of structure.

Regarding the availability of data, a topographical cross-section survey and hydraulic structure survey are being undertaken in all of the basins within the framework of this study as mentioned above. The topographic survey was completed for six basins, although some other watercourses and basins will

also be addressed this year. The survey is being undertaken in close collaboration and communication with the project's hydraulic modelling expert who is providing advice and support regarding the location of the cross-sections to be surveyed, introduced the use of a survey brief for the preparation of the survey and also provided guidelines for data formats and data management. The cross-section survey obtained for the first three catchments in 2019 is shown in Figure 228.

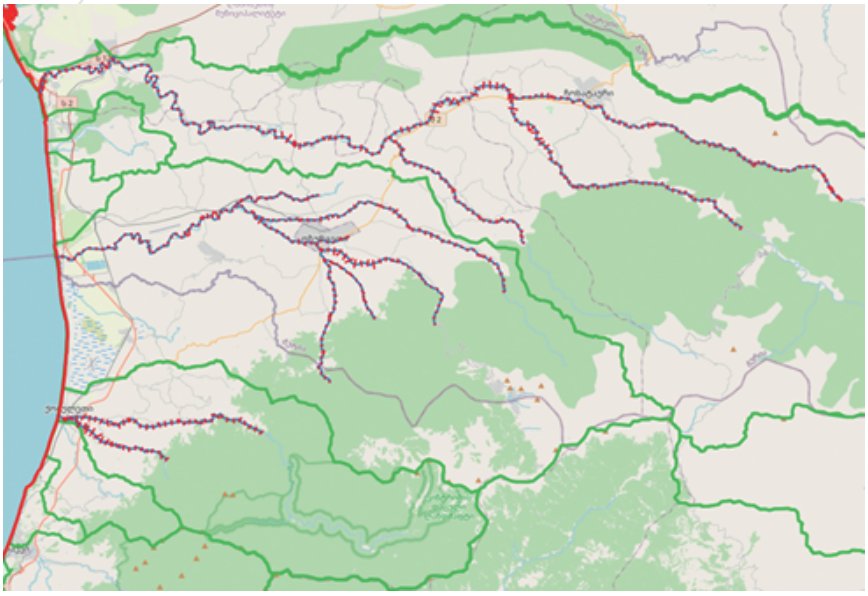


Figure 2-28. Cross-section Survey for the Natanebi, Kintrisi and Supsa Catchments

In addition to the data shown above, cross-sections have been surveyed for the Enguri River, the Khobi River, and some tributaries of the Mtkvari River around Tbilisi in 2020. For the forthcoming survey to be undertaken in 2021, some additional tributaries of the Mtkvari River, some tributaries of the Rioni River and the Chorokhi River and the Acharistskali River will be surveyed (Figure 229).

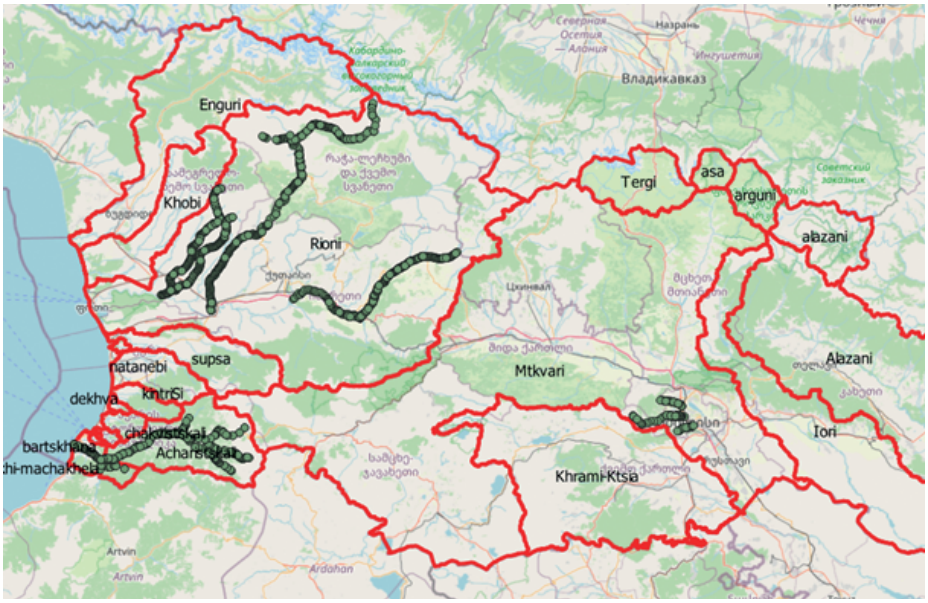


Figure 2-29. Cross-section Planning for 2021

The definition of the cross-section survey was undertaken by NEA experts with close consultations with the project's lead hydraulic modelling expert regarding the spacing and the location of the cross-sections.

- Base-mapping: apart from global sources (OpenStreetMaps, Figure 230, there is no digital base-mapping in Georgia for the implementation of flood models. There are, however, digitised old Soviet images for background purposes (Figure 231 in the same location as in OpenStreetMaps example).

Figure 2-30. OpenStreetMaps in Georgia

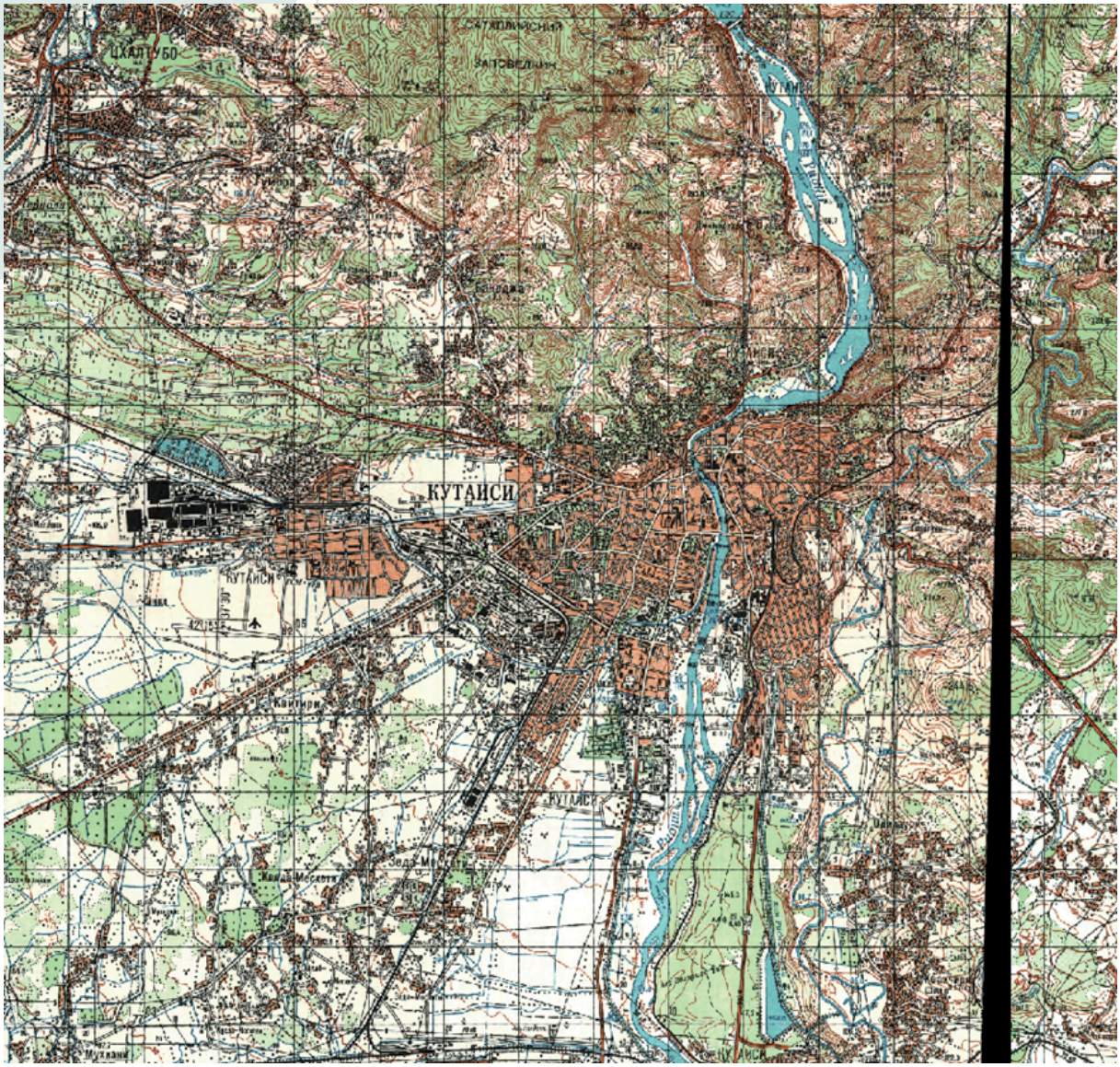


Figure 2-31. 1:50,000 Digitised Old Soviet Map

In some countries, national base-mapping is available and in other countries, digitised and interactive digital base-mapping can be acquired from private companies.

The role of base-mapping information in a flood hydraulic model is mainly for informational purposes. This can also be combined with the information available from aerial imagery. Base-mapping can be very important in order to understand the different flood processes, the presence of infrastructure, buildings, and transportation; elevation data (contours), old river channels and so on.

- Aerial Imagery (aerial photos and satellite imagery): there are orthophotos available for the whole territory of Georgia from the Public Registry. So far, the orthophotos images have not been acquired.

  Aerial imagery or orthophotos are in most cases acquired by national stakeholders and made available to flood modellers. It should be noted that the usage of aerial images is similar to the

use of base-mapping in flood modelling. In addition to the uses described above, the aerial images can be used for the definition of roughness in the hydraulic models and to identify extra features that may affect different flood mechanisms.

Figure 2-32. Orthophoto in the Ambrolauri Area in Georgia

1.3.2 Hydrometric Data Sets

- Rainfall Data: rainfall data are not a direct input to fluvial hydraulic models (unless the direct rainfall method is used). Rainfall data, however, are an input for hydrological models and they have a direct relationship to flood events in most cases. From a hydraulic modelling point of view, the use of rainfall data helps the modeller during the implementation of the models and especially during the calibration process. While the discharge information comes directly from hydrological assessments for specific events, it is important to understand the evolution of

rainfall during any particular event during the calibration of the models, especially if the calibration results are not being satisfactory. Therefore, it would be important to collect all of the available data, understand the location of the different stations and plot the precipitation data against the discharge and water level data as predicted by the modelling framework. Additionally, the spatial distribution of the stations will also have an impact on the results as will also be discussed below. For instance, if there are no precipitation stations located close to the area of interest, the calibration results may not be as accurate as if a precipitation station were close to this area. Therefore, the location of the rain gauges should be fully considered during the implementation.

The rainfall data availability in the three first catchments (Supsa, Natanebi and Kintrisi) have been analysed. The data for the Supsa catchment will be shown in this section. The NEA will be undertaking this analysis for each of the catchments to be addressed within the framework of this project. Additionally, these analyses will also be undertaken from a hydrological modelling point of view where the role of rainfall data is more significant.

The Figure 233 shows the location of both the hydrological and the meteorological station in the Supsa catchment. Figure 234 shows the Voronoi (or Thiessen) polygons for the Supsa catchment. As can be observed, the density of the precipitation stations in the upper catchment is not very high while it is slightly better in other parts of the catchment.

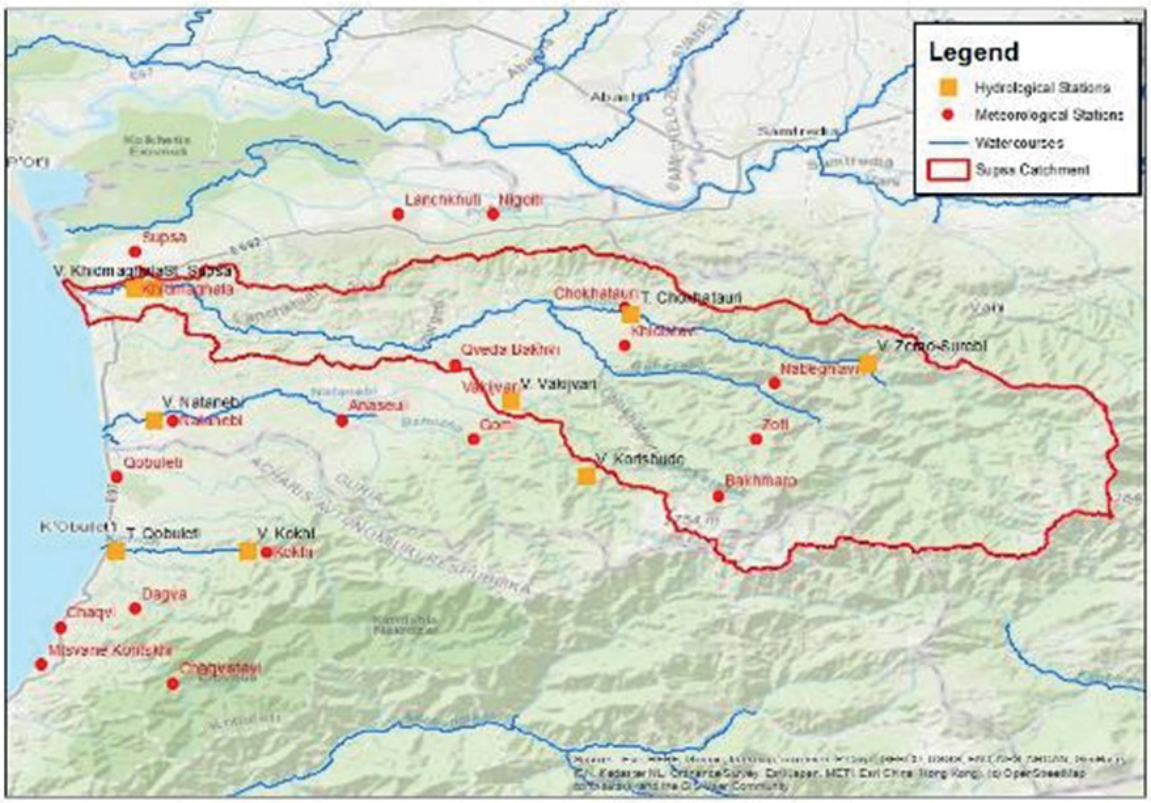


Figure 2-33. Meteorological and Hydrological Stations in the Supsa Catchment

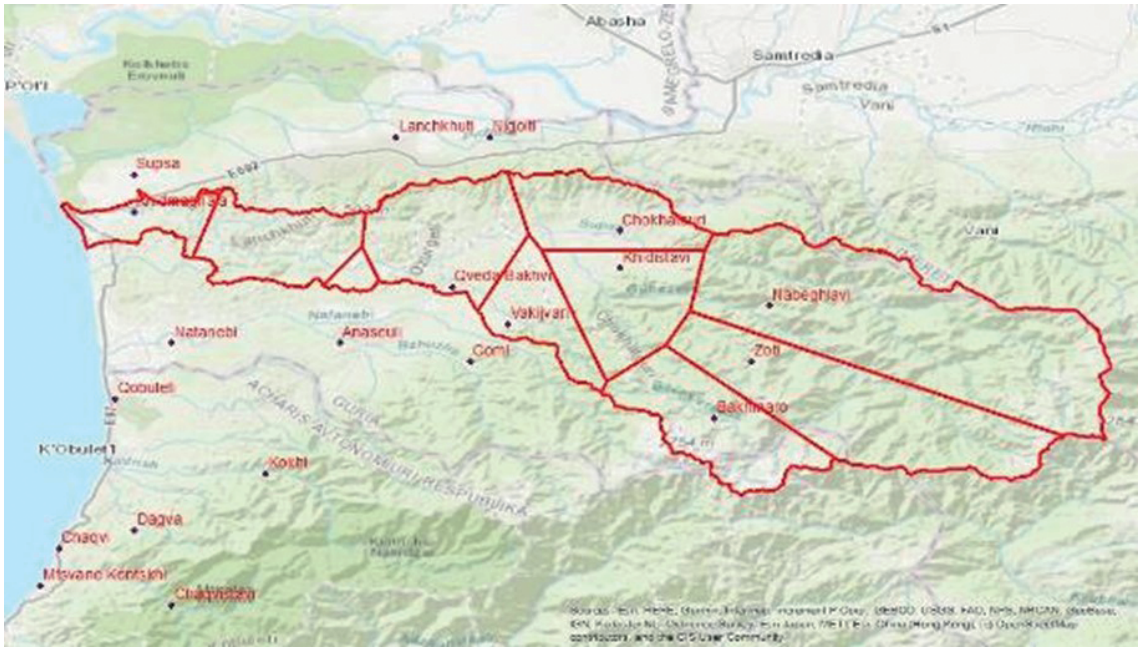


Figure 2-34. Voronoi Polygons for the Supsa Catchment

Figure 235 below shows the time availability for these stations. Some of them show a long availability while others have been deployed for only a short period of time.

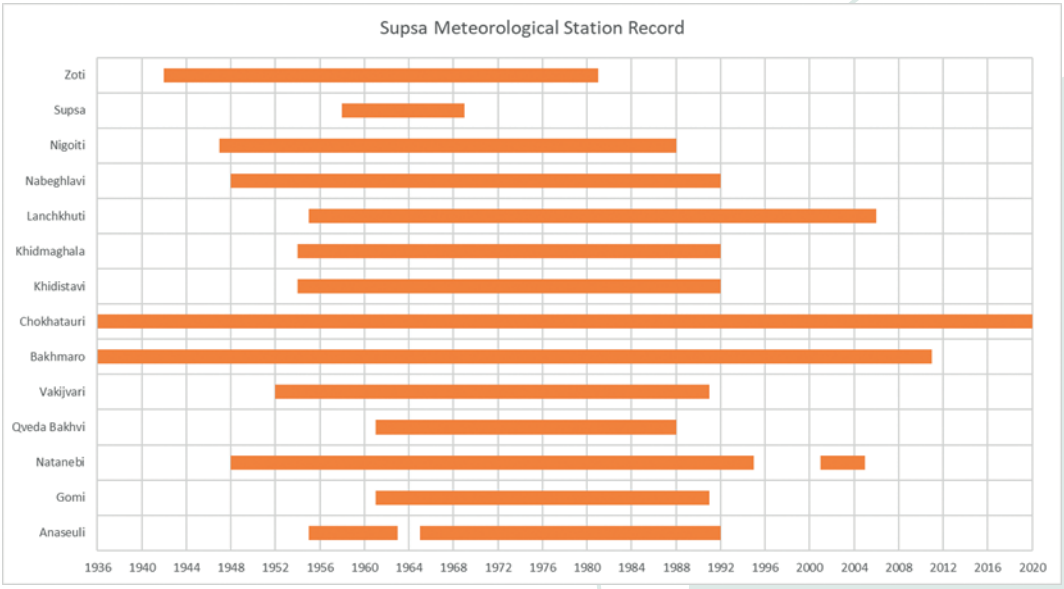


Figure 2-35. Rainfall Data Availability in the Supsa Catchment

The consultant does not have the actual data from these stations and so no further analysis could be undertaken.

As noted earlier, a detailed analysis per catchment will be undertaken by NEA modellers. An analysis of the precipitation (and other) data available will be undertaken before the implementation of the flood modelling framework for any catchment.

The collection of rainfall data per catchment is undertaken using existing stations and decommissioned ones, bearing in mind that the network coverage was higher in Georgia during Soviet times. All of the old stations and most of the existing ones, however, record data on a daily basis which will pose issues from a hydrological and hydraulic modelling point of view, especially in small catchments. Stations recording sub-daily data (hourly) are located in the Rioni Basin and around Tbilisi. The figure below shows the location of all of the existing precipitation observational points in Georgia, including meteorological posts and meteorological stations.

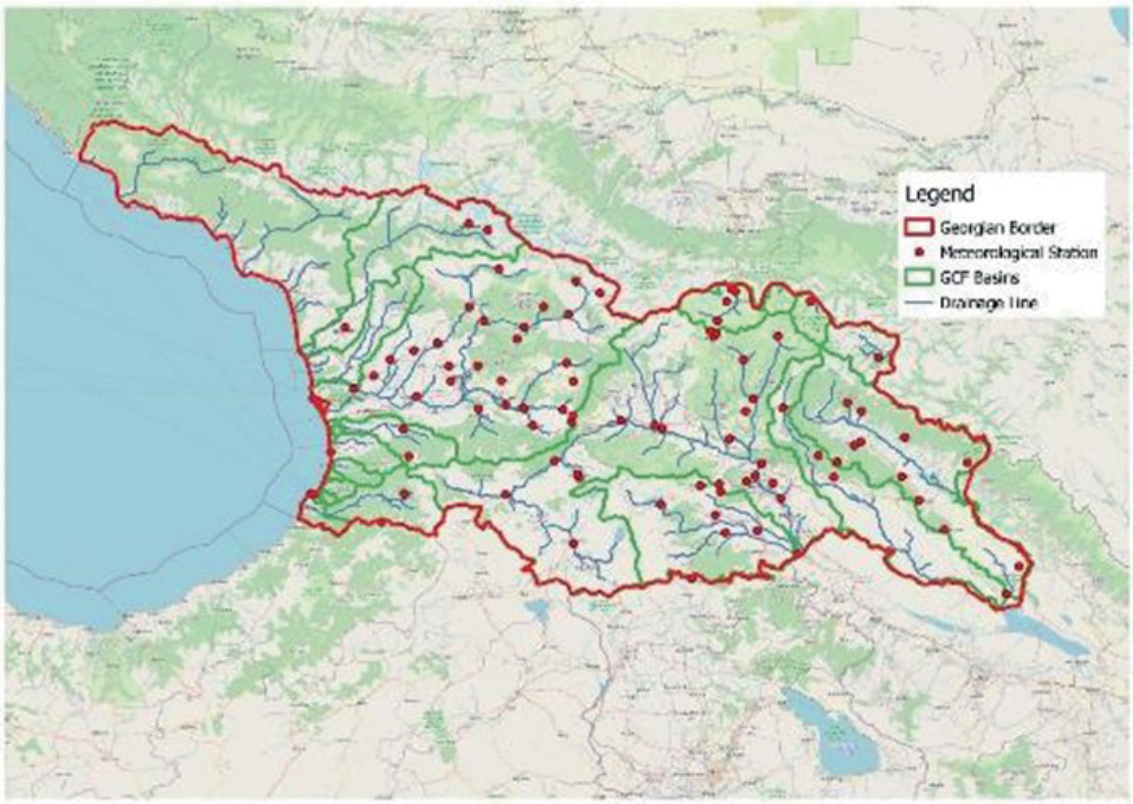


Figure 2-36. Existing Meteorological Stations and Posts in Georgia

The meteorological monitoring network in Georgia will be expanded within the framework of this project. The Figure 237 below shows the location of proposed additional meteorological posts and stations. While these observational points will be deployed in the near future, it is unlikely that they will provide relevant information for the direct implementation of models. However, the information coming from these stations could be useful for sub-daily purposes and, therefore, their locations should be considered for modelling purposes.

An assessment of the locations and the types of the stations was undertaken by the project's hydro-meteorological expert and this information is available in a deliverable prepared by this expert.

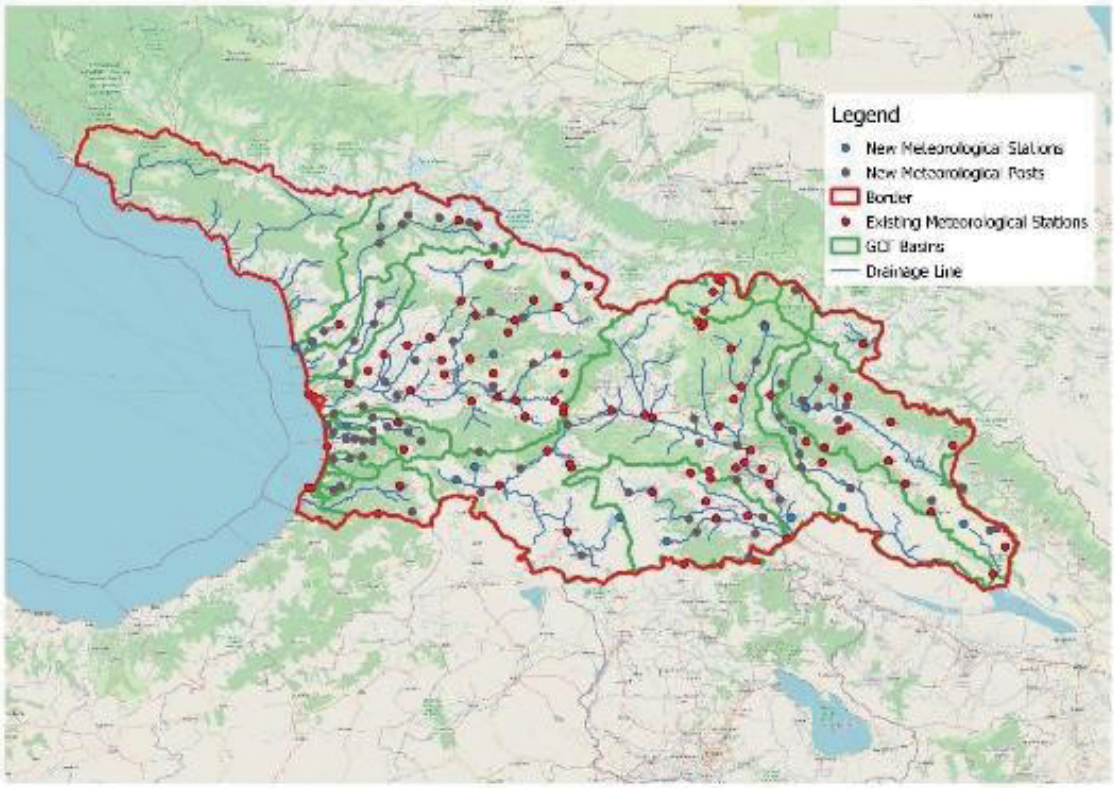


Figure 2-37. Proposed New Meteorological Stations and Posts

A further quick assessment has been undertaken with the information of the existing and proposed meteorological stations. Sub-catchments have been derived using the MERIT DEM for the whole territory of Georgia and this has been compared with the location of the existing and proposed stations (Figure 238). As can be observed, most sub-catchments are covered by stations. There are some areas in the south-west and the north of Tbilisi where the coverage may be limited but the whole territory is covered in general. The derivation of the sub-catchments was undertaken using default values from the ArcHydro and, therefore, a more detailed assessment will be necessary per catchment and also in consideration of the location of significant decommissioned stations.

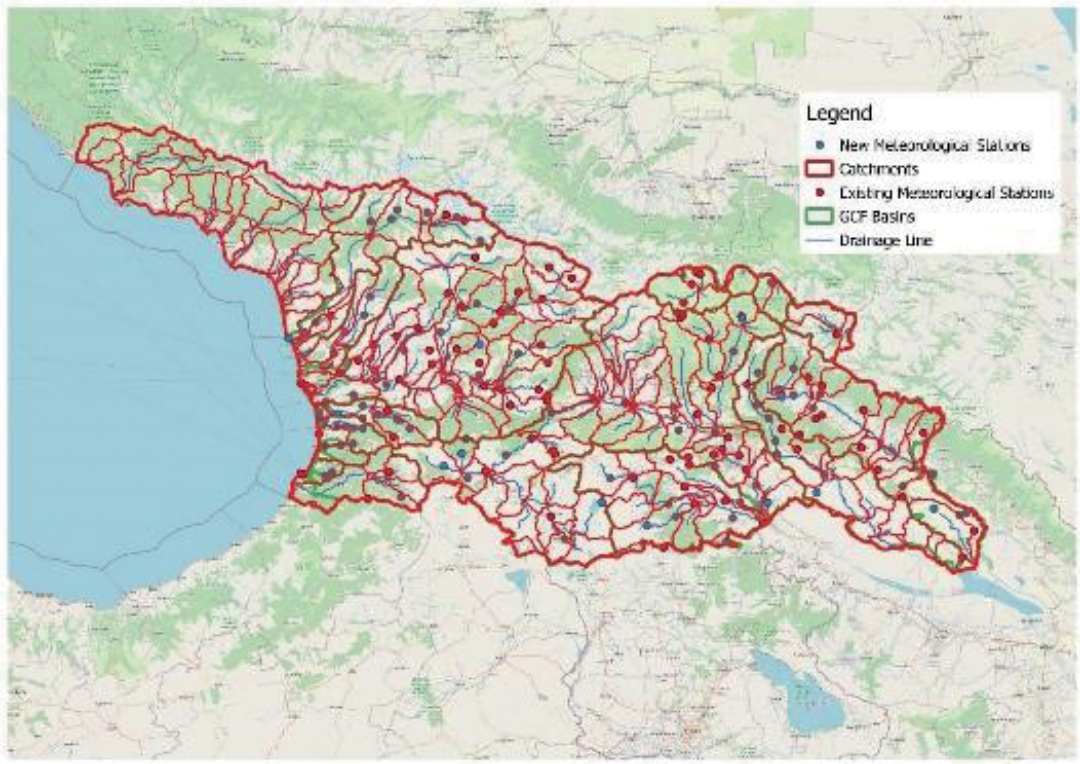


Figure 2-38. Sub-catchments, Existing and Proposed Meteorological Stations

- Flow and level data: flow and level data come from hydrological stations. Most hydrological stations measure the water level (though different means) while discharge data are obtained through the use of rating curves. These curves are derived from taking periodic measures of the velocity in the cross-section where the station is located during several stage conditions. These should be considered during the hydraulic modelling implementation and calibration because while the water level is a measured value, the discharge is a derived value that depends on the quality of the rating curve. Therefore, it is recommended that models are mainly calibrated against water level, although the discharge values should also be considered in detail, especially in order to understand velocities vis-à-vis the location of the station.

  The procedures for the use of discharge data in hydraulic models is fully described in the sections below. These data, however, are mainly used for calibration purposes and for understanding the evolution of the discharge and the water level during a flood event. It is important that the hydraulic modeller processes all of the discharge data and has the data available for the calibration. This can be done within the same hydraulic modelling software or using other resources.

  The availability of these data for hydraulic modelling purposes is a requirement for a model to be calibrated. The location of the stations should be fully considered when the modelling domains are being defined in order to cover the locations of as many stations as possible.

  The situation with hydrological stations is very similar to that of meteorological stations. Data are recorded on a daily basis in most cases, but in stations deployed in the Rioni basin and in the urban Tbilisi area. The consultant has no access to the data from these stations as of yet.

Information about precipitation gauges; that is, the location of existing stations (not including decommissioned ones, Figure 239) as well as stations proposed within the framework of this project (Figure 240) has been obtained and processed.

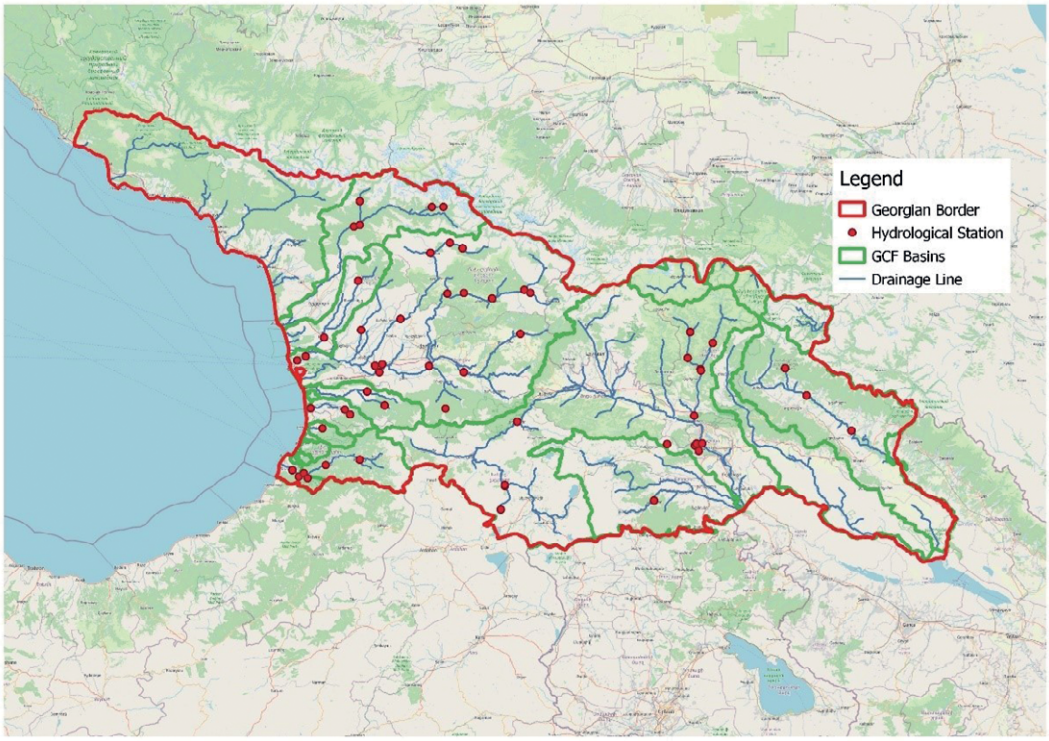


Figure 2-39. Existing Hydrological Stations

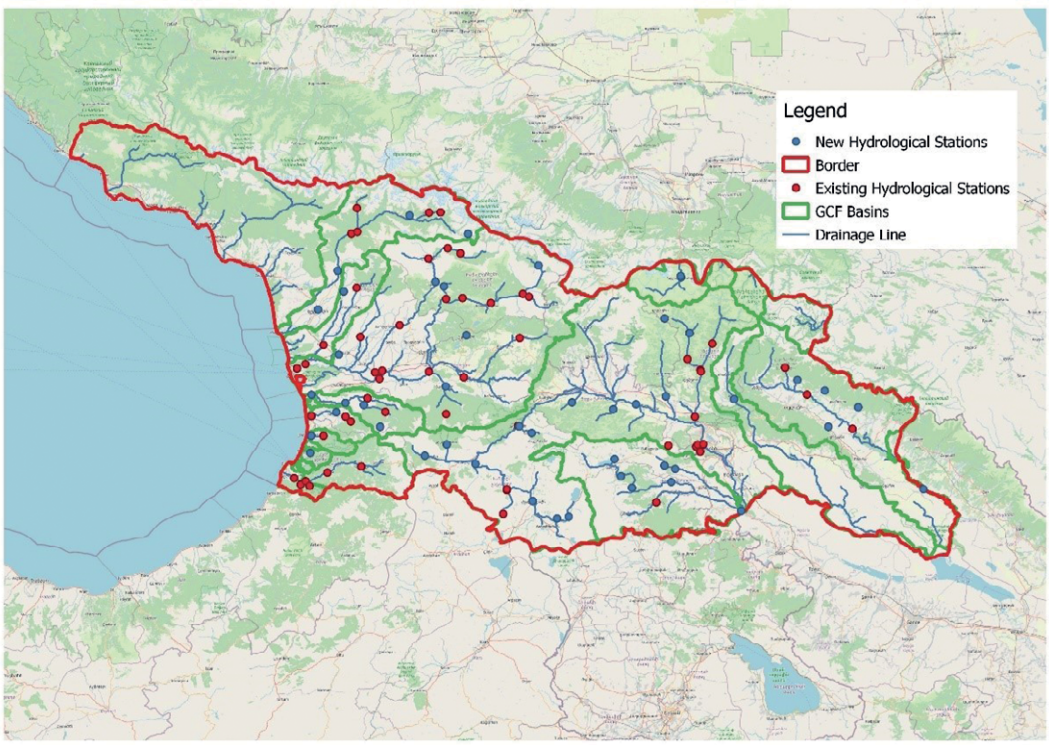


Figure 2-40. Proposed Hydrological Stations

The location of hydrological stations is shown in Figure 233 with four stations on the main Supsa River and one station on one tributary, although the records for the latter are only available for a short range of time. This can be observed in Figure 241 below where the actual availability of records for this catchment is shown. There is also no information regarding the type of hydrological station or the rating curves for these stations.

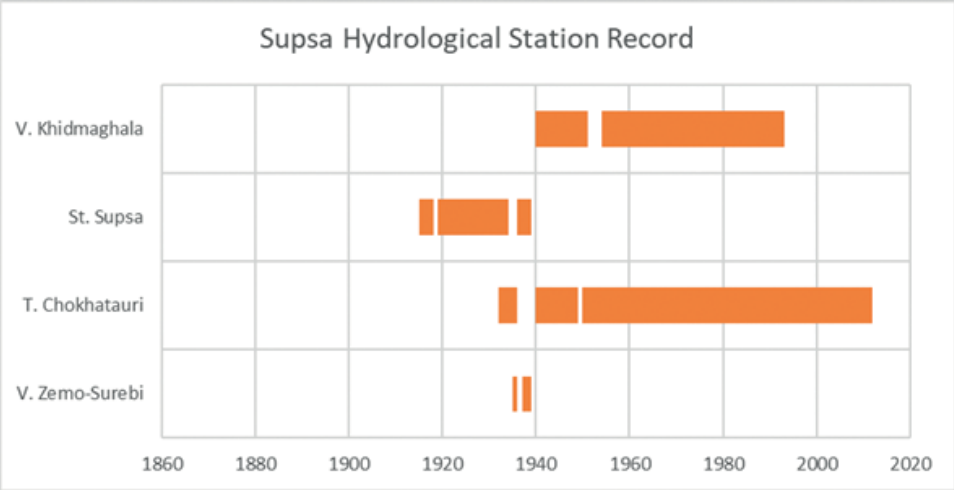


Figure 2-41. Flow Data Availability in the Supsa Catchment

- Records of Past Flooding:
  - Maps of observed flood events: as previously noted, these maps can be used for calibration purposes. These maps will be used in the calibration process in order to understand the extent of any flood event. They are usually derived from local records, aerial photographs, and consultations with the local population. No maps of observed flood events have been found apart from the Vere impact assessment report and flood outlines as developed by the NEA (Figure 242).

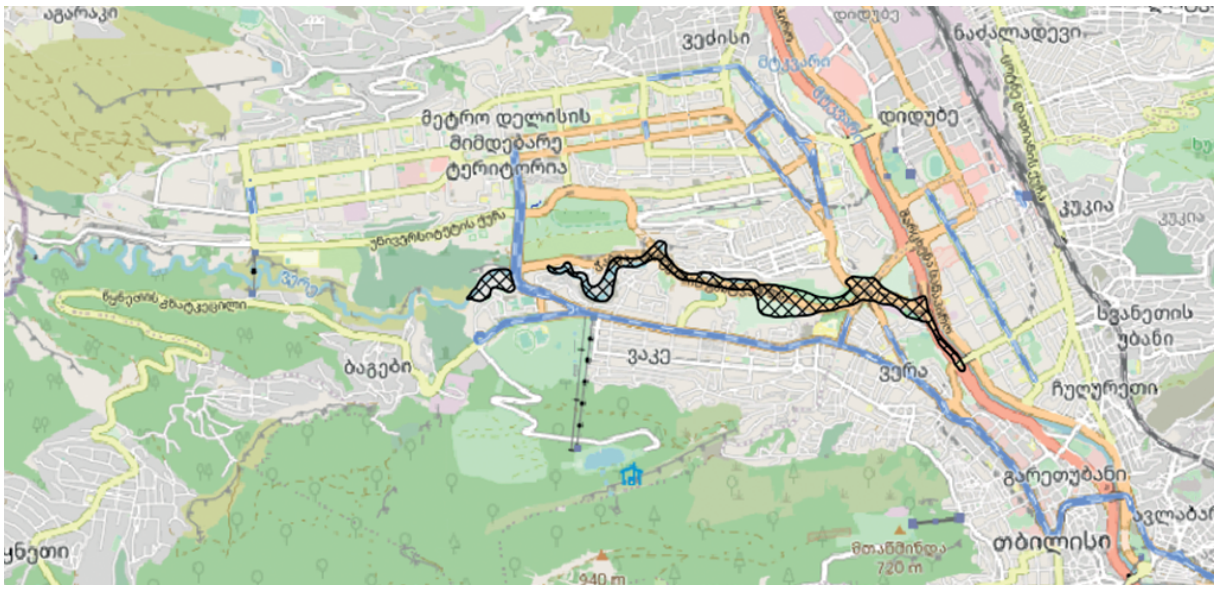


Figure 2-42. Observed Flood Mapping for the Vere River for the June 2015 Event

- No indicative flood extent maps of previous events have been found.
- Satellite imagery: different satellite imagery providers have been assessed in terms of finding suitable flood outlines. Copernicus, the International Charter for Space and Disasters, the Darmouth Flood Observatory, Landsat and MERIS data sources have been assessed. Unfortunately, no suitable satellite images have been found for calibration purposes. The only information found was broad and unrealistic shape polygons in the Darmouth Flood Observatory repository. Nonetheless, satellite images are a good source of information for flood mapping of previous flood events. The following satellite sources should be noted:

- MODIS: The MODIS instrument is operating on both the Terra and Aqua spacecraft. It has a viewing swath width of 2,330 km and views the entire surface of the Earth every one to two days. Its detectors measure 36 spectral bands between 0.405 and 14.385 µm and it acquires data at three spatial resolutions: 250 metres, 500 metres and 1,000 metres. MODIS data are open-source and available for free to any user.
- Sentinel: Sentiel (ESA) is a polar-orbiting, all-weather, day-and-night radar imaging mission for land and ocean services. The first Sentinel-1 satellite was launched on a Soyuz rocket from Europe's Spaceport in French Guiana on 3 April 2014. The Sentinel-1, Sentinel-2 and Sentinel-3 Scientific Data Hub provides free and open access to a rolling archive of Sentinel Level-0 and Level-1 user products.
- Envisat: Launched in 2002, Envisat was the largest Earth observation satellite ever built. It carried ten instruments, one of which was the Advanced Synthetic Aperture Radar (ASAR). ASAR was designed to operate at C-band and in four modes: image, wave, wide-swath, and global monitoring. The ground resolution in the first two modes is approximately 30 × 30 metres. In the wide swath mode, it is around 150 × 150 metres and in the global monitoring mode – 1000 × 1000 metres. The Envisat-ASAR wide swath mode is a good source of images for historical flood monitoring purposes, and it is recommended that the availability of images for this mode for the area of interest is assessed.
- ERS-2–SAR: Launched in 1995, ESA's ERS-2 carried a C-band SAR sensor that was designed to operate in two modes. The wide-swath mode has a swath of 100 km and spatial resolution of 26 metres across track and 6-30 metres along track. The wave mode provides small 5 × 5 km images at 200 km intervals along track.
- Cosmo-SkyMed: The Italian Cosmo-SkyMed mission is a four-satellite constellation, each equipped with an X-band SAR sensor. The fourth satellite was launched in 2010. The mission operates in three different modes: StripMap, with a 3,040 km swath width and a ground resolution of 3-15 metres; ScanSar, with a 100 × 100 × 200 × 200 km swath and a ground resolution from 30×30 metres to 100 × 100 metres and Spotlight-2 with a 10 × 10 km swath and a 1 × 1 metre ground resolution.
- Radarsat-2: The Canadian Radarsat-2 was launched in 2007 and follows on from Radarsat-1. The advanced C-band radar imager provides commercially available high-quality data products for many applications. It can operate in a number of modes with resolutions ranging from 3 to 100 metres and swath widths from 20 to 500 km.

- TerraSAR-X: The German TerraSAR-X was launched in 2007 carries and a high-resolution X-band SAR sensor. TerraSAR-X operates in three alternate operating modes: SpotLight, giving a 1 metre resolution for a surface area of 5 × 10 km; StripMap, giving a 3-metre resolution for a surface area of 30 × 50 km, and ScanSAR, giving a 16-metre resolution for a surface area of 100×150 km.
- TanDEM-X: The German TanDEM-X was launched in 2010 and is almost identical to TerraSAR-X. The two satellites fly in closely controlled formation with between 250 and 500 metres between the two. The mission will provide consistent global digital elevation models with an unprecedented accuracy.
- PAZ: Launched in 2014, the PAZ satellite, previously known as SeoSAR, is Spain's first high-resolution X-band SAR mission. It operates in three modes: SpotLight, with a 10 × 10 km swath and a ground resolution of 1 metre; StripMap, with a 30 × 30 km swath and a ground resolution of 3 metres, and ScanSAR, with 100 × 100 km swath and a ground resolution of 6 × 18 metres.

  All the data from the missions described above contribute to the European Space Agency (ESA) Copernicus mission. It should be noted that access to the Sentinel Mission rolling archive is open to everyone directly. Access to the other missions should be requested from the ESA. Additionally, some of the missions detailed below are no longer operational. However, the retrieval of data for calibration and validation purposes of old events should be considered.

1.3.3 Physical Catchment Data Sets

- Land use maps: land-use maps are mainly used in hydraulic modelling to derive roughness values for the area of interest. These data are used both in 1D and 2D modelling, although it should be noted that the 1D roughness definition should be mainly based on photographs from the survey campaign and/or from aerial photographs. As has been described several times throughout the report, the definition of the roughness is a key process in the implementation and calibration of hydraulic models. The roughness indicates how 'easy' water can flow over a specific surface. The higher the roughness, the more difficult it will be for water to flow and vice versa. There are several approaches available in most modelling software for defining the roughness in a model, although a Manning's approach is recommended and used in most cases. Information about the Manning's equation and number has been provided in previous sections as well as information on how to process land-cover data for roughness and Manning definition purposes.

Several land-use maps are available in Georgia. Apart from local resources (no information about the production year, the resolution, or the source, Figure 243), there are also global resources. Special attention should be paid to the Copernicus Land Use project, providing a 100-metre grid land-use worldwide and updated on a yearly basis. The Copernicus data have been acquired (Figure 244) and assessed.

The process for using these data for hydraulic modelling purposes is fully described in the section below.

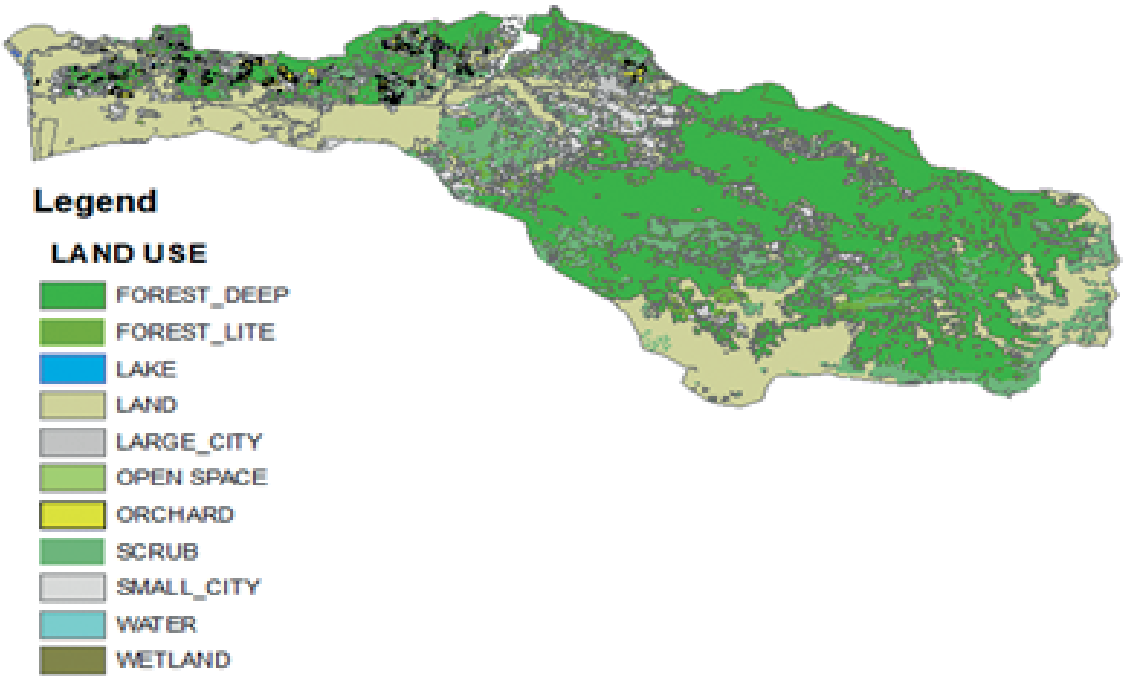


Figure 2-43. Land-use Map for the River Supsa Basin

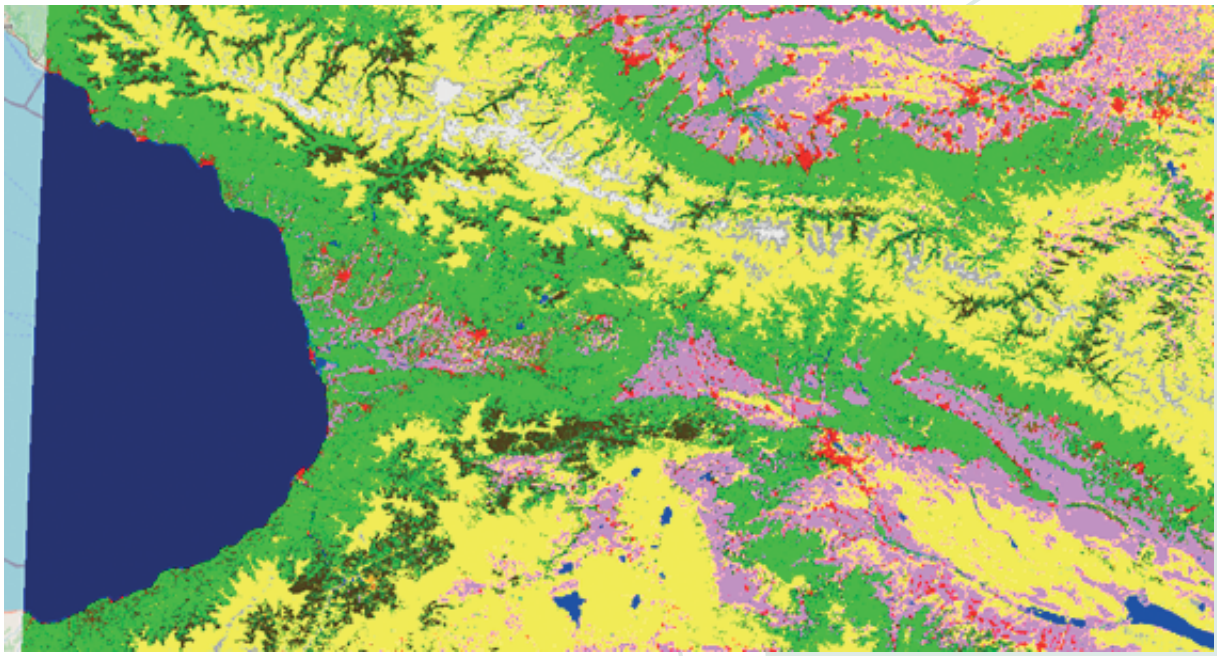


Figure 2-44. Copernicus Land-use.27 Legend Available in the Publication Below

27. M. Buchhorn, B. Smets, L. Bertels, B. De Roo, M. Lesiv, N.E. Tsendbazar, L. Linlin and A. Tarko. (2020). Copernicus Global Land Service: Land Cover 100 m: Version 3 Globe 2015-2019: Product User Manual; Zenodo, Geneva, Switzerland, September 2020; doi: 10.5281/zenodo.3938963.

- Map of existing flood defences: no information is available regarding the location of flood defences. This information is usually recorded by relevant institutions such as the Ministry of Regional Development and Infrastructure and/or the NEA. This is information is vital for hydraulic modelling purposes. The lack of details vis-à-vis this information creates a big constraint for modelling implementations. For instance, modelling results in a particular location may be showing flooding in a certain area that was protected at the time of the event. The information required for flood defence structures includes:
  - Detailed location of the flood defence.
  - Type of flood defence. This can be either a levee or a flood training wall, an on-line or offline storage facility, weirs, diversions and so on.
  - Time of deployment. It is important to understand and have information about the construction or deployment of the flood defence. This is very significant for the implementation and/or calibration of models. The flood defence may have already been present for some events but not for others. In some cases, flood defences are deployed after the occurrence of a flood event.
  - If the flood defence is a 'linear structure' type, such as levees or walls, it is important to gather detailed information about the structure such as:
    - Location
    - Length
    - Width
    - Level
    - Material
    - Shape
    - Photographs

  All this of information is required for modelling purposes. A linear structure will be modelled using the lateral structure available in most modelling software in most cases. Otherwise, the structure can be included in the cross-sections of the model, although this approach is not recommended as the details of the structure in between the cross-section will not be considered.
  - If the flood defence is a 'storage' type, either online or offline, it would be important to gather detailed information about the structure such as:
    - Location
    - Operating rules for offline storage and/or the presence of weirs (and details as per the description for linear structures).
    - Storage details
    - Photographs
  - In both cases, a good source of information would be 'as-built' drawings from the construction and design process. If these are not available, or if they are older than ten years, the structure should be surveyed, considering all of the data requirements outlined above.

1.4 Data Quality for Fluvial Flood Modelling in Georgia and Future Data Availability

1.4.1 Topographic Data and Base-mapping

An assessment of the following data sets will be undertaken:

- Digital Elevation Model (DEM): the DEM is one of the key parameters for the modelling of all flood sources, including fluvial floods. An assessment has been undertaken regarding the quality of all of the different sources already available. The following can be outlined:
  - LiDAR: while the accuracy of the LiDAR data to be produced within the framework of this project cannot be assessed as of yet, this is believed to be within the expected accuracy and resolution. A 1 metre DEM will be provided by the LiDAR contractor and this DEM is supposed to be adequate for the areas where data have been acquired.

    The LiDAR data area of interest (AoI) was defined using indicative modelling, using very high flows in all of the basins within the framework of this project. However, due to restriction issues, the LiDAR could not be acquired in some of these pre-identified areas and there are, therefore, some limitations in the future implementation of the models in these locations.

    There are some other LiDAR data sources available as previously described. The consultant only had access to LiDAR data in the urban Tbilisi area. These LiDAR data were assessed and found to be of adequate accuracy for modelling purposes. Although some minor deviations from the collected topographic survey data were found, these are not believed to pose an issue for modelling purposes. The other LiDAR data sources could not be assessed.
  - Orthophoto and global DEMs: the main issue to be considered at this stage is to complement the LiDAR DEM in areas where this is not available with other DEMs. The first 'candidate' for this would be the orthophoto DEM. This DEM was derived from orthophoto images and is managed by the Public Registry Office of Georgia. So far, this DEM has been provided for the first three catchments (Supsa, Natanebi and Kintrisi), although it is apparently available for the whole territory of Georgia. This DEM has been analysed in the section above and while it was supposed to have an accuracy of less than four metres when comparing it with actual topographic survey data, differences in excess of ten metres have been found on the flood-plains. In some cases, global DEM data sources have performed better than the orthophoto DEM. This issue was raised by the consultant at the very beginning of the project's implementation period and is being investigated. It may be the case that the final (or more accurate) version of the orthophoto DEM has not been provided as of yet. Nonetheless, this is a matter of concern, and this would limit the accuracy of fluvial models. If the accuracy of this DEM is questionable, pluvial models that rely on these data sources are not recommended to be implemented. A full assessment of the DEMs is proposed within the flood methodology with several options depending on the results from the accuracy assessment. More information about the importance of the resolution and the accuracy of the DEM is provided in the pluvial modelling section owing to its importance.

    There are commercial global DEM resources that could be considered if the final resulting or-

thophoto DEM accuracy is not satisfactory. These would be the DEMs from Airbus and JAXA. This information has been collected and can be considered if needed.

- Cross-sections: as noted, the cross-section scoping has been undertaken by the NEA in close communication with the project's hydraulic modelling expert. In most cases, the cross-section information has been collected in locations where the consultant has provided his input and the scope of the survey is assumed to be of sufficient coverage and quality. There are concerns, however, regarding the quality of the survey information from hydraulic structures. No information about these structures is available to the consultant as of yet. Based on previous modelling experiences in Georgia, however, a lack of capacities for surveying hydraulic structures has been identified. In order to overcome this, the consultant has prepared a document detailing the modelling data needs for these structures. However, the consultant has prepared this document in previous instances but without success. Therefore, these concerns remain. When data are available, the consultant will analyse this information in detail.
- Base-mapping: global resources for base-mapping can be used for hydraulic modelling. While digitised old Soviet base-mapping is available, these resources are only digitised images. The use of global resources is considered better for modelling purposes.
- Aerial imagery (aerial photos and satellite imagery): both global and national resources exist for aerial imagery. The use of national resources relies on the acquisition and processing of orthophotos. Global resources are in the form of satellite imagery from either Google Satellite or Bing. Both data sources are adequate as are the existing ones for flood hydraulic modelling.

1.4.2 Hydrometric Data Sets

- Rainfall data: as noted, rainfall data are not a direct input to fluvial hydraulic models (unless the direct rainfall method is used). The quality, availability and spatial and temporal coverage of the rainfall data will be assessed in the hydrological modelling methodology. From a hydraulic modelling and a data coverage point of view, however, there are concerns about the temporal resolution of rainfall data. There are alternative sources of data which can be used in order to overcome these issues. These include satellite precipitation estimates, meteorological reanalysis data and weather radar data. Weather radar data are addressed in the pluvial modelling section owing to their relevance in urban areas.

  Information from the assessment of the quality of different satellite precipitation estimates and meteorological products regarding rainfall data, as undertaken by the NEA and the project's international meteorological expert, should be considered for these purposes.
- Flow and level data: flow and level data will be used for calibration purposes in the hydraulic modelling implementation. There are some concerns regarding the data availability. The consultant has not had access to the raw data. Only information regarding the location of the meteorological stations and the data availability period are available at this stage:
  - Most of the stations are collecting data on a daily basis. While the hydrological inputs to the hydraulic model will most likely be produced by a hydrological model in small catchments, the lack of sub-daily data is of great concern for implementation (hydrological modelling)

and calibration purposes (for both the hydrological and the hydraulic models). There are very little options for overcoming this issue. The use of donor catchments does not sound realistic for this process (in terms of hydraulic modelling calibration). Therefore, special attention will be paid to the calibration of peaks and the calibration of volumes instead of the calibration of the actual shape of the hydrographs. This would be more important for 'small' catchments such as the first three catchments to be considered in this project (Kintrisi, Supsa and Natanebi).

- There are concerns about the rating curves. While historically the collection of rating curves has been a very intensive activity in Georgia, there is a lack of it in recent times. In the consultant's opinion, this is especially acute in new stations (for instance, in the Rioni basin) where no rating curves have been collected for the stations deployed within the framework of the UNDP Rioni project. No rating curves exist so far, and they will have to be analysed in detail when they become available. The fact that the rating curves are derived from data collected some time ago also poses additional issues. Georgian rivers are very 'active' in most cases from a geomorphological point of view and an old rating curve may not be applicable to current conditions, especially considering that the cross-section survey has been recently concluded. In order to overcome this, the consultant will pay attention to the current conditions, although possible issues with old rating curves may arise despite trying to keep the calibration accuracy as high as possible. The calibration of levels will also be favoured as this will be direct data from the stations.
- Spatial coverage: there is a limited number of stations available for calibration. This will be considered in the implementation process. The use of intensive sensitivity testing is recommended, although calibration will be attempted in locations where data are available. Additionally, some other sources of calibration will be sought.

- Records of past flooding: as noted, all of the possible calibration sources have been investigated, including maps of observed events, indicative flood maps and satellite imagery. No significant success has been obtained in this task, however, and there is limited information available to supplement the calibration process. This will be a matter of continuous research and more efforts will be paid to try to identify as many calibration sources as possible for every basin. Again, the sensitivity tests will play a major role in increasing the robustness of implemented hydraulic flood models.

1.4.3 Physical Catchment Data Sets

- Land-use maps: several data sources have been considered for the definition of land-use. The Copernicus land-use data (100 metre grid and updated yearly) has been found to be of sufficient accuracy and its use is recommended for roughness definition purposes.
- Map of existing flood defences: no information is available regarding the location of flood defences. This is a matter of concern, and the consultant will increase his efforts to collect more information to this end. It should be noted that 'as-built' drawings are not generally available in Georgia and, therefore, the expected success of this activity is limited. When a list of flood defences becomes available and depending on the data available per defence and its significance,

additional survey efforts should be dedicated to collect data from these structures. The use of orthophotos and LiDAR sources for flood defence data should also be considered. While flood defence structures will be included in the fluvial modelling, they will be analysed from a failure point of view in the AWBS section.

1.5 Data Quality for Fluvial Flood Modelling in Georgia and Future Data Availability

1.5.1 Topographic Data and Base-mapping

An assessment of the following data sets will be undertaken:

- Digital Elevation Model (DEM): the DEM is one of the key parameters for the modelling of all flood sources, including fluvial floods. An assessment has been undertaken regarding the quality of all of the different sources already available. The following can be outlined:
  - LiDAR: while the accuracy of the LiDAR data to be produced within the framework of this project cannot be assessed as of yet, this is believed to be within the expected accuracy and resolution. A 1 metre DEM will be provided by the LiDAR contractor and this DEM is supposed to be adequate for the areas where data have been acquired.

    The LiDAR data area of interest (AoI) was defined using indicative modelling, using very high flows in all of the basins within the framework of this project. However, due to restriction issues, the LiDAR could not be acquired in some of these pre-identified areas and there are, therefore, some limitations in the future implementation of the models in these locations.

    There are some other LiDAR data sources available as previously described. The consultant only had access to LiDAR data in the urban Tbilisi area. These LiDAR data were assessed and found to be of adequate accuracy for modelling purposes. Although some minor deviations from the collected topographic survey data were found, these are not believed to pose an issue for modelling purposes. The other LiDAR data sources could not be assessed.
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is questionable, pluvial models that rely on these data sources are not recommended to be implemented. A full assessment of the DEMs is proposed within the flood methodology with several options depending on the results from the accuracy assessment. More information about the importance of the resolution and the accuracy of the DEM is provided in the pluvial modelling section owing to its importance.

There are commercial global DEM resources that could be considered if the final resulting orthophoto DEM accuracy is not satisfactory. These would be the DEMs from Airbus and JAXA. This information has been collected and can be considered if needed.

- Cross-sections: as noted, the cross-section scoping has been undertaken by the NEA in close communication with the project's hydraulic modelling expert. In most cases, the cross-section information has been collected in locations where the consultant has provided his input and the scope of the survey is assumed to be of sufficient coverage and quality. There are concerns, however, regarding the quality of the survey information from hydraulic structures. No information about these structures is available to the consultant as of yet. Based on previous modelling experiences in Georgia, however, a lack of capacities for surveying hydraulic structures has been identified. In order to overcome this, the consultant has prepared a document detailing the modelling data needs for these structures. However, the consultant has prepared this document in previous instances but without success. Therefore, these concerns remain. When data are available, the consultant will analyse this information in detail.
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modelling implementation. There are some concerns regarding the data availability. The consultant has not had access to the raw data. Only information regarding the location of the meteorological stations and the data availability period are available at this stage:

- Most of the stations are collecting data on a daily basis. While the hydrological inputs to the hydraulic model will most likely be produced by a hydrological model in small catchments, the lack of sub-daily data is of great concern for implementation (hydrological modelling) and calibration purposes (for both the hydrological and the hydraulic models). There are very little options for overcoming this issue. The use of donor catchments does not sound realistic for this process (in terms of hydraulic modelling calibration). Therefore, special attention will be paid to the calibration of peaks and the calibration of volumes instead of the calibration of the actual shape of the hydrographs. This would be more important for 'small' catchments such as the first three catchments to be considered in this project (Kintrisi, Supsa and Natanebi).
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- Spatial coverage: there is a limited number of stations available for calibration. This will be considered in the implementation process. The use of intensive sensitivity testing is recommended, although calibration will be attempted in locations where data are available. Additionally, some other sources of calibration will be sought.

- Records of past flooding: as noted, all of the possible calibration sources have been investigated, including maps of observed events, indicative flood maps and satellite imagery. No significant success has been obtained in this task, however, and there is limited information available to supplement the calibration process. This will be a matter of continuous research and more efforts will be paid to try to identify as many calibration sources as possible for every basin. Again, the sensitivity tests will play a major role in increasing the robustness of implemented hydraulic flood models.

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- Map of existing flood defences: no information is available regarding the location of flood defences. This is a matter of concern, and the consultant will increase his efforts to collect more information to this end. It should be noted that 'as-built' drawings are not generally available in Georgia and, therefore, the expected success of this activity is limited. When a list of flood defences becomes available and depending on the data available per defence and its significance, additional survey efforts should be dedicated to collect data from these structures. The use of orthophotos and LiDAR sources for flood defence data should also be considered. While flood defence structures will be included in the fluvial modelling, they will be analysed from a failure point of view in the AWBS section.

1.6 Methodologies and Procedures for Preparation, Data Analysis, and Incorporation into Hydraulic Models

There are several procedures to consider when preparing and importing data into a fluvial hydraulic model. Although these procedures are different depending on the choice of the hydraulic modelling software in most cases, there are some common issues that should be considered.

1.6.1 DEM Data

The digital elevation model (DEM) information is one of the key data sources for flood modelling purposes. DEM resolution and accuracies (vertically and horizontally) highly influence flood simulation results such as inundation extent, flow velocity, flow depth and flow patterns. Accurate and high-resolution DEM data can produce the most accurate and reliable flood inundation map as compared to an inaccurate DEM. Additionally, the ingestion of DEM data into a flood model is of specific importance and depends on the modelling software approach. It is not possible to provide recommendations regarding the ingestion process because, for example, a DEM has to be created in the software format, such as MIKE, specifying the resolution, whereas a DEM can be created with the same resolution as the original one in other software, such as HEC-RAS, and then the modelling resolution depends on the grid resolution. There are also some other considerations in this respect. While MIKE considers a single value for each grid-cell for the DEM, HEC-RAS, on the other hand, creates an elevation profile with all of the points contained within each grid point and considering the resolution of the input DEM.

Additionally, there are some comments regarding the data format. While HEC-RAS accepts almost any format and/or projection in the DEM importing process, MIKE requires the same projection as the modelling one and a DFS2 or ASC format. DFS2 is the native DHI-MIKE ZERO format for 2D files while ASC is the Esri grid raster file format. HEC-RAS supports numerous raster file types through its use of the GDAL libraries, including the binary raster floating point format (.flt), esri grid files (.adf) or GeoTiff (.tif). A full list of the raster formats supported can be found on the GDAL website (https://gdal.org/drivers/raster/index.html).

Some recommendations can be provided vis-à-vis the analysis of the DEM before its ingestion into the modelling software, independently of the software package being used. In this case, it is paramount

that all of the different sources of DEM are analysed. As noted, there are different sources such as LiDAR for different areas, the orthophoto DEMs and the global DEMs. The best source of data should be selected for each specific location and the creation of a 'master' DEM with this information is recommended for flood hydraulic modelling purposes. While using HEC-RAS software, this DEM can be imported into MIKE and be used in the definition of grids. In MIKE (and other software packages), individual grids will have to be developed for each model, depending on the extent of the modelling domain to be implemented.

Before importing the DEM into the hydraulic modelling software, the following actions should be undertaken:

- The modeller should check for significant inconsistencies in the DEM data. DEM data will be compared to ground elevation data in all of the available locations where these data are available.
- The modeller should check for voids or lines with no data within the DEM. This should not occur but, as noted above, the orthophoto DEM presents gaps in the data that should be corrected. The procedure for this correction would depend on the size and nature of the gap.
    - Sinks: the modeller should process the DEM using GIS resources to fill the sinks in the DEM.
    - In the case when the sink approach is not sufficient, it is recommended that the modeller fill these gaps with data from other DEM sources and using the most accurate data source.
- The modeller should check for data continuity issues in the border of different data sets. It is expected that when merging different data sets, there may be significant differences in the border of these different data owing to their different sources. In this case, the modeller should smooth the differences in order to prevent artificial damming in the hydraulic model.

Once the master DEM has been created and imported into the hydraulic modelling software, the modeller should use it throughout the whole modelling process, including the 1D modelling implementation. The DEM would be a good source of data to analyse inconsistencies and derive data when required.

There is a further issue that should be discussed when integrating DEM (or LiDAR data) into a hydraulic model. The DEM or LiDAR data generally have a higher spatial resolution than the model grid that will be used in the modelling implementation. As noted, this issue is more relevant to software like MIKE which uses a single value of elevation per grid cell (HEC-RAS uses an elevation profile). There are several procedures for defining the elevation of a single grid from a DEM, such as TIN (triangulated irregular network) or IDW (inverse distance weighted) interpolation methods, with their associated parametrisation. It is recommended that the TIN method is used for this, although the accuracy of the resulting DEM against the initial DEM should be ascertained. Additionally, special care should be taken during this process to avoid smoothing out important topographic features of a high spatial frequency such as embankments.

1.6.2 Cross-section Data

Cross-section data from the topographical survey campaigns should be processed in order to ensure that these data would be in the right format for importing into the hydraulic model. Additionally, it is of paramount importance to analyse and process the cross-section data.

The format required for the hydraulic model differs greatly depending on the modelling software, although there are no precise guidelines for choosing the format. For instance, HEC-RAS cross-section data can be imported from CSV or GIS files while the MIKE format requires a TXT file with a very specific format. While HEC-RAS uses a single file for the cross-section and the network data, MIKE uses two different files with two very different formats.

In order to facilitate the preparation of the files, however, some common procedures can be outlined:

- A river centreline should be digitised if not available. It is important that the river centreline is as up to date as possible. The digitisation of this polyline can be undertaken using satellite images and/or aerial photographs.
- Each watercourse should be assigned a name (river) and a number (reach). Depending on the software, the approach for the naming should differ. If, for instance, HEC-RAS is used, the watercourse will be split at each cross-section and, therefore, the river should be identified with different names depending on the number of junctions. In MIKE, for instance, the watercourses are not split by junctions and, therefore, the same river name and number can be kept.
- Each of the surveyed cross-sections should be assigned a chainage number in reference to the river centreline. The order of the chainage to be assigned will depend on the modelling software. For instance, in HEC-RAS software, the most upstream cross-section should be assigned a chainage zero while the most downstream cross-section should be assigned a chainage with the length of the watercourse. In MIKE, it would be the other way around and the most downstream cross-sections are assigned a chainage of zero.
- Accordingly, the river name and number have to be assigned to the cross-section. It is important to have the information for each surveyed point (from left to right looking downstream) for each cross-section in terms of latitude, longitude, station (x) and elevation (y).
- At this stage, it is also important to assign resistance values to each of the cross-sections using photographs from the survey or information from aerial photographs and/or satellite images.

The assessment of the quality of the cross-section data has been described in the previous sections.

1.6.3 Land-cover Data

As noted, land-cover data are of critical use in fluvial flood hydraulic modelling. The land-cover data will be used for providing roughness information in the 2D domains. Copernicus is the recommended source of land-cover data with its 100 metre resolution data updated annually.

Copernicus data are assigned different classes and codes depending on the land-cover. Table 23 presents the recommended Manning's number for each land-cover category.

Table 23. Land-cover and Roughness Manning's Number Recommended Value

Map Code	Land-cover Class	Definition According to UN LCCS	Manning's Number
100	Moss and lichen	Moss and lichen	0.03
111	Closed forest, evergreen needle leaf.	Tree canopy >70 %, almost all needle leaf trees remain green all year. Canopy is never without green foliage.	0.1
114	Closed forest, deciduous broad leaf.	Tree canopy >70 %, consists of seasonal broadleaf tree communities with an annual cycle of leaf-on and leaf-off periods.	0.1
115	Closed forest, mixed.	Closed forest, mix of types.	0.1
116	Closed forest, unknown.	Closed forest, not matching any of the other definitions.	0.1
121	Open forest, evergreen needle leaf.	Top layer - trees 15-70% and second layer - mixed of shrubs and grassland, almost all needle leaf trees remain green all year. Canopy is never without green foliage.	0.07
124	Open forest, deciduous broad leaf.	Top layer - trees 15-70% and second layer - mixed of shrubs and grass-land, consists of seasonal broadleaf tree communities with an annual cycle of leaf-on and leaf-off periods.	0.07
125	Open forest, mixed.	Open forest, mix of types.	0.07
126	Open forest, unknown.	Open forest, not matching any of the other definitions	0.07
20	Shrubs.	These are woody perennial plants with persistent and woody stems and without any defined main stem being less than five metres tall. The shrub foliage can be either evergreen or deciduous.	0.06
200	Open sea.	Oceans, seas. Can be either fresh or salt-water bodies.	0.07
30	Herbaceous vegetation.	Plants without persistent stem or shoots above ground and lacking definite firm structure. Tree and shrub cover is less than 10%.	0.045
40	Cultivated and managed vegetation/agriculture (cropland).	Lands covered with temporary crops followed by harvest and a bare soil period (e.g., single, and multiple cropping systems). Note that perennial woody crops will be classified as the appropriate forest or shrub land-cover type.	0.03
50	Urban/built up	Land covered by buildings and other man-made structures.	0.015
60	Bare/-sparse vegetation	Lands with exposed soil, sand or rocks and never has more than 10% vegetated cover during any time of the year.	0.025
70	Snow and ice.	Lands under snow or ice cover throughout the year.	0.01
80	Permanent water bodies.	Lakes, reservoirs, and rivers. Can be either fresh or salt-water bodies.	0.05
90	Herbaceous wetland.	Lands with a permanent mixture of water and herbaceous or woody vegetation. The vegetation can be present in either salt, brackish or fresh water.	0.04

Approaches for providing the above information to the model will differ greatly depending on the modelling software being used. Defining land-cover and roughness in HEC-RAS depends on the provision of a grid file with different codes. Subsequently, a Manning's number value is assigned to each of the codes and an internal land-cover file is created. Several land-cover files can be created where the user defines the file to use depending on the geometry and the simulation.

In MIKE software, a DFS2 file with the associated Manning's values have to be created. In MIKE, the user can choose between working with Manning's n values or Manning's M (1/n) values, but it should be noted that the Manning's M option is selected as a default.

1.6.4 Hydrometric Data

Please refer to methodology for hydrological modelling

1.6.5 Hydrological Modelling Data

Please refer to methodology for hydrological moelling

1.6.6 Remote Sensing Data

Remote sensing data sources have been recently used for flood monitoring and flood validation. There are several sources of remote sensing data that can be used for these purposes.

SAR Images

Synthetic Aperture Radar (SAR) images for flood monitoring and validation have recently been widely proven to be useful. SAR measurements from space are independent of daytime and weather conditions and can provide valuable information vis-à-vis monitoring flood events. The fundamental characteristic recorded on a radar image is the backscattering coefficient which may vary from surface to surface. The strength of the returned signal from the surface is influenced by the combination of both system and ground parameters. These parameters are the average surface roughness and soil dielectric properties. Horizontal smooth surfaces, such as water bodies, reflect nearly all incident radiation away and the weak return signal is represented by a dark tonality on radar images. This is mainly due to the fact that smooth water surfaces provide no return to the antenna in a microwave spectrum and appear black in SAR imagery.

Optical Sources

The use of optical imagery for flood monitoring is limited by severe weather conditions; in particular, the presence of clouds and during dark conditions. The main satellite source to consider in this case would be MODIS. The high spatial resolution of MODIS (Table 24) and its twice daily near-global coverage are very interesting features and capabilities.

Table 24. MODIS Bands

Band	Bandwidth (nm)	Resolution	Primary Use
1	620–670	250	Absolute Land-cover Transformation, Vegetation Chlorophyll
2	841–876	250	Cloud Amount, Vegetation Land-cover Transformation
3	459–479	500	Soil/Vegetation Differences
4	545–565	500	Green Vegetation
5	1230–1250	500	Leaf/Canopy Differences
6	1628–1652	500	Snow/Cloud Differences
7	2105–2155	500	Cloud Properties, Land Properties

MODIS imagery is currently being processed within NASA and yielding a near-real-time global flood mapping product. Within this product, water is detected with an algorithm that uses a ratio of MODIS Band 1 and Band 2, and a threshold on Band 7 to provisionally identify pixels as water. The water detection is then composited over the product window (two days, typically). If a pixel is identified as water over several (two or more) observations during the product window, it is then definitively marked as water and output in the MSW or 'MODIS Surface Water' product. Two (or more) observations are required because cloud shadow can appear spectrally similar to water. In cases where cloud shadow occurs in the same spot in two observations, the product may incorrectly flag such areas as water. The detected water is then compared to a reference water layer (MOD44W) and any pixels found outside of the normal water extent are marked as a flood and output in the MFW ('MODIS Flood Water') product. This product is currently available on-line and is an open-source product.

Processing of SAR Images

There are different techniques for SAR data processing such as grid system techniques, threshold segmentation algorithm techniques and change detection techniques. Within this deliverable, a short methodology will be proposed for the processing of satellite images using the multi-temporal technique. This technique is in use by ESA in the flood extent extraction from SAR images (ESA Earth Watch) and is considered to be a robust technique to use. The main drawback of this technique is the fact that a manual threshold definition is required, and speckle filtering should be undertaken. The multi-temporal technique uses SAR images of the same area taken on different dates (one image is acquired during flooding and the second one in 'normal' conditions). The resulting multi-temporal image would reveal a change in the Earth's surface by the presence of colour in the image. The normal condition image can also be derived from optical sources. These optical sources are actually recommended due to the higher resolution of some optical images.

The following stages (Figure 245) should be followed in order to derive flood extents using this technique.

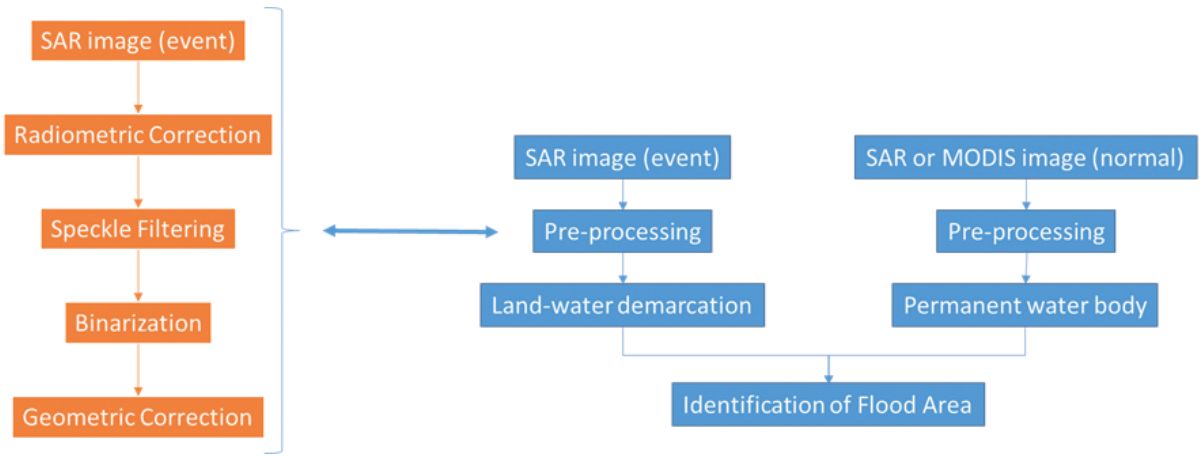

Figure 2-45 . SAR Image Processing for Flood Definition

Image Acquisition

The acquisition of images will be undertaken manually, checking the availability of satellite imagery in the area of interest for specific flood dates and considering all of the different sources available as described in previous sections.

Pre-processing

It is suggested that the pre-processing of all the satellite images is carried out using ESA applications. Two different applications should be noted for this:

- NEXT - Nest ESA SAR Toolbox: this toolbox can be used for visualising, analysing and post-processing ESA and third-party SAR data processed from Level-1 or higher. It has the following features (Figure 246):
  - Provides both basic and advanced tools for the SAR user community.
  - Shares the core architecture with the ESA BEAM toolbox.
  - Fully portable to multiple hardware platforms and operating systems thanks to a 100% pure Java implementation.
  - Modular design for easy modifications and upgrades.
  - An API enables users to easily add their own modules and extend the capabilities of NEST.
  - Fully open-source.
  - Batch possibilities.

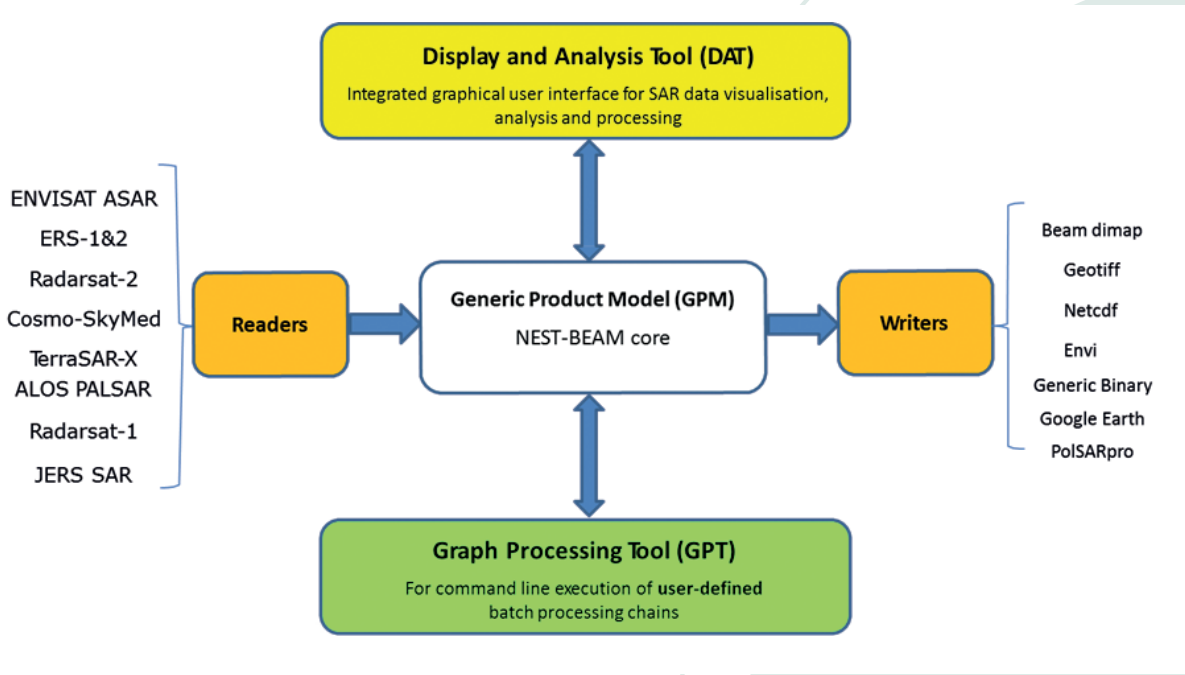

Figure 2-46. NEST Architecture

- ESA BEAM toolbox: the ESA BEAM toolbox has the same features as the NEXT toolbox but for optical satellites. It can process data for Landsat, MERIS and MODIS sources, among others.

Base (Normal) Scenario Image

The normal scenario image (permanent water body) can be obtained through different means. There are already existing permanent water body files derived from satellite images. Special attention should be paid to the MOD44W product derived from MODIS images by NASA.

MOD44W

The MOD44W land-water mask within the area of interest was primarily created with two different data inputs:

- The Shuttle Radar Topography Mission's (SRTM) Water Body Data set (SWBD).
- The MOD44C, a non-public, 250 metre global 16-day composite collection based on 8+ years of Terra MODIS data and 6+ years of Aqua MODIS data. This data set originally provided the input to produce the Vegetative Cover Conversion and Vegetative Continuous Fields products (areas between 60° N to 90° N).

Other appropriate and publicly available data sets were also used to supplement the production of the MODIS 250 metre land-water mask.

MODIS

A permanent water body can also be derived from MODIS images for the area of interest during the flood service implementation. This is not recommended at this stage but should be considered in case the MOD44W is not adequate.

SAR

A permanent water body can also be derived from SAR images for the area of interest. In these cases, the process would be exactly the same as the one described for deriving flood outlines for SAR images.

It is recommended that the MOD44W permanent water body is evaluated and analysed during the pre-processing stage. If the results from this evaluation are successful and satisfactory, it is recommended that this becomes the reference for defining a water body under normal conditions. In the case that the results are not satisfactory, it is recommended that MODIS images are used to derive the water outline during normal conditions.

Flood Scenario Image Processing

There are several processes in order to derive flood outlines from SAR images. In this case, a process based on the use of the NEXT toolbox is used.

Pre-processing - Calibration

In the first step, the acquired image has to be calibrated using a radiometric correction. This calibration should be done considering the polarisation of the image. This process will yield a new product with calibrated values of the backscatter coefficient in dB.

Pre-processing - Speckle Filtering

Speckle is inherent to SAR images, and it occurs because each resolution cell associated with an extended target contains several scattering centres whose elementary returns, by positive or negative interference, originate light or dark image brightness. This creates the grainy appearance usually associated with SAR images. There are several filters available for removing the speckle effect, although applying these filters would reduce the accuracy of the SAR image and so a balance between the filter and the speckle has to be found. As stated, there are several filters available with the Sigma0_HH_dB - Lee filter being the suggested one for use. The filter window size should be selected after some testing. A new product will be created after applying this filter.

Processing Steps - Binarization

A threshold needs to be selected in order to separate water from non-water. A histogram of the filtered backscatter coefficient, for example, could be analysed to this end. The histogram is in the form of two peaks of different magnitudes. Low values of the backscatter will correspond to the water class and high values will correspond to the non-water class. A value that separates these two peaks should be found. The threshold value for the binarization is usually obtained by comparing this image with the permanent water body.

The image should also be segmented (or binarized) applying band arithmetic. The main output will be a new image for water objects by applying the threshold value previously obtained.

Post-processing - Geometric Correction

The obtained image is in the geometry of the sensor. This should be a re-projection to the geographic projection. SRTM sources within NEXT can be used for this purpose.

The resulting image for this analysis can now be compared with the permanent water body product.

Special Cases

The SAR approach for flood extent delineation can be conditioned in some cases, especially under high-speed wind conditions. A wind-ruffled surface can give a backscatter larger than that of the surrounding land (Figure 247).

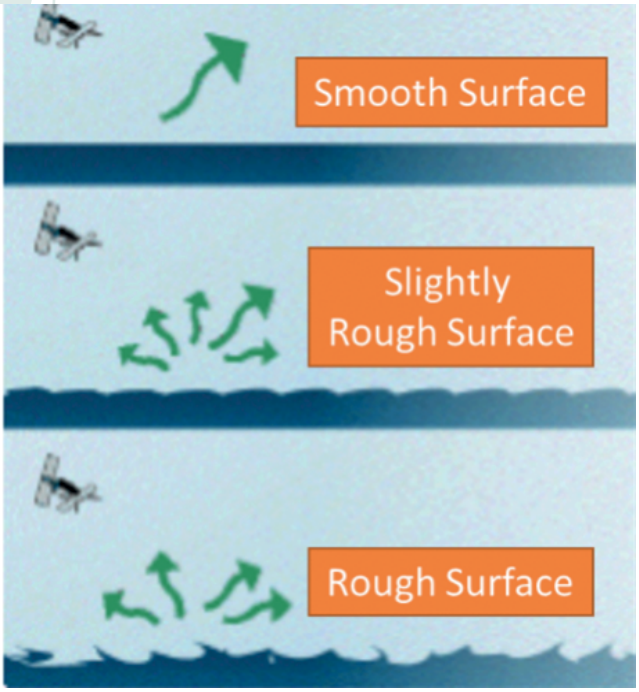

Figure 2-47. Roughness Impact on SAR

Roughness is a relative concept depending upon the wavelength and the incidence angle. A surface is considered 'rough' if its structure has dimensions that are comparable to the incident wavelength. Calm water tends to be relatively smooth with most of the energy being reflected away from the radar and no backscatter towards the radar which results in a dark tonality on radar images.

Rough surfaces are characterised by a high backscatter. This is mainly due to the strong relation between roughness characteristics and backscattering properties which gives an isotropic shape to the radiation pattern of the electromagnetic energy. Windy conditions and very turbulent waters can increase the roughness of the water table and this, in turn, complicates the detection of water surfaces on SAR images for flood applications. Although river floodplains are not easily affected by windy conditions (especially due to the reduced fetch area), mechanisms should be established in order to prevent spurious and incorrect flood monitoring under windy conditions.

Additionally, as previously noted, turbulent water conditions can lead to an increase in the water table roughness and, therefore, to an increase in the backscatter received. This should not be an issue here due to the nature of the rivers in this study and their flood scope. However, this could be further analysed using the results from the modelling exercise and comparing them with satellite images in areas where turbulent water may be an issue.

Processing of Optical Images

There are some other procedures which can be used to derive flood water extent from MODIS images. For instance, there is the work of the German Remote Sensing Data Centre (DFD). In this case, flood masks are calculated based on MODIS bands 1, 2, 3, 4 and 6. Once the image has been properly

pre-processed and corrected, a thematic analysis of the image is undertaken, classifying MODIS data into six output classes; namely, 'Flood,' 'Non-flood,' 'Receding Water,' 'Standing Water,' 'Mixture' and 'Clouds.' This classification process is undertaken in the following steps:

1. Computing of spectral indices: the spectral indices EVI (Enhanced Vegetation Index), LSWI (Land Surface Water Index) and DVEL (Difference Value between EVI and LSWI) are computed from MODIS spectral Bands 1, 2, 3 and 6.
2. Initial thresholding of the spectral bands and indices using pre-defined data.
3. Post-processing including the integration of auxiliary data: information derived from a DEM is employed to reduce the number of misclassified water-related pixels in very steep areas.
4. Region growing steps are applied for a refinement of the classification accuracy by relaxing the thresholds in the neighbourhood of the initial flood classification result.
5. Separation between water and cloud shadows.

1.7 Software

Several fluvial flood hydraulic modelling packages have been evaluated in order to provide recommendations regarding the software to be used for flood hazard mapping. The software analysis and the recommendations will be based on the study's proposed methodology; namely, a 1D-2D approach for modelling fluvial flood hazards.

In this review, five flood hydraulic modelling packages are evaluated: Delft3D Suite, HEC-RAS, MIKE Flood, Iber and SOBEK. A general description of each package is provided below:

- Delft3D Suite (Deltares) is a hydrodynamic model that simulates storm-surges, typhoons/hurricanes, tsunamis, detailed flows and water levels, waves, sediment transport and morphology, water quality and ecology. In addition, the software is capable of handling interactions between these processes. The software can be configured to simulation flow using either a 1D, 2D or 3D finite difference algorithm. Delft3D can be linked to Delft-Fews to perform real-time flood warnings and to define water quality for simulating water quality conditions.
- HEC-RAS (USACE) is a 1D and 2D hydraulic model developed by the USACE's Hydrologic Engineering Centre to perform hydraulic calculations for natural water bodies, constructed channels and floodplains. Although developed in the US, HEC-RAS is used extensively around the world to perform open channel river hydraulics work, especially due to its open-source nature. The HEC-RAS system contains four 1D river analyses: (1) steady flow water surface profile computations, (2) unsteady flow simulation, (3) movable boundary sediment transport computations and (4) water quality analysis. Further, it contains two 2D floodplain analyses: (1) unsteady flow simulation and (2) sediment transport modelling. The possibility of including non-Newtonian flows is included in the latest version of HEC-RAS, allowing the simulation of mudflows and debris-flows. Other applications used with HEC-RAS include HEC-HMS (rainfall-runoff model), ResSim (reservoir simulation model) and FIA (flood impact analyses). HEC-RAS is a component in the HEC-WAT system (comprehensive flood planning)

and the HEC-RTS system (real-time flood warning and systems operations), but it can also be linked to Delft-Fews.

- MIKE FLOOD (DHI) is a 1D and 2D hydrodynamic software package that can be applied to most flood problems, whether they involve rivers, floodplains, street flooding, drainage networks, coastal areas, dams, levees and dike breaches or any combination of these. MIKE FLOOD dynamically couples MIKE11 and MIKE21 (a 2D flood simulation) to assess flows but can also link MIKE URBAN and MIKE21. In MIKE FLOOD, water quality can be simulated using the ECO Lab. The MIKE11 and MIKE21 sediment transport modules can be used independently but they do not apply to MIKE FLOOD. The 1D component of MIKE FLOOD (MIKE 11 or MIKE HYDRO River) is a 1D river modelling software that has been used around the world regarding flooding, navigation, water quality, forecasting and sediment transport or a combination of all of these as well as for other aspects of river engineering. Modules allow users to expand the simulation capabilities to include rainfall-runoff (RR), water quality (WQ and the ECO Lab), sediment transport (ST), structure operations (SO) and dam breaks (DB). MIKE 11 is the riverine component of the hydrologic cycle in MIKE SHE. MIKE 11 is also used in real-time operations and flood warning systems through the dedicated software MIKE OPERATIONS, but it can also be linked to Delft-Fews.
- Iber is a two-dimensional numerical model for the simulation of free surface flow in rivers and estuaries. Iber solves full depth-averaged shallow water equations in order to compute water depth and the two horizontal components of the depth-averaged velocity. These equations are solved with an unstructured finite volume solver explicit in time. The algorithms implemented in the model have been extensively validated and applied in previous studies related to river inundation and tidal currents in estuaries.
- SOBEK (Deltares) is an integrated software package for river, urban or rural management. Seven programme modules work together to give a comprehensive overview of waterway systems that allows users to link river, canal, and sewer systems for a total water management solution. SOBEK incorporates 1D algorithms for rivers, canals, and sewers, and 2D for overland flow. Its built-in functionality allows users to expand the simulation capabilities to include RR, water quality (1DWAQ, 2DWWAQ, Emissions), sediment transport (1DMOR) and real-time control (RTC). SOBEK can also be linked to Delft-Fews.

1.7.1 Computational Overview

All packages offer a 1D (except Iber) hydrodynamic simulation for characterising the flows in rivers and canal systems. The 1D modules of the four packages with 1D capabilities have been widely implemented for rivers worldwide and can be applied to simple floodplain flows and/or simple floodplain topography. Delft3D, HEC-RAS, MIKE FLOOD and SOBEK have the capability to dynamically couple 1D and 2D models which allows the flexibility to model the river in 1D and floodplains in 2D. For the 2D schematisation, Delft3D and MIKE FLOOD allow users to employ a flexible mesh for varying the analytical resolution of flow in areas of importance whereas HEC-RAS mesh can be rectangular or unstructured depending on the definition of break-lines. All packages come with a variety of options to simulate bridges, culverts, dams, gates, pumps, siphons, weirs, and user defined structures. In addi-

tion, all packages can simulate operational structures allowing users to vary water control structures with additional logic. Aside from HEC-RAS, these packages require separate modules when simulating operational structures. Delft3D, MIKE FLOOD and SOBEK are capable of using multicore resources to decrease computational time. HEC-RAS also supports multicore tasks but problems have been identified in the latest versions. MIKE FLOOD software is capable of using cloud services to run simulations, thereby saving computational time and local resources. HEC-RAS can also be run in cloud services through other companies (outside of USACE).

Delft3D, SOBEK and MIKE FLOOD dynamically link with RR modules, allowing for the rapid testing of different rainfall events. The latest version of HEC-RAS includes the possibility of including direct rainfall in models, including infiltration and losses, although no proper rainfall-runoff module is available. Delft3D and SOBEK dynamically incorporate the US National Weather Service's Sacramento Soil Moisture Accounting model (a lumped conceptual model) or WFlow (an open-source, command line driven and distributed DHM model) to compute runoff. MIKE FLOOD uses NAM (a lumped conceptual model) or the Unit Hydrograph method to pre-calculate inflow hydrographs. MIKE11 is dynamically coupled with MIKE SHE to represent the riverine component. HEC-HMS is a rainfall-runoff module used for computing runoff from precipitation; however, it does not dynamically link to HEC-RAS and thus the pre-run rainfall-runoff results must be transferred to HEC-RAS. The transfer can be automated to eliminate manually transferring results between models using HEC-DSS (Data Storage System), HEC-WAT or HEC-RTS. Iber also has its own hydrological module embedded within the software with the possibility of defining rainfall fields from rain gauges or from raster files, rainfall losses with different infiltration models (Green-Ampt, Horton and constant infiltration) and a specific numerical scheme for hydrological applications.

All packages (except Iber) have external modules and programmes to calculate flood damages associated with property and infrastructure.

Table 25. Algorithms and Functionality of Flood Hydraulic Software

Function	Delft3D Flow	HEC-RAS	MIKE FLOOD	Iber	SOBEK
Mesh	1D,2D,3D:	1D, Pseudo 2D with loops	Coupled 1D/2D: Cartesian and flexible grid	2D flexible grid	1D, Pseudo 2D with loops
	Curvilinear and spherical grids	Couple 1D/2D: flexible grid			Coupled 1D/2D: rectilinear grid
Discretization	Finite Difference	Finite Difference	Finite Difference	Finite Volume	Finite Difference
Rainfall-Runoff (RR)	*Sacramento RR Model	HEC-HMS	*NAM, Unit Hydrograph, SMAP, FEH, DRiFit	Iber RR Model	*SOBEK RR Model
	*WFLOW		*MIKE SHE		*Sacramento RR Model

Structure Types	*Barrier, bridge, culvert, deflection wall, floating structure, gate, weir, user defined	*Bridge, culvert, dam, gate, pump, siphon, weir, user defined	*Bridge, culvert, dam, gate, pump, siphon, weir, user defined	*Barrier, bridge, culvert, pump, weir, user defined	*Barrier, bridge, culvert, deflection wall, floating structure, gate, weir, user defined
Output	*Water levels, water surface profiles, flow velocity, flow quantity	*Water levels, water surface profiles, flow velocity, flow quantity	*Water levels, water surface profiles, flow velocity, flow quantity	*Water levels, water surface profiles, flow velocity, flow quantity	*Water levels, water surface profiles, flow velocity, flow quantity
	*Flood maps	*Flood maps (GEO-RAS)	*Flood maps	*Flood maps	*Flood maps
	*2D animations	*Frequency analysis (HEC-SSP)	*2D animations	*2D animations	*Frequency analysis
	*Frequency analysis		*Frequency analysis	*Frequency analysis	
Programme Manager (PM)/ Real-Time (RT)	PM/RT: Delft-FEWS	*PM: HEC-WAT / *RT: HEC-RTS	*PM: MIKE ZERO Interface / *RT: MIKE 11 RT	PM: Iber	PM/RT: Delft-FEWS
Water Quality	D-Water Quality module	Built-in	Advection-Dispersion (AD) module, ECO Lab Module	Water Quality module (Iber-WQ)	SOBEDK 1DWAQ
Sediment	DELFT3D-Sed module	Built-in	None within MIKE FLOOD (ST and AD within MIKE 11)	Sediment Transport module	Built-in (limited functionality)
Ecological	Delft3d-ECO module	HEC-FIA	ECO Lab module	Habitat module	None

1.7.2 GUI Overview

All software packages have professional graphical user interfaces (GUIs) for model development, simulation, and result viewing. Supporting 1D model construction, model builders in GIS allow users to create and import the model's geometry. For 2D packages, mesh generators are available to aid mesh creation. All packages have internal or modular tools to pre-process the time series and DEM data. In addition, all packages have project management systems to manage files. THE HEC-FRA Compute Option and Life-Cycle Cost within HEC-WAT allow users to evaluate an uncertainty analysis throughout the entire computation process (rainfall-runoff, hydraulics, food damage impact) using the Monte Carlo Method.

Creating flood maps and animations is crucial for understanding the flooding extent and

conveying its extent to water managers and stakeholders. For 1D applications, MIKE 11 and SOBEK have external GIS programmes to build flood maps. For 2D applications, HEC-RAS, Delft3D, SOBEK (1D/2D) and MIKE FLOOD all have internal mapping features to develop flood maps and animations.

1.7.3 Licensing and Support

HEC-RAS is a non-proprietary package that requires no license and can be freely downloaded om the Internet. Similarly, Delft3D is open-source software, although it requires a license that can be acquired through registration with Deltares. However, when downloaded as open-source code, Delft3D must be compiled before using it. Iber is also open-source software, available to be downloaded after registration. Non-proprietary water quality and sediment transport modules are available for the three packages.

MIKE FLOOD and SOBEK are proprietary flood hydraulic modelling software packages that require the purchase of a license.

All packages are supported with manuals, tutorials, training courses and user groups. Training courses and consultancy support is available for an additional fee. The USACE does not provide training courses for HEC-RAS, but third party private and educational firms provide these courses.

Some of these packages have been previously applied in Georgia such as Iber, HEC-RAS, SOBEK and MIKE FLOOD. Delft3D has been used in Georgia but from a marine and sediment transport modelling perspective. MIKE FLOOD has been applied for flood hazard mapping and mitigation purposes in the Rioni, Vere and Alazani catchments. SOBEK has also been implemented in the Rioni catchment while HEC-RAS has been used in the Leghvtakhevi basin.

1.7.4 Flood Hydraulic Modelling Software Recommendation

All packages support flood hazard modelling and mapping. Given the widespread use, user-friendly GUI interface, non-proprietary status, its 1D-2D capabilities and large user community, HEC-RAS is the recommended tool for assessing flood hazards in most river basins. Additionally, the application of HEC-RAS for other flood sources should also be considered due to its direct rainfall feature as well as the possibility of using non-Newtonian flows. Nonetheless, due to the existence of legacy hydraulic models in MIKE software, it is recommended that the models already in MIKE are kept with this software. As will be noted further below, the use of MIKE is also recommended in areas with a significant coastal impact on fluvial flooding.

Therefore, a comparison of both the MIKE and HEC-RAS hydraulic modelling software is given in Appendix II in order to provide a more detailed description of the capabilities of both software packages for hydraulic modelling purposes.

02

Pluvial Flood Hazard and Risk Modelling and Mapping

2.1 Pluvial Flooding

Pluvial/surface water flooding occurs when heavy rainfall saturates drainage systems and creates a flood independent from a body of water, but its outflow will eventually enter a fluvial system or network.

The expansion of impermeable surfaces in the urban environment increases the surface water flows in sewers and climate change is likely to exacerbate this problem. This increases the risk of systems overloading in extreme and sustained precipitation events and potentially causes the pollution of watercourses when combined with sewer overflows (CSOs). By transferring water rapidly away from where it falls, there is also the possibility of a receiving watercourse being inundated and causing flooding.

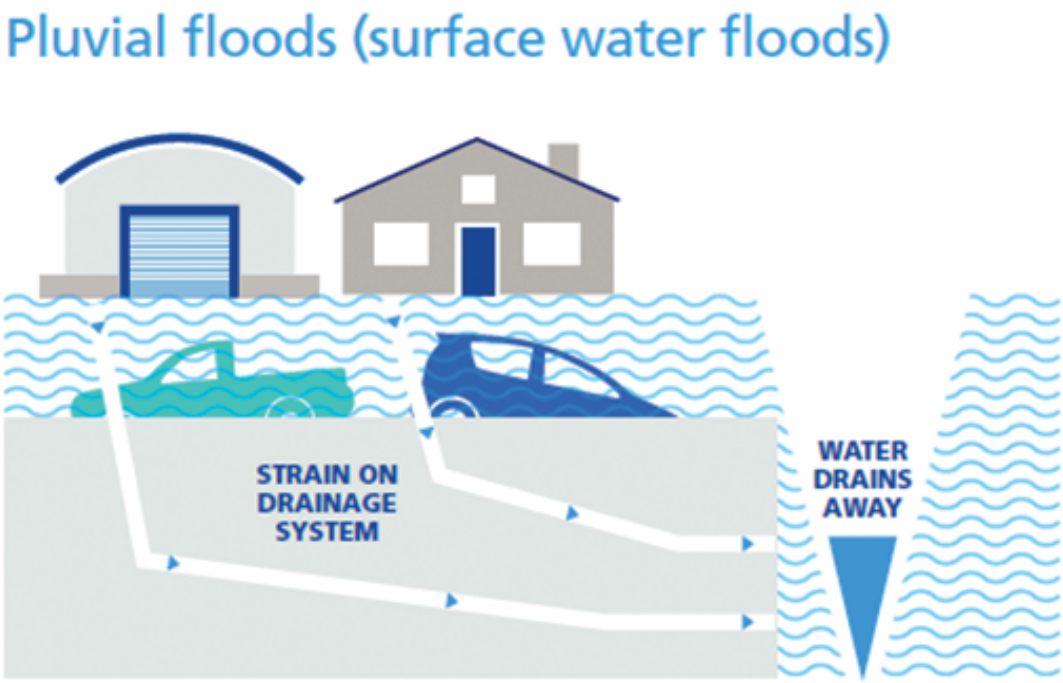

Figure 3-1. Pluvial Flooding (Source: Zurich Insurance)

The following main processes can be identified in terms of the source-pathway-receptor approach[28] (Table 26).

Table 26. Source-Pathway-Receptor for Pluvial Flooding

Source	Pathway	Receptor
Precipitation Surcharge sewer	Overland flow Blockages	Property Population Environment Infrastructure

As noted above, pluvial flooding will not be treated within this methodology in the same way as flash-flooding because the latter is related to a pre-existing watercourse. Pluvial flooding can also be related to urban flooding, especially because it is more intense in urban areas when it occurs (where impermeable areas are more present) and because of the exposure elements (higher density in urban areas). However, pluvial flooding should not be confused with the flooding caused by a sewerage network (either storm, combined or foul network) because the latter is considered an artificial water-bearing structure source of flooding.

Thus, the pluvial flooding considered in this methodology will flooding caused by extreme rainfall over a short period of time producing "torrents" of water moving at great speed.

The basic approach suggested for pluvial flooding can be observed in Figure 3-2. The data requirements and the process for pluvial flooding will be detailed below.

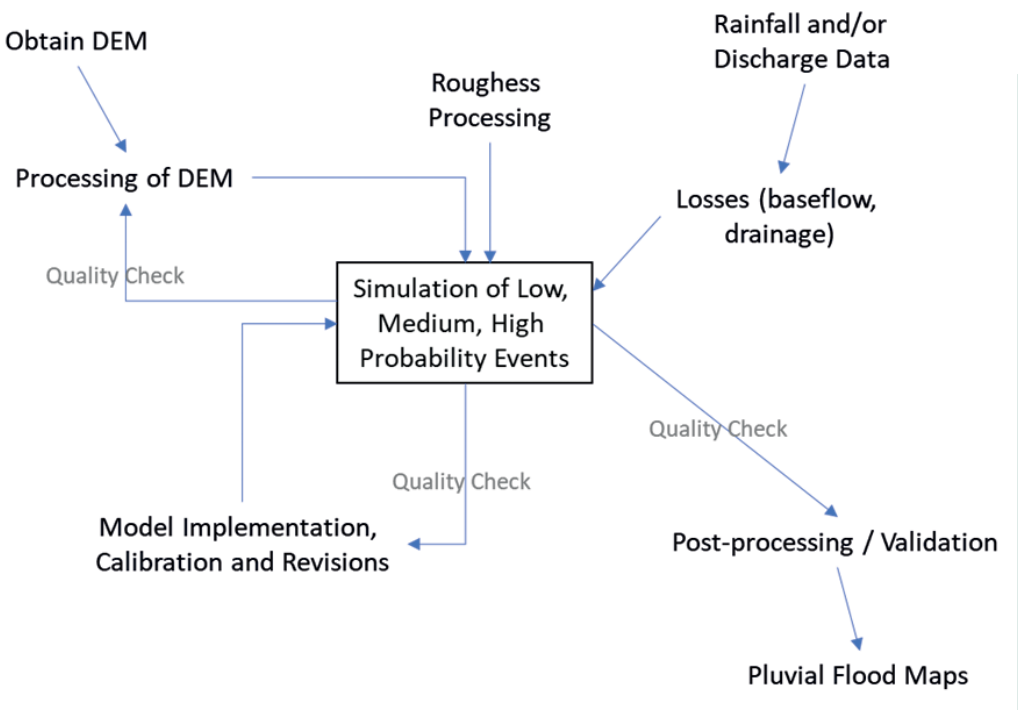

Figure 3-2. Basic Approach for Pluvial Flooding

As will be detailed in the pluvial methodology section, flood modelling in urban areas should use a low-resolution implementation where a grid cell may occupy several buildings and different approaches

28. Sayers, Gouldby, Simm, Meadowcroft and Hall. (2003). DEFRA/Environment Agency R&D Technical Report FD2302/TR1.

to the calculation of effective friction on the cell have been developed based on object classification from LiDAR or map data. The first approach simply masks out cells that are more than 50% occupied by buildings, treating the edges of the masked cells as zero flux boundaries. The second uses a porosity approach where the porosity of a cell is equal to the proportion unoccupied by buildings and, therefore, available for flow (Defina, 2000, Bates, 2000). Friction in the porous portion of the cell may then be assigned locally or globally.

The effect of errors in LiDAR DTMs on inundation predictions in urban areas has been considered in Neelz and Pender, 2006 and Hunter et al., 2008. These studies concluded that uncertainty in friction parameterisation is a more dominant factor than a LiDAR topography error vis-à-vis typical problems. This is considered in more detail in the following chapter.

2.1.1 Overland Flow of Pluvial Flooding

Urban pluvial floods may be caused by a number of factors. One of the main causes is the limited capacity of a drainage system which may result in sewer flow being discharged to the catchment surface during extremely wet weather conditions where it interacts with the incoming overland flow. The flood water either fills a natural or a constructed surface storage or subsequently travels across the terrain through preferential pathways that create a surface flow network.

The preferential pathways in urban areas typically comprise roads, footpaths, and natural ground depressions as well as small watercourses. The major system can transfer flood water over significant distances causing flooding at locations which are remote from the point at which the drainage system capacity is exceeded. Surface runoff from adjacent areas that have no direct connection to the sewer system also contributes to flood flow. Therefore, urban drainage modelling requires a detailed representation of the overland flow network of ponds and pathways to reliably represent surface retention storage, flow-paths and volume conveyed.

Although surface pathways over urban areas are mainly directed by buildings and streets, water often flows elsewhere through gardens and other open spaces. It is, therefore, important to have a realistic depiction of the terrain and the urban structures on the surface.

2.2 Methodologies and Procedures for Pluvial Flood Hazard Modelling, Mapping and Assessment

2.2.1 Modelling Scoping

During the modelling scoping phase, the modelling team has to agree on the main approach to follow for the pluvial modelling and on the data availability. In summary, the proposed method is a direct rainfall (rain-on-grid) two-dimensional hydrodynamic modelling which will dynamically model overland flow-paths and surface ponding. The concept is for rainfall to be applied to the hydraulic modelling grid and the flood water routed overland. Most 2D models with this capability apply 2D shallow-water equations. The direct rainfall approach is suited to lowland and urban catchments where point inflow estimation is challenging, there are lowland areas with standing water and more impermeable urban

surfaces reduce the contribution of soil through flow to flood flows. This method, therefore, appears to be the most suitable for pluvial flooding. The 2D hydraulic models allow for an analysis of the spatial and the temporal distribution of rainstorms and the dynamic interactions between different topographic catchments and any river tributaries.

As will be detailed below, it should be considered if allowances need to be made for infiltration, interception or the stormwater or combined network during the model implementation, while the runoff coefficients and the hydraulic roughness will also be calibrated when possible. It is not envisaged that there will be sufficient data for integrating any drainage network pipes, pumps or other infrastructure at this stage.

During the modelling scoping phase, the modeller must consider the following issues in order to ensure that the proposed approach is suitable for the specified location and to validate any models. The modelling scoping report addresses the following questions:

- Does overland routing of flow adequately represent the processes by which surface water flooding is generated?
- Are there DEM data of sufficient accuracy and resolution in the modelling area?
- Should losses due to infiltration, drainage networks, etc., be modelled?
- How sensitive are the results to the grid size and parameters of the 2D model?
- How will the distributed hydraulic roughness parameter be derived? Are the land-cover data sufficiently accurate?

2.2.2 Hydrological Assessment

The hydrological assessment will provide information regarding the precipitation input required for the implementation of2D pluvial hydraulic models. The required information would be a precipitation time-series that will be used directly as a boundary condition for the 2D models. Depending on the area to model, more than one time-series (hyetograph) may be needed considering the spatial variation of rainfall.

No further information would be required regarding upstream and/or downstream boundary conditions for pure pluvial modelling as the precipitation will be the upstream boundary condition and sea-level or normal water depth will be the downstream boundary condition depending on the geographical location of the domain.

2.2.3 Hydrodynamic Modelling Implementation

The methodology for hydrodynamic pluvial flood modelling is described in Figure 3-3 below. The processes involved in each of the stages are briefly described in the sections below.

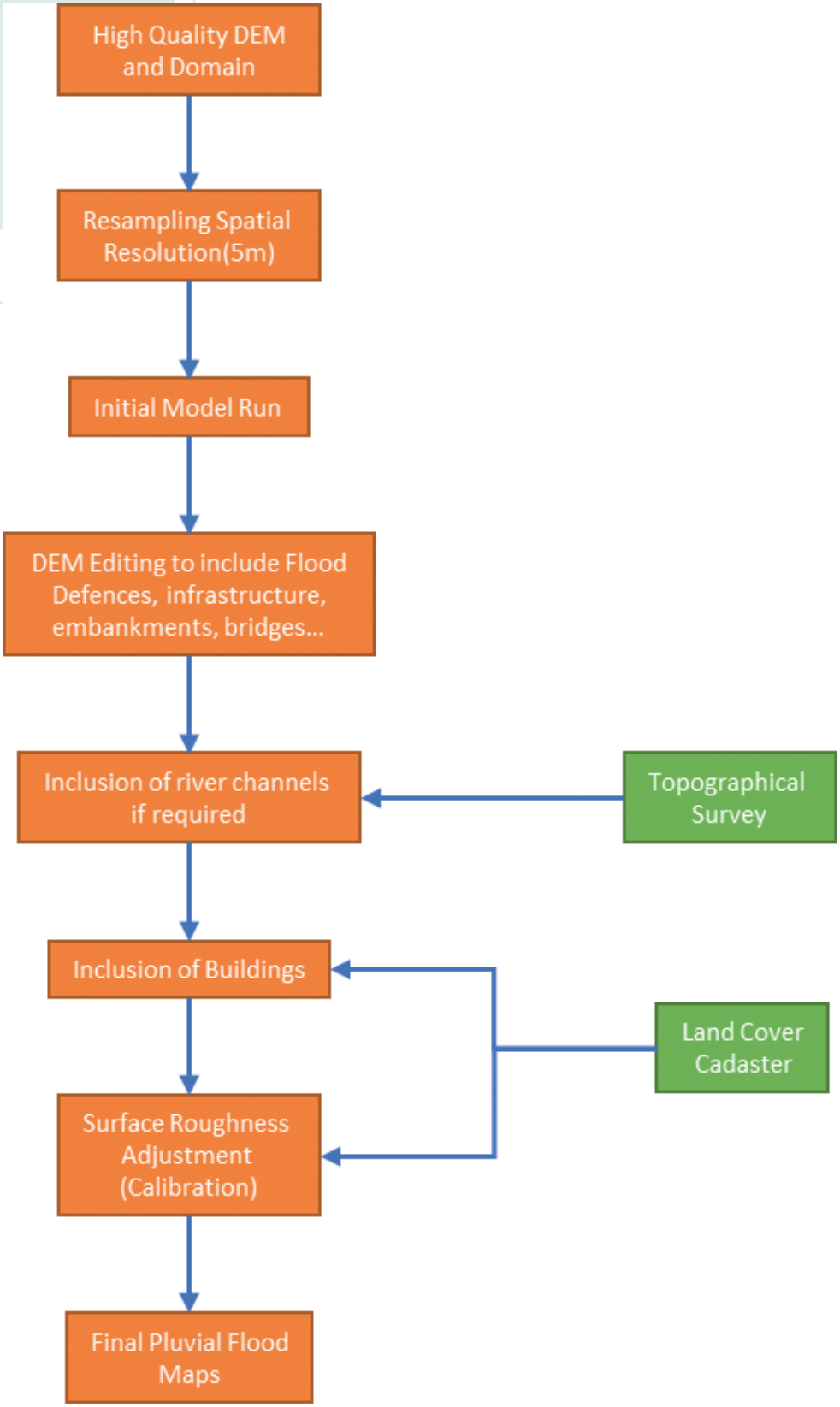

Figure 3-3. Pluvial Flood Hydrodynamic Methodology

2.2.3.1 High-Resolution DEM and Domain

As stated above, the quality of the DEM is one of the most critical aspects of any flood modelling, but this is especially relevant for pluvial modelling. It is not recommended to undertake a pluvial flood modelling exercise in areas where there is no high-resolution DEM. Therefore, the following is suggested (Figure 3-4).

- Modelling domain: the modelling domain for pluvial modelling will be defined considering the following:
  - Historical flooding: locations that have historically experienced pluvial flooding will be selected. The domain will cover the whole area of interest, considering the topography and the possible boundaries of the model.
  - Urban areas: significant urban areas of Georgia will be selected for pluvial modelling. In this case, as much of the urban area as possible will be included within the modelling domain, considering computational resources, the topography and boundary locations.
  - Comparison of the modelling domain and the DEM quality: the selected domain will be compared against the DEM coverage and the quality of the DEM resources. It should be noted that the modelling domain may be altered after some initial runs if the results are not satisfactory. The whole comparison assessment would then have to be undertaken again.
  - Within LiDAR: if the modelling domain is entirely within a LiDAR area, the modelling will proceed.
  - Within orthophoto: if the modelling domain is within an area with no LiDAR data, the quality of the orthophoto DEM will be assessed. In order to undertake this assessment, the orthophoto DEM will be compared to the LiDAR derived DEM in areas where both sets of data are present.
  - Good agreement with LiDAR data: if there is a good agreement between the orthophoto DEM and the LiDAR DEM, then the modelling can proceed. The criteria for a 'good agreement' are that the difference between those two data sets is under 1 metre.
  - Bad agreement with LiDAR data: if there is not a good agreement between these two data sets, then the modelling for that specific area (domain) will be halted.
  - As discussed above, issues have been identified with the orthophoto DEM in Georgia. It is recommended that further work is undertaken with this DEM in order to enhance the quality and accuracy of the elevation data.
  - Only global DEM: if the domain is only within an area with global DEM, the modelling will be halted at this stage. While the orthophoto DEM is supposedly covering the whole territory of Georgia, this data set has not been made available to the consultant and, therefore, this has not been possible to assess.

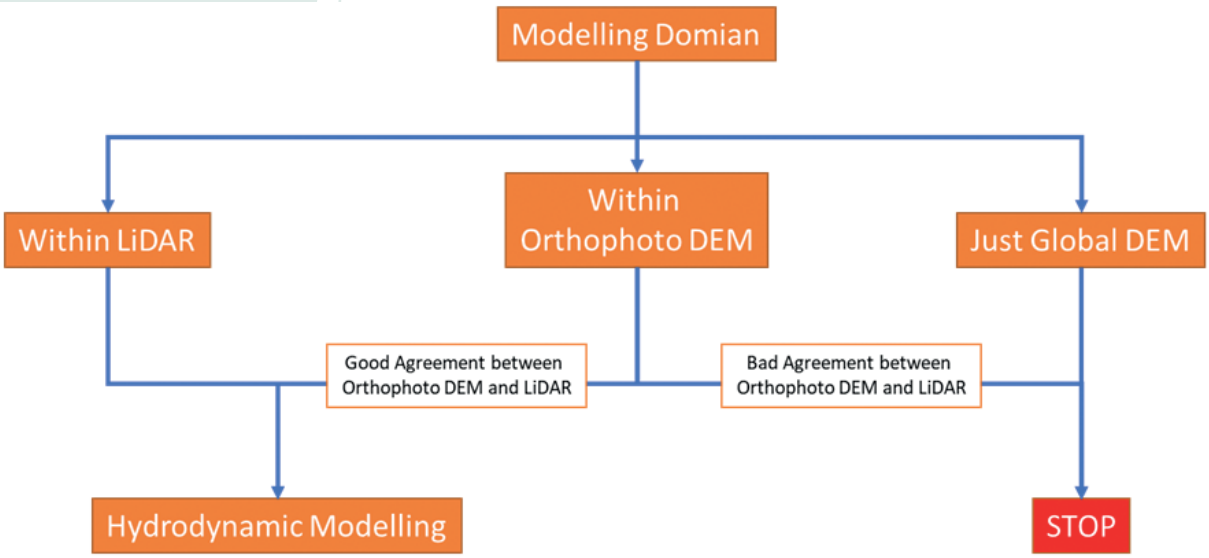

Figure 3-4. DEM Assessment

2.2.3.2 Resample Spatial Resolution of Grid

In this modelling stage, the DEM will be resampled. Direct rainfall models are very sensitive to grid cell size, rainfall hyetograph time interval and model time-step. A maximum of a 5-metre cell size is recommended. Some model software allows for variable cell sizes, flexible mesh, and multiple domains and, therefore, this will be considered when implementing the modelling domain and defining the grid size. If a flexible mesh is used, no cells higher than an equivalent 5 metre rectangular grid should be used. The inclusion of break-lines to represent some key features is also recommended, provided that the topographical resolution allows for this. Nonetheless, an uncertainty assessment regarding the cell size it is also recommended.

The model time-step should be set with reference to the cell size and the rainfall profile interval, always allowing for the Courant number to be under a value of 1. Adaptive time-step modelling is recommended.

2.2.3.3 Initial Model Run

An initial model run should be carried out early in the modelling process in order to understand the scale of edits and the adjustments required, including any requirements for altering the modelling domain. If the rainfall and hydrological analysis has not yet been completed, realistic “dummy” conditions can be used for these runs. These initial model runs can also be used to determine if any survey of key structures and features that influence overland flow-paths and ponding is required.

Topographic depressions where surface water ponds should be identified so that these can be accounted for in the loss model. Water in these ponds may be lost due to evaporation and/or infiltration and the loss model to be implemented within the 2D hydraulic model will need to be adjusted considering input from the hydrological modelling.

2.2.3.4 Edits to DEM for Flood Defence Assets, Infrastructure, Embankments, Bridges, etc.

Any feature which influences overland flow-paths, flood depths or surface water ponding should be reviewed and incorporated into the model where necessary. These features can either be as edits to the 2D model domain, such as break-lines or dry riverbeds, or as embedded dynamically linked 1D domains (such as 1D channels for ditches or 1D pipe networks or culverts through an embankment). The use of 1D elements should be limited to where necessary so as to reduce model complexity and increase model stability. The most critical features will be openings or culverts which are critical to the distribution of surface water flow and ponding depths.

Openings in embankments and under roads, railways and other infrastructure should be represented in the DEM with invert levels interpolated from the DEM elevation on either side of the opening or embankment. Topographic maps can be used to identify possible culverts, tunnels, and embankments. The geometry (bottom sill or crest, soffit or height, width, shape, length, and slope) of these structures can be inferred from site visits, DEM surveys or photographs. If survey data are available, this should be used in preference to infer geometry. Figure 3-5 is an example of where the DEM would be used to derive geometry for un-surveyed structures.

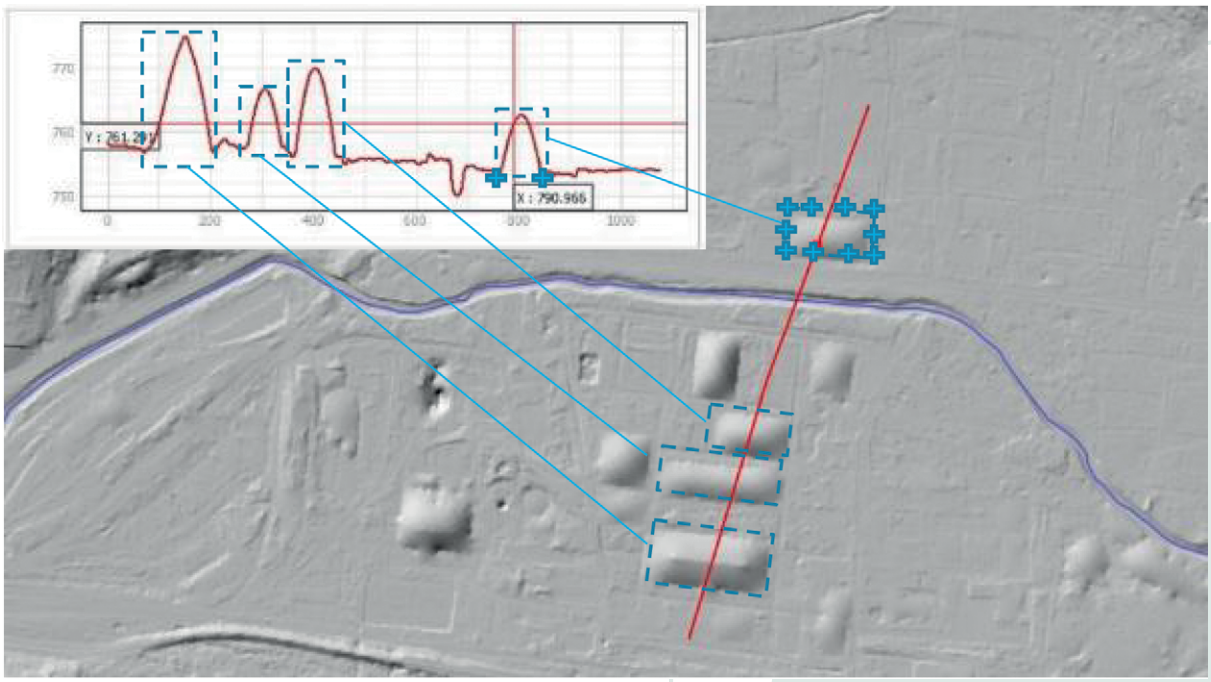

Figure 3-5. Culvert Example

If flood extents and depths are sensitive to the assumed geometry, and this influences vulnerability and the likelihood of flood damages or flood exposure to people, then uncertainty must be clearly communicated to users of the map with the uncertainty assessment documenting any data deficiencies.

2.2.3.5 River Channels, Watercourses

River channels, watercourses and other surface water features should be included in the model. Both constantly flowing and ephemeral streams should be included in either the 2D domain or as dynami-

cally linked 1D networks. A survey of the cross-section, structure, the long profile, and crossings should be collected beforehand. If a survey is not available or is not possible to be made, then the models will consequently represent the channels, crossings and structures in less detail and will need to clearly document this uncertainty.

Small streams which have not been subject to a detailed survey do not need to be included in the DEM unless they have a significant influence on surface water flow-paths and flood depth. The GIS process should be applied when it is necessary to include channels in the DEM. The GIS exercise must ensure that changes in the channel gradient are retained. The assumed channel depth and width can be taken from the DEM, visual inspection during site visits or photographs. Crossings and culverts which have not been surveyed will need to be represented with an assumed geometry.

Similar to structures, if flood extents and depths are sensitive to the assumed channel geometry, and this influences the likelihood of flood damages or flood exposure to people, any uncertainty must be clearly communicated to users of the map, or a channel and a structure survey should be made if possible.

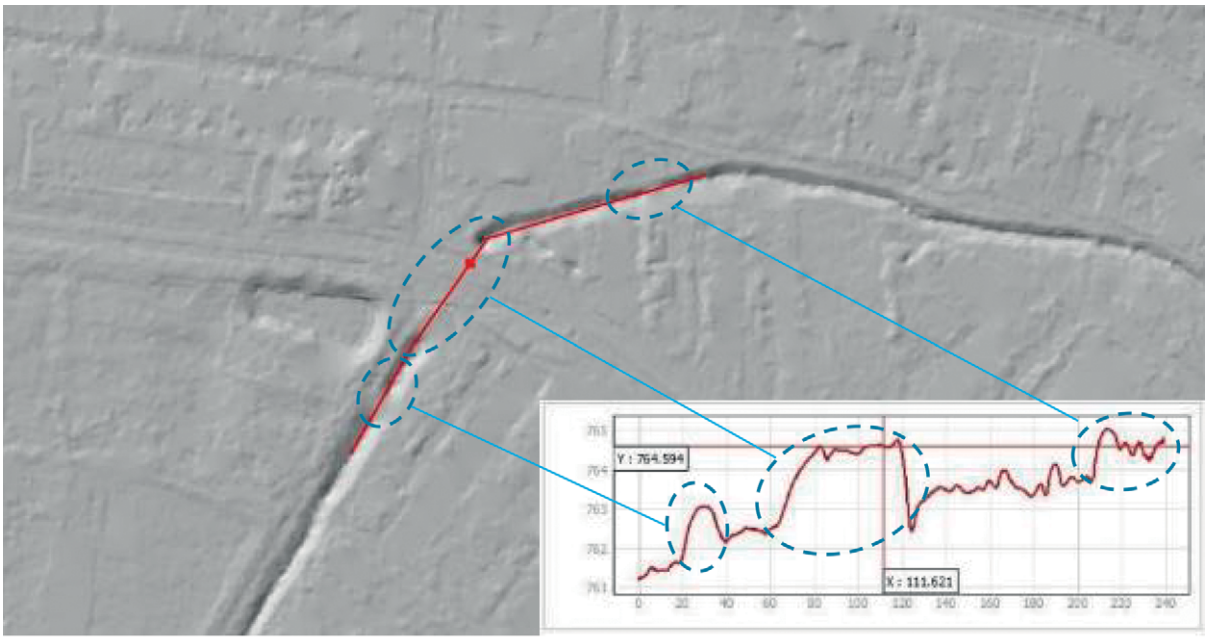

Figure 3-6. Example of DEM Riverbed Elevation

2.2.3.6 Buildings (and Other Obstructions to Flow)

The influence of buildings on surface water flows can be important. Buildings and other features which obstruct, direct or control overland flow-paths should be represented in the model. The data requirements for this were discussed above. There are two possibilities for the inclusion of buildings in pluvial flood models:

1. To raise the levels in the buildings outlines to the finished floor level (with the subsequent effect that this flow restriction would represent flow in and through buildings).
2. To represent the buildings with a higher roughness value than the surrounding land-use.

The suggested approach would depend on the data availability and on the ease of implementing the approach, although the abovementioned second approach is recommended.

If the first one is selected, the choice of the height to raise the building's layout is important and can have a significant influence on the resulting hazard maps and risk assessment. Property threshold information should be used if available, otherwise an assumed floor level (i.e., 200 mm) can be applied.

If the second approach is selected (applying a higher roughness value for buildings than the surrounding land-use), a roughness value of 0.3 is recommended.

In addition to this, the filtering to create the DEM may not have fully removed building elevations in some situations, especially if the orthophoto DEM is used. The DEM should be adjusted in these locations. Figure 3-7 shows the concept and process for adjusting building elevations.

Sufficient grid cells, generally at least four, are recommended for the modelling of flow-paths between buildings and other obstructions.

Regarding the number of grid cells, there are concerns about the computational capabilities to model large urban areas, mainly Tbilisi. A domain for the whole of Tbilisi with a grid size of 5 metres (or lower), including significant watercourses and bridges, may result in a pluvial model with associated computation requirements and a simulation run-time of several days (even weeks). In that case, it is recommended that the model is split into shorter domains if possible or that alternative computing resources are used.

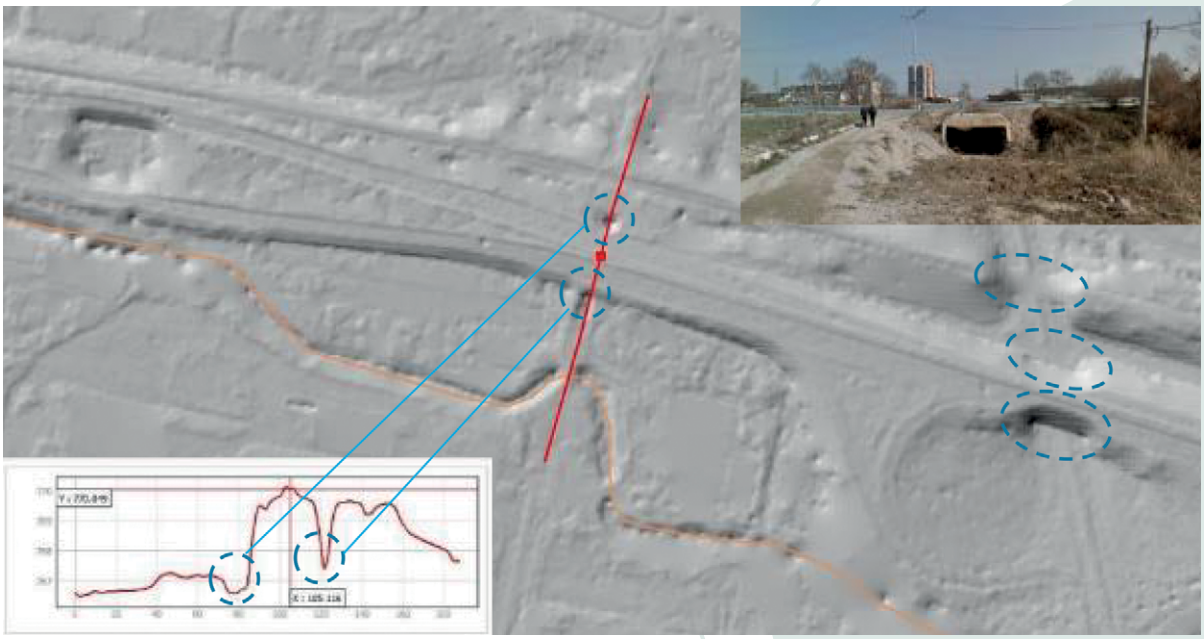

Figure 3-7. Example of Buildings that Require Removal from the DEM

2.2.3.7 Surface Roughness

The surface roughness should be defined using the Manning's approach, assigning Manning's roughness values to the model surface. Pluvial models are sensitive to roughness and, therefore, impermeable, and permeable areas (buildings, roads and streets, paved areas, parks, etc.) should be properly defined and each land-use type should have a specific roughness value.

Standard values for land-use data should be applied in the initial modelling runs using land-cover data. These values should be adjusted during the calibration process to ensure the model's representation of the local conditions. The inclusion and adjustment of the roughness depends on the software used but a 2D grid can be used to represent this in most cases.

2.2.3.8 Model Boundary Conditions

The model boundary conditions for pluvial flooding are defined in a different way from other types of flooding. No direct definition of the upstream boundary condition is made. Different precipitation events will be used on a grid basis or per domain. In terms of the downstream boundary conditions, its definition will depend on the location of the domain. For example, a coastal boundary condition (water level time-series) will be defined close to the coast. In the case of a possible pluvial-coastal event, a joint probability assessment will be undertaken. In inland domains, the downstream boundary will be located as far away as possible from the areas of interest and a normal depth boundary condition will be used.

The watercourses included in the pluvial modelling domain will also need to be defined with a boundary condition. In these cases, a nominal hydrograph will be used for the pluvial assessment. As per the coastal case where pluvial and fluvial flooding may occur simultaneously, a joint probability assessment will be undertaken and flows, and precipitation will be defined accordingly.

2.2.4 Hydrodynamic Model Validation and Runs

The pluvial hydrodynamic model implemented will be validated using the following approach.

2.2.4.1 Model Calibration and Validation

The pluvial models will be calibrated and validated if possible. If there is uncertainty regarding the data availability for model calibration and validation which then renders these processes impossible, the sensitivity and uncertainty analysis will play a more significant role. Model calibration and validation can only be done if sufficient sub-daily precipitation data exist in order to derive event rainfall boundary conditions and if event reports which describe the depths and the extent of flooding are available. The collection of spatial satellite flood outlines is also recommended if available. However, an assessment of available satellite flood impact data has been undertaken but with no significant results. Nonetheless, models can be calibrated through adjustments to the 2D domain, roughness, and the loss model (if implemented). At a minimum, validation should involve a discussion of the results with the local municipalities to ground truth the modelling results.

2.2.4.2 Sensitivity

Due to the expected lack of data for the calibration and the validation of the models, sensitivity testing is recommended. The main sensitivity test required for pluvial modelling will concern precipitation. In this case, two different tests should be undertaken; one for rainfall intensity (±15% increase and decrease in precipitation) and one for duration (±50% increase and decrease of storm duration [with no change in total rainfall volume]). In addition to this, it is recommended that sensitivity tests are undertaken for grid size in which the grid size is varied by 50% and the impact on the results is analysed.

2.2.5 Design Event and Climate Change Runs

The EUFD requires pluvial flood hazard maps to be derived for 5%, 1% and 0.1% probabilities. Within the framework of this implementation, however, it is recommended that a broad spectrum of probabilities is tested with a range of storm durations. Historical flood records can assist in the selection of storm durations vis-à-vis those which result in flooding. The maximum extent and depth for each grid cell from the different storm durations for a probability should be used in the hazard and risk mapping.

2.2.6 Pluvial Flood Hazard Mapping

Pluvial flood depth should be colour coded as follows.

Depth [m]	R	G	B	Colour
0.05 < 0.5	204	255	255	
0.5 < 1.0	153	255	255	
1.0 < 1.5	102	255	255	
1.5 < 2.0	51	255	255	
2.0 < 2.5	153	204	255	
2.5 < 3.0	102	178	255	
3.0 < 4.0	0	128	255	
> 4	63	0	125	

Flood depths of less than 0.1 metre should not be mapped except for within buildings where all flood depths should be mapped because the footprints of buildings have already been considered in the modelling implementation.

2.2.7 Urban Drainage Flood Hazard Mapping

As noted above, it is not envisaged that urban drainage (sewerage) flood hazard modelling will be undertaken within the framework of this project. Nonetheless, a brief methodology for modelling urban drainage flooding will be proposed. There are several issues to consider here:

- Drainage systems in urban areas can be:
- Combined network: if the stormwater (surface runoff from rainfall) and the sewerage water are drained by a combined sewer network. In these cases, the presence of combined sewer overflows (CSOs) should be noted. CSOs are constructed in combined sewer systems to divert flows in excess of the peak design flow of the sewerage treatment plant.
- Separate systems: where there is a network with two separate systems, one for the storm network and the other for the sewerage (foul network). In this case, the foul network is usually of a reduced size as compared to the storm network and always depends on the climatological features of any specific region.
- Due to historical reasons, a mixture of the two systems can be found in most cases with combined, foul and storm pipes comprising the urban system.
- Data are paramount: while modelling data are critical for all flood sources, this is especially the case for sewer system flood hazard modelling. Data about the manhole covers and depth, the invert levels and diameters of pipes and very detailed information about the CSOs and pumping stations are required to successfully implement a waste-water network model. CCTV surveys (to assess the state of the network, illegal connections, and infiltration), runoff contribution surveys and flow-rainfall surveys are also required in most cases. These network models have to be calibrated and validated against information from flow survey campaigns in order to assess the accuracy of the models.
- The calibration of waste-water network models is undertaken in most cases following a dry-weather and wet-weather calibration process, mainly with combined systems.
- The interaction between the urban drainage network and other sources of flooding (pluvial, fluvial, coastal and groundwater) should also be considered.
- Waste-water modelling software takes into account all of these peculiarities. Unfortunately, while for other sources of flooding there is reliable open-source software available, most urban network modelling relies on the implementation of commercial software such as Innovyze (previously InfoWorks) and/or MIKE URBAN (previously MOUSE) for the implementation. The main open-source option (SWMM by EPA (US Environmental Protection Agency)) does not contain all of the required features for the implementation, calibration, and validation of these models.
- There are several guidance documents available detailing the implementation of such models. The guidance and code of practice by the UK Urban Drainage Group[29] (previously WaPUG) is especially worth noting.

29. CIWEM Urban Drainage Group. https://www.ciwem.org/assets/pdf/Special%20Interest%20Groups/Urban%20Drainage%20Group/Code%20of%20Practice%20for%20the%20Hydraulic%20Modelling%20of%20Ur.pdf

Unfortunately, there is not a history of urban drainage network modelling in Georgia and initial investigations have outlined that no data are available for this modelling. Intensive manhole survey campaigns in combination with flow survey campaigns should be undertaken in order to be able to model urban drainage networks. Additionally, the acquisition of specialised software would be recommended for this purpose.

Considering all of the information outlined above, it is not recommended that sewerage (or urban drainage) network modelling is undertaken within the context of this project at this stage. Nonetheless, it is suggested that modelling exercises are undertaken for the simulation of urban drainage networks when this information becomes available.

2.3 Data Requirements and Availability for Pluvial Flood Modelling and Mapping

The data availability and data requirements for flood-hydraulic modelling have been discussed in several reports. This issue has also been a matter of discussion with the NEA and other stakeholders. Nonetheless, the specific requirements for pluvial flooding will be detailed in this section. Due to the nature of pluvial flooding and its impact on urban areas, one of the main data requirements is topographical information. One special characteristic to be considered at this stage is spatial recurrence. Pluvial flooding may occur anywhere. From a historical point of view, there are locations that are statistically more prone to pluvial flooding, but this type of flooding can occur anywhere. The impact and the severity of flooding will be determined by the topography and the urbanisation of a particular location.

Thus, in order to outline the methodology for pluvial flood modelling, the data requirements and data availability in Georgia will be considered:

Details of historical and recorded pluvial flooding in Georgia: the records of previous historical pluvial flooding will be collected and analysed. This is something that should have been undertaken under the 'historically significant flooding' stage. However, because this stage will not be undertaken fully within the framework of this project (data will be collected but the significance process will not be fully undertaken), special care will be paid to this activity within the pluvial methodology implementation in the FHRM stage. In the opinion of the consultant, there are no pluvial flooding source records in Georgia at the moment. As detailed for the fluvial flooding stage, all of the extreme flood events collected by the NEA will be analysed considering all of the relevant parameters and variables (precipitation, flows, impact, etc.) and every flood event will be assigned a flood source type. The historical pluvial flood events will be analysed in detail at this stage and this information will be used for calibration and validation purposes.

Details on the availability, quality, and coverage: the following modelling data are required for the pluvial model's implementation.

DEM data: as will be detailed below, DEM input is one of the most critical input data to be considered for pluvial modelling. There are several data sources to be considered at this stage. As noted above, the main one will be the LiDAR data to be collected within the framework of this project (Figure 2-19).

More details on the topographical and spatial resolution will be outlined below (section 4.2.3.1).

- Rainfall depth-duration-frequency relationships.
- Temporal resolution of rainfall hyetographs (often intense storms with high intensity and short duration rainfall is the driver of flash-flooding).
- Soil and geology data.
- Land-cover and use data: land-cover and land-use data will provide information for pluvial modelling regarding roughness (or resistance). This is an important factor in determining how the water will flow in a particular area. Particular attention will be paid to this data source due to the relevance of permeability on pluvial modelling results. Land-cover data will be combined with the building's footprint data for roughness purposes. The same sources as described for fluvial flooding will be considered here.
- Building footprint data: the building footprint data are relevant in pluvial flooding because they provide information and data for the flow routing within the modelling implementation. Cadastre data will be used to provide a building's footprint across the Georgian urban area. These data have not been acquired as of yet, but they appear to be available. In the absence of cadastre data, other sources of information will be used such as the building's polygon information from OpenStreetMaps (Figure 38). The methodology for the inclusion of the building's footprint data into the pluvial models will be described in detail below.

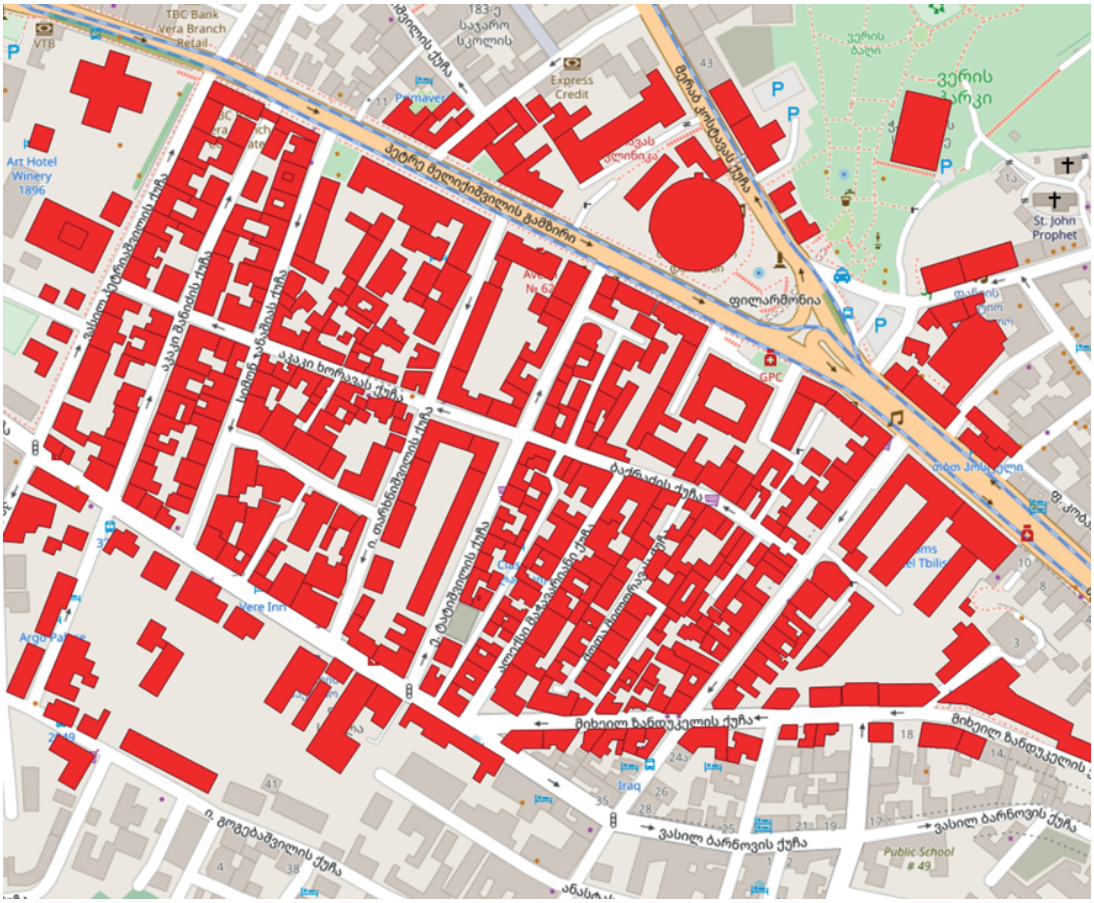

Figure 3-8. OpenStreetMaps Buildings (in Red) in Tbilisi

- Road and rail infrastructure data: road and rain infrastructure data will be needed as well for pluvial modelling. These data will be collected from cadastre sources or from OpenStreetMaps as per the building layouts. The process for including these data into pluvial modelling will be discussed below.
- Flood defence data (e.g., levees and embankments): flood defence infrastructure is critical for all flood modelling sources. This is especially the case for pluvial flooding because these objects of infrastructure may affect the water flow and water direction. Data and details from flood defence data will be collected and included in the model when available. At the moment, attempts at collecting these data in Georgia has been unsuccessful.
- Sewerage network data: the influence of the sewerage network on pluvial flooding is a matter of research. Nonetheless, it can be considered from a pluvial point of view that the sewerage or storm-water network system does not play a major role based on previous studies. Special attention should be given to the flood modelling project undertaken within the framework of the Rapid Response Flood Modelling[30] study for Houston after Hurricane Harvey made landfall along the Texas coast in August 2017 followed by a flood event. In this study, 26 hydrodynamic models (including 1D, 1D-2D, 2D and urban drainage models) were tested against the resulting flood impact. HEC-RAS 2D had the least bias and the highest correlation with the observed flood without considering the sewerage network. A similar approach was followed in other cases such as in Sydney[31] (Australia), Tabuk City[32] (Kingdom of Saudi Arabia), Pune[33] (India) and Valencia City[34] (Philippines). Nonetheless, the availability of high-quality information and data on the sewerage network determines whether integrating underground sewer and pipe networks in pluvial flood models can improve the uncertainty in the resulting flood hazard and risk maps.

2.3.1 Importance of Spatial Resolution

Topography plays a major role in determining the accuracy of flood inundation areas. This is the case for all sources of flooding but the impact on pluvial flooding may be more relevant. The type, accuracy and resolution of the elevation data are extremely important in developing flood maps with these factors widely believed to have a direct impact on the resulting flood mapping extents and depths (Figure

30. Rapid Response Flood Modelling Final Report. (2019). US Department of Homeland Security FEMA Mitigation Branch.
31. Issa Makdissi and Ataur Rahman. (2019). A Case Study on Urban Flood Modelling in Sydney Using DRAINS and HEC-RAS. Proceedings 2nd International Conference on Water and Environmental Engineering Education (iCWEE), 19-23 January 2019, Dhaka.
32. Ashraf Abdelkarim, Ahmed F. D. Gaber, Ahmed M. Youssef, and Biswajeet Pradhan. (2019). "Flood Hazard Assessment of the Urban Area of Tabuk City, Kingdom of Saudi Arabia by Integrating Spatial-Based Hydrologic and Hydrodynamic Modelling." *Sensors*, 19, 1024; doi:10.3390/s19051024
33. Rahul Nandurkar, Ravina More and Shailesh Deshpande. Urban Flash Flood Modelling Using Remotely Sensed Data and Hec-Ras: Pune Case Study. Proceedings.
34. B.A.M. Talisay, G.R. Puno and R.A.L. Amper. (2019). "Flood Hazard Mapping in an Urban Area Using Combined Hydrologic-hydraulic Models and Geospatial Technologies." *Global J. Environ. Sci. Manage.* 5(2): 139-154, Spring 2019.

3-9, Saksena & Merwade, 2015[35]). Flooding may be greatly over- or under-estimated if poor quality elevation data are used. The resolution, or horizontal resolution, of elevation data is the size of each cell which is given a single height value, generally in metres. The smaller the cell size, the higher the resolution of the data.

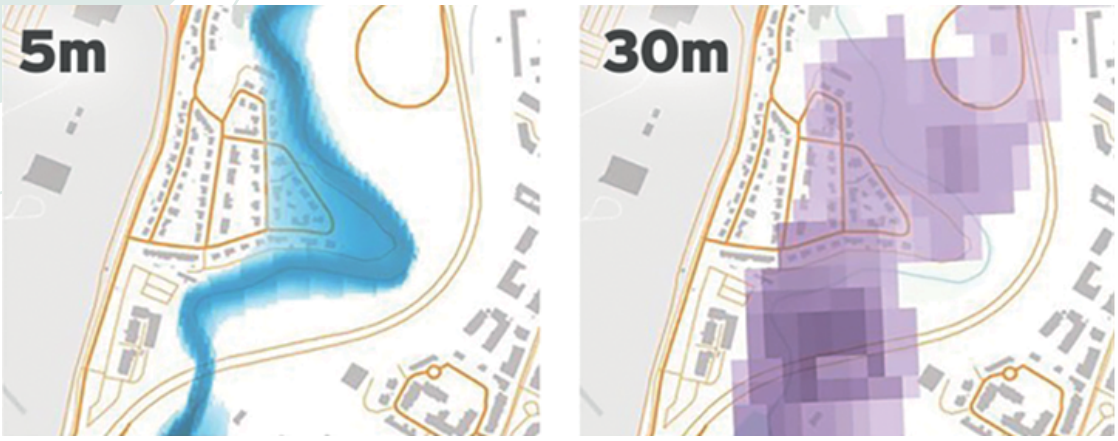

Figure 3-9. Flood Mapping Difference Depending on the Resolution, 5 m versus 30 m

The spatial resolution, vertical accuracy, and source availability of existing Georgian national DEMs are presented in Table 27.

Table 27. High Resolution DEMs in Georgia with National Coverage

DEM Type	Spatial Resolution	Vertical Accuracy	Source
LiDAR Data	1 m	~0.15 m (technical specification)	UNDP – GCF-SDC programme
Orthophoto DEM Data	15 m	~4.0 m	Public Registry Office
SRTM Global DEM	30 m	~15 m	Global Sources
MERIT DEM	90 m	~4.0-5.0 m	Global Sources

The global sources listed in the table above are described in another deliverable by the consultant (Report on Identified Areas for LiDAR Survey, Field Surveys and Control Cross-section Survey Points for Selected River Basins). The impact of DEM sources on modelling results is also discussed in the abovementioned report. Based on this information and considering pluvial modelling requirements, the resolution and accuracy in the LiDAR areas is considered to be sufficient for pluvial modelling purposes. Further analyses are required for the orthophoto DEM. This DEM is supposed to cover the whole territory of Georgia, but the consultant has not yet had access to this DEM and, therefore, its accuracy has not been assessed.

35. Saksena, Siddharth and Merwade, Venkatesh. (2015). "Incorporating the Effect of DEM Resolution and Accuracy for Improved Flood Inundation Mapping." *Journal of Hydrology*. 530. 10.1016/j.jhydrol.2015.09.069.

2.3.2 Importance of Temporal Resolution

The temporal resolution of rainfall data is an important consideration for modelling intense rainstorm and pluvial flooding risks. Figure 3-10 demonstrates one example where ten-minute interval rainstorm hyetographs could miss the intense peak rainfall intensity when compared to one-minute interval data.

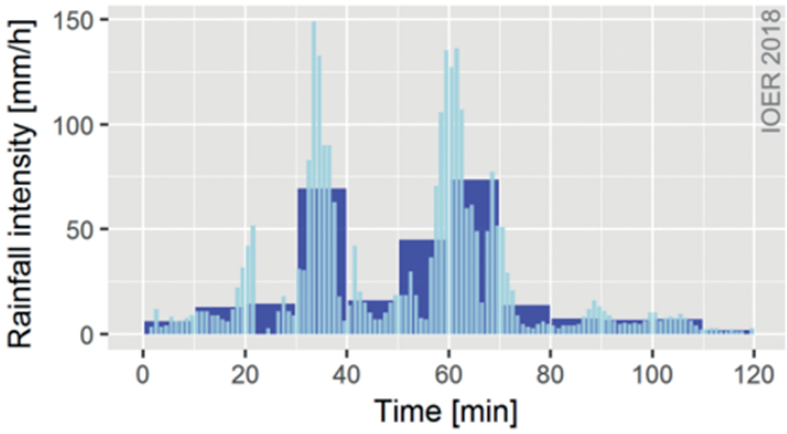

Figure 3-10. Comparison of Rainfall Intensity with 1One-minute and Ten-minute Intervals (Source: Sauer et al., 2018)[36]

This is one of the main envisaged constraints within the implementation of this assessment for pluvial flooding. A correct representation of precipitation patterns is required in order to ensure that the results are accurate. At the moment, most of the historical rainfall information in Georgia is in a daily format. Recently deployed stations collected data in a 15-minute time interval. The influence of the temporal resolution on the hydrological analysis should be established. Other sources of data, such as weather radar data or satellite precipitation estimates (Kiesel, 2018[37]), used three-minute time interval weather radar data in the hydrological assessment for the Legh-vtakhevi River in Tbilisi with significant success and improved results as compared to any other source of precipitation data. It is suggested, therefore, that the acquisition of weather radar data for pluvial modelling purposes is explored further.

36. Axel Sauer, Lisa Körte and Regine Ortlepp. (2018). "An Uncertain Business: Mapping Flood Hazards Caused by Heavy Rain." *Beton und Stahlbetonbau International Probabilistic Workshop*, 95.

37. Jens Kiesel. (2018). Hydrological Modelling Report. Assessment of Suitable Flood Mitigation Measures (Based on the Dukniskhevi River Extreme Flood Analysis) in Tbilisi, Georgia. CTC-N Report.

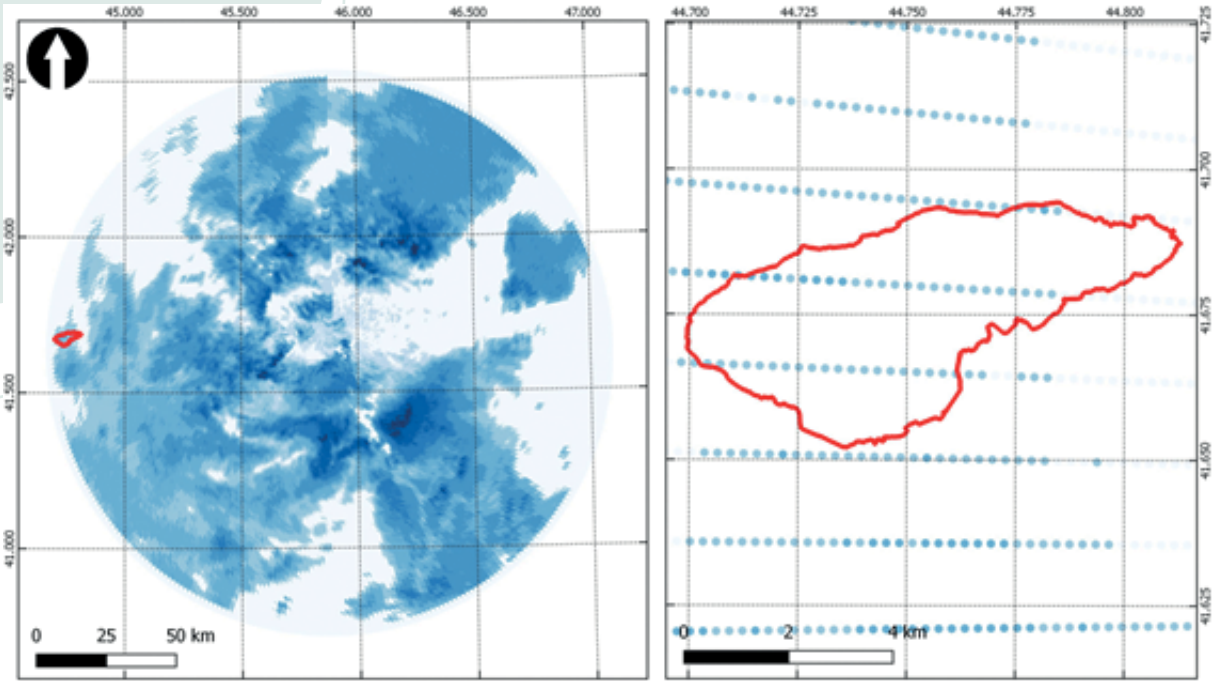

Figure 3-11. Weather Radar Points Projected to the WGS84 Projection for the Whole Spatial Data Coverage (Left) and for the Leghvtakhevi Catchment (Right). (Source: Kiesel, 2018)

In addition to the weather radar sources, the use of satellite precipitation estimates may be considered. These data, however, should be previously validated and calibrated, especially for bias adjustments while noting that these data are usually not available in the required resolution for pluvial modelling. Nonetheless, these data can be very useful when sub-daily data are not available as is the case for several catchments in Georgia. In this respect, NASA's Integrated Multi-satellite Retrievals for GPM (IMERG), JAXA's Global Satellite Mapping of Precipitation (GSMaP), the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) and the NOAA's Climate Prediction Centre (CPC) MORPHing method (CMORPH) should be considered.

2.3.3 Urban Drainage Flooding

A specific section for urban drainage flooding has been included within the discussion of pluvial flooding. While there is no direct equivalence between urban drainage flooding and pluvial flooding, the latter usually occurs in urban areas (and elsewhere but it is more significant in urban areas due to the elements at risk) and its impact may be exacerbated by the lack of an appropriate urban drainage system. There are several studies about this issue, and it has been determined that the impact of the drainage network on pluvial flooding is very limited in most cases (at least from a modelling point of view). Additionally, it should be added that urban drainage systems are usually designed to withstand a limited return period event (for example, in the UK this period is 30 years while in Spain it is ten years) and, therefore, any precipitation event with a higher probability is going to act as pluvial flooding. Further, this is considering that the system was designed accurately and that it is working at 100% which rarely is the case.

Nonetheless, including a section regarding data requirements for urban drainage flooding was considered to be important for this study. While modelling data are critical for all flood sources, this is especially the case for urban drainage system flood hazard modelling. The following is required:

- Network data: there are several requirements for the network data:
  - Manhole covers and depth.
  - Pipe invert levels and diameters.
  - Ancillaries: pumping stations and combined sewer overflows (CSOs) are two of the most significant ancillaries in an urban drainage network. Very detailed information about the CSOs and pumping stations is required to successfully implement a network model.
- CCTV surveys (to assess the state of the network, illegal connections, and infiltration).
- Runoff contribution surveys to assess the runoff contribution of specific areas to either a combined or a separate system when both are present.
- Flow-rainfall surveys: urban drainage network models have to be calibrated and validated against information from flow survey campaigns in order to assess the accuracy of the models. The calibration of network models is undertaken in most cases following a dry-weather and wet-weather calibration process, mainly with combined systems and, therefore, the flow survey duration should consider that at least two dry-weather events (with no rainfall for 48 hours in advance) and three rainfall events (with sufficient precipitation depending on the location) are recorded by the flow survey.

The consultant has undertaken a brief analysis of data availability in Georgia, although no information has been found at this stage. The main stakeholder for urban drainage in Georgia is Georgian Water and Power, a private company in charge of the operation of the clean and waste-water networks. No data from Georgian Water and Power have been obtained at this stage.

2.4 Data Quality Assessment for Pluvial Flooding

Some of the data sources required for pluvial flooding were analysed in detail in the fluvial section. Some additional information regarding DEM impact on the results are shown below, including information about additional sources required for pluvial modelling:

Details of historical and recorded pluvial flooding in Georgia: no records of historical pluvial flooding are available in Georgia. This is a matter of concern, although it is believed that more information can be gathered in the future. The list of flood events at the NEA should be detailed further and more work should be undertaken in terms of categorising each of the events depending on the flood source.

DEM data: topography plays a major role in determining the accuracy of flood inundation areas for pluvial flooding. This is the case for all sources of flooding but the impact on pluvial flooding may be more relevant. The type, accuracy and resolution of the elevation data are extremely important in developing flood maps with these factors widely believed to have a direct impact on the resulting flood

mapping extents and depths. Therefore, the use of a sufficient spatial resolution is required in pluvial modelling. This will be an issue if only LiDAR data are available. Based on some initial consultations, it was determined that some areas covered by the orthophoto DEM are in a five-metre grid. However, this could not be ascertained. Nonetheless, the present quality of the orthophoto DEM it not recommended for pluvial modelling purposes. Therefore, it is recommended to implement pluvial models at this stage only where LiDAR data exist unless a more accurate orthophoto DEM becomes available.

Building footprint data: building footprint data are relevant in pluvial flooding because they provide information and data for the flow routing within the modelling implementation. The data available from the cadastre appear to be of sufficient quality. Even if these data were not available, the OpenStreetMaps resources were analysed and found to be of sufficient quality and density.

Road and rail infrastructure data: the same as for buildings can be said for road and rail infrastructure data.

Flood defence data: no flood defence data are available as of yet. While this would not prevent the implementation of the models, the accuracy of the results may be highly compromised. It is recommended that further efforts are taken to collect these data.

Urban drainage network data: no urban drainage network data could be collected. It is not recommended that this is pursued at this stage.

2.5 Methodologies and Procedures for Preparation, Data Analysis, and Incorporation into Hydraulic Models

The methodologies outlined for the preparation of data for fluvial models should also be fully considered in this section. There are some differences vis-à-vis the way in which some of the data will be managed and prepared; however, this will be outlined in this section.

2.5.1 DEM Data

The main difference between fluvial and pluvial models is that the latter requires a finer resolution, especially in fully urbanised areas. Although the grid resolution will be controlled by the numerical modelling software, the quality and the accuracy of the DEM should be fully ascertained in order to ensure that the DEM data are suitable for this type of modelling. This data analysis should be undertaken using GIS resources and comparing the DEM to any existing reliable elevation data.

In addition to this, modifications should be undertaken to the DEM as described throughout the methodology for pluvial modelling in order to consider culverts, road-crossings and any other structures that may have an impact on overland flow-paths.

1.5.2 Land-cover

The basis for the land-cover data input file and processing would be the same as was described for fluvial modelling. However, the inclusion of buildings and roads is recommended in this case as previously

noted. If HEC-RAS is used for pluvial modelling, it will be necessary to develop a single land-cover file to be used in the modelling process and to import it into the modelling framework. In this case, roads, and buildings as well as the land-cover data from Copernicus should be merged into a single file with preference given to buildings and road data in the merging. High roughness values should be assigned to the buildings while road data should be assigned a low roughness value (0.015-0.025 would be recommended).

2.6 Software

A brief software analysis has been undertaken for fluvial modelling. However, some of the modelling software outlined above will not be useful for a pluvial flood analysis. The key features that the software has to meet are outlined below:

- A direct rainfall approach should be possible. This is not possible with the MIKE or the SOBEK software.
- It should be possible to include infiltration and evaporation losses. While Delft3D allows for evaporation losses, it does not consider infiltration losses.
- It should be possible to modify the DEM and include structures. Iber does not have these capabilities. Moreover, the computational capacities and speed of Iber are limited.

Therefore, and also considering the information outlined in the fluvial section, the recommended software for pluvial flood hazard modelling and mapping is HEC-RAS. In this case, while HEC-RAS 5.0.6 is recommended for fluvial modelling, HEC-RAS version 6.0.1 is recommended for pluvial modelling.

03

Groundwater Flood Hazard Modelling and Mapping

3.1 Groundwater Flooding in Georgia

Groundwater has not traditionally been recognised as posing a significant risk and thus remains relatively less well understood than other forms of flooding. This type of flooding occurs when the natural underground drainage system cannot drain rainfall away quickly enough, causing the water table to rise above the ground surface. In recent years, groundwater flooding is becoming the object of several research studies, especially after the requirements by the EUFD to assess all sources of flooding, including groundwater sources.

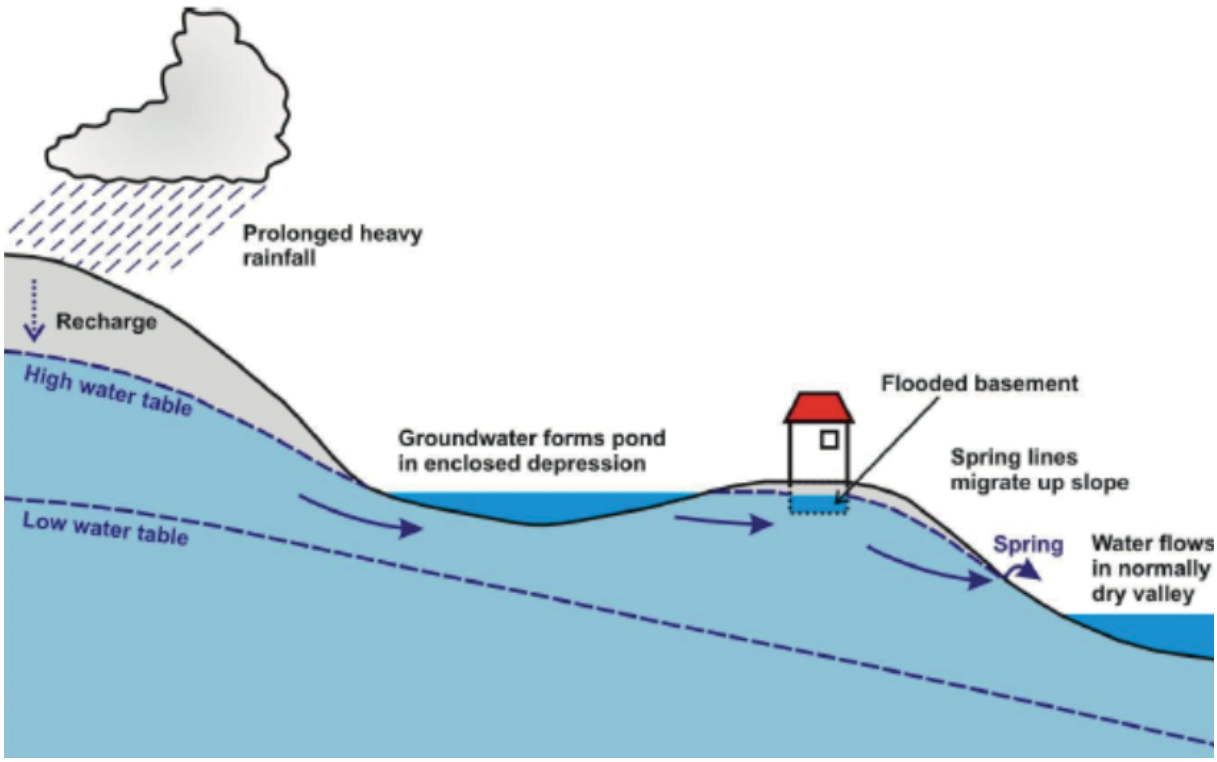

Figure 4-1. Groundwater Flooding (Source: JBA)

In terms of the source-pathway-receptor approach,[38] the following main processes can be identified (Table 28).

Table 28. Source-Pathway-Receptor for Groundwater Flooding

Source	Pathway	Receptor
Groundwater	Rising Groundwater level	Property
Precipitation	Flooding through alluvials	Population
		Environment
		Infrastructure

Groundwater flooding differs from other types of flooding in terms of the data requirements and the modelling process. There is little information regarding groundwater dynamics with research studies mainly focusing on the Alazani catchment in East Georgia.[39, 40] Based on consultations with local experts, there are two main areas at risk of groundwater flooding in Georgia; namely, areas with the presence of karst (located in the mid-western and mid-eastern part of Georgia, Figure 14 and Figure 42) and around Tbilisi, an area represented by tuffs, sandstones, conglomerates and breccias characterised by intensive jointing which promotes the free circulation of groundwater.

As will be detailed in the section below, karst aquifers are a special case within groundwater modelling and, therefore, special attention will be paid to them in light of the different approach required.

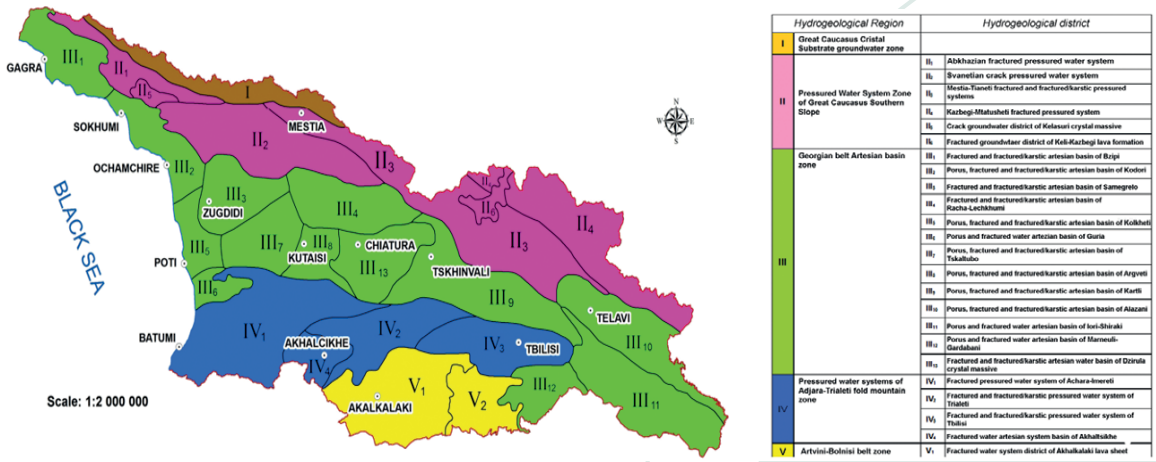

Figure 4-2. Hydrogeological Zoning Map of Georgia41

38. Sayers, Gouldy, Simm, Meadowcroft and Hall. (2003). DEFRA/Environment Agency R&D Technical Report FD2302/TR1.

39. S. Vepkhvadze, G. Melikadze, M. Todadze, P. Malík and A. Gventsadze. (2019). "Recharge and Dynamics of a Karst Groundwater System in Kakheti (Eastern Georgia)." *Austrian Journal of Earth Sciences.* Volume 112/1 42-49.

40. G. Melikadze, N. Zhukova, M. Todadze, S. Vepkhvadze, N. Kapanadze, A. Chankvetadze, T. Jimsheladze and T. Vitvar. (2014a). "Evaluation of Recharge Origin of Groundwater in the Alazani-Iori Basins Using Hydrochemical and Isotope Approaches." *Journal of the Georgian Geophysical Society, Physics of Solid Earth*, 17A, 53-64.

41. G. Gaprindashvili and M. Gaprindashvili. (2014). "Fresh Groundwater Resources in Georgia and Management Problems." *International Journal of Geosciences*, 5, 877-881.

3.1.1 Karst Dynamics

Karst terrains are uniquely susceptible to flooding from groundwater sources due to a combination of the low storage and high diffusivity characteristics of these aquifers.[42] Water levels within karst groundwater systems can rise dramatically during periods of intense or prolonged rainfall. As sub-surface storage and drainage reach their capacity, the rising water table can rise to the topographic surface and produce floods. From a flood modelling point of view, the main issue is that unlike linear flood features, such as river channels or coastlines, the manifestation of groundwater flooding from karst aquifers may be discontinuous and determined by the spatially variable hydrodynamic properties and responses within the karst system. The surface expression of groundwater flooding may only occur during extreme weather events and at relatively long recurrence intervals. Thus, the flood frequencies traditionally used in flood risk assessment (such as a 10% or a 1% annual exceedance probability) may be undefinable for groundwater and karst flooding.

These inherent difficulties are explicitly acknowledged within the European Union Floods Directive, whereby member states are permitted to limit groundwater flood hazard maps to extreme event scenarios only.

There are two fundamental approaches to the mathematical modelling of karst systems: distributive models and global models. Distributive models use theoretical concepts such as simplified aquifer geometry and hydrodynamic flow equations to simulate the hydraulic behaviour of karst aquifers. Global models concentrate on mathematically deriving a relationship between input and output where the input is usually a precipitation event and output is the spring discharge time series.

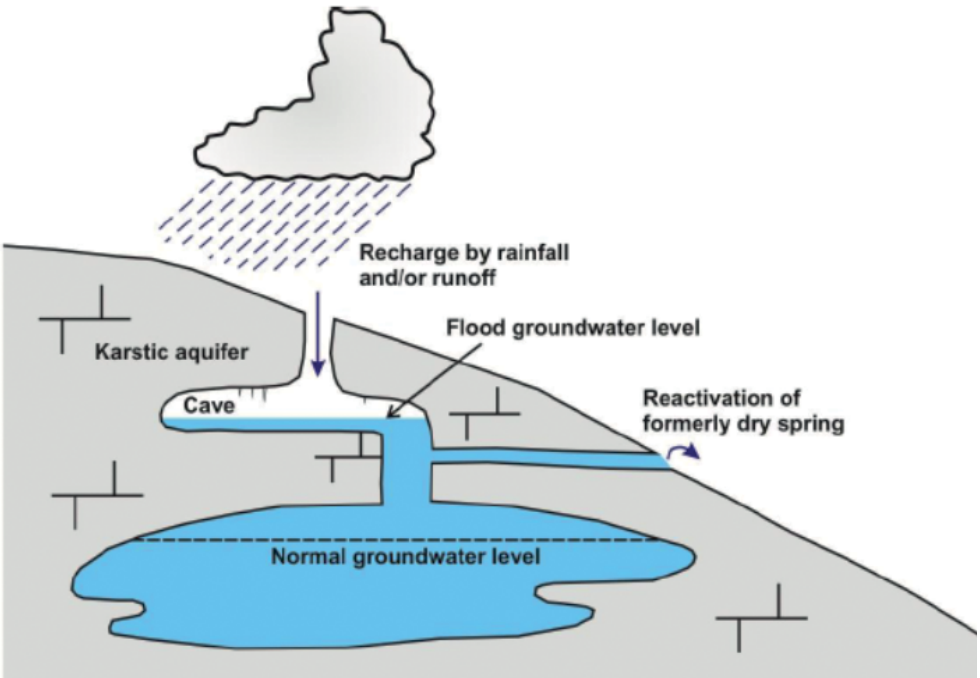

Figure 4-3. Karst Flooding (Source: JBA)

42. M. Parise, N. Ravbar, V. Živanović, A. Mikszewski, N. Kresic, J. Mádl-Sző Nyi, and N. Kukurić. (2015). "Hazards in Karst and Managing Water Resources Quality. Karst Aquifers – Characterization and Engineering." *Professional Practice in Earth Sciences*. Springer, Berlin, 601-687.

3.2 Groundwater Modelling

The main approach for the groundwater flooding methodology is outlined in Figure 44 with the approach depending on the data availability and the type of aquifer. While the approaches differ, the main methodological stages will be the same for any groundwater type. Furthermore, the main stages of the modelling implementation, calibration and validation will also be the same.

3.2.1 Modelling Scoping

As per any other source of flooding, the first stage in the modelling implementation process is the conceptualisation of the groundwater model. The conceptualisation should involve the development of maps that show the groundwater types and the location of aquifers and the hydraulic heads in each of these aquifers within the study area. These maps will help to illustrate the direction of the groundwater flow within the aquifers, and they may also infer the direction of vertical flow between aquifers. This will provide valuable information regarding the approach to follow.

The conceptual model will be based on a number of assumptions that must be verified in a later phase of the study. In early phases, however, information about the number of aquifers (or a combination of several ones) in the area of interest should be provided. If the groundwater basin consists of one single aquifer (or any lateral combination of aquifers) bounded below by an impermeable base, then the modeller can proceed to the development of the numerical model phase. Developing and testing the numerical model requires a set of quantitative hydrogeological data that fall into two categories:

- Data that define the physical framework of the groundwater basin.
- Data that describe its hydrological stress.

These two sets of data should be used to assess the groundwater balance of the basin. The following maps should be produced based on the required information for this:

- Contour maps of the aquifer's upper and lower boundaries.
- Maps of the aquifer's characteristics.
- Maps of the aquifer's net recharge.
- Water table contour maps.

Some of these maps cannot be prepared without first making a number of auxiliary maps. These maps will define the modelling strategy. Most of these maps will already be available in the Geological Department of the NEA. If no information is available for the preparation of these maps, the modelling should be stopped at this stage because it will not be possible to implement further stages of the modelling approach.

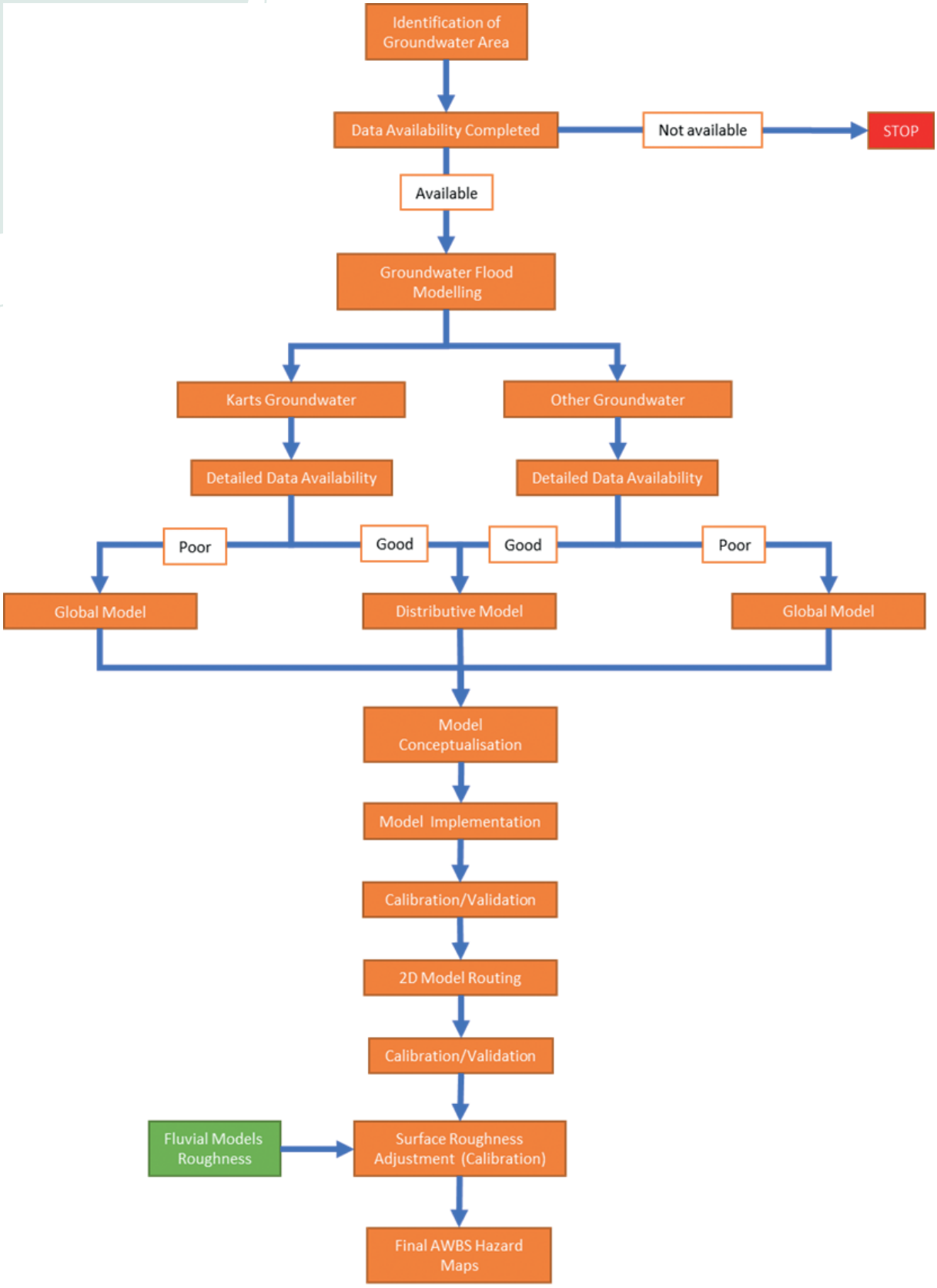

Figure 4-4. Groundwater Flood Modelling Methodology

3.2.2 Hydrological Modelling

The hydrological modelling of the groundwater will be undertaken depending on the type of aquifer, either karst or any other groundwater.

3.2.2.1 Karst

As previously noted, karst groundwater is considered of significant importance in Western Georgia and other basins. As noted, there are two different approaches for karst flood modelling: namely, global, or distributive models. Distributive models use theoretical concepts such as simplified aquifer geometry and hydrodynamic flow equations to simulate the hydraulic behaviour of karst aquifers. Global models concentrate on mathematically deriving a relationship between input and output where the input is usually a precipitation event, and the output is the spring discharge time series.

The modelling approach will be selected depending on the data available and the modelling resources. At this stage, the implementation of a global model is recommended, considering the modelling capabilities and the data availability.

There have been attempts to undertake modelling of karst aquifers in commonly used hydrological models such as HEC-HMS. However, none of these attempts show promising results as they rely only on collected data and artificially adjusted modelling parameters in order to match the recorded flows. This type of approach it is not advised. Other hydrological models may be more suitable for this.

Karst aquifers are known for their heterogeneity and irregular complex flow patterns which make them more difficult to model and demand specific modelling approaches. The groundwater flow pattern in karst aquifers is predetermined by an irregular distribution of channels and fissures. The spatial distribution of these conduits is difficult to predict due to the complexity of the processes that led to their development. Therefore, hydrological modelling in karst areas is both an issue and a challenge. The implementation of the global model will be used to simulate the available precipitation vis-à-vis karst terrains and the system's response. This global model can be the same as the one used for whole basins, although special care should be taken in karst areas in order to properly model the response of the terrain.

The global model (Figure 45) will be formed by three different reservoirs, one simulating the capacity of the soil (soil reservoir), the second one simulating the karst saturated zone (karst reservoir) and the third one in the form of the surface stream reservoir simulating the karst component discharge to the watercourse or inundation area.

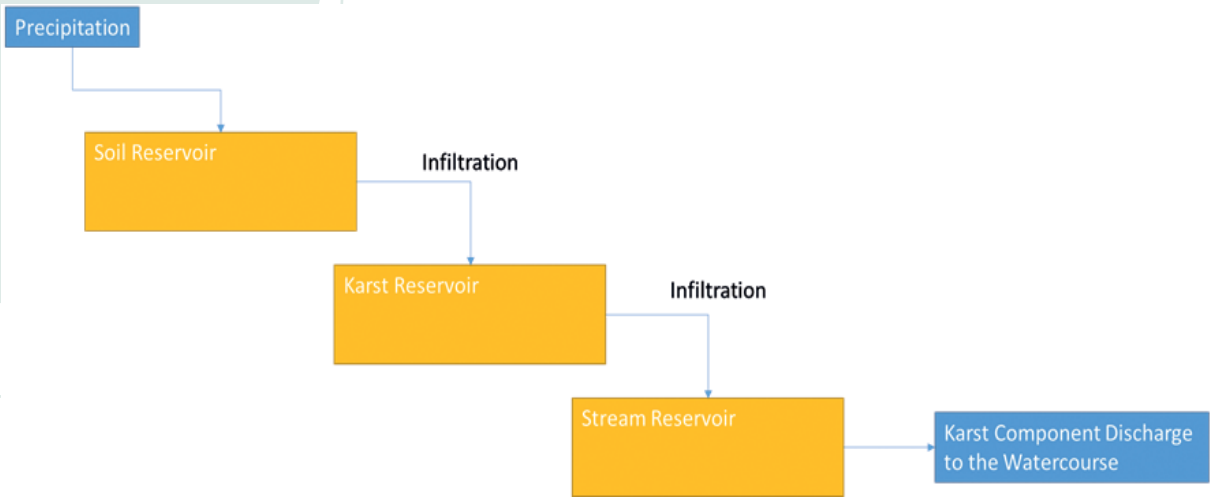

Figure 4-5. Karst Conceptual Model

A thorough hydrogeological assessment of karst terrain dynamics should be carried out in order to develop a global model. This should be undertaken with the use of groundwater monitoring, water level and discharge measurements and precipitation observations. The final outcome of this study and the global model is to be able to obtain reliable discharge predictions from the karst terrain yielded by a specific precipitation rate considering antecedent conditions.

3.2.2.2 Other Groundwater

Please refer to methodology for hydrological modelling

3.2.3 Hydrodynamic Modelling Implementation

The hydrodynamic implementation of groundwater models will follow a similar approach to the coastal, pluvial, and fluvial 2D inundation models. Groundwater will be considered, from a hydrodynamic point of view as input to the hydrodynamic models. The karst or other groundwater type hydrograph input will be used as the boundary conditions for the hydrodynamic models. The type of hydrodynamic models would depend on the area of interest and on the flood pattern. Nonetheless, the same models as the ones developed within the fluvial source modelling (1D-2D) will be used (if they cover the groundwater input area). If they do not cover the area of interest, dedicated models will be implemented in these areas.

For karst groundwater, it is expected that the input to watercourses will be in the form of springs in most cases and, therefore, a boundary condition on the channel will be defined and routed through the 1D domain. For other groundwater inputs, it is expected that this input would be in the form of either upstream boundary conditions or lateral (distributed) inflow to either the 1D or the 2D domain depending on the area of interest. In most cases, it is expected that the input would be in the form of a lateral distributed input to the 2D modelling domain which will be routed.

The modelling approach in terms of the modelling implementation, the modelling calibration, the boundary conditions, and the model sensitivity will be similar to the fluvial source modelling, and it will not be repeated in this section.

A joint probability assessment will have to be undertaken for fluvial, pluvial and groundwater flooding in order to ascertain the interdependency of these sources of flooding.

3.2.4 Hydrodynamic Model Calibration, Validation and Runs

Calibration and validation of the groundwater flood models will be required. At this stage, it is not expected that the required data for this will be available. The calibration of the groundwater flood model could be focused on either the hydrological or the hydrodynamic sides of flooding. If the latter is addressed, the main input for the calibration would be the spatial flood extents or historical records of groundwater flood extent from extreme events. It is not believed that this information is available at the moment. If that were not the case, however, and information were available, at least a ±30% accuracy in the flood extent is expected. The calibration will be undertaken considering the same procedures as per fluvial flooding, considering the hydrological inputs and the roughness as the main two parameters to adjust. The alteration of these values should be properly justified and included in the modelling report.

At this stage, it would be very important to establish the flood mechanisms involved in the events selected for calibration. While groundwater flood events are expected to have a more delayed response to precipitation than fluvial events, this would vary depending on the precedent conditions and the groundwater type of the area of interest. Therefore, while undertaking the calibration, it would be important to establish that the event is caused purely by groundwater sources. On the other hand, once a groundwater model is calibrated, a joint probability assessment should be completed, especially with fluvial sources in order to ascertain the interdependence of these two sources. Joint events may then be simulated and calibrated/validated. The design event analysis should follow a similar procedure.

3.2.5 Design Events

As noted above, the recurrence of groundwater flood events differs from those of other flood sources. The EUFD acknowledges the difficulty in deriving flood events for a range of probabilities for groundwater flooding and, as such, only requires the representation of rare extreme events. Depending on the modelling approach, it may be possible to derive extreme events if they are purely related to the probability of precipitation. This may not be entirely accurate, however, due to the delayed and different response depending on the groundwater type. Nonetheless, within the design event analysis, 1:100 and 1:1,000 events will be derived.

3.2.6 Groundwater Flood Hazard Mapping

Groundwater flood depth should be colour coded as follows.

Depth [m]	R	G	B	Colour
0.1 < 0.5	204	255	255	
0.5 < 1.0	153	255	255	
1.0 < 1.5	102	255	255	
1.5 < 2.0	51	255	255	
2.0 < 2.5	153	204	255	
2.5 < 3.0	102	178	255	
3.0 < 4.0	0	128	255	
> 4	63	0	125	

Flood depths of less than 0.1 metre should not be mapped.

3.3 Data Requirements and Availability Assessment for Groundwater Flood Modelling

The implementation of any groundwater model requires significant data input. This is especially the case for groundwater flood modelling projects where an understanding of groundwater and surface water interactions during extreme conditions is a prerequisite for the characterisation of a groundwater flood hazard. This will include information on surface and sub-surface geology, water tables, precipitation, evapotranspiration, pumped abstractions, stream flows, soils, land-use, vegetation, irrigation and aquifer characteristics and boundaries.

As per any other flood source modelling, the modelling implementation is highly dependent on the information available, and a groundwater model will not represent the existing conditions from a hydrological point of view if it is not based on a rational hydrogeological conception of the basin. The following data needs are considered:

- DEM: sufficiently detailed and accurate topographic data are required. The DEM should be of sufficient quality as to show all surface water bodies and divides. The expected LiDAR data in combination with existing DEM resources are considered adequate for these purposes.
- Information about the location of a surface drainage system, springs, wetlands, and swamps should also be available. There is some information about the existence of wetlands and swamps (Table 29) but no specific information about their location.

Table 29. List of Marshes and Wetlands in Georgia

Name	Location	Metres a.s.l.	Area, km²	Average depth, m
Pichori-Paliastomi	Pichori River floodplain	0.5-1.8	191	8
Chaladidi-Poti	Between the Rioni and Khobi Rivers	12.5	144	1.5
Eristskali II	Between the Okumi and Gagida Rivers	0.5-1.8	117	1
Churia	Between the Enguri and Khobi Rivers	3	90	0.8
Nakargali	At the confluence of the Enguri River	4	21	1.5
Ispani I and Ispani II	Chorokhi River and Ochkhamuri River basin	1.5	19	2
Eristskali I	Between the riverbank and the dunes	1.5	15	1
Natanebi-Supsa	Between the Natanebi and Supsa Rivers	0.5-1.5	15	7
Pichori-Kvishona	Between the Isareta and Gagida Rivers	4	13.2	2
Torsa	River floodplain	80.5	9	1

- Geologic data and cross-sections showing the areal and vertical extent and boundaries of the system.
- Aquifer data, including information about the aquifer thickness and lateral extent, aquifer boundaries, lithological variations within the aquifer and aquifer characteristics.
- Land-use or land-cover data.
- Contour maps showing the elevation of the base of the aquifers and confining beds.
- Maps showing the extent and thickness of stream and lake sediments.

All the data above are required for the definition of the geometry of the groundwater domain under investigation, including the thickness and areal extent of each unit. In addition to this, the following information is required:

- Water table and potentiometric data for all aquifers to be included in the modelling domain.
- Hydrographs of groundwater head and surface water levels and discharge rates.
- Data and cross-sections showing the hydraulic conductivity and/or transmissivity distribution.
- Data and cross-sections showing the storage properties of the aquifers and confining beds.
- Hydraulic conductivity values and their distribution for stream and lake sediments.
- Spatial and temporal distribution of the rates of evaporation, groundwater recharge, surface water, groundwater interaction, groundwater pumping and natural groundwater discharge.

As per any other flood source, the data collection and analysis stage of the modelling process involves the confirmation of the availability of the required data, the assessment of the spatial distribution, the richness and the validity of the data, the analysis of the data and the level of confidence in them. A detailed assessment could include a complex statistical analysis together with an analysis of errors that can be used in a later uncertainty analysis.

One of the key aspects in the implementation of any flood groundwater modelling project is to understand and assess the parameter distributions for modelling implementation. The results from this analysis should yield:

- Initial parameter value estimates for all hydrogeological units.
- Quantification of any flow processes or stresses (e.g., recharge, abstraction).

The latter of the abovementioned results is critical to understanding the flooding mechanism and the hydro-geological behaviour of any particular basin. A groundwater 'basin' does not necessarily correspond to a fluvial basin (from a geographical point of view) and, therefore, this should also be considered in the modelling implementation.

Some of the data outlined above might be used only during the modelling conceptualisation while some other data will also be used during the design and calibration of the model. This includes data about the model's layers and the hydraulic parameters as well as observations vis-à-vis the hydraulic head, the water table elevation, and fluxes.

An analysis has been undertaken regarding the availability of these data in Georgia. There are 56 groundwater monitoring stations in Georgia (Figure 46) with most of these stations having been recently deployed (from 2015) and with the main purpose of collecting data for water resources purposes.

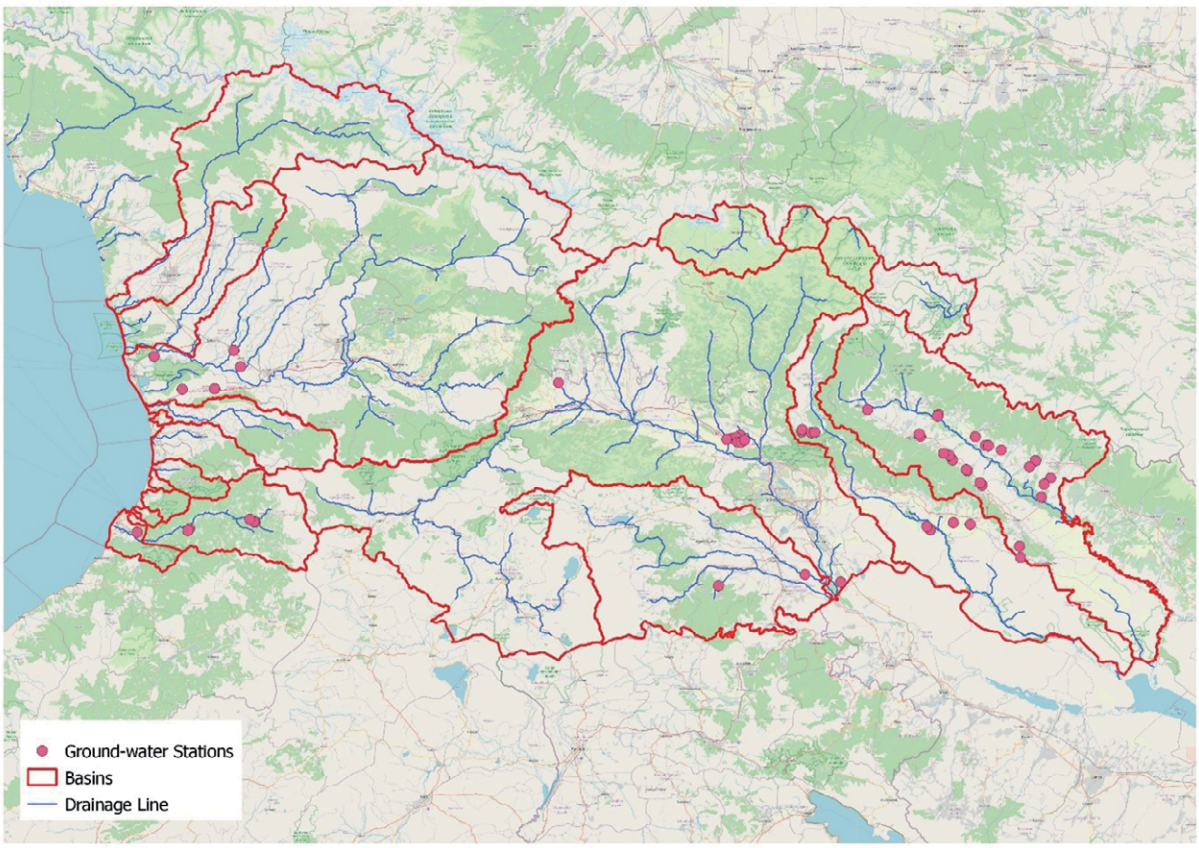

Figure 4-6. Ground-water Monitoring Network in Georgia

Monitoring devices have been deployed in both artesian (Figure 47) and sub-artesian wells (Figure 48), resulting in discharge and water data, respectively, on a daily basis.

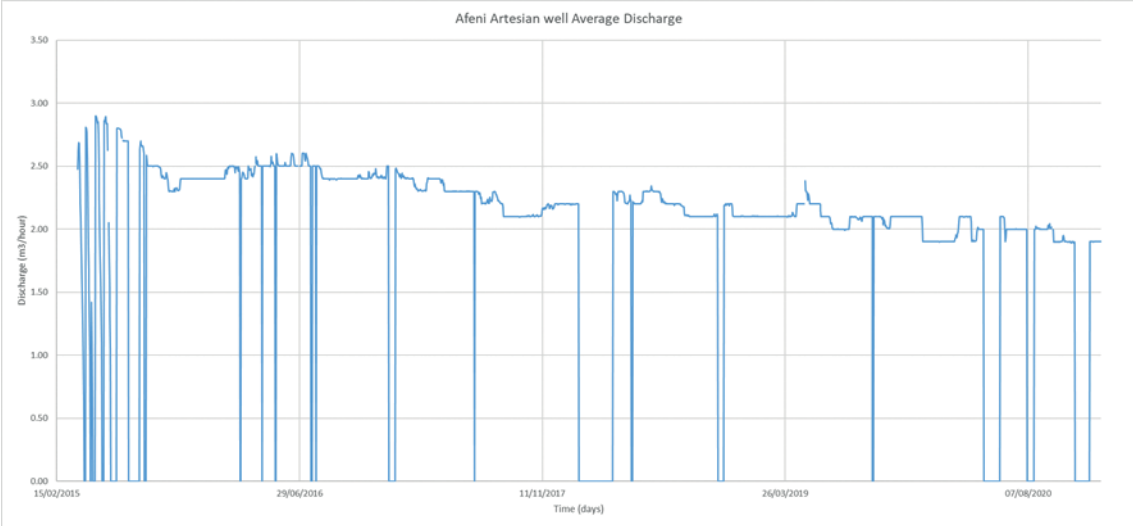

Figure 4-7. Afeni Well Average Discharge

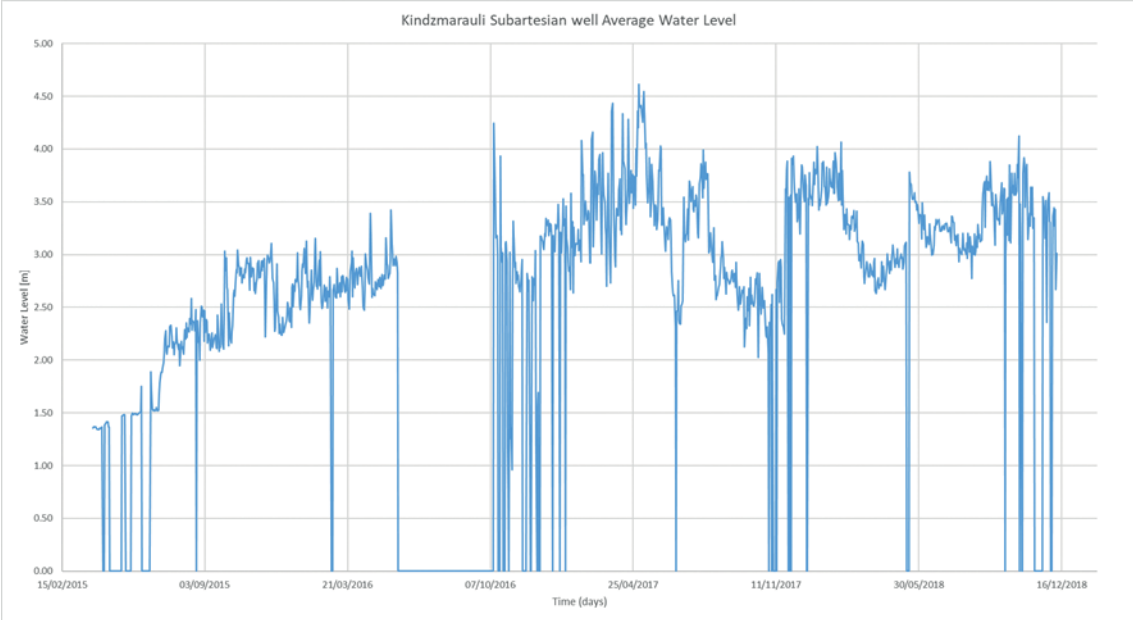

Figure 4-8. Kindzmarauli Well Average Water Level

There is no further information regarding groundwater data at this moment. Considering the data requirements and the data availability it is believed that the groundwater modelling cannot be undertaken with any degree of accuracy at this stage. The groundwater modelling capabilities of the national stakeholders are also limited in this respect. Nonetheless, a brief methodological approach for groundwater modelling will be considered in the sections below.

3.4 Data Quality Assessment for Groundwater Flooding

There is limited information about groundwater flooding data. The location of the groundwater monitoring network has been obtained along with two examples of the collected data. The main objective of this network targets water resources and, therefore, it is not believed that this can serve flood modelling purposes. There are no capacities regarding groundwater flood modelling in Georgia and it has not been the focus of monitoring network activities. While a methodology will be proposed for this modelling, only the implementation of global (conceptual) models may be possible considering the present constraints.

3.5 Methodologies and Procedures for Preparation, Data Analysis, and Incorporation into Hydraulic Models

The methodologies for data analysis and preparation do not differ from the already outlined ones for fluvial and pluvial modelling. Additionally, no data processing is required considering the lack of data at this stage.

3.6 Software

The modelling software for groundwater flood hazard mapping will depend on the modelling approach. From a hydraulic modelling point of view, using the same modelling software as was described in the previous section is recommended; that is, HEC-RAS and MIKE. However, this will only be the case for routing the outflow from the groundwater surcharge flow.

A different modelling package will be required if a more integrated modelling is needed where hydrological and hydraulic models are considered together. In this case, the use of MIKE SHE is recommended. This software simulates dynamic groundwater and surface water interaction and seamlessly integrates all of the other important hydrological processes at a catchment scale.

MIKE SHE modelling software covers the major processes in the hydrologic cycle. It includes process models for evapotranspiration, infiltration, overland flow, unsaturated flow, groundwater flow, channel flow and their interactions.

MIKE SHE can be linked to MIKE 11 (1D hydraulic model) and thus a fully dynamic linkage between the river model and the sub-surface components is available within MIKE SHE. The linkage between MIKE 11 and MIKE SHE, however, is not fully adjustable. The software links the two models depending on the location of the cross-sections.

MIKE SHE also has embedded an overland flow module using basic 2D equations. These are recommended for surface flows resulting from groundwater input, but it is not recommended for routing surface flood waves as this approach can lead to an under-estimation of flood levels.

In summary, if the hydrodynamic model is only going to be used for routing groundwater inputs, HEC-RAS 5.0.6 is recommended. If an integrated model is required, MIKE SHE is recommended, although this is commercial software.

04

Coastal Flood Hazard and Risk Modelling and Mapping

4.1 Coastal Flooding Processes

Coastal flooding flood hazard mapping will be developed considering data availability as well as the different coastal process involved in coastal flooding in Georgia. While coastal flooding is due to a combination of astronomical tides, surge and waves, the initial assessment and review of existing research studies indicates that waves play the major role in coastal flooding in Georgia as was noted in the preliminary flood risk assessment section. There are several issues to consider for the coastal flooding in addition to the information outlined in the preliminary flood risk assessment section:

- Local models need to be implemented for storm-surge and waves.
- The validity of astronomical tide predictions needs to be assessed. Astronomical tides are calculated in 18.6-year cycles obtained from local tide gauges.
- A full data availability assessment will need to be undertaken.

This abovementioned information is critical in order to understand both the possibility of undertaking coastal flooding modelling and also to better understand the main drivers for the coastal flooding. There is not very much information regarding the occurrence of coastal flood events in Georgia. There are reports of flooding in Batumi[43, 44, 45] but it is uncertain if these floods are only of a coastal nature or are more of a combination of pluvial and fluvial flooding. It is evident, however, that coastal erosion is a much bigger issue in Batumi due to the implementation of several projects on this problem and recent analyses of coastal degradation. This issue, however, can have implications from a flooding point of view because the natural defences to flooding may be disappearing in the coastal area of Georgia. This issue, however, is out of the scope of this methodology.

43. World Bank. (2020). *Impacts of Climate Change on Georgia's Coastal Zone: Vulnerability Assessment and Adaptation Options*.

44. https://vestnikkavkaza.net/articles/Batumi-flooded.html

45. https://agenda.ge/en/news/2019/2963

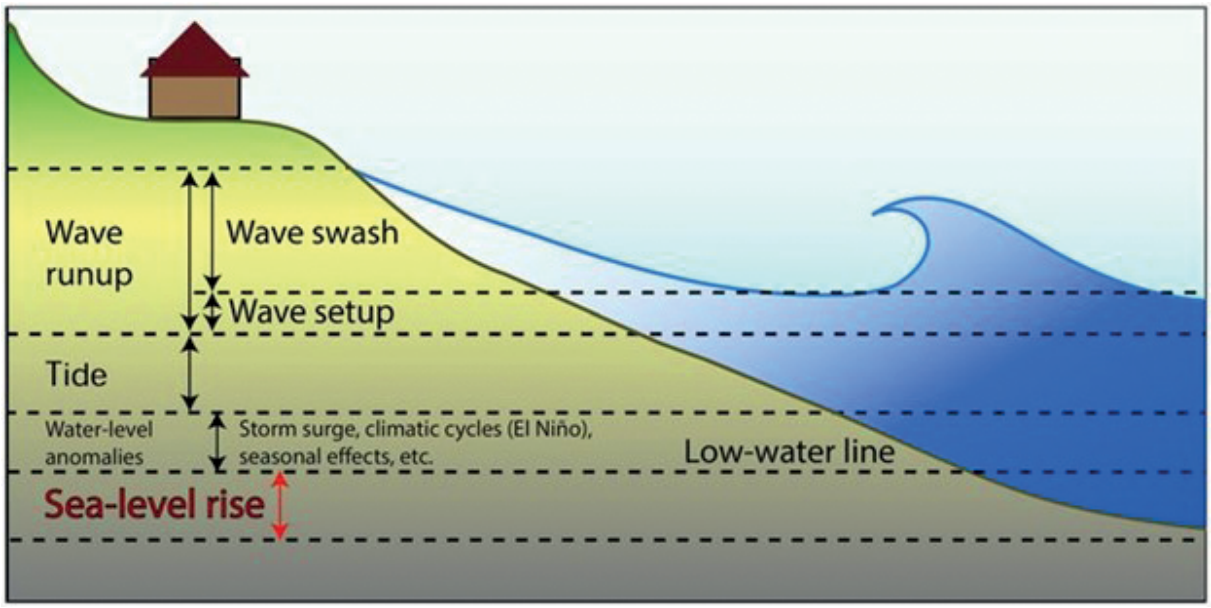

Figure 5-1. Coastal Flooding processes

The following main processes can be identified in terms of the source-pathway-receptor approach[46] (Table 30).

Table 30. Source-Pathway-Receptor for Coastal Flooding

Source	Pathway	Receptor
Tide Storm-surge Wave	Flood defence Breach of structures Failure of structures Overtopping Coastal erosion	Property Population Environment Infrastructure

4.2 Coastal Flooding Hydrodynamic Modelling Methodology

As detailed above, while the focus of this methodology will be costal flood (inundation) models, the coastal processes have to be properly understood, especially considering the influence and importance of each of the coastal flood components (tide, storm-surge, and waves), meaning that further modelling may be required to bring boundaries inland. In order to generate the required boundary conditions for coastal inundation models, in some cases it may be required to:

- Implement a hydrodynamic model to look at surge and tide change as they move up the continental shelf and estuaries.
- Implement a wave transformation model which looks at how waves change as they move inland.
- Implement a wave overtopping model to look at the rate of water overtopping flood defences.

46. Sayers, Gouldy, Simm, Meadowcroft and Hall. (2003). DEFRA/Environment Agency R&D Technical Report FD2302/TR1.

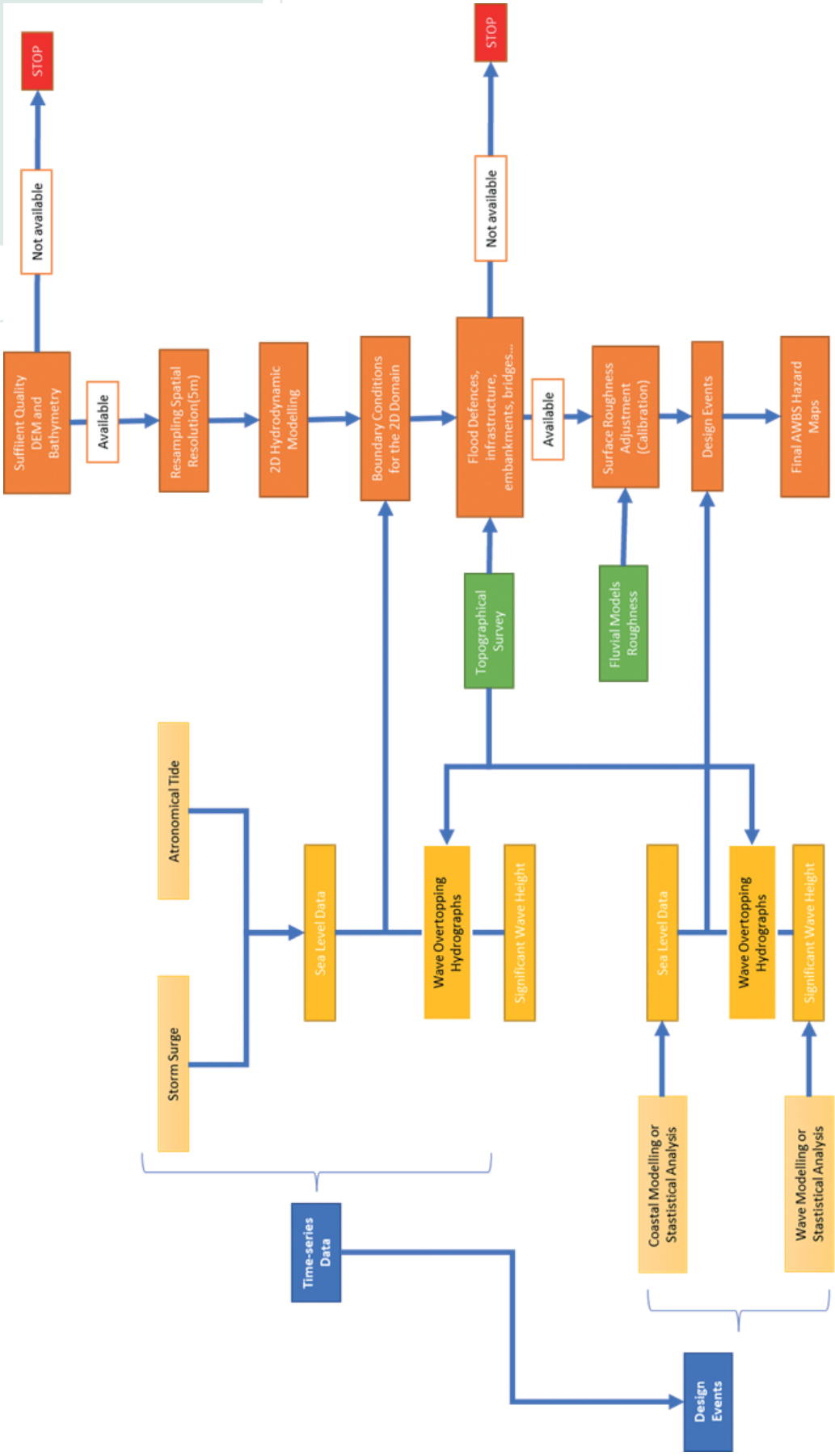

Figure 5-2. Coastal Flood Modelling Methodology

The abovementioned requirements are outlined under the assumption that there are available data sources, either for the derivation of return period values (both for sea-level and waves) or for the implementation of coastal hydrodynamic models and wave models. More data acquisition efforts have to be undertaken and a more thorough analysis of the different processes will have to be undertaken during the implementation of the coastal flooding methodology.

The methodology proposed below (Figure 52) Assumes that these data and modelling sources are either available or they can be produced within the framework of this project. The methodology for the implementation of local models will not be discussed in this section; instead, focus will be on the implementation of inundation models that will yield the coastal flood hazard mapping.

Nonetheless, there are two options for calculating inland flooding:

- Inland flooding due to still water levels may be modelled by applying a level boundary to an inland flood model.
- If a hydrodynamic model is implemented for modelling the sea-level, this may be extended inland.

Regarding wave input, the inundation caused by wave overtopping can be modelled by applying a flow boundary to an inland flood model (using either of the two options mentioned above).

The methodology below will describe the recommended stages in the implementation of the inundation model for coastal flood purposes, considering the input data requirements. The inundation modelling will be similar to the 2D model implementation for the fluvial and pluvial flooding.

4.2.1 Modelling Scoping

The modelling scoping of the coastal flood model should consider different issues, especially the data availability, the modelling availability, the modelling strategy, and the modelling approach. As noted, all of the information outlined above regarding coastal flood processes will be considered in the modelling scoping.

4.2.1.1 Data Availability

The modelling requirements were outlined in section 5.2 and in other deliverables by this consultant. The lack of some of the data (or the lack of quality) will prevent the implementation of coastal flood models. As described in the methodological approach above (Figure 52), it is not recommended that coastal models are implemented if there is a lack of DEM and bathymetrical data of sufficient quality and/or if there is no availability of coastal flood defences/beach data. The results of an implementation with inaccurate data (or no data) vis-à-vis these two factors will seriously compromise the quality of the results with no possibility of ensuring their validity. Therefore, significant efforts will be spent trying to collect these two data sources in this stage. Several coastal studies have been undertaken in Georgia with most of them from an erosion (coastal stability) point of view. In these studies, the project's main stakeholder is outside of the main stakeholder group and, therefore, it is recommended that the Georgian partner (NEA) establishes links with

the stakeholders participating in the studies in order to collect the necessary data. Once these data are available, a further data quality assessment will be completed to ascertain the possibility of model implementation.

4.2.1.2 Modelling Availability

Additionally, as was noted above and as will be noted below, there are several models available regarding both ocean circulation (and sea-level) and waves in the Black Sea. Some of these models cover the whole Black Sea and so their validity for coastal flood purposes can be questionable. It may be the case that some additional coastal models may have been implemented on the Georgia coast via some of the projects noted above. The collection of data from these models (or even the modelling implementations) will be assessed during this activity.

4.2.1.3 Modelling Strategy and Models

The modelling strategy will be defined by the data and modelling availability and in consideration of the information outlined above. The modelling strategy and the modelling software will be selected at this stage. There are several modelling strategies that can be pursued within the coastal flood modelling approach. Three approaches to inundation modelling of coastal hazards are widely used: namely, the rapid flood spreading method, the water level projection method and the 2D hydrodynamic approach.

4.2.1.3.1 Rapid Flood Spreading Model

The rapid flood spreading methodology addresses coastal flooding through the division of pre-identified potential areas at risk of flooding into a series of interconnected basins (or reservoirs) with spill crests identified between each basin. The main concept behind this methodology relies on the use of several interconnected basins where water fills one basin and then spills into the next basin until the coastal flood volume has been accounted for. In this methodology, the boundary conditions are split depending on the basins or the units with consistent overtopping conditions. A tide, a storm-surge and wave levels in metres over a tidal cycle or the duration of a storm-surge will be the base level for any wave overtopping volume in m^3/second per metre of length of the coastline. The input volume is a total m^3 per metre length of coastline for the flood event, the storm, or the tidal cycle. This method does not allow for any interactions with other flood sources such as fluvial or pluvial. However, the rapid spreading method can be modified to take the form of a 1D hydrodynamic model with weir equations applied to the overtopped shoreline. This alternative method requires a time series input of overtopping and tidal/surge/wave levels in m^3/second per metre of length of the coastline. Fluvial and pluvial sources can be integrated in this modified approach.

4.2.1.3.2 2D Hydrodynamic Model

The 2D hydrodynamic inundation model approach would be similar to the modelling process for the 2D component of a fluvial flood or for the pluvial methodology, although obviously different boundary conditions would be used. In this case, model boundary conditions would be obtained from the other set of assessments or models as described above and they would be a time series

input of tide and storm-surge levels in metres and m^3/second per metre of length of the coastline for wave overtopping. With this approach, pluvial and fluvial models and boundary conditions can be readily incorporated into the model where coincident flooding from different sources needs to be considered (after a careful assessment of the joint probability of these sources).

4.2.1.3.3 Water Level Projection Method

This is the most basic of the methods outlined. No formal modelling is undertaken in this case and this method relies on GIS resources. This method can only be used for storm-surge and tide events, and it implies the use of a constant water level against the existing DEM information. This assessment will assume that anything below the estimated sea-water level will be flooded. This method is not recommended in extensive coastal areas (such as in the Rioni basin) and it does not account for flood defence infrastructure.

The implementation of a 2D inundation hydrodynamic model will be proposed in the case of Georgia. Although this could be the most time-consuming methodology, it is considered that this is also the most accurate in terms of the inclusion of different flood mechanisms. While there are several 2D hydrodynamic models available, the use of a coastal model will be recommended. For instance, HEC-RAS has 2D modelling capabilities, but this software is not conceived for coastal applications. On the other hand, MIKE 21 (as part of MIKE FLOOD) was actually conceived as a coastal model (that is now being used in inland applications). A coastal model can consider marine processes such as viscosity, the Coriolis effect or the wind impact and it handles the bathymetry from a coastal point of view.

4.2.2 Hydrological Modelling

The hydrological modelling implementation provides boundary conditions for the implementation of the coastal hydrodynamic models.

4.2.3 Hydrodynamic Modelling Implementation

The hydrodynamic modelling implementation of the coastal flood models will be mainly based on the implementation of the several models previously described (Figure 53), namely:

- Storm-surge models.
- Wave models.
- 2D inundation model.

While the implementation of the first two models is recommended, this should not preclude the implementation of the 2D inundation model because other implementations or data may be available in order to provide the necessary information for the inundation model.

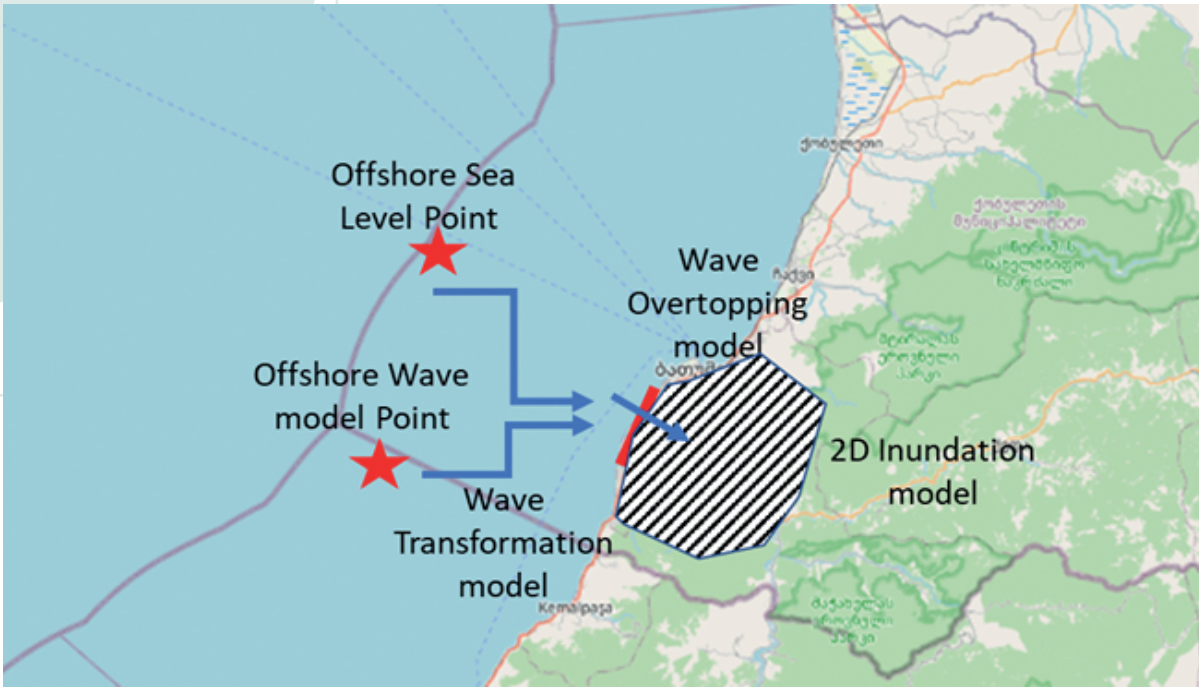

Figure 5-3. Modelling Implementation Approach

4.2.3.1 Modelling Domain

The modelling domain for coastal inundation modelling will be defined in this section. The modelling domain for coastal flooding would depend on the approach followed but also on the topography of the coastal area. An example for Batumi has been defined (Figure 54). It is very important that the modelling domain cover all of the areas that may be inundated (e.g., under 20 metres) using a conservative approach and also that a small section of the coastal area is covered. The longitudinal extension of the modelling domain would depend on the number of municipalities or coastal towns that can be targeted by a single model. It would be recommended to limit the number of modelling implementations (to cover as long of a costal stretch as possible with a single model).

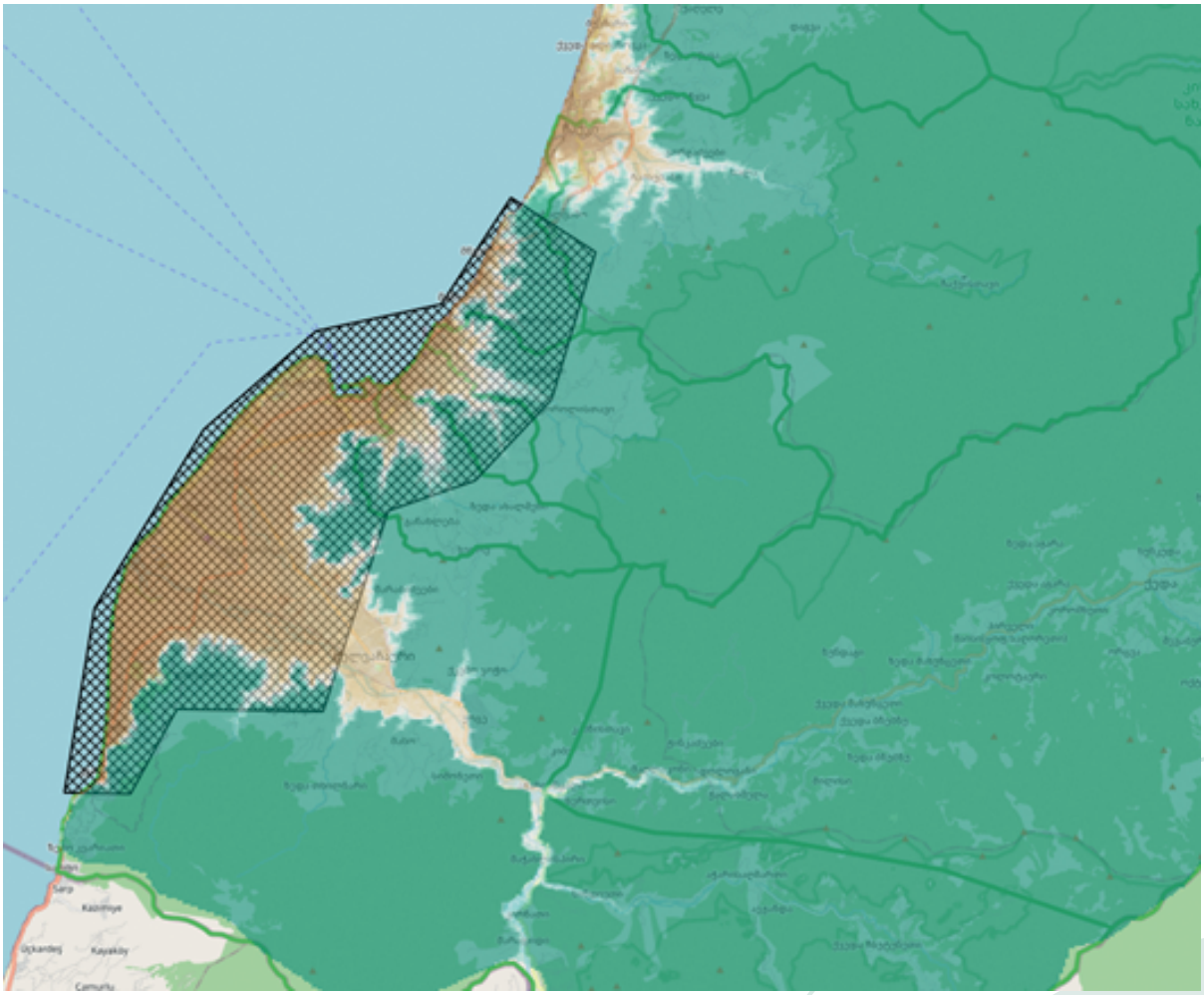

Figure 5-4. Example of 2D Inundation Domain for Batumi Coastal Area (brown and dark brown areas are under 20 metres while light brown and green areas are over 20 metres)

4.2.3.2 Coastal Model Implementation

The coastal modelling implementation will be started in this stage. The approach would be similar as per the 2D section in a fluvial implementation. A DEM and information from the bathymetry will be used to define the grid. While normal global DEMs have zero values as the lowest threshold for elevation values, it is recommended that the bathymetry is included to allow for a smooth transition from offshore to inland processes in this case. The use of bathymetrical sources, therefore, is required as noted above.

The definition of the grid will follow the same procedures as also outlined above. Adding break-lines or a finer resolution along the coastline is recommended.

4.2.3.3 Boundary Conditions

There several boundary conditions to be considered from a coastal flood modelling point of view.

4.2.3.3.1 Still Water Boundary Conditions

The development of still water boundary conditions needs to consider:

- Extreme water levels, surge, and tide shapes on the open coast.
- The change in extreme water levels and surge and tide shapes within estuaries.
- The effect of wind and wave set-up on still water levels.

The modelling scoping phase should have identified which of these factors are important. The change in in extreme water levels and surge due to estuaries is not considered to be a major factor in Georgia at this stage but this should be clarified. The resonance of the estuaries can amplify the tide and water levels significantly and, therefore, it is important to have certainty on this issue.

For locations on the open coast boundary conditions, modelling coastal implementations by other institutions can be considered. This is the case of the MyOcean (Copernicus) implementations. The consultant has extracted reanalysis results from the Copernicus (former MyOcean) Reanalysis Model in the Back Sea (BLKSEA_MULTIYEAR_PHY_007_004) vis-à-vis sea level. The Black Sea (BS) Physical Reanalysis system provides monthly and daily ocean fields for the Black Sea basin starting from 1992. These fields are temporal averages of 3D variables like temperature, salinity, zonal and meridional velocity components and 2D variables such as mixed layer depth, bottom temperature, and sea surface height. From these variables, sea surface height is the most significant for coastal inundation models. The hydrodynamic core is based on the NEMO general circulation ocean model which is implemented in the Black Sea domain with a horizontal resolution of 1/27° x 1/36° and 31 vertical levels. In Figure 55 below, the time-series for the sea-level from this model in Batumi can be observed. These data are in a daily format and are available until 2019.

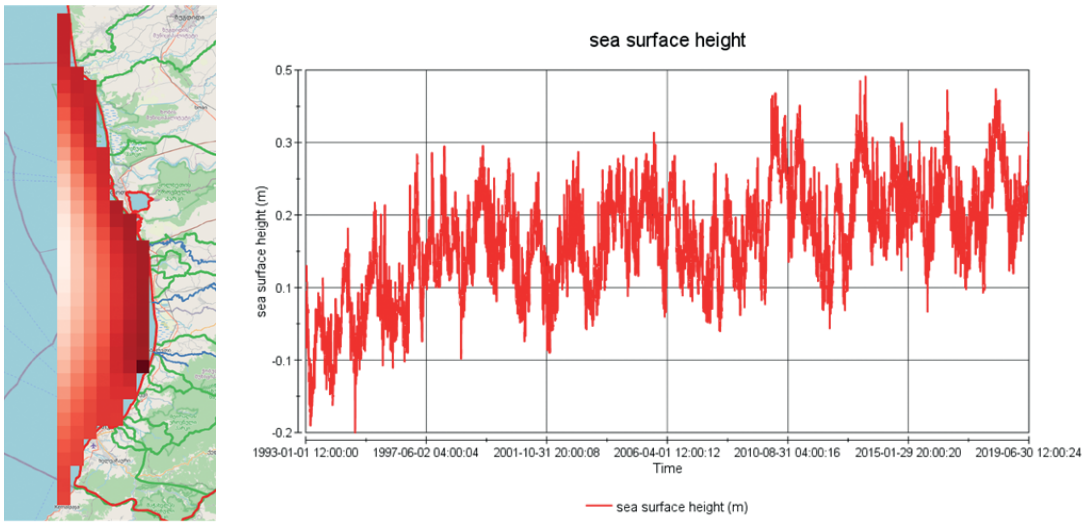

Figure 5-5. Reanalysis Daily Sea Surface Height in the Black Sea47

47. L. Lima, A. Aydogdu, R. Escudier, S. Masina, S.A. Ciliberti, D. Azevedo, E.L. Peneva, S. Causio, A. Cipollone, E. Clementi, S. Cretí, L. Stefanizzi, R. Lecci, F. Palermo, G. Coppini, N. Pinardi and A. Palazov. (2020). Black Sea Physical Reanalysis (CMEMS BS-Currents) (Version 1) [Data set]. Copernicus Monitoring Environment Marine Service (CMEMS). https://doi.org/10.25423/CMCC/BLKSEA_MULTIYEAR_PHY_007_004

These sea-level reanalysis data should be validated against local observed data (tide gauge) to assess their validity for implementations elsewhere on the Georgian coast. The sea-level will be one of the boundary conditions that will be used during the calibration and validation of events and, subsequently, for the design events (and flood hazard mapping). The fact that the sea-level reanalysis data may be of some concern means that more information needs to be gathered regarding sea-level dynamics in Georgia. The Black Sea shows a semi-diurnal tide pattern (6.21 hours between the low and high tides), and the storm-surge may have a smaller period in the Black Sea. The assessed tide gauge data in Georgia (Poti and Batumi) are also in a daily format.

The Copernicus Ocean circulation forecasting product in the Black Sea (BLKSEA_ANALYSIS_ FORECAST_ PHYS_007_001) it is available from 2019 on an hourly basis. The implementation is similar to the reanalysis model (NEMO), but the results are provided on an hourly basis (Figure 56). It is recommended that the hourly data are compared with the daily data and that an estimation of the relevance of hourly values is drawn.

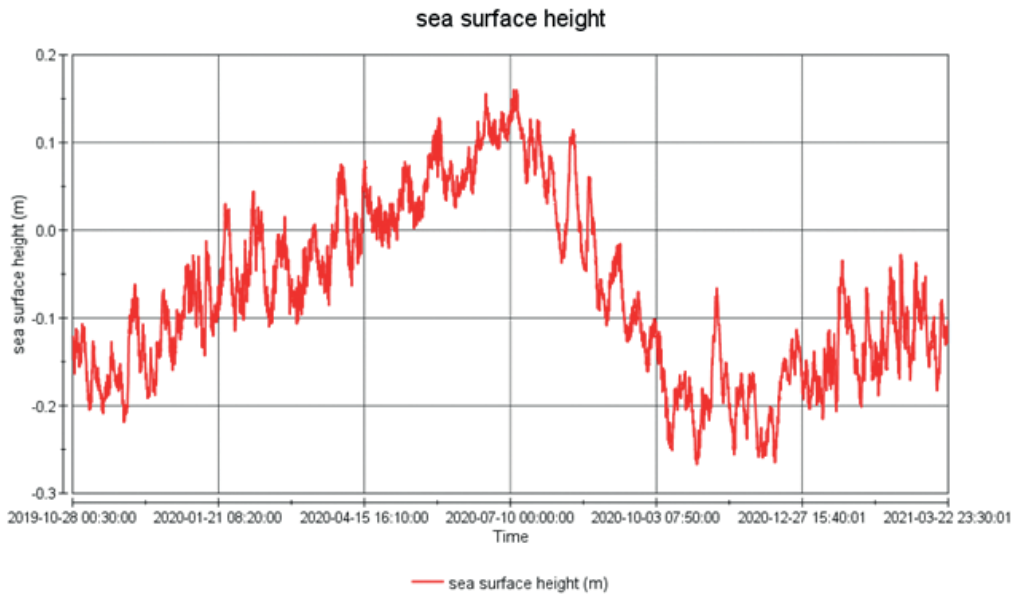

Figure 5-6. Black Sea Physics Analysis and Forecast (hourly)48

One of the main inputs of the sea-level assessment will be the derivation of return period sea-levels for the design events and the information from the hourly-daily assessments will be important in order to properly derive extreme sea-water levels.

48. S.A. Ciliberti, E.L. Peneva, E. Jansen, D. Martins, S. Cretí, L. Stefanizzi, R. Lecci, F. Palermo, F. Daryabor, L. Lima, G. Coppini, S. Masina, N. Pinardi and A. Palazov. (2020). Black Sea Analysis and Forecast (CMEMS BS-Currents, EAS3 system) (Version 1) [Data set]. Copernicus Monitoring Environment Marine Service (CMEMS). https://doi.org/10.25423/CMCC/BLKSEA_ANALYSIS_FORECAST_PHYS_007_001_EAS3

4.2.3.3.2 Waves

There are two different types of waves as noted above:

- Wind-waves (also referred to as sea waves). These are generated by the local wind, have a shorter period and are often irregular.
- Swell waves. These waves are generated by more distant weather systems, have a longer wave period and are more regular.

As discussed above, the wind-waves are more relevant to Georgia as there is no significant fetch area for swell waves in the Black Sea with the sea wave state being a combination of wind-waves and swell.

While there are records of a wave buoy deployed in Batumi until 1991, it is uncertain if these data will be available.

As per the sea-level, hindcast or reanalysis data are available from the Copernicus programme. The Copernicus product (BLKSEA_MULTIYEAR_WAV_007_006) is a third generation (WAM) hourly wave parameter model at around a 3 km grid resolution. The model takes into account depth refraction and wave breaking and significant wave heights and wind speeds are assimilated using Jason satellite data. The system is forced by wind fields obtained from the ERA5 reanalyses wind data. The reanalyses period starts in 1979 with one-hourly output until 2019. Figure 57 shows the extracted reanalysis data from Batumi. As can be observed and as outlined above, the predicted values for waves are more significant than the sea-level with values almost up to five metres and with several peaks over three metres. The validity of these results should be ascertained with observed data if possible.

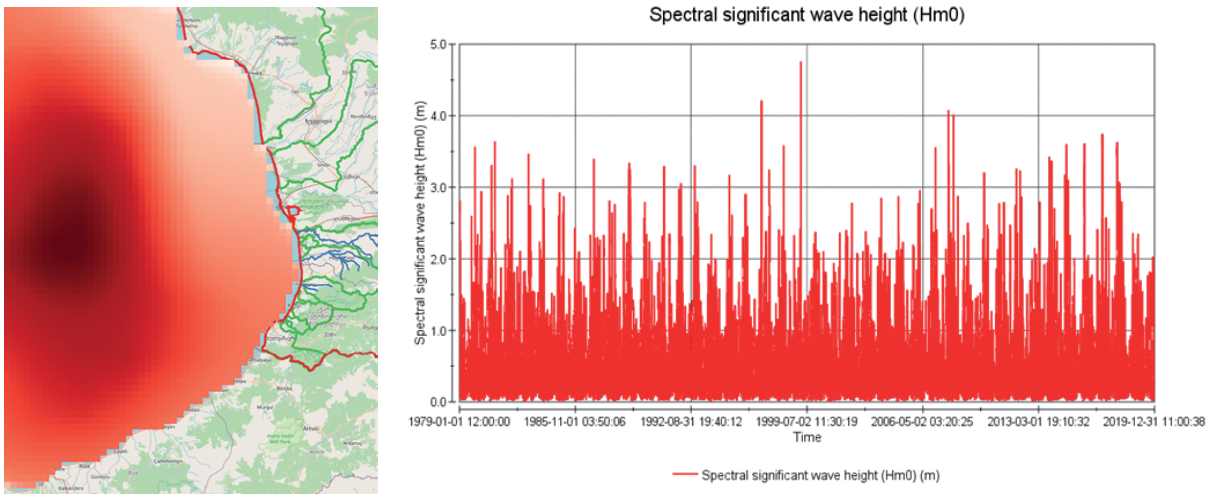

Figure 5-7. Significant Wave Height from the Copernicus Reanalysis Model49

The validity is important because the hindcast or reanalysis points from this model are located some

49. J. Staneva, A. Behrens, M. Ricker and G. Gayer. (2020). Black Sea Waves Reanalysis (CMEMS BS-Waves) (Version 2) [Data set]. Copernicus Monitoring Environment Marine Service (CMEMS). https://doi.org/10.25423/CMCC/BLKSEA_MULTIYEAR_WAV_007_006

distance offshore and, therefore, they need to be transformed inshore, usually through use of a numerical wave transformation model. The wave dynamics are fairly affected by the depth profile close to the coast. The sea-level will not be affected as much as the waves in this respect. While extreme still water levels and extreme wave conditions may occur independently, the worst-case situation for flooding is likely to be when large waves occur at high tide or during a high tide and surge; a joint probability analysis of extreme waves and extreme still water levels will be required. Wave conditions in open sea should not be input directly into a hydraulic model and run-up and overtopping models will be needed in order to determine the rate of flow over the defences (as will be described below, the CLASH or the EurOtop models) and the resulting outputs from these models can then be used as an input to the hydrodynamic model. Therefore, developing wave boundary conditions for input into a flood inundation model requires:

- Offshore design wave conditions.
- A joint probability analysis of still water levels and extreme wave conditions.
- Wave transformation modelling.
- Overtopping modelling.

4.2.3.3.2.1 Offshore Design Wave Conditions

The offshore design wave conditions will be derived from an extreme value analysis of the wave model reanalysis as previously described (from Copernicus). As with all models, wave reanalysis models and results are not perfect and may systematically over- or under-estimate the extreme wave conditions of interest for flood studies. The performance of any model used for boundary conditions should be assessed against observed data where possible (again noting the wave buoy deployed on the Batumi coast until 1991 in this case). Wave model reanalysis data will be used to generate annual maxima (AMAX) and peak over threshold (POT) series for design event analysis.

4.2.3.3.2.2 Joint Probability of Extreme Still Water Levels and Extreme Wave Conditions

A joint probability analysis of the extreme still water level and the wave height should be undertaken. Different approaches for joint probability analysis exist, although a desk study approach is recommended, comparing data and outputs from both parameters and the interdependence between the sea-level and the waves should be established. It is necessary to consider a number of different wave and sea-water level scenarios in order to obtain the worst=case flood extents, each with the same joint probability of occurrence.

4.2.3.3.2.3 Wave Transformation Modelling

As noted, reanalysis and hindcast wave model points are usually some distance offshore while flood modelling requires wave conditions on the coast. Wave conditions from the wave reanalysis points must, therefore, be transformed inshore in order to provide wave conditions on the coast. This should be undertaken using a numerical wave transformation model.

The implementation of these models would require some input data such as wave and water level boundary conditions and wind boundary conditions. These should be taken from the models outlined

above (for waves and water level) and from the ERA5 model (for wind). The ERA5 is the model source used for the implementation of all of the reanalysis models outlined above.

Development of a wave transformation model requires good quality bathymetric data. Implementing multiple wave transformation models may be required with a coarse resolution regional model covering a larger area in order to provide boundary conditions for higher resolution nested models of inshore areas. The suggested wave transformation modelling approach is shown in Figure 58 in terms of the domains to consider for the Georgian coast with a coarser model (getting the boundary conditions from the Copernicus model), one nested model for the whole Georgian coast and two small models for Poti and Batumi.

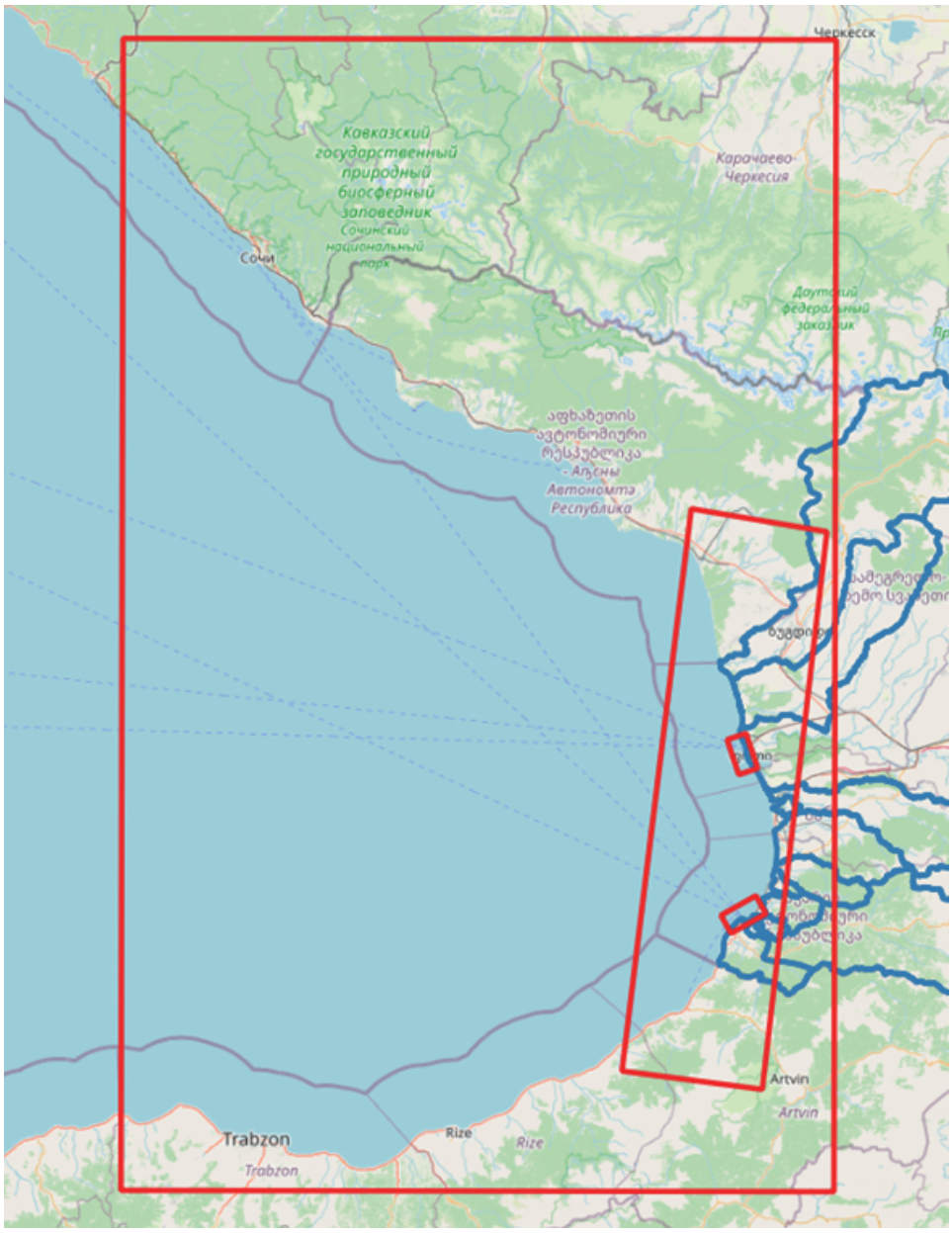

Figure 5-8. Suggested Wave Modelling Domain Strategy

The wave transformation model should be calibrated using observed data where possible and the set-up and calibration of any wave transformation model used should be described in the modelling report.

4.2.3.3.2.4 Wave Overtopping

Wave overtopping models are used to calculate an overtopping rate from:

- Inshore wave and still water level conditions.
- Detailed information on the flood defence or beach profile. Typically, the crest height, the toe level and the profile or the type of the defence is required.

There are several different overtopping models available, and the modelling report should justify the overtopping model used with reference to the available literature. The use of the EurOtop or the CLASH models are recommended at this stage. Both models have been developed through a European research project and while the CLASH model is based on lesser empirical input, it proposes a more direct implementation. Both models rely on the implementation of artificial neural networks for the calculation of the resulting overtopping discharge that will be used as input for the 2D inundation model.

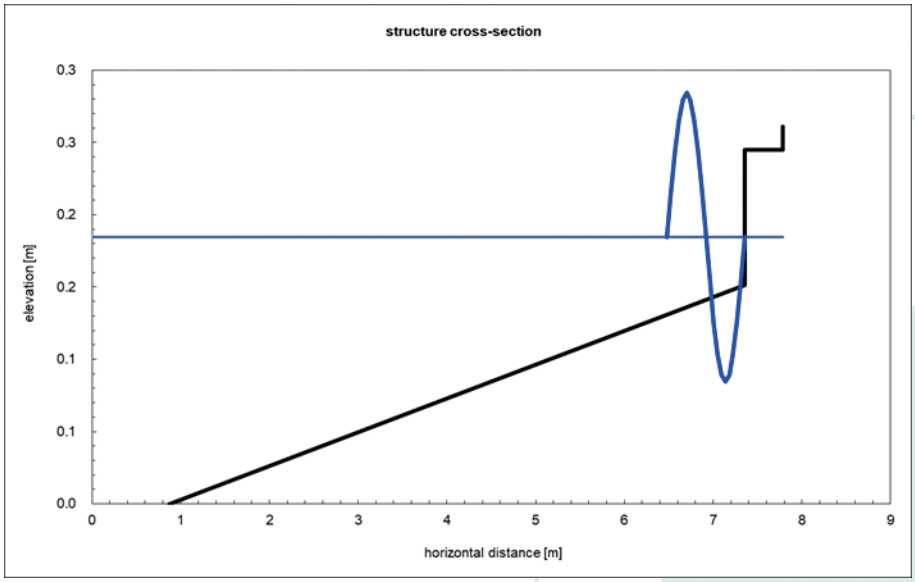

Figure 5-9. CLASH Wave Overtopping Model

The information required for the implementation of the CLASH model would be a cross-section of the coastal flood structure or a beach profile and the corresponding wave information (significant wave height and period). The model yields information about the wave overtopping discharge (Figure 59).

The EurOtop model can be also implemented through a web-application (as available through https://www.deltares.nl/en/software/overtopping-neural-network/, Figure 510) where the information required is similar to that of the CLASH model. It is recommended that both models are assessed properly and that a decision is made vis-à-vis the model after a sensitivity test of several parameters is undertaken.

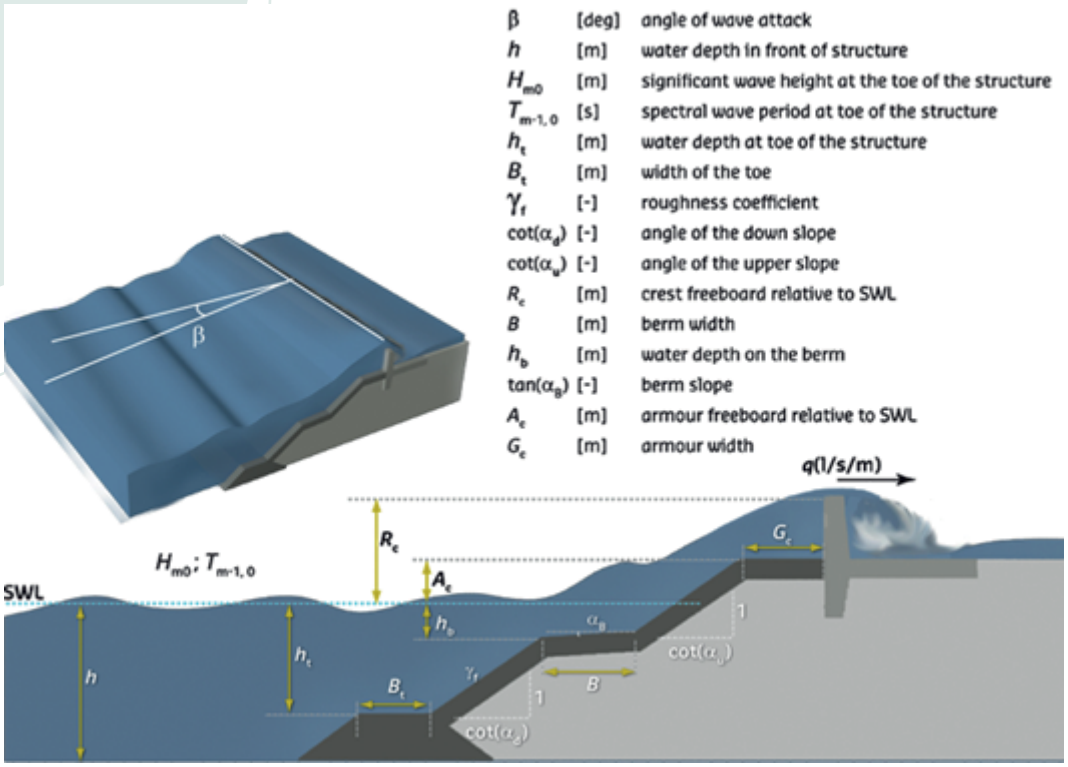

Figure 5-10. EurOtop Model Data Requirements

All of the boundary conditions defined above will be used for the implementation of the coastal inundation models. Thus, a water level boundary will be defined along the coast for still water flooding while flow due to wave overtopping will be added as a flow hydrograph.

4.2.3.4 Initial Runs

As per the fluvial and pluvial 2D hydrodynamic models, the next stage in the implementation would be to undertake several initial runs with the model in order to ascertain the stability and the initial results and outputs from the implementation. The procedure would be the same as per other flood sources, assessing the initial results and considering the boundary conditions inputs in detail.

4.2.4 Hydrodynamic Model Calibration and Validation

The 2D inundations models should be calibrated and validated following the procedures outlined below when possible.

4.2.4.1 Calibration Strategy

Hydrodynamic models used to bring extreme still water estimates inland and wave overtopping hydrographs should be calibrated for the level at tide gauges. Performance should be checked against tide tables over a spring neap cycle (28 days in semi-diurnal locations such as in Georgia) where tide gauges are not available. The hydraulic parameters which are usually varied during model calibration are the bed roughness and eddy viscosity. Changes may also be made to model boundaries and bathymetry if necessary (and properly justified in the modelling report).

Wave transformation models should be calibrated for significant wave height at wave buoys. Calibration should be over a sufficient period to cover all wave direction sectors. The hydraulic parameter which are usually varied during model calibration is the bed roughness, although boundary conditions may also be adjusted.

It is unlikely that sufficient data will be available for the calibration of wave overtopping and coastal inundation models, but this will be addressed and as much information as possible will be collected.

The proposed calibration strategy will consider the following tolerances:

- Levels are within ±0.3 metre at the coastal open areas.
- Timings of high water are within ±30 minutes.
- Accuracy of flooded area within ±30%.

The validation and the calibration of models will only be possible if sufficient hydrographic sea level and wave action data are available as well as event reports to describe depths and extent of flooding. In general, the models will be calibrated through adjustments to the 2D domain extent, the inundation model roughness and viscosity, and the results from the overtopping model. Any changes in the roughness and viscosity should be justified in order to avoid force-fitting and the information used should be plausible and tested across a range of events.

4.2.4.2 Sensitivity Tests

The sensitivity testing stage will play a major role in the coastal flood modelling methodology, especially considering the expected lack of suitable data for the calibration of the overtopping or the inundation models. As per the other flood sources, sensitivity tests should be used to determine confidence in the model which should be communicated in the modelling report. In addition to the 2D hydrodynamic model sensitivity tests outlined above (roughness and boundary condition data), a thorough sensitivity test should be undertaken for the wave overtopping models. This is expected to provide the most significant input into the models because the lack of information may be an issue. Therefore, the beach/defence profile and overtopping model parameters should be varied and assessed in detail through this testing. Due to the large variety of data for the beach/defence profiles and the overtopping model parameters, it is not possible to provide indications regarding the number and values for the testing. Nonetheless, sensitivity tests with a ±20% variation are recommended for the wave height and period vis-à-vis the information from the wave input. Further sensitivity tests should be undertaken with the still water level (±20% variation).

4.2.5 Design Events

Models must be run for the 1:20, 1:100 and 1:1,000-year events. The derivation of the different design event boundary conditions (for waves and sea-level) was outlined above. A joint probability assessment will need to be undertaken at this stage for sea-level and waves in order to determine the return period and the probabilities for each of the boundary conditions. This may mean that a range of combinations of extreme water level and waves need to be run for each flood probability.

4.2.5.1 Climate Change Projections

Climate change scenarios should be incorporated as additional model runs which take into account the latest available climate change projections for sea level rise for Georgia.

4.2.6 Coastal Flood Hazard Mapping

Coastal flood depth should be colour coded as follows.

Depth [m]	R	G	B	Colour
0.1 < 0.5	204	255	255	
0.5 < 1.0	153	255	255	
1.0 < 1.5	102	255	255	
1.5 < 2.0	51	255	255	
2.0 < 2.5	153	204	255	
2.5 < 3.0	102	178	255	
3.0 < 4.0	0	128	255	
> 4	63	0	125	

Flood depths of less than 0.1 metre should not be mapped.

4.3 Data Requirements for Coastal Flood Modelling

There are several data requirements for coastal flood modelling purposes:

- Topographical-bathymetrical information: the bathymetrical and topographical information determines the approach to follow for coastal flood modelling. The availability of the elevation data of coastal and floodplain features and structures which can influence coastal processes and overland flow-paths and ponding is critical for this assessment. If these data are not available or are not of sufficient quality, it is not recommended to undertake a coastal flood assessment. If these data are available, a 2D hydrodynamic model approach is recommended. There are several sources of information for bathymetrical data that should be considered:
    - GEBCO: the General Bathymetric Chart of the Oceans (GEBCO) consists of an international group of experts in ocean mapping with the aim to provide the most authoritative publicly available bathymetry of the world's oceans. The GEBCO bathymetry for the Georgian Black Sea coast was collected (Figure 511). The information is available in a 1/8 arc minute resolution (around 350 m x 490 m) grid format from the GEBCO database. A quick assessment of the data has outlined that the values are scarce but constant in the coastal area.

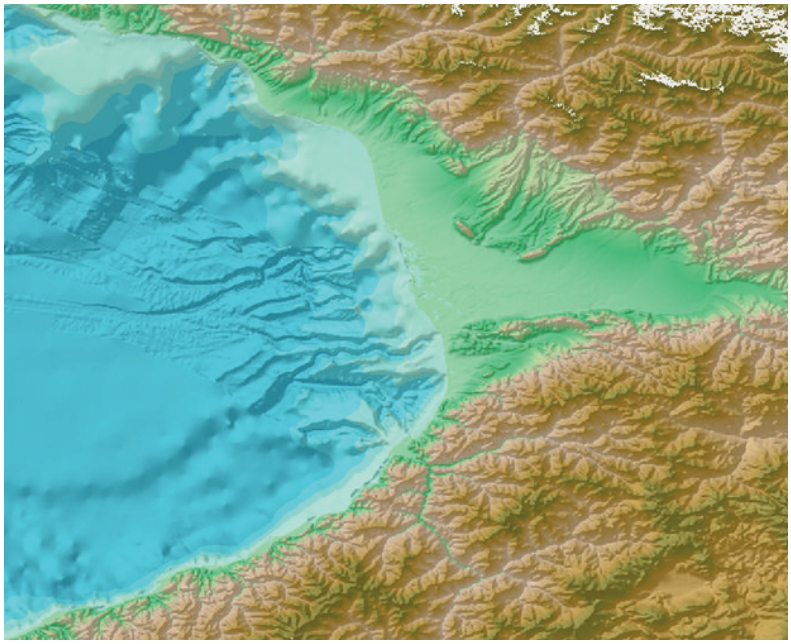

Figure 5-11. GEBCO Bathymetrical Information in Georgia

- The European Marine Observation and Data Network EMODnet was also explored. While providing a finer resolution (1/4 of an arc minute, around a 90 m x 190 m grid), the information provided by the EMODnet does not give further information for the coastal area (Figure 512).

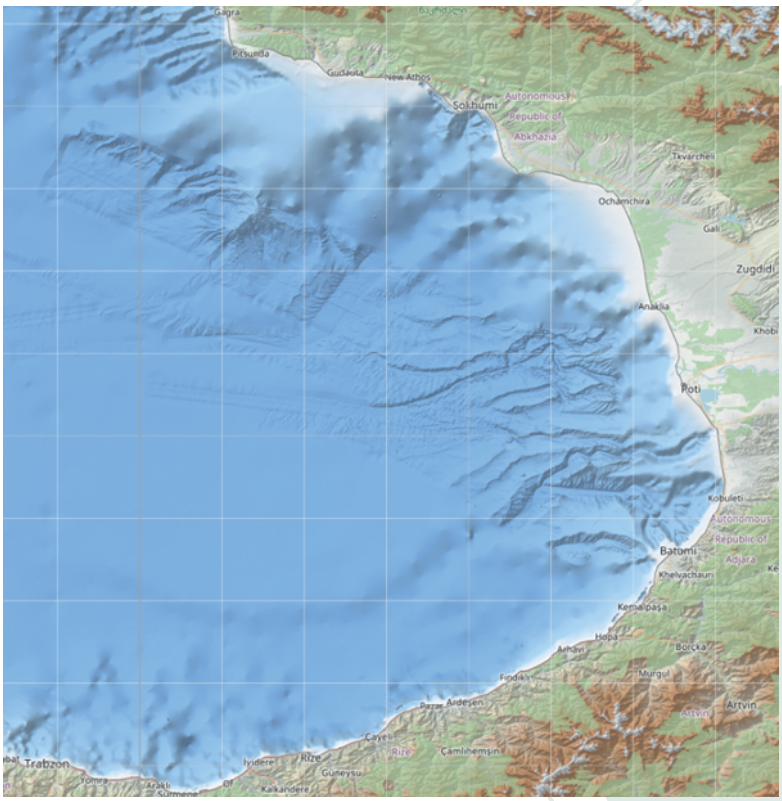

Figure 5-12. EMODnet Bathymetrical Information in Georgia

- Information from nautical charts: bathymetrical information from nautical charts (Figure 513) can also help to complement other sources of information, especially if this information is in a digital format. Nautical charts, however, are commercial and in order to assess their validity they will need to be acquired.

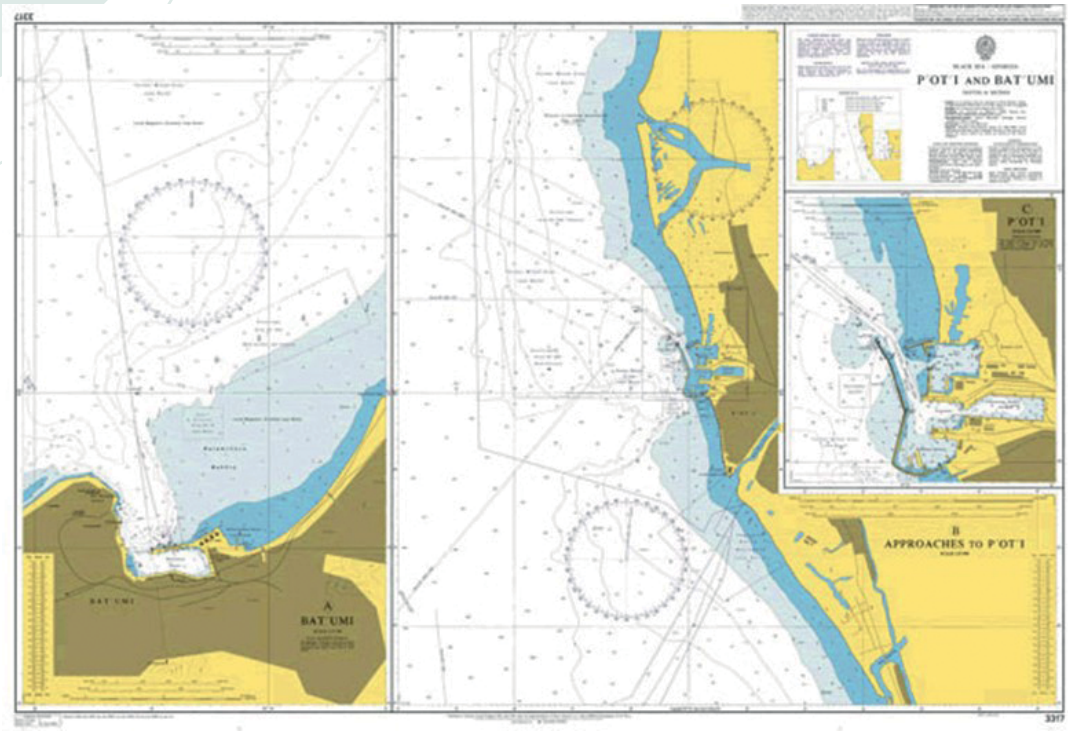

Figure 5-13. Nautical Chart of the Georgian Coast

This preliminary assessment indicates that while there are some bathymetrical data available, these may not be of the necessary accuracy for coastal flood modelling nor accurate enough for wave and storm-surge modelling. Bathymetry has a major influence on the results from wave and storm-surge modelling.

- Coastal data: information about waves and the sea-level will be critical for the implementation of any coastal model (waves, storm-surge, or coastal flooding) as it will determine the possibility of calibrating such models. There are two tide gauges on the coast of Georgia (in Poti [Figure 514] and in Batumi) and there is information about a wave gauge being deployed in Batumi until 1991.[50]

50. S. Khorava and A. Kikava. (2015). "Protection of the Ajara Coast Zone by an Artificial Beach." Proceedings of International Conference, Applied Ecology: Problems, Innovations. Ltd Kalmosani Publishers, Georgia, 192-197.

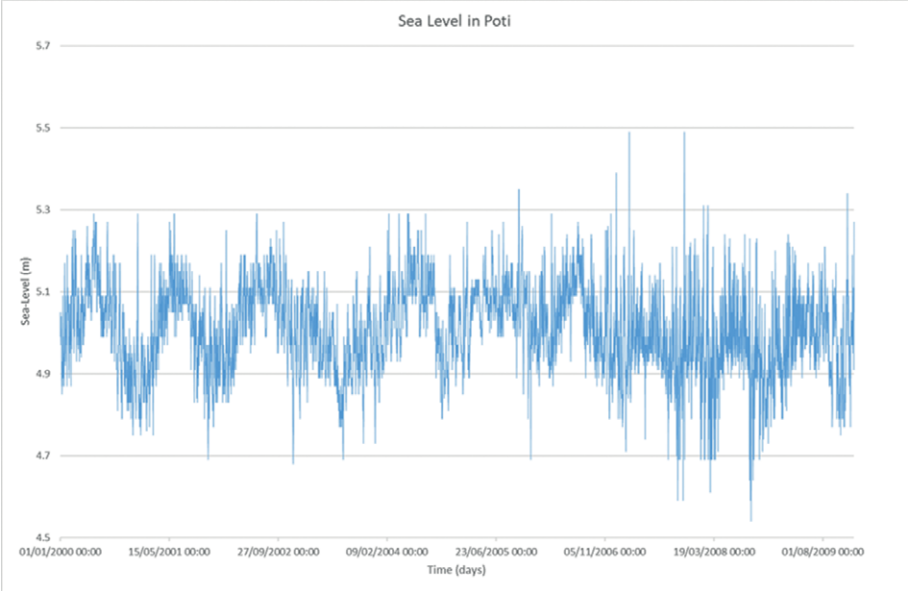

Figure 5-14. Sea-level in Poti

- Flood and coastal defences: these refer to the location and details of flood barriers, seawalls and levees located on the coast. It is expected that several coastal defences will be present on the Georgian coast such as groynes and breakwaters for erosion/sedimentation purposes. Although these structures will benefit the coastal flood magnitude in the long term, they are not relevant from a coastal modelling point of view.

4.4 Data Quality Assessment for Coastal Flooding

There are several data requirements for coastal flood modelling purposes:

- Topographical-bathymetrical information: the preliminary assessment of the bathymetrical data for coastal purposes indicates that while there is some information available, this may not be of the necessary accuracy for coastal flood modelling nor accurate enough for wave and storm-surge modelling. Bathymetry has a major influence on the results from wave and storm-surge modelling. It is not envisaged that a bathymetrical survey will be undertaken within the framework of this project. This will limit the implementation of coastal models, although the use and accuracy of the existing resources should be assessed in more detail if more data become available in a local scale.
- Coastal data: there are tide gauges in Poti, and Batumi and it is not expected that the sea-level is going to vary significantly between these two locations. While the Poti data are available to the consultant, this information is not available for Batumi. A comparison between these two data sources should be undertaken in order to assess the validity of these data for the full Georgian coast.

  As will be noted in the methodology, the wave data may be of more importance due to the higher expected impact of waves overtopping on coastal flooding. As noted, there seems to be

historical data from a wave buoy but the data from it are only available until 1991 (and it is not available to the consultant). More efforts will be paid to the collection of further coastal data but there are significant limitations at this stage regarding the sea-level and the wave data. If no more data become available, the implementation of coastal flood models would be questionable. In this regard, there is information from other sources regarding the different return periods for the sea-level in Georgia. This comes from coastal studies implemented in either Poti or Batumi. While this information has been collected by the consultant, these data cannot be reproduced in this report without further authorisations. The process for the derivation of these return period values is also unknown to the consultant.

- Flood and coastal defences: there are no information about coastal flood defences available. This is a major issue and while more efforts will be paid to the collection of these data, the acquisition of this information is not expected, and this could have a significant influence on the results. In order to overcome this potential problem, the commission of a survey to collect these data would be recommended if a list of flood coastal defences becomes available.

4.5 Methodologies and Procedures for Preparation, Data Analysis, and Incorporation into Hydraulic Models

There are some peculiarities vis-à-vis data processing for coastal flood hazard purposes. This relates mainly to the information required for boundary conditions, especially if these are collected from Copernicus Marine sources. The data management for the DEM, land-cover, remote sensing, and hydrological data, should follow the same procedures as the one outlined above in the fluvial section.

4.5.1 Boundary Conditions

As noted, it is recommended that wave and sea-level data are collected from Copernicus Marine sources. There are several points to consider for the collection and processing of these data.

- The user should be registered in the Copernicus service in order to be able to collect these data.
- These data are in netCDF 4.0 format. All of the time-steps are included within a single file and, therefore, it is not possible to process these files with common GIS software. It is recommended that data are extracted using either Panoply software or through the nco routines (only available in Linux based systems).
- It is recommended that an analysis is undertaken regarding the variation of both sea-level and wave data along the whole Georgian coast. It is not expected that extreme values for the sea-level are going to vary much along the Georgian coast due to the lack of bays and inlets, but this should be fully assessed. However, it is expected that wave data will vary significantly along the coast and, therefore, data should be extracted for the points closer to each of the locations to be assessed.
- The data extracted from both sea-level and wave modelling results should be fully processed and made available for further modelling. In both cases, extreme values should be calculated for the

design modelling.

- For the sea-level data, these can be directly used as the downstream boundary condition for the local coastal inundation models following the procedures outlined above.
- The wave data should be used for the wave-overtopping assessment as described in previous sections. The results from this exercise will produce a hydrograph that will be used directly in the flood inundation models.

4.6 Software

A 2D hydrodynamic model is recommended in consideration of the fact that the hydraulic modelling will be used for routing the inflows from the wave overtopping scenarios, using as a boundary condition the extreme sea-levels. In this respect, all of the models outlined in the fluvial software assessment would be suitable for these implementations.

Considering that HEC-RAS and MIKE FLOOD have been the software recommended for modelling previous flood sources, the use of these two software packages is also recommended in this case.

Even if HEC-RAS is more flexible than MIKE in terms of the definition of the modelling domain and the DEM input, it should be considered that MIKE 21 (the 2D module within MIKE FLOOD) is a coastal software and, therefore, it has embedded capabilities for marine processes such as viscosity, the wind influence, and the Coriolis effect. While these factors are not supposed to have a significant influence in the flood hazard results, it is recommended that MIKE 21 is used for coastal flooding.

05

Artificial Water-bearing Infrastructure Flooding Hazard and Risk Modelling and Mapping

5.1 AWBS Flooding

As was detailed in the PFRA section, the analysis of flooding from artificial water-bearing structure (AWBS) will focus on flood defence infrastructure (such as levees, river training walls, seawalls) and on dams.

A dam or a flood defence infrastructure breach flood is an abrupt short-term flood. These events have an associated low probability, but they are high risk events that can create an abrupt short-term and very destructive flood event with significant economic and social impacts on both neighbouring and downstream areas. An AWBS event is described as the opening formed in the structure body that leads to failure, making the stored water flow uncontrollably towards downstream regions.

There have been about 200 dam failures worldwide in the 20th century and with significant consequences.[51] These failures have caused multiple disasters in downstream valleys in terms of both loss of life and widespread damage to infrastructure and public and private property. According to International Commission on Large Dams (ICOLD) data[52] covering the period from 1900 to 1975 on dams higher than 15 metres, the cause of dam failures depends on natural hazards, human activities, the dam type (whether embankment or concrete) and the age of the dam. For concrete dams, the main cause is foundation failure. For embankment dams, leaks are the biggest cause of failure and the consequent overflow of water over the crest. Other possible causes of failure are earthquakes, landslides, extreme weather conditions (such as intense precipitation storms), overtopping, piping, foundation/structural faults, failures, or damage and sabotage.

51. F. Luino, G. Tosatti, V. Bonaria. (2014). "Dam Failures in the 20th Century: Nearly 1,000 Avoidable Victims in Italy Alone." *Journal of Environmental Science Eng.* 3, 19-31.

52. International Commission on Large Dams (ICOLD) (1978). Lessons from Dam Incidents; ICOLD: Paris, France.

In terms of the source-pathway-receptor approach,[53] the following main processes can be identified (Table 31)

Table 31. Source-Pathway-Receptor for ABWS Flooding

Source	Pathway	Receptor
Precipitation	Breach of structures	Property
Landslides	Failure of structures	Population
Earthquake	Overtopping	Environment
		Infrastructure

5.1.1 Dam Terminology

Dam terminology and basic concepts will be outlined in this section in order to facilitate the understanding of the methodology outlined below.

The following should be considered vis-à-vis dam terminology (Figure 61):

Inflow is the flow entering the reservoir behind the dam. It can be from several sources.

Headwater is the level of the water surface immediately behind the dam. It is the height of the water going through the spillway or the water cresting the dam when overtopping.

Outflow is the flow leaving the dam. This can be through the gates, the spillway or both. In a breach situation, it also includes the water overtopping the dam, piping through the dam, or flowing through the breach.

Tailwater is the level of the water at the base of the dam on the downstream side.

Dam elevation is the height relative to a datum and is referenced to something like mean sea level.

Dam height refers to the vertical height of the dam, usually from its lowest to highest points.

Dam width refers to the thickness of the dam. The width at the crest is typically less than the width at the base of the dam.

Dam length refers to the length of the crest of the dam as it spans across the river from one side to the other.

Spillway elevation is the elevation, relative to a datum, at its highest point.

Spillway height refers to the vertical height of the spillway above the base of the dam.

53. Sayers, Gouldy, Simm, Meadowcroft and Hall. (2003). DEFRA/Environment Agency R&D Technical Report FD2302/TR1.

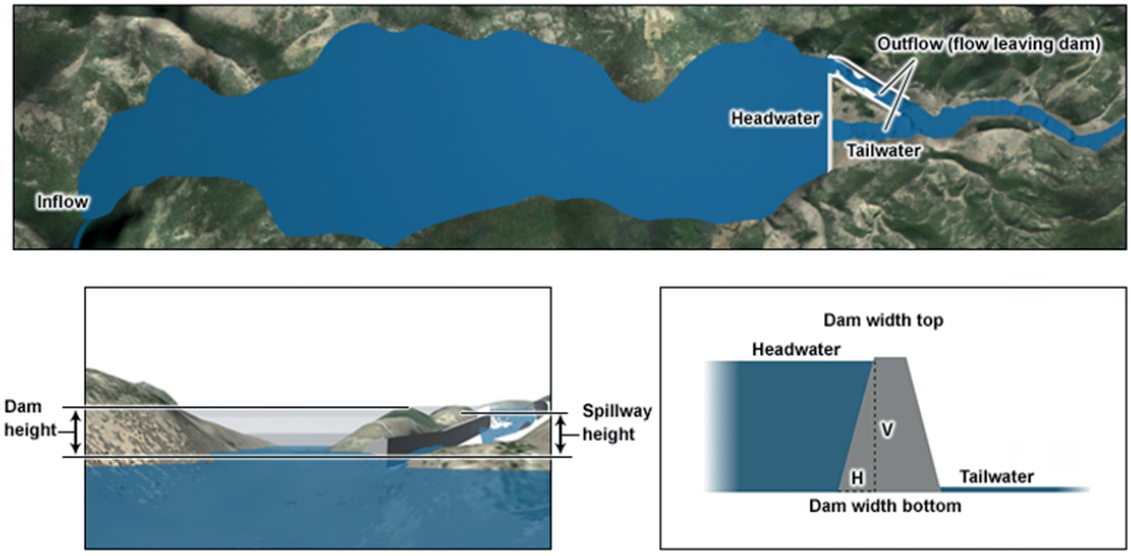

Figure 6-1. Dam Terminology (Source : COMET Programme)

Determining breach characteristics is essential in dam failure modelling. A number of components of the breach must be estimated. The terms used are (Figure 62):

Breach width typically refers to the width of the bottom of the breach unless the top width is specified.

Side slope refers to the slope of the sides of the breach.

Bottom elevation is the elevation of the bottom of the breach.

Time to fully develop or time to breach is the time from the beginning of the breach to when it reaches its fullest extent.

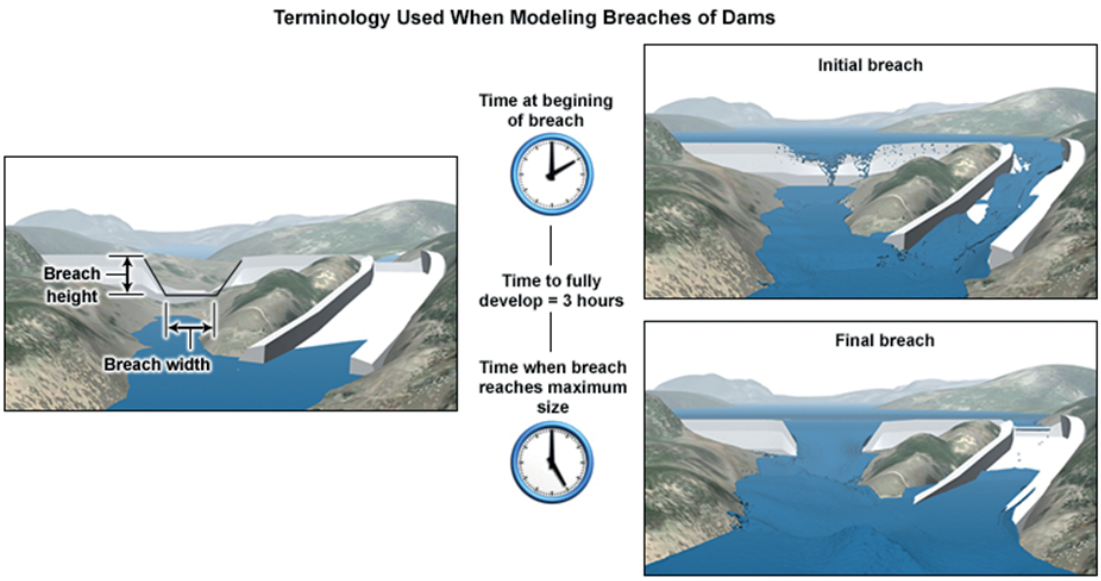

Figure 6-2. Dam Breaching Terminology (Source: COMET Programme)

5.1.2 Flow Attenuation

For any dam or flood defence failure, the impacts of downstream flooding are affected by the total volume and the rate of water leaving the structure. The use of hydraulic routing is required for simulating these impacts as well as how the flood wave will attenuate (Figure 63) as the distance from the structure increases.

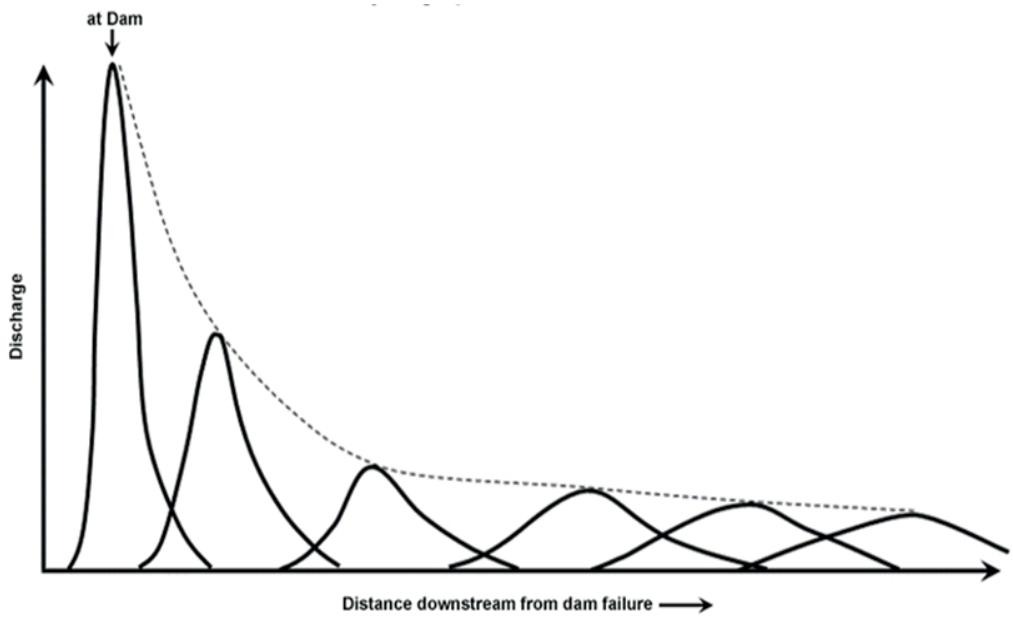

Figure 6-3. Flow Attenuation (Source: COMET Programme)

The flood hydrograph downstream of a structure failure will attenuate slower in a steep basin with little floodplain storage than the same flood hydrograph in a moderate slope basin with large areas of floodplain storage. Additionally, the roughness will play a role which means that higher roughness will attenuate further than lower resistance.

5.2 Data Requirements for Coastal Flood Modelling

There are several data requirements for coastal flood modelling purposes:

- Topographical-bathymetrical information: the bathymetrical and topographical information determines the approach to follow for coastal flood modelling. The availability of the elevation data of coastal and floodplain features and structures which can influence coastal processes and overland flow-paths and ponding is critical for this assessment. If these data are not available or are not of sufficient quality, it is not recommended to undertake a coastal flood assessment. If these data are available, a 2D hydrodynamic model approach is recommended. There are several sources of information for bathymetrical data that should be considered:

- GEBCO: the General Bathymetric Chart of the Oceans (GEBCO) consists of an international group of experts in ocean mapping with the aim to provide the most authoritative publicly available bathymetry of the world's oceans. The GEBCO bathymetry for the Georgian Black Sea coast was collected (Figure 64). The information is available in a 1/8 arc minute resolution (around 350 m x 490 m) grid format from the GEBCO database. A quick assessment of the data has outlined that the values are scarce but constant in the coastal area.

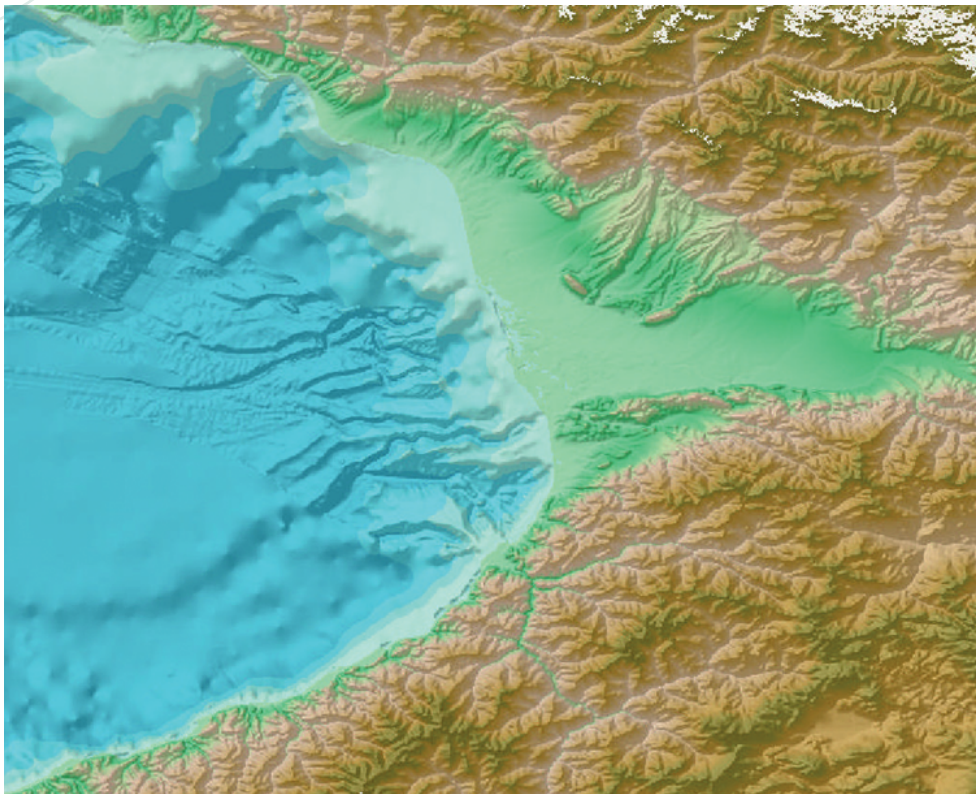

Figure 6-4. GEBCO Bathymetrical Information in Georgia

- The European Marine Observation and Data Network EMODnet was also explored. While providing a finer resolution (1/4 of an arc minute, around a 90 m x 190 m grid), the information provided by the EMODnet does not give further information for the coastal area (Figure 65).

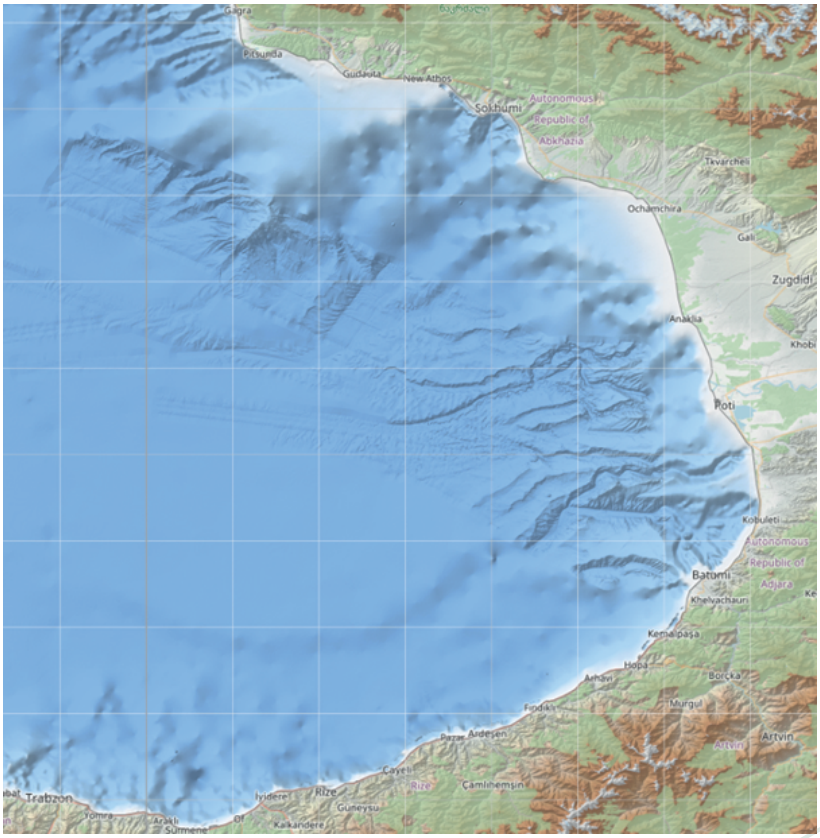

Figure 6-5. EMODnet Bathymetrical Information in Georgia

- Information from nautical charts: bathymetrical information from nautical charts (Figure 66) can also help to complement other sources of information, especially if this information is in a digital format. Nautical charts, however, are commercial and in order to assess their validity they will need to be acquired.

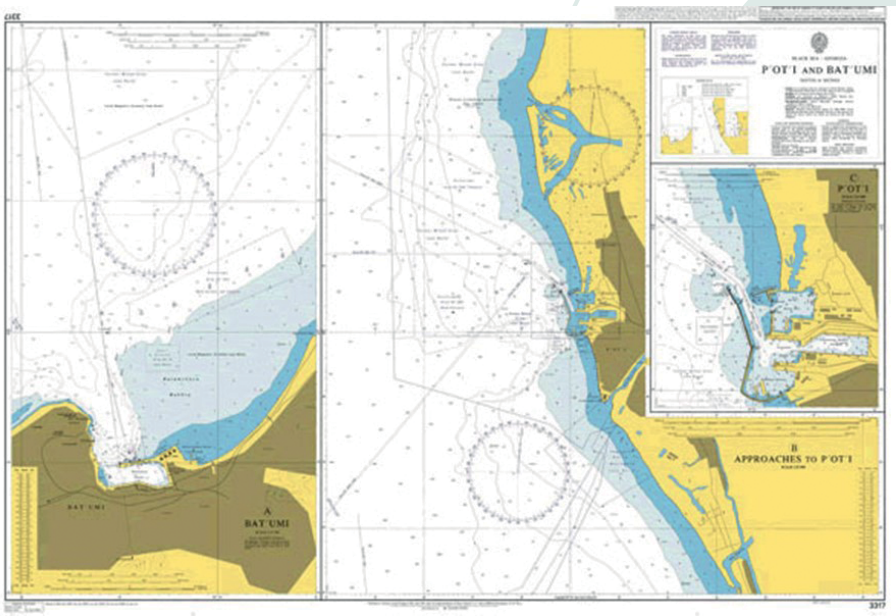

Figure 6-6. Nautical Chart of the Georgian Coast

This preliminary assessment indicates that while there are some bathymetrical data available, these may not be of the necessary accuracy for coastal flood modelling nor accurate enough for wave and storm-surge modelling. Bathymetry has a major influence on the results from wave and storm-surge modelling.

- Coastal data: information about waves and the sea-level will be critical for the implementation of any coastal model (waves, storm-surge, or coastal flooding) as it will determine the possibility of calibrating such models. There are two tide gauges on the coast of Georgia (in Poti [Figure 67] and in Batumi) and there is information about a wave gauge being deployed in Batumi until 1991.[54]

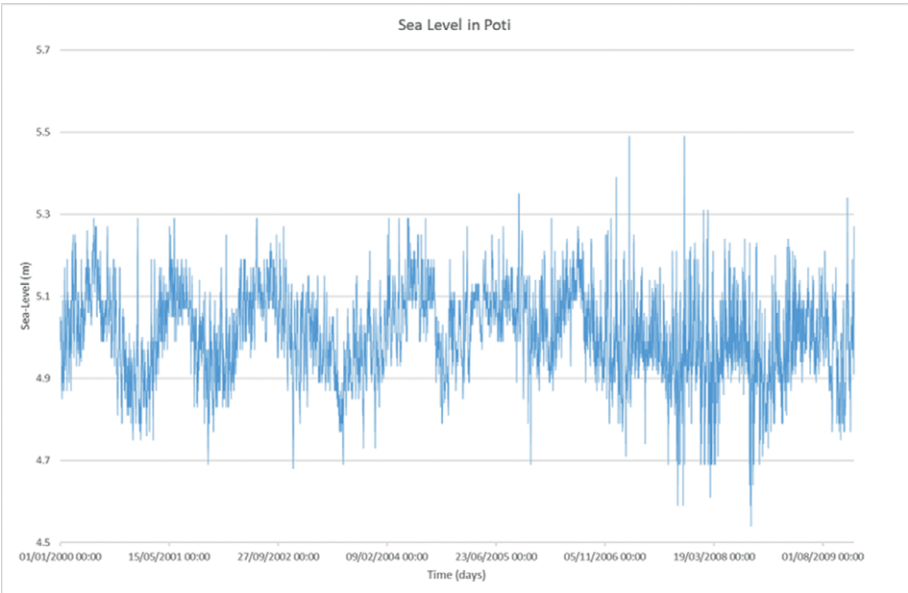

Figure 6-7. Sea-level in Poti

- Flood and coastal defences: these refer to the location and details of flood barriers, seawalls and levees located on the coast. It is expected that several coastal defences will be present on the Georgian coast such as groynes and breakwaters for erosion/sedimentation purposes. Although these structures will benefit the coastal flood magnitude in the long term, they are not relevant from a coastal modelling point of view.

5.3 Data Quality Assessment for Coastal Flooding

There are several data requirements for coastal flood modelling purposes:

- Topographical-bathymetrical information: the preliminary assessment of the bathymetrical data for coastal purposes indicates that while there is some information available, this may not be of the necessary accuracy for coastal flood modelling nor accurate enough for wave and storm-

54. S. Khorava and A. Kikava. (2015). "Protection of the Ajara Coast Zone by an Artificial Beach." Proceedings of International Conference, Applied Ecology: Problems, Innovations. Ltd Kalmosani Publishers, Georgia, 192-197.

surge modelling. Bathymetry has a major influence on the results from wave and storm-surge modelling. It is not envisaged that a bathymetrical survey will be undertaken within the framework of this project. This will limit the implementation of coastal models, although the use and accuracy of the existing resources should be assessed in more detail if more data become available in a local scale.

- Coastal data: there are tide gauges in Poti, and Batumi and it is not expected that the sea-level is going to vary significantly between these two locations. While the Poti data are available to the consultant, this information is not available for Batumi. A comparison between these two data sources should be undertaken in order to assess the validity of these data for the full Georgian coast.

  As will be noted in the methodology, the wave data may be of more importance due to the higher expected impact of waves overtopping on coastal flooding. As noted, there seems to be historical data from a wave buoy but the data from it are only available until 1991 (and it is not available to the consultant). More efforts will be paid to the collection of further coastal data but there are significant limitations at this stage regarding the sea-level and the wave data. If no more data become available, the implementation of coastal flood models would be questionable. In this regard, there is information from other sources regarding the different return periods for the sea-level in Georgia. This comes from coastal studies implemented in either Poti or Batumi. While this information has been collected by the consultant, these data cannot be reproduced in this report without further authorisations. The process for the derivation of these return period values is also unknown to the consultant.

- Flood and coastal defences: there are no information about coastal flood defences available. This is a major issue and while more efforts will be paid to the collection of these data, the acquisition of this information is not expected, and this could have a significant influence on the results. In order to overcome this potential problem, the commission of a survey to collect these data would be recommended if a list of flood coastal defences becomes available.

5.4 Methodologies and Procedures for Flood Hazard Modelling, Mapping and Assessment

5.4.1 Dam-breaching Models

5.4.1.1 Dam-breaching Using Empirical Models

Empirical models are derived from test case studies or observed dam failures but are not process-based. They are only able to provide the user with an estimated peak breach discharge and a time to peak discharge and they require prior knowledge of the structure geometry (e.g., its height, width, and length) and/or the reservoir (e.g., its volume, depth, and surface area) which can be used in a simple equation.

Several empirical models have been developed in order to define the breach outflow hydrograph in a dam or a flood defence failure event. These models estimate the peak outflow discharge and the

time required for the flow rate to rise to the peak as a function of dam and/or reservoir properties. Most of the formulas were developed by a regression analysis of case study data from real dam failures. These formulas offer a means to estimate the complete breach hydrograph if one assumes a hydrograph shape and knows the volume of water to be released through the breach. The most commonly assumed hydrograph shape is triangular. The most widely applied peak flow prediction equations have been those of MacDonald & Langridge-Monopolis[55] (1984), Costa[56] (1985) and Froehlich[57,58] (1995 and 2004).

Table 32 shows an analysis of a number of peak flow equations with their respective statistical curve fit, whether they are real or simulated cases, and the regression analysis results[59] where Q_p = peak outflow (m^3/s), h_w = height of the water behind the dam at failure (m), h_d = height of the dam (m), S = reservoir storage at normal pool (m^3) and V_w = volume of the water behind the dam at failure (m^3).

Table 32. Peak Flow Prediction Equations

Research	Type	R^2	Real Cases	Simulated Cases	Equation
Kirkpatrick (1977)	Best-fit	0.790	13	6	$Q_p = 1.268(H_w+0.3)^{2.5}$
SCS (1981) for dams > 31.4 m	Envelope	NA	13		$Q_p = 16.6(H_w)^{1.85}$
USBR (1982)	Envelope	0.724	21		$Q_p = 19.1(H_w)^{1.85}$
Singh and Snorrason (1982)	Best-fit	0.488		8	$Q_p = 13.4(H_d)^{1.89}$
Singh and Snorrason (1984)	Best-fit	0.918		8	$Q = 1.776(S)^{0.47}$
Evans (1986)	Best-fit	0.836	29		$Q_p = 19.1(H_w)^{1.85}$
Hagen (1982)	Envelope	NA	6		$Q_p = 1.205(V_w H_w)^{0.48}$
MacDonald and Langridge-Monopolis (1984)	Best-fit	0.788	23		$Q_p = 1.154(V_w H_w)^{0.412}$
MacDonald and Langridge-Monopolis (1984)	Envelope	0.156	23		$Q_p = 3.85(V_w H_w)^{0.411}$
Costa (1985)	Best-fit	0.745	31		$Q_p = 0.763(V_w H_w)^{0.42}$
Froehlich (1995)	Best-fit	0.934	22		$Q_p = 0.607(V_w^{0.295} H_w^{1.24})$

55. T.C. MacDonald and J. Langridge-Monopolis. (1984). "Breaching Characteristics of Dam Failures." *Journal of Hydraulic Engineering.* 110,5, 567-586.

56. J.E. Costa and R.L. Schuster. "The Formation and Failure of Natural Dams." *Geological Society of America Bulletin*, vol. 100, 1054-1068.

57. D.C. Froehlich. (1995). "Embankment Dam Breach Parameters Revisited." Proceedings of the 1st International Conference on Water Resources Engineering, American Society of Civil Engineers, New York, 887-891.

58. D.C. Froehlich. (2004). "Two-dimensional Model for Embankment Dam Breach Formation and Flood Wave Generation." Proceedings of the Dam Safety 2004, 21st Annual Conference of the Association of State Dam Safety Officials, Association of State Dam Safety Officials, Lexington, Ky.

59. M.W. Pierce, C.I. Thornton, and S.R. Abt. "Predicting Peak Outflow from Breached Embankment Dams." National Dam Safety Review Board Steering Committee on Dam-breach Equations.

The R^2 results are based on the analysis undertaken by Pierce et al. for all of the different equations available at this stage with the dam data used by the different researchers. Based on this, Froehlich (1995) provides the best agreement. A further analysis carried out by Wahl[60] (2004) also found the Froehlich (1995) equation to have the lowest uncertainty of the peak flow prediction equations available. Froehlich undertook further analysis by adding 52 dam-breach events and refining the equations as shown below.

The advantages of the empirical approach are its simplicity and quickness which makes it useful as a screening tool for analysing large dam and flood defence inventories and offers a quick way to check the reasonability of results from other methods. The disadvantages of this approach are the fact that none of the equations includes factors related to material erodibility and the fact that the time parameters predicted by these equations help define the shape of the hydrograph but do not fully answer the question of how much warning time is available prior to the release of peak outflow. This said, the issue of warning time is not significant for hazard mapping. The time parameter predicted by these methods is the rise time of the hydrograph from the end of breach initiation to the time of peak outflow. The end of breach initiation is the time at which erosion through the embankment has progressed to the upstream side of the crest. Prior to this, the time from the first overtopping or the first observable seepage flow of concern to the end of breach initiation can be lengthy, especially if the embankment is erosion resistant.

Results from previous worldwide-level analysis have been considered in order to assess the adequacy of the empirical approach for the determination of peak flows as a result of dam-breaching. As stated above, the Froehlich approach was determined to be the most accurate in terms of peak flow predictions and this is the recommended approach vis-à-vis the information available at this stage. There are, however, some limitations regarding the dam height. The height of the dams used in the Froehlich assessment is shown in Figure 68. As can be seen, most of the dams have a height in between ten and 20 metres whereas there is only one dam with a height over 80 metres.

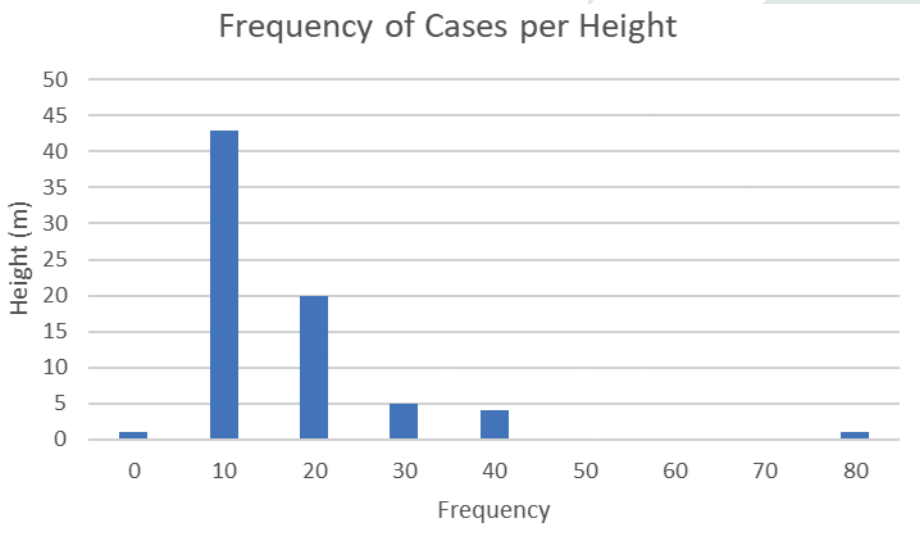

Figure 6-8. Frequency of Cases by Dam Height within Froehlich (2005)

60. T. Wahl. (2010). "Dam-breach Modelling – An Overview of Analysis Methods." Joint Federal Interagency Conference on Sedimentation and Hydrologic Modelling. 27 June-1 July 2010.

A review of all of the different empirical equations available has been undertaken in order to identify the height of dams used in the derivation of the empirical equations. As shown in Figure 69, a similar analysis was undertaken by Pierce et al. (2010[61]) for the heights used in other studies apart from the Froehlich ones. As can be seen, no studies have used data for dams over 100 metres high. The Froehlich empirical equation does provide the best results for the prediction of dam-breaches.

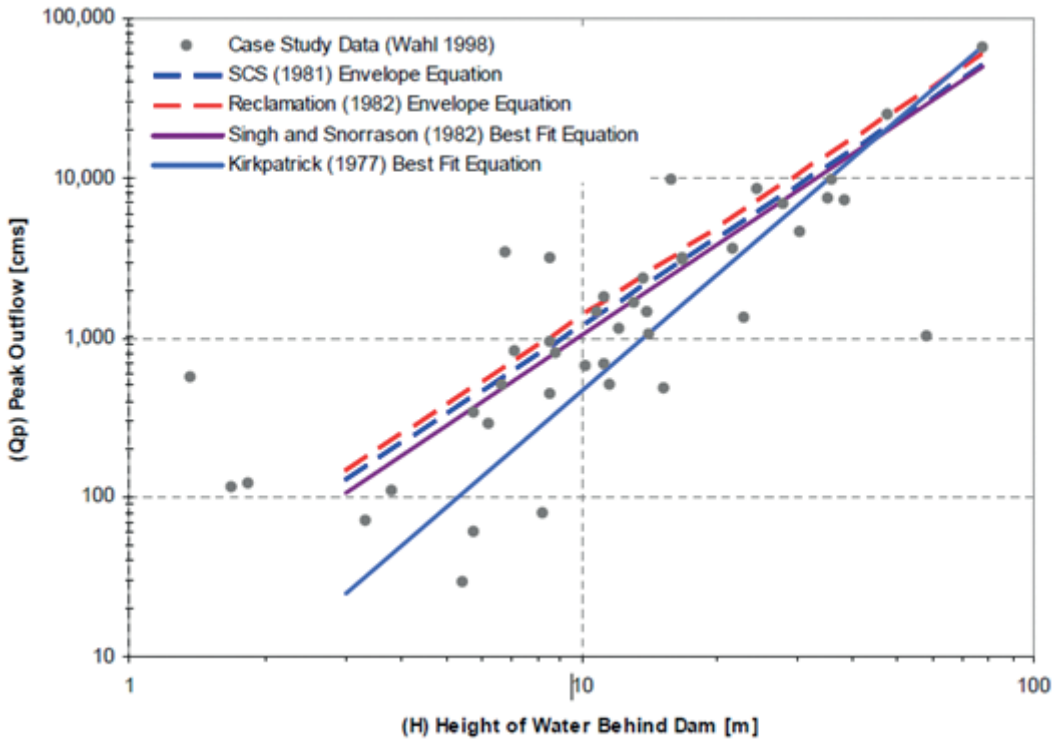

Figure 6-9. Peak Outflow as a Function of the Depth of Water Behind the Dam (Source: Pierce et al.)

The height of dams in Georgia also has to be considered. As noted above, there is very little information regarding the existing dams in Georgia and/or their height. The information in the table below was collected either from internet sources or was provided by the NEA.

Table 33. Height of Dams in Georgia

Dam	River	Height of Dam (m)
Zhinvali	Aragvi	102
Khudoni	Enguri	200.5
Enguri	Enguri	271.5
Vardnili Cascade	Enguri	60
Lajanuri	Lajanura	69

61. M.W. Pierce, C.I. Thornton, and S.R. Abt. "Predicting Peak Outflow from Breached Embankment Dams." National Dam Safety Review Board Steering Committee on Dam-breach Equations.

As can be seen in Table 33, most of the dams for which information could be collected are at or below 100 metres in height, although two dams in the Enguri River basin are at or above 200 metres. It is recommended to use the Froehlich approach for all dams in Georgia, including the Enguri dams, although further and more detailed assessments will be undertaken for the Enguri dams using a direct hydraulic modelling approach.

The following data will be needed for the implementation of the Froehlich approach (Figure 610):

- Failure mode: either piping or overtopping.
- Height of water over base elevation of breach (H_w).
- Volume of water in the reservoir at the time of failure (V_w).
- Reservoir surface area at H_w (A_s).
- Height of breach (H_b).
- Breach side-slope ratio (Z_b).

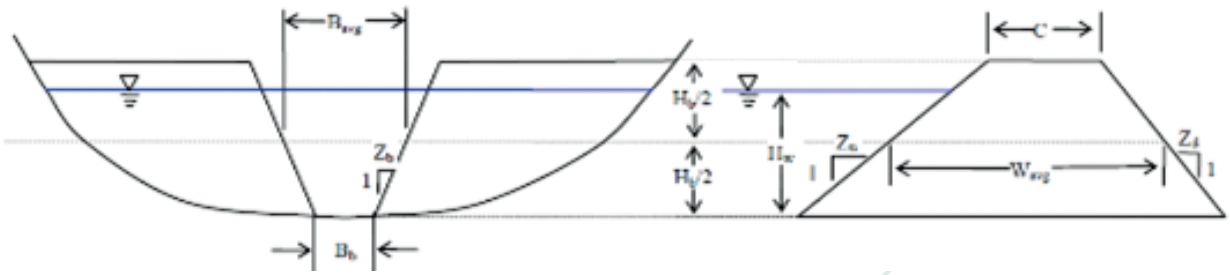

Figure 6-10. Dam-breach Parameters

In the case if some of the parameters mentioned above are not obtained, the available DEM can then be used to infer the missing data. The implementation of the empirical modelling will yield:

- Average breach width (B_{avg}).
- Bottom width of breach (B_b).
- Breach formation time (T_f).
- Storage intensity (SI).
- Predicted peak flow (Q_p).

There are spreadsheets available for the implementation of this method. These spreadsheets can be used to calculate the results per dam/flood-defence.

In terms of the approach and data requirements for flood defences, this would depend on the design of the actual flood defence. In the case of levees and walls, the main information requirement would be similar to that for dams, and they will be treated as such from a breach flow point of view. In this case, it is important to get detailed information about the crest of the flood defence, preferably a longitudinal profile along the full length of the structure with data at

small intervals. Other structural data requirements will have to be evaluated on a case-by-case basis. Additionally, flood defence structures will form a part of the modelling for other sources of flooding and so their details will also be included in the modelling framework. The same modelling framework should be used for AWBS modelling, although the failure of each particular structure will be explored.

5.4.1.2 Dam-breaching Using Analytical Models

Analytical models for peak breach outflow are based on an equation or a set of equations derived from the physics of dam-breach erosion and hydraulics and not on regression analysis. An early example of such a model is the work of Cristofano (1965[62]). This model related the rate of the erosion of the breach channel to the discharge through the breach using an equation that accounted for the shear strength of soil particles and the force of the flowing water. Key assumptions were a trapezoidal breach of a constant bottom width, the side slopes of the breach were determined by the angle of the repose of the material and the bottom slope of the breach channel was equal to the internal angle of friction. The advantages of this approach are the fact that it recognises the differences in behaviour between small and large reservoirs. Small reservoirs (or those dams that fail very slowly due to erosion-resistant embankments) drain significantly before the breach is fully formed so the peak outflow occurs while the breach is still forming. Large reservoirs (or dams that fail quickly) maintain their reservoir head until the breach has reached its ultimate size, so the peak flow occurs when the breach is fully formed and is subjected to a maximum head. The disadvantages of this technique are that it still does not aid in the determination of the time required for breach initiation since the analytical model only treats the breach formation process.

5.4.1.3 Dam-breaching Using Hydrodynamic Models

The physically based numerical models approach can be divided into the dimensionality of the models themselves.

5.4.1.3.1 1D Numerical Model

There are a number of simulation software packages with dam-breaching capabilities. The simulation mostly involves the solution of 1-D Saint Venant equations using implicit finite difference models in order to determine discharge and depth variation at different sections with time. Information regarding the most widely used models is as follows.

i) MIKE 11 Hydrodynamic Model developed by the Danish Hydraulics Institute (DHI). It is based on an implicit finite difference computation of unsteady flows in rivers and estuaries. The formulation can be applied to branched and looped networks and flood plains. The MIKE 11 dam-breaching model can also be erosion based.

62. E.A. Cristofano. (1965). “Method of Computing Rate of Failure of Earth Fill Dams,” Bureau of Reclamation, Denver, Colorado.

ii) The Hydraulic Engineering Centre's River Analysis System (HEC-RAS) uses algorithms to model both overtopping and piping breaches. HEC-RAS uses hydraulic principles through cross-sections upstream and downstream of the dam to define how the reservoir drains during the formation of a dam-breach. The dam crest is modelled as an inline weir and either a piping failure or overtopping failure is simulated with enlargement of the breach occurring over time as defined by a specified breach progression.

iii) DAMBRK was initially developed by the National Weather Service in 1984 and was then updated by BOSS International. It predicts the dam-breach wave formation and its downstream progression. The software allows the user to input geometric and temporal data for the dam break to accurately predict the initial breach wave, including modelling piping and overtopping failures.

5.4.1.3.2 2D Numerical Model

In recent years, 2D numerical models for the simulation of the dam-breach hydrograph have started to be used. Two different approaches exist in this case:

- Static 2D Model: in this case. a 2D topography is built, using the final breach shape. The volume of water held by the dam is then routed through the dam to calculate the dam-breach hydrograph.
- Variable 2D Model: different 2D topography files are used in this approach. At particular time-steps. the topography file used in the 2D modelling engine is altered to include the evolution of the dam-breach.

These two methods, especially the latter, are very data demanding and their implementation is not considered an advantage in the absence of detailed data. Nonetheless, considering the information outlined above in the empirical models section, this approach (static 2D model) would be recommended for the large dams in the Enguri basin if sufficient data are available.

5.4.2 Modelling Scoping

As per other flood sources, the modelling methodology or the procedure for undertaking this assessment will be based on the data available. It is obvious that no modelling will take place when no information for the AWBS is available. Therefore, the following approach is suggested.

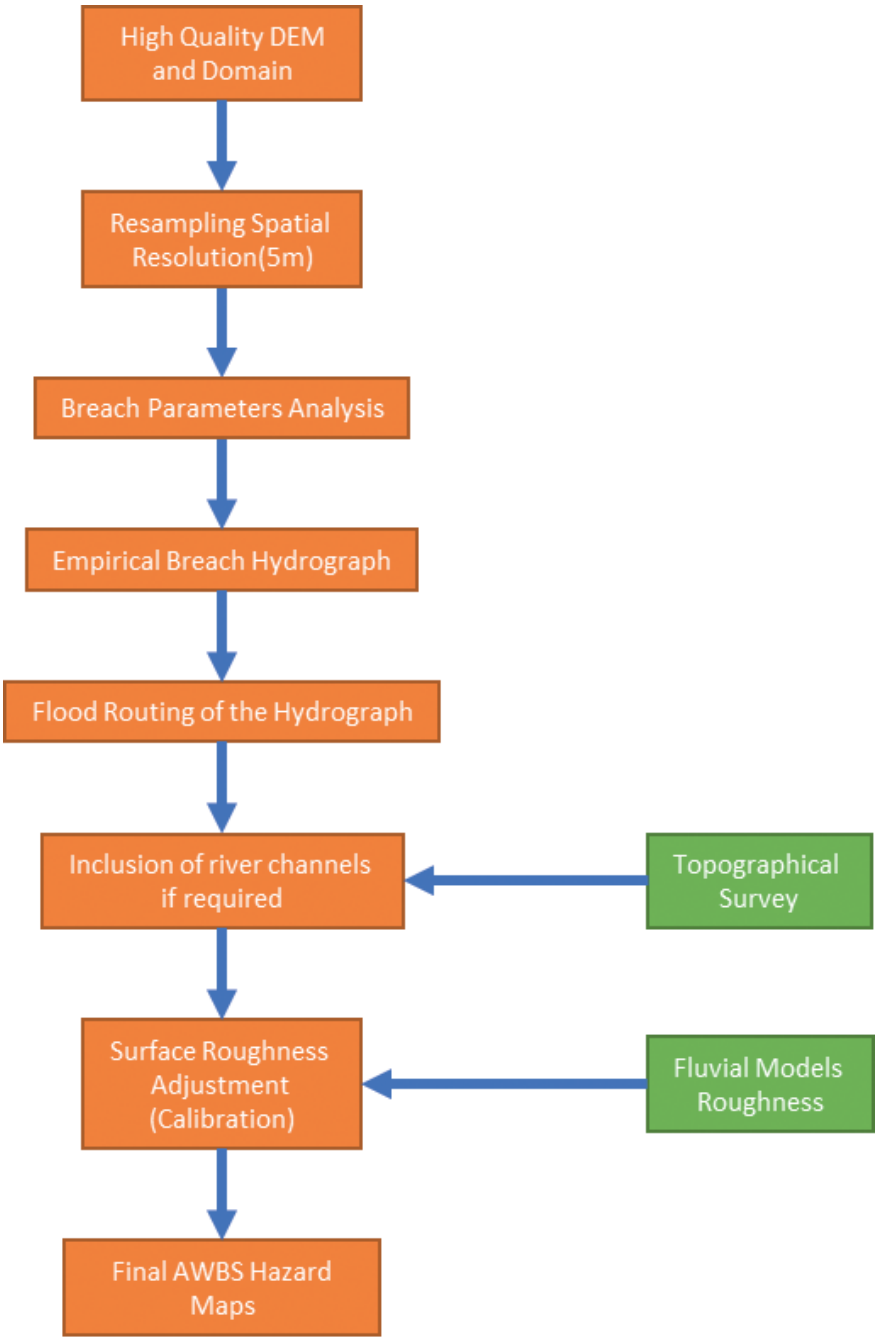

Figure 6-11. AWBS Flood Hydrodynamic Methodology

5.4.2.1 AWBS Data, High-Resolution DEM, and Domain

The AWBS flood modelling can only be undertaken if the required data are available. Additionally, a high quality and high-resolution DEM is required in the area immediately downstream of the structure as was mentioned above. Undertaking an AWBS flood modelling exercise is not recommended where there is no high-resolution DEM in areas close to the structure. Therefore, the following is suggested.

- Modelling domain: the modelling domain for the AWBS modelling will be defined considering the following:
- Historical flooding: locations that have historically experienced AWBS flooding will be selected. The domain will cover the whole area of interest, considering the topography and the possible boundaries of the model.
- In most cases, historical information will not be available and, therefore, an initial run with 'dummy' high flows is suggested. In this case, the areas of interest (and, therefore, the domain) will cover the full area downstream that may be affected by a sudden release of water from the AWBS; this will be defined through these preliminary runs releasing a significant amount of flow and considering any significant watercourse where the water may flow. Therefore, the model domain will be extended from the AWBS to a location where the impact of the breach hydrograph is no longer significant. In order to ascertain that location, the model will be extended for a significantly long distance from the AWBS and the results in the boundary will be checked. If a significant water level (more than 0.5 metre increase) is still predicted in the downstream boundary, the model will be extended further downstream.
- Comparison of the modelling domain and the DEM quality: the selected domain will be compared against the DEM coverage and the quality of the DEM resources. The modelling domain may be altered after some initial runs if the results are not satisfactory (regarding the impact of the AWBS) and the whole comparison assessment will have to be undertaken again.
- Within LiDAR: if the modelling domain is entirely within a LiDAR area, the modelling will proceed.
- Within orthophoto: if the modelling domain is within an area with no LiDAR data, the quality of the orthophoto DEM will be considered. This assessment will have been undertaken within the pluvial flooding activity. Nonetheless, it is important to ascertain that the quality of the DEM is similar across different land-uses and land-covers. Therefore, this analysis can yield the following two options:
- Good agreement with LiDAR data: if there is a good agreement between the orthophoto DEM and the LiDAR DEM, then the modelling can proceed. The criteria for a 'good agreement' are that the difference between these two data sets is under 1 metre.
- Bad agreement with LiDAR data: if there is not a good agreement between these two data sets, then the modelling for that specific area (domain) will be halted.
- Global DEM only: if the domain is only within an area with global DEM, the modelling will be halted at this stage. While the orthophoto DEM is supposedly covering the whole territory of Georgia, this data set has not been made available to the consultant and, therefore, this has not been possible to assess.

Therefore, the following approach is suggested (Figure 612).

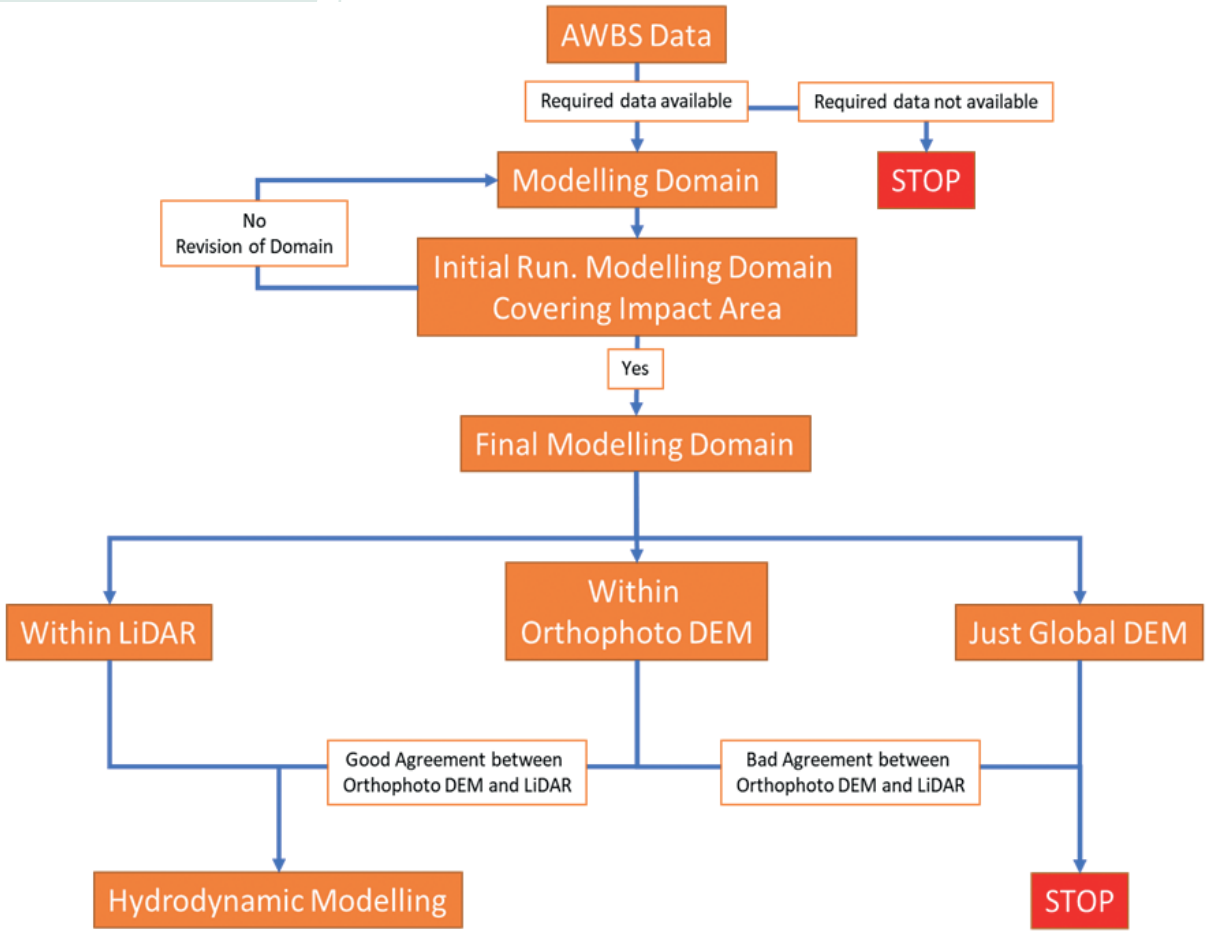

Figure 6-12. Data, Domain and DEM Assessment

The hydrological modelling will cover the calculation of the dam-breaching flows in this case.

5.4.3 Hydrological Modelling

The hydrological modelling and assessment will cover the dam-breaching analysis in consideration of the information and the methodology outlined above, especially for small (100 metre or less) dams. For large dams, the recommended implementation of dam-breaching is through physical modelling as noted above. The process for including a dam-breach is based on the same implementation as the 'weir' implementation as described in the fluvial section but with the inclusion of the dam-breaching option (for HEC-RAS, other software differs).

5.4.4 Hydrodynamic Modelling Implementation

The hydrodynamic modelling implementation of the AWBS flood hazard assessment will be undertaken using 2D modelling resources. A 1D model will only determine the water level and the discharge at pre-defined locations, meaning that the flow path has to be known and defined in advance. This may not be a problem with low-to-medium flows in areas where the topography information is accurate, and the flow path is known. However, the amount of flow being released usually exceeds previous

records in most dam-breach scenarios and the water may not follow a pre-defined path. In addition to this, the advantages of using 2D numerical models for a hydrodynamic simulation of AWBS include their ability to simulate multi-directional and multi-channel flows, the super-elevation of flow around channel bends, hydraulic jumps, trans-critical flow regimes and flow recirculation. The following modelling approach is suggested following the methodology outlined in Figure 611.

5.4.4.1 Resample Spatial Resolution of Grid

In this modelling stage, the DEM will be resampled, especially in the location close to the structure. Dam-breaching models are very sensitive to grid cell size in the vicinity of the structure. Therefore, it is recommended that a maximum cell size of 5 metres is used in the vicinity of the dam (using break-lines) while the resolution can be coarser further downstream. It is recommended to use break-lines with a resolution of at least 10 metres in the location of the main channels, but a courser resolution (20 metres or more) can be used in the floodplain, especially in initial runs until the actual extent of the flood inundation as a result of routing the dam-breaching wave is assessed. Some model software allows for variable cell sizes, a flexible mesh, and multiple domains, and, therefore, this will be considered when implementing the modelling domain and defining the grid size.

The model time-step should be set with reference to the cell size and the rainfall profile interval, always allowing for the Courant number to be under a value of 1 and, therefore, an adaptive time-step modelling approach is recommended.

5.4.4.2 Initial Model Run

An initial model run should be carried out early in the modelling process in order to understand the scale of edits and adjustments required, including any requirements for altering the modelling domain. If the hydrological (dam-breaching) analysis has not yet been completed, realistic 'dummy' conditions can be used for these runs. These initial model runs can also be used to determine if any survey of key structures and features that influence flow-paths and ponding is required.

5.4.4.3 Edits to DEM for Flood Defence Assets, Infrastructure, Embankments, Bridges, etc.

Any feature which influences flow-paths, flood depths or surface water ponding should be reviewed and incorporated into the model where necessary. These features can either be as edits to the 2D model domain, such as break-lines or dry riverbeds, or as embedded dynamically linked 1D domains (such as 1D channels for ditches or 1D pipe networks or culverts through an embankment). The use of 1D elements should be limited to only where necessary so as to reduce model complexity and increase model stability. The most critical features will be openings or culverts, bridges and flood defences which are critical to the distribution of surface water flow and ponding depths. Due to the expected extent of a dam-breaching flooding, the number of structures to be included should be limited for resources purposes. Only the structures that may pose a significant impact on the flow pattern should be included, especially considering the large amount of water volume usually flowing downstream during a dam-breach or flood defence scenario.

5.4.4.4 Surface Roughness

The surface roughness should be defined using the Manning's approach, assigning Manning's roughness values to the model surface in a similar way as in the fluvial analysis.

Standard values for land-use data should be applied in the initial modelling runs using land-cover data. These values should be adjusted during the calibration process to ensure the model's representation of the local conditions. The inclusion and adjustment of roughness depends on the software used but a 2D grid can be used to represent this in most cases.

5.4.4.5 Model Boundary Conditions

The model boundary conditions for ABWS flooding should be defined by the input from the dam-breaching analysis and this should be included as upstream boundary conditions. It is important to note that dam-breaching hydrographs usually come from a very detailed time-step (five minutes or less) to properly capture the rapid variation on flows, and this will be fully considered in the inclusion of the boundary condition in the modelling framework.

In terms of the downstream boundary conditions, the definition will depend on the location of the domain. Close to the coast, a coastal boundary condition (water level time-series) will be defined. In the case of a possible AWBS-coastal event, a joint probability assessment will be undertaken. In inland domains, the downstream boundary will be located as far away as possible from the areas of interest and a normal depth boundary condition will be used. In order to define the location of the downstream boundary, it will be located where the flow in the main channel has been attenuated to in-bank flow. As described in the sections above, the flood wave resulting from a AWBS failure is attenuated as it flows downstream.

5.4.5 Hydrodynamic Model Validation and Runs

The AWBS models will be calibrated and validated if possible. There is high uncertainty regarding the data availability for model calibration and validation, especially because a flood from an AWBS that has occurred in the past cannot occur again (almost no recurrence) in most cases. Information from the fluvial modelling results will be used in terms of model calibration in this case, especially for the surface roughness. If a model has been calibrated in the fluvial modelling and the roughness has been adjusted, especially in a 2D domain, then it is highly recommended that estimated Manning's values are used in the AWBS modelling.

5.4.5.1 Design Event and Climate Change Runs

The EUFD requires flood hazard maps to be derived for a range of probabilities. However, the application of a probability can be challenging depending on the trigger that led to the AWBS breaching.

5.4.5.2 Uncertainty and Sensitivity

Sensitivity testing is recommended due to the expected lack of data for the calibration and the validation of the models. Dam-breach hydrographs have the greatest uncertainty of all of the aspects of dam-breach flood wave modelling because of the use of empirical equations. Therefore, it is recommended that sensitivity testing is undertaken for all of the different variables considered in the dam-breach modelling, especially the values with less confidence. One of the key factors would be the storage volume behind the dam which has a significant impact on the flood peak and the volumes predicted. However, the storage volume is either estimated from some point data or by applying surface-volume relationships. It is critical that a sensitivity test varying 25% the storage volume is undertaken. In this case, this implies undertaking a whole modelling framework testing from the dam-breaching to the dam-breach hydrograph routing. The testing of other parameters is also recommended but this will depend on the quality of the data as previously noted.

Undertaking the same sensitivity testing for the flood wave routing model (2D hydrodynamic model) as for the fluvial modelling is recommended.

5.4.6 AWBS Flood Hazard Mapping

AWBS flood depth should be colour coded as follows.

Depth [m]	R	G	B	Colour
0.1 < 0.5	204	255	255	
0.5 < 1.0	153	255	255	
1.0 < 1.5	102	255	255	
1.5 < 2.0	51	255	255	
2.0 < 2.5	153	204	255	
2.5 < 3.0	102	178	255	
3.0 < 4.0	0	128	255	
> 4	63	0	125	

Flood depths of less than 0.1 metre should not be mapped.

5.5 Data Requirements for AWBS Flood Modelling

The specific requirements for AWBS flooding will be detailed in this section. Only additional data sources will be detailed as the other ones (such as land-cover or topographical information) have been discussed in detail in previous sections. The main data source to consider for AWBS flood modelling is information about the structures themselves.

Thus, the data requirements and data availability in Georgia in terms of drafting the methodology for AWBS flooding will be considered:

- Details of dams and flood defences: this is the most relevant data needed for the AWBS flood modelling. The data details needed are outlined in section below. These data details assume that the locations and the basic characteristics of every single item of infrastructure to consider are already collected. This would be done during the PFRA stage or in a preliminary stage within the FHRM activity. This information is not available at the moment, and it is paramount that a list of critical dam and flood defence infrastructure is collected and analysed as soon as possible.

  Details of historical and recorded AWBS flooding in Georgia: the records of previous historical AWBS flooding will be collected and analysed. This is something that should have been done under the 'historically significant flooding' stage. However, because this stage will not be undertaken fully within the framework of this project (data will be collected but the process of determining their significance will not be done fully), special care will be paid to this activity within the AWBS methodology implementation in the FHRM stage. The historical AWBS flood events will be analysed in detail at this stage and will be used for calibration ad validation purposes.

  Details on the availability, quality, and coverage of data: the following modelling data are required for the AWBS model implementation. As noted, these data have been outlined in previous flood sources and only the peculiarities and special requirements regarding the AWBS modelling implementation from a hydraulic modelling point of view will be discussed in this section.

- DEM data: the DEM input for the AWBS modelling should consider the area immediately downstream of each of the structures. The derivation of the dam-breach flows (hydrographs) is not expected to be implemented using physical modelling and so an empirical approach is suggested at this stage. Therefore, DEM information in the exact location of the structure (or upstream of them) is not a significant requirement. The implementation of the hydrodynamic model will be undertaken with special care vis-à-vis the area immediately downstream of the structure. Due to the expected and sudden release of significant discharge quantities, the hydrodynamic model will be further refined in this location, defining a finer grid size through the inclusion of break-lines in the model domain grid. Therefore, a good quality DEM is required at this location in order to properly represent the flow dynamics immediately downstream of the structure. The main input for this would be the recently acquired LiDAR data (Figure 2-19). Another source of DEM data can be considered as detailed below.

- Land-cover and land-use data: as per the other flood sources.

5.5.1 Dam and Flood Defence Details

The following information is needed in order to implement both the empirical and the physical dam-breach models.

Table 34. Data Needs

Dam or Flood Defence Data
Maximum height of dam
Maximum depth of water stored behind the dam
Volume of water behind the dam
Reservoir surface area
Dam crest top width
Dam bottom width
Average dam width
Side slope of dam
Slope of downstream dam face
Slope of upstream dam face
Dam length
Properties of Dam Material
Earth fill type
Porosity (if required)

As noted above, it is recommended that an empirical approach is used to calculate the dam/flood-defence flow hydrograph as a result of the breach of a structure. Structure breach modelling involves the study of dam or flood defence breach parameters and using them to predict reservoir or river outflow hydrographs which are then routed downstream of a river reach. The breach hydrograph modelling approaches can be divided into empirical models, analytical models and fully physically based numerical models.

5.6 Data Quality Assessment for Artificial Water-bearing Structure Flood Modelling

As noted above, the only information presently available regarding AWBS is a list of reservoirs with information about their capacity, surface area and depth. This information is not sufficient for dam-breach modelling. The acquisition of further information is being investigated by the NEA. No flood modelling activities are recommended if only the current information is available.

5.7 Methodologies and Procedures for Preparation, Data Analysis, and Incorporation into Hydraulic Models

The methodologies for data processing will be similar to the ones described above for fluvial and pluvial flood hazard mapping and modelling. The main addition in this case will be the data used for dam-breaching.

5.7.1 Dam-breaching Data

As discussed above, dam data will be required for the derivation of dam-breaching hydrographs. In the first place, it is important to analyse all of the collected data and ascertain if the data requirements for a dam-breaching analysis are available.

The use of Froehlich is recommended in order to undertake a dam-breach hydrograph calculation. A spreadsheet with the input data, the equations, and the output data (in system international measures) is available for deriving dam-breach results. This has already been distributed to NEA modellers.

This spreadsheet should be used with great care because any incorrect data may lead to very different values. The results from this will form the basis for the dam-breach resulting flood wave to be included in the 2D hydraulic models.

5.8 Software

The recommendations for software to be used for AWBS flood hazard modelling follow the same guidelines as the ones described above for fluvial, pluvial, and coastal modelling because all of the software outlined above (except Iber) have dam-breaching capabilities.

In this case, however, MIKE FLOOD and HEC-RAS are the two most recommended modelling software packages, but it is the latter which is preferable because MIKE FLOOD does not allow for dam-breaching to occur in 2D and because the inclusion of a dam-breach in a 1D module is not user-friendly, especially if a reservoir or storage is going to be defined. MIKE does not have storage structure capabilities and, therefore, a branch with additional storage has to be defined which considerably increases the time required for the implementation of any dam-breaching model. The use of HEC-RAS 5.0.6, therefore, is recommended.

06

Combination of Flood Types

As noted above, the combination or different flood sources will be considered. The main approach for assessing the possibility of more than one flooding source occurring during the same event will be based on a joint-probability assessment. Nonetheless, the first step would be to determine the relevant flood sources where different combinations of boundary conditions are present. The following combination of flood sources will be considered:

- Fluvial + coastal
- Pluvial + coastal
- Pluvial + fluvial
- Fluvial + groundwater
- Pluvial + groundwater
- Coastal + groundwater
- Fluvial + pluvial + groundwater
- Fluvial + pluvial + coastal
- Pluvial + coastal + groundwater
- Fluvial + coastal + groundwater
- Fluvial + pluvial + coastal + groundwater

More combinations can be drawn up, especially considering the AWBS flood source. However, this has been left out of the assessment due to the difficulties of assessing previous historical AWBS events and the probabilities of this source of flooding.

Nonetheless, it seems unrealistic and impractical to assess the joint probability of all of the combinations outlined above and so this list should be refined. The final combination list should be drawn up considering the impact of each hazard individually as well as the modelling implementation availability.

The joint probability assessment will be undertaken considering previous events. For instance, the assessment of a simultaneous occurrence of a fluvial and a coastal event will be done in order to un-

derstand the interdependence of these events. The degree of interdependence will condition the joint probability results.

In all the cases, the combination of different flooding sources is considered mainly as a hydrological modelling aspect. The following should be considered from a hydraulic modelling approach point of view:

- "Reusing" the model as much as possible is recommended in order to limit modelling efforts. For instance, the same 2D model can be used for inundation for coastal, fluvial, and pluvial flood sources in Batumi. For fluvial issues, a 1D model may also be implemented so as to represent watercourse channels. The 1D channel may be included in the modelling framework.
- Different flood sources able to affect an area of interest will be considered in detail in the model's conceptualisation. Following with the Batumi case, the possibility of groundwater, AWBS, fluvial, pluvial, and coastal flooding in this area will be fully considered and modelling domains will be extended (if required) to cover for all of the flood types present in the area.
- If the aforementioned approach is followed, individual and different flood sources may be analysed with a variation of boundary conditions. For instance, Batumi fluvial flooding may be analysed with the flows from the Chorokhi River and no other input while coastal flooding will look at relevant wave overtopping hydrographs and still sea-water levels and pluvial flooding will consider precipitation design events and so on. Once the joint probability assessment is undertaken, a combination of flood sources may be drawn up with the same calibrated model.
- In this respect, a different approach for the definition of building outlines and their impact on flow dynamics is suggested by the pluvial event methodology specified above. If the roughness approach is selected for the representation of buildings, then different roughness input files for the same location can be determined for joint probability assessments. In this case, the buildings-roughness should be used for the pluvial modelling and the normal one for the joint probability assessment modelling.
- The joint probability assessment of groundwater and other sources of flooding should consider the difficulty of discerning the groundwater input from other lateral inputs in some cases. Special attention needs to be paid to this issue.

07

Uncertainty

Uncertainty is inherent in all models. Uncertainty arises at each level or stage in the process of modelling flood risks, and this comes from a range of sources. Figure 71 shows examples of potential sources of uncertainty in flood risk models. The level of confidence in the output will reflect the uncertainties within each of the stages of assessment such as within the input data, parameters, and the model itself. It is recommended that uncertainty is clearly presented in flood hazard and risk assessments, showing what approaches have been used to quantify them and how decisions have been influenced by uncertainties. Any assumptions made should be explained and justified.

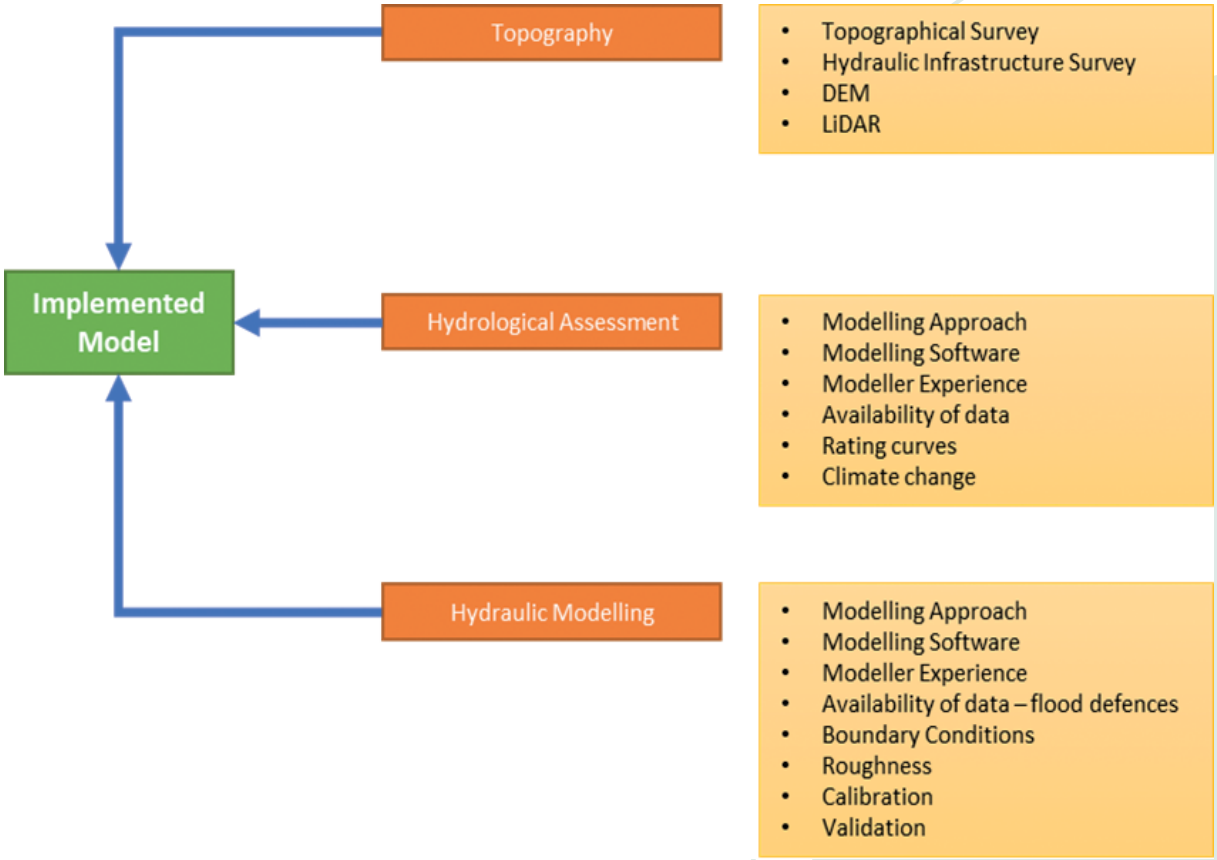

Figure 7-1. Potential Sources of Uncertainty in Hydraulic Models

The identification of the relative importance of different sources of uncertainty, such as those related to the magnitude of their impact on the final output, should be undertaken because future reductions in uncertainty could be gained by targeting its largest sources (through collecting more cross-section data, improvements to the DEM or additional gauging to improve the investigation of inflow boundaries).

There is a range of existing methods for analysing uncertainty, including both qualitative and quantitative methods. These methods range from simpler forms of analysis (sensitivity analysis and approaches which qualitatively score uncertainty) to complex approaches (formal, expert elicitation where the opinion of several authorities on the subject is used to inform confidence intervals, Bayesian methods, regressions and approaches involving defining distributions for propagating the effects of different sources of uncertainty to see how these influence model output). The ability to conduct a detailed evaluation of uncertainty may be affected by the availability of the data required.

Generally, detailed, or complex quantitative approaches are expected to be the most applicable at the detailed modelling scale where there is potential for significant investment in measures, meaning that a detailed indication of the potential uncertainty is of particular of benefit. Quantitative approaches can provide a greater insight into how uncertainty in inputs is propagated through models (to the outputs) and, in some cases, detailed information about uncertainty in different sources can be produced in the form of the probabilities of outcomes, confidence intervals and/or probability distributions. A quantitative uncertainty analysis may be used to calculate freeboard levels for flood prevention schemes.[63]

Qualitative approaches focus on the identification and grouping of the sources of uncertainty. These sources usually characterise uncertainty using judgements vis-à-vis the level of uncertainty. Qualitative estimates and/or a sensitivity analysis may be the selected way for assessing uncertainty when the approach is constrained by available data (for instance, where no historical data are available in order to determine the estimates of uncertainty).

7.1 Approach to the Uncertainty

A series of proposed sensitivity tests for flood mapping modelling will be outlined below for one of the design events (i.e., the 1:100-year event).

Different sensitivity tests have been outlined throughout this report and an analysis of these tests will be given in order to derive the inherent uncertainty vis-à-vis each of the flood sources. More tests can be undertaken by the modeller, especially in areas where site specific knowledge of the hydraulic modeller within the catchment may be of relevance.

63. K. Beven. (2011). "FRMRC: Framework for Addressing Uncertainty in Fluvial Flood Risk Mapping." *FRMRC Research Report* SWP1.7. Flood Risk Management Research Consortium.

The objective of the proposed methodology for representing uncertainty is to incorporate the best available knowledge of the modelling limitations into the analysis without requiring significant additional input by the modellers and, therefore, the sensitivity tests described above will be fully used to determine the level of uncertainty.

The uncertainty will be represented as an additional (with uncertainty) 1:100-year flood extent that can be compared to the 'normal' 1:100-year flood extent.

The development of the uncertainty flood extent outline will be based on the results from those sensitivity tests that were found to produce the largest increase in the predicted flood extent. The stages for the uncertainty analysis are outlined in Figure 72 below.

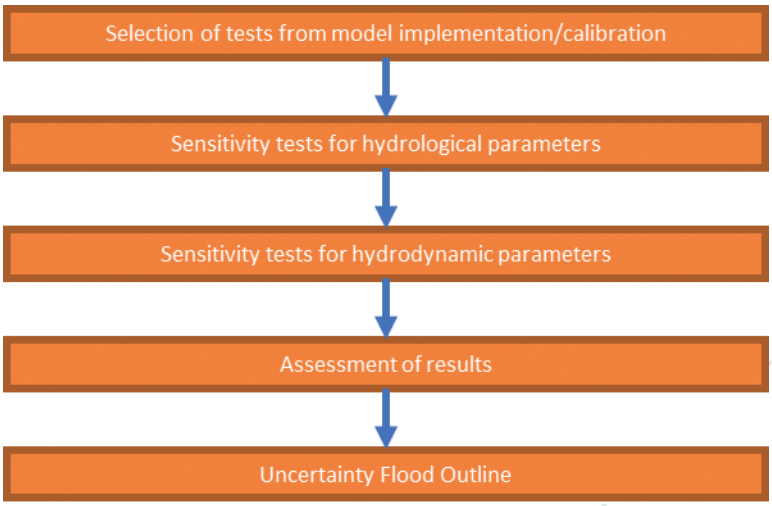

Figure 7-2. Uncertainty Stages

7.2 Sensitivity Tests

Although sensitivity tests have been described throughout this methodological report, this section includes a summary of the main tests to be undertaken and the values that can be used. Some of the tests are of a hydrological nature and so they will not be described in this report.

The following sections discuss the range of the sensitivity tests required and provide examples of how parameters should be adjusted in order to reflect known uncertainties. In all cases, it is important to consider the sensitivity tests as a sensible shift within the bounds of plausibleness.

The following sensitivity tests are outlined for consideration:

- Discharge (fluvial only).
- Precipitation (pluvial only).
- Storm-surge (coastal only).
- Wave overtopping volume (coastal only).

- Roughness (all).
- Blockage of structures (fluvial, pluvial, and coastal).
- Spill coefficient (for 1D-2D models).

This list is not exhaustive and where a predicted flood hazard is dependent on additional parameters or modelling assumptions, these should be highlighted in the model report and investigated through further sensitivity tests.

7.2.1 Discharge

As flow is probably the most critical of all of the sensitivity tests for fluvial flooding, it will be important to consider the quality of the data available in the derivation of the design flows.

A flow sensitivity tests for ±20% on the full flow hydrograph is recommended. This percentage may be adjusted depending on the river modeller but the reasons for doing so must be documented in the uncertainty statement.

7.2.2 Rainfall

Rainfall boundary conditions for pluvial assessments should be subject to sensitivity tests with an increase and decrease in precipitation intensity of ±15% of the total rainfall and an increase and decrease of ±50% of the storm duration.

7.2.3 Coastal Boundaries

Wave height and period boundary conditions should be subject to a ±20% variation in the overtopping rate for sensitivity tests and also a ±20% variation in the storm-surge water level.

7.2.4 Roughness

Sensitivity tests will be applied to uniform change in roughness by ±15% of the calibrated value. This will be undertaken at the same time in both the 1D and the 2D domains in fluvial model implementations and only in the 2D domain for the other flood sources.

7.2.5 Blockage of Structures

The blockage of structures has already been raised as a significant issue in Georgia. Three different scenarios were discussed above with 25%, 50% and 75% blockages. While the 75% blockage may be realistic in some scenarios, it would be unrealistic to present results assuming this percentage of blocking in all culverts and structures; moreover, it would certainly compromise the level of understanding of the uncertainty maps. A 25% blockage will be assumed in key culverts for uncertainty purposes.

7.2.6 Spill Coefficients

As detailed above, the spill coefficients for the links between 1D and 2D modules are a source of uncertainty because the complex flow processes occurring in these cases are 3D in nature while they are solved by the weir equation. The spill coefficient will be varied in key locations with a ±10% increase and decrease. This test will only be undertaken in key locations.

7.3 Assessment of Results and Uncertainty in Flood Mapping

Once all of the tests outlined above are undertaken, a thorough assessment of the results will be done. The main idea behind this assessment is to select the uncertainty flood outline (or bound). There are several procedures for this such as a cumulative assessment or the selection of the larger extent; the recommendation is for the latter to be followed. All of the flood extents from the sensitivity test for a particular flood source and for a particular location will be superimposed. The larger extent of all of the combinations will be used as the uncertainty flood map. This means that the uncertainty extent will be determined by the combination of the maximum combined extent from two sources of uncertainty if the roughness test, for example, provides the larger extent in an upstream location and the spill coefficient test provides a larger extent in a downstream location. This is summarised for Batumi in Figure 7-3 below where the final uncertainty flood extent is shown in yellow.

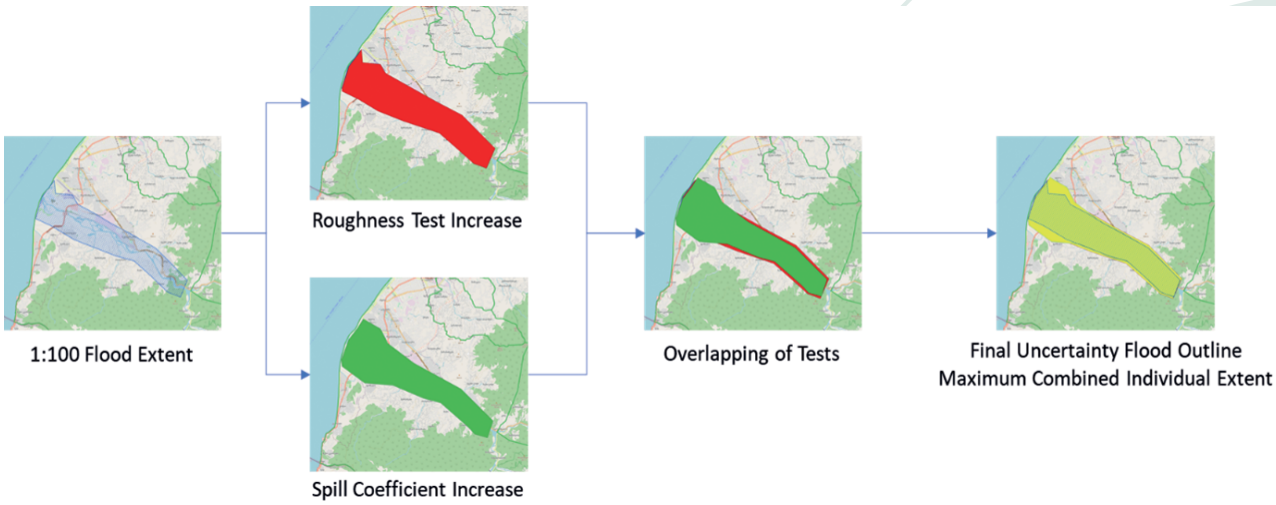

Figure 7-3. Uncertainty Result Assessment and Mapping

08

Flood Risk Management Plans

As noted above, the third stage requires the implementation of flood risk management plans in the catchments where flooding was predicted (or historically recorded) within the implementation of the European Union Floods Directive. The general objectives of the flood risk management plans are:

1. Increasing awareness of flood risks and improving self-protection strategies among the population; economic and social actors are to deal with this risk.
2. Enhancing the coordination and the collaboration of all stakeholders involved, taking into account that flood risk management is a shared responsibility among all administrations and society.
3. Improving the understanding of flood phenomena through specific studies in order to better manage flood risk.
4. Improving flood forecasting and early warning systems for a better response in the case of flood events.
5. Helping to enhance land-use and urban planning policies and the management of the exposure of people and assets in flood prone areas.
6. Reducing flood risk through the reduction of the hazard by means of the enhancement of infiltration, giving rivers more space and also the construction, modification or removal of structures that have a significant impact on the hydrological regime.
7. Improving resilience and reducing the vulnerability of goods and the different land-uses located in the floodplain.
8. Enhancing or maintaining, where appropriate, the good status of water bodies by means of the improvement of their hydro-morphological conditions according to the Water Framework Directive objectives.

The Directive also requires member states to coordinate their flood risk management practices in cross-national river basins so as to avoid measures that would increase flood risk in neighbouring countries.

The European Commission has identified the following in terms of flood mitigation measures:

- Prevention:
  - Land-use planning policies.
  - Removal and relocation of land-use activities which cause flooding.
  - Adapting land-use to flood risk.
  - Other measures.
- Protection:
  - Measures to reduce the flow, enhancement of infiltration or the restoration of natural systems.
  - Construction, modification and/or removal of water retaining structures.
  - Construction, modification and/or removal of defensive structures in a channel or floodplain.
  - Measures to reduce surface water flooding such as SUDS (Sustainable Urban Drainage Systems).
  - Other measures.
- Preparedness:
  - Flood forecasting and warning.
  - Emergency event response planning.
  - Public awareness and preparedness.
  - Other measures.
- Recovery and review:
  - Restoration activities, health and psychological support actions, disaster-relief financial activities.
  - Environmental recovery, clean-up activities.
  - Lessons learnt.

The methodology for the implementation of flood risk management plans is outside of the scope of this report but it will be important to consider the fact that this needs to eventually happen after flood hazard and risk mapping and that the models and methodologies implemented at this stage will be very useful in the risk management stage.

09

Flood Forecasting

The hydraulic modelling implementations will be the basis for a flood forecasting early warning system to be deployed within the framework of this project. There are several recommendations from a forecasting point of view, considering each of the flood sources:

9.1 Fluvial

The fluvial hydraulic implementation would rely on 1D-2D models. One of the reasons to follow this approach is to consider the implementation of forecasting models. Fluvial flooding is the most relevant source of flooding in Georgia and, therefore, all of the flood hazard models will be implemented in an operational mode using the 1D component.

9.2 Pluvial

As noted above in the methodology, the pluvial flood hazard assessment will be based on the implementation of 2D hydrodynamic models forced directly by precipitation. From a forecasting point of view, however, it is not expected that the 2D models will be implemented on an operational basis. At this stage, the forecasting implementation of pluvial flooding cannot be defined, especially until the hazard assessment defines the areas at risk. The pluvial forecasting approach will be undertaken and defined by the flood forecasting EWS expert. Nonetheless, depending on the impact assessment and the data sources ultimately used in the modelling, it would be recommended to use a precipitation threshold approach. Therefore, an analysis of the different rainfall depth-intensity and the resulting flood hazard and risk impact would be undertaken, and a matrix of thresholds can be developed and implemented.

9.3 Groundwater

The implementation of the groundwater flood modelling is the most uncertain at the moment due to data availability and the limited modelling resources existing in Georgia at the NEA. At this stage, the implementation of a global conceptual-box model is the most probable. This model will mostly need

rainfall input for its operation and the computing resources are not expected to be significant. Therefore, it is believed that the groundwater flood model can be fully implemented on an operational basis.

9.4 Coastal

The coastal flood forecasting implementation will depend on the main processes involved in the flooding. As noted, it is considered that waves play the major role in the coastal flooding impact at this stage. If this is indeed the case, wave forecasting information will be collected in the system after a more detailed assessment has been undertaken. The modelling products previously outlined from MyOcean (Copernicus) are also available in a forecasting mode and it would be important to establish links to collect these data automatically and feed them into the system. The coastal modelling methodology is based on using the sea-level and wave inputs as boundary conditions for the coastal inundation models (in 2D). As per the pluvial source, it is not expected that these 2D models can be run in an operational mode and, therefore, a wave threshold approach is also recommended.

9.5 AWBS

The AWBS flood source methodology relies on the derivation of flood hydrographs after an infrastructure failure and the routing of those hydrographs through a 2D hydrodynamic model. The derivation of the breach hydrograph would depend on the triggering mechanism for the failure and the breaching mechanism. Nonetheless, as per previous cases and because the inundation mapping is based on the implementation of a 2D hydrodynamic model, it is not believed that this will be implemented operationally. The forecasting and the EWS for the AWBS is slightly more complicated from an institutional point of view since reservoir and dam operators have responsibilities for this. Therefore, the implementation of the AWBS forecasting will be undertaken on a case-by-case basis.

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Annexes

11.1 Annex I

DATA AVAILABLE FOR HYDROLOGICAL-HYDRAULIC MODELLING

Overview

The Supsa, Natanebi and Kintrishi River catchments are located in the Lanchkhuti, Ozurgeti and Kobuleti municipalities. The Lanchkhuti and Ozurgeti municipalities are administrative-territorial units of the Guria region with areas of 533 and 645 $km^{2,}$ respectively. From the west, the municipalities are bordered by 18 and 20 km of Black Sea coast (resort). The Kobuleti municipality is located in the south-western part of Georgia and in the northern part of the Autonomous Republic of Adjara. It is located between the Black Sea, the Choloki River, and the ridge of Meskheti. Its area is 712 km^2 and the length of the coastline is 24 km.

The investigated area is located on the border of moderate and sub-tropical climate zones. The proximity of the Black Sea and the high ridges to the east cause high humidity. The average annual rainfall is 2,100-2,800 mm. The maximum precipitation falls in September and the minimum in May. The average annual air temperature is 14.5°C to -4°C. The coldest month is January (+ 5°C to -5°C) and the warmest is August (+ 23°C to + to 13°C). The absolute minimum temperatures are -17°C-18°C (coastal lowlands) and -30-32°C (high mountains). The absolute maximum ranges between 31-41°C. The territory of the municipality is characterised by seasonal winds: south-east winds in winter and west winds in summer. The average wind speed is 3.2 metres/second. The Föhn winds blow in winter and spring. The municipalities are in the danger zone of 5-6 magnitude earthquakes.

The project's technical methodology identified the main data sets that are needed for the hydrological and hydraulic modelling of the Supsa, Natanebi and Kintrishi River basin. The following is a discussion of the data sets that are normally required for hydrological modelling and their availability for the abovementioned basins separately.

Supsa River

Catchment Topography

The Supsa River is the longest and highest discharge river in Guria in the Lanchkhuti municipality. It is separated from the Rioni River watershed by the Guria ridge and from the Natanebi River by the

Nasakirali ridge. The Supsa River originates on the northern slope of the Adjara-Imereti Range, 0.8 km south of Mount Mepistskaro (2850.6 m) and close to Lake Jaji (Jeli; 2,327 m, 0.01 km^2, endorheic lake) at 2,600 m and flows into the Black Sea near the village of Grigoleti. The length of the river is 108 km, the average slope is - 24.1 ‰, the catchment area is 1,130 km^2 and the average height is 970 m.

The catchment area includes 790 rivers with a total length of 1,428 m, among them the larger rivers are: Baramidzistskali (length 21 km), Gubazeuli (length 47 km), Atsavra (length 12 km), Bakhvistskali (length 42 km) and Shuti (length 12 km). The density of the river network is 1.26 km/km^2. The shape of the Supsa River basin is asymmetrical, 85 km long and with an average width of 13.3 km. Its northern border is a latitudinal Guria ridge with a height of 500-900 m. The southern border in the upper part of the river is the longitudinal Adjara-Imereti ridge, the main mountain system of which is about 2,600-2,850 m high. The lower reaches of the river basin on the south are bordered by the Nasakirali ridge with a height ranging from 110-216 m. From the east, the basin is bordered by a system of mountains 2,730-2,210 m high. The relief of the Supsa River from the confluence to the village of Bukistsikhe is mountainous and crossed with narrow and deep river valleys. Below the village of Bukistsikhe, the terrain of the river is mountainous and straighter but retains deep and dense river tributaries. According to the geomorphological structure, the upstream of the catchment is mainly composed of tuffogenic rocks, granular quartz sandstones and clay-sand layers with the rest of the basin featuring conglomerate sediments and a mixture of marls, pebbles, and sand. The source of the river basin is covered with alpine plants. Vegetation below 2,000 m is represented by mixed forest, mainly fir, pine, beech, hornbeam, oak and etc. A large part of the basin below the village of Bukistsikhe is occupied by agricultural lands. The afor-estated area of the basin is about 70% of its total area.

Figure 1 shows the SRTM DEM of the Supsa catchment. The elevation in the basin ranges from > 2,850 m down to 0 m at the Black Sea outlet with steep terrain in the furthest upstream areas and gentle to flat terrain downstream of the village of Supsa. The DEM will be used to delineate the sub-catchments to the main rivers within the basin for which hydrographs will be derived for the hydraulic model.

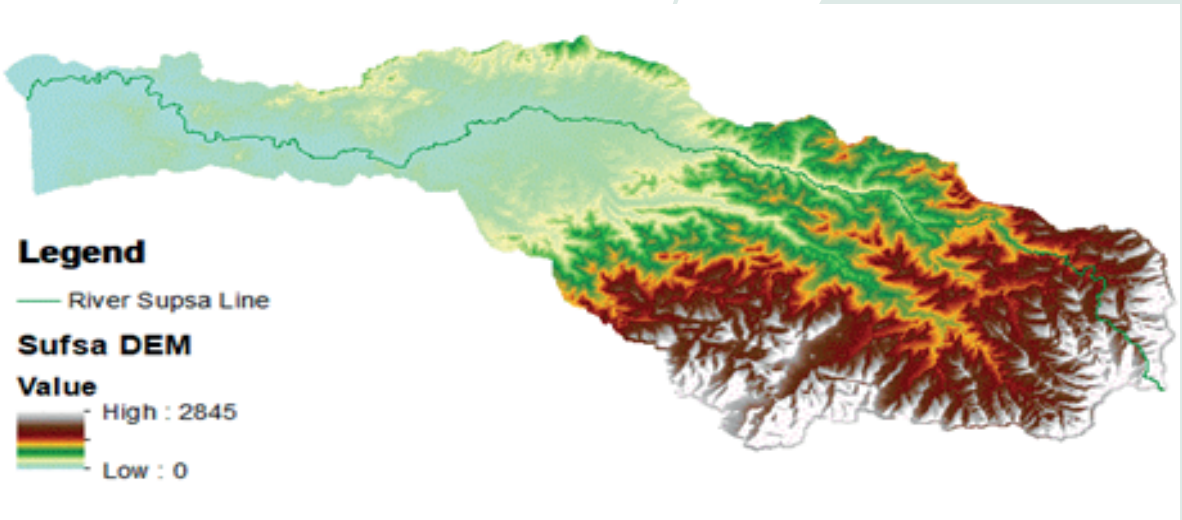


Figure 1. DEM of the Supsa Catchment

Field Investigation

The Supsa River can be divided into two sections according to the characteristics of the valley, the floodplain, and the riverbed.

First: from the source to the village of Bukistsikhe (108-63 km). Here, the river valley has a V-shaped form and its width from the bottom to the slope varies from 20 to 50 meters, rarely reaching 100-300 m (near the village of Bukistsikhe). The floodplain slopes are quite steep from 30-40° to 50-70° and are separated by the river's tributaries and dry gullies that are full of water during the melting period. The riverbed is moderately meandering and not branching. The average inclination of the river in this section is 55 ‰. The width of the river varies from 2 (107-100 km from the confluence) to 20 m (near the village of Didi-Vani) with an average width of 10 m. The depth of the river varies from 0.1 to 0.6 m and the flow velocity is 0.7-1.2 metres/second and in some places 2-3 metres/second (107-95 km from the confluence). The bottom of the river is rough, covered with boulders, gravel, and large and small pebbles.

Second section: from the village of Bukistsikhe to the confluence of the river (63 km long). Here, the valley has the shape of a trapezoid except for the 8-10 km section at the confluence where the river flows on the lowland. The bottom of the valley is 1-4 km wide with the widest part at 3-4 km between the villages of Bukistsikhe and Nagomari and the narrowest at 1.0-1.5 km. The slopes of the gorge have a slope of 10-20 with different widths of terraces at the foot of the slopes (1.5-3 km in the village of Bukistsikhe-Nagomari and 0.5-1.2 km in the village of Ianeti-Supsa) and a height of 3-8 m. The slopes are channelised with numerous rivers on the Guria ridge. The Supsa River between the villages of Bukistsikhe and Supsa has a 30-120 m floodplain with a height of 0.3-1 m which is covered with boulder-pebble and silt while shrubs are rarely found. The riverbed is moderately meandering and branching. The river often flows with two or three tributaries and forms islands. The width of the Supsa River in the section between the villages of Bukistsikhe and Nagomari do not exceed 30 m. It rises to 70-80 m below Nagomari but is mostly 35 m. The river's depth varies from 0.2 m (Bukistsikhe) to 1.8 m (at the confluence) and is mostly 0.8 m. The flow velocity is 0.5 metres/second near the confluence and 1.2 metres/second near the village of Bukistsikhe, mostly 0.6 metres/second. The riverbed is mostly straight and covered with boulders, gravel, pebbles and sometimes with silt and sand.

During the field investigation, a topographical survey was carried out in the Supsa River catchment. On the Supsa River and its two main tributaries, the Gubazeuli and the Bakhvistskali, different sized bridges and gas pipes were identified. Cross sections were made in 187 sections and identified 17 different sized bridges and gas pipes on the Supsa River, 28 cross sections and six bridges on the Bakhvistskali River and 75 cross sections and 17 bridges on the Gubazeuli River.

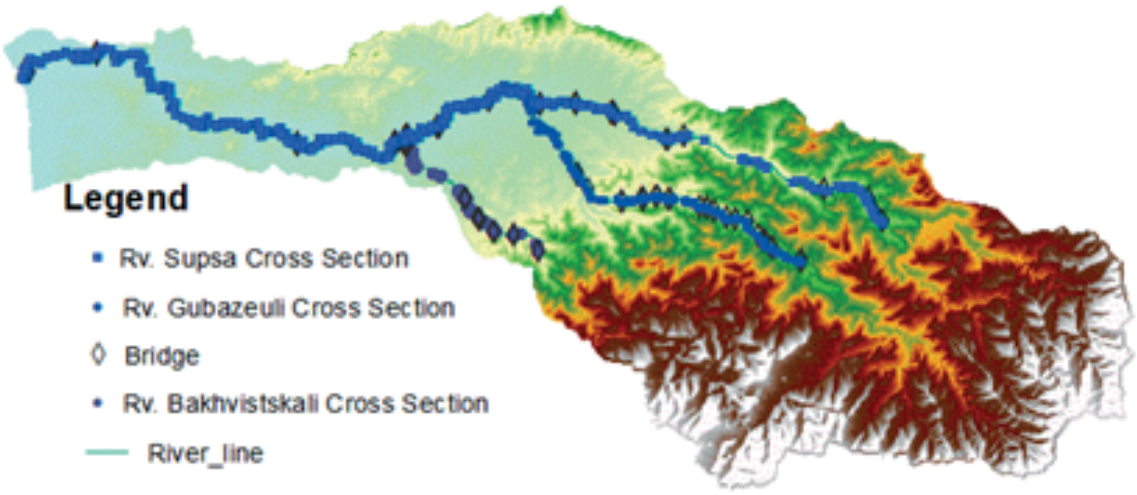


Figure 2. Topographical Survey of the Supsa Catchment

Land-use

Land-use data comprise one of the data sets which is used to set the runoff parameters to estimate the roughness for the sub-catchments when undertaking hydrological modelling. It is key to determining what percentage of the precipitation falling on the ground will be converted to runoff. Figure 3 shows the land-use of the Supsa catchment.

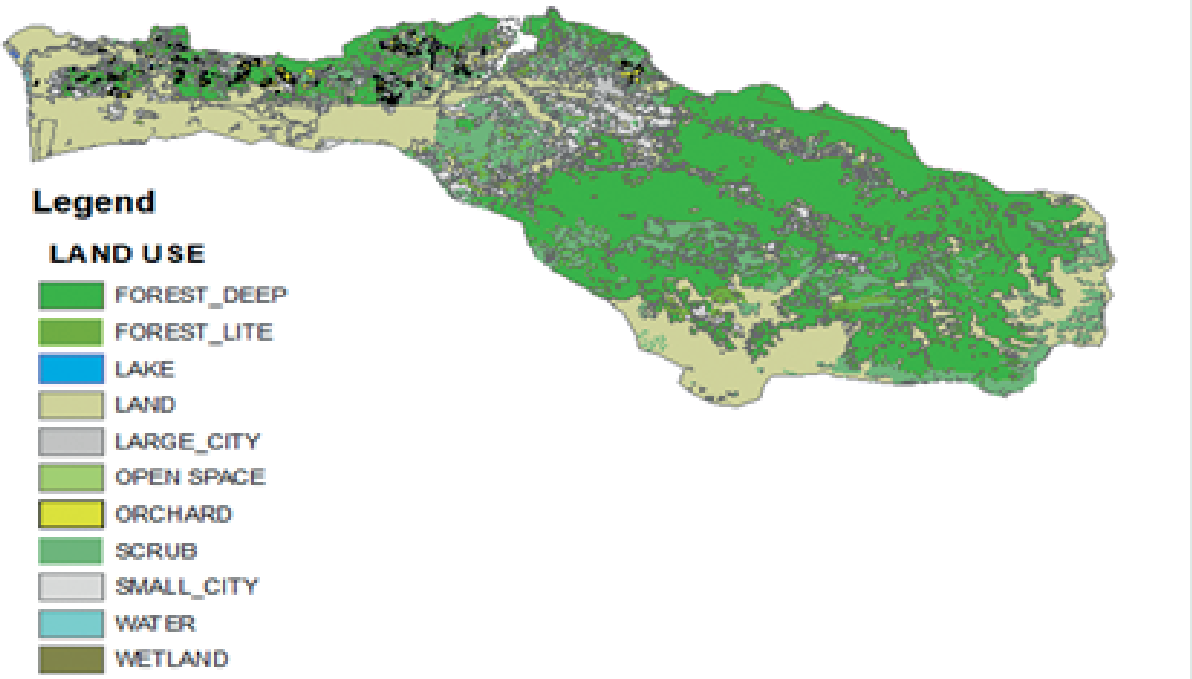


Figure 3. Land-use Map of River Supsa Basin

A large part of the Supsa River catchment area is occupied by forests, swamps, and various objects of the cultural landscape. There is a deciduous forest (alder, hornbeam, beech) at 700-1,700 metres above sea-level and a coniferous forest (pine, fir, spruce) at 1,700-2,100 metres above sea-level. Peat swamps and Colchis forests with evergreen undergrowth are unique in the Kolkheti lowlands. Due to anthropogenic degradation, a significant part of the Colchian forests and swamps is currently occupied by secondary meadows, forest-shrubland and arable lands, and citrus and tea plantations.

Soil Type and Geology

Paper-based digitised soil type and geological maps are available. Some data have been provided by the National Agency of Public Registry and the Ministry of Environmental Protection and Agriculture. Due to the influence of climatic-relief and geological conditions, there are different types of soils in the study of the river basins. Peat bog and meadow sandy soils as well as podzolic and swampy varieties of alluvial soils are developed on weakly fragmented surfaces in a significant part of the Kolkheti lowland in the conditions of abundant atmospheric precipitation and redundant surface runoff. Large areas in the elevated portions of the plains are occupied with bleached sub-tropical podzols. Figure 4 shows the soil type of the Supsa catchment.

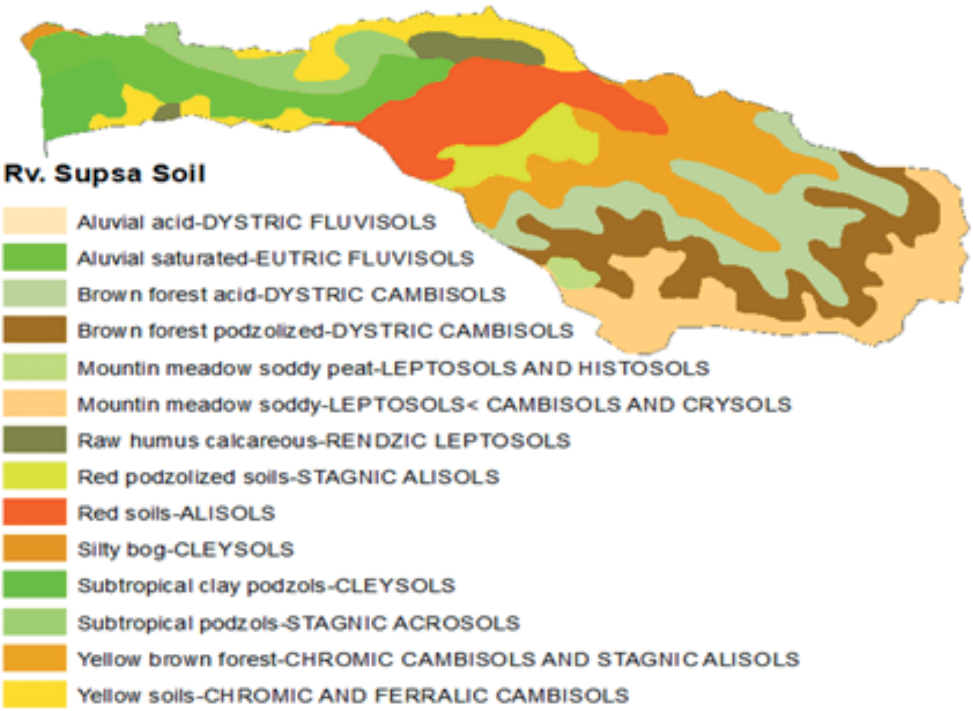


Figure 4. Soil Type Map of the Supsa River Basin

Table 1 shows the soil types, depth, and hydrological group of the Supsa River catchment.

Table 1

#	Soil Name	Soil Depth cm	Soil Hydrological Group
1	Dystric fluvisols – Alluvial Acid	60-80	A
2	Eutric fluvisols – Alluvial Saturated	60-80	A
3	Dystric cambisols – Brown Forest Acid	50-70	A
4	Dystric cambisols – Brown Forest Podzolized	50-70	A
5	Leptosols and histosols – Mountain Meadow Soddy	30-40	A
6	Leptosols and histosols – Mountain Meadow Soddy Peat	50	A
7	Rendzic leptosols – Raw Hummus Calcareous	50-80	A
8	Stagnic alisols – Red Podzolized Soils	80-100	A
9	Alisols – Red Soils	120-150	A
10	Gleysols – Silty Bog	120-150	A/D
11	Gleysols – Subtropical Gley Podzols	70-80	B
12	Stagnic acrisols – Subtropical Podzols	50-80	B
13	Chromic cambisols and stagnic alisols–Yellow Brown Forest	100-120	A
14	Chromic and ferralic cambisols – Yellow Soils	100-120	B

Neogene and oligocene sediments are mainly prevalent in most parts of the study area. Quaternary sediments are represented by the river and marine types with terraces of different ages having been built. Here, there are alluvial-proluvial sediments, deluvial-proluvial sediments on the slopes of the valley and proluvial outcrops in the valley. Modern alluvial-proluvial sediments, which are located at the bottom of the valley, are characterised by a diverse composition: there are both boulder and fragmented rock sediments with fillers of clay, sand-gravel and sometimes loam.

Meteorological and Hydrological Data Sets

Systematic and frequent hydro-meteorological observations over a long time are vital for the full modelling and representation of the hydro-meteorological response of a catchment and can provide evidence of how the climate has changed throughout the record.

The historical hydrological and meteorological observational records that exist for the Supsa basin are digitised. Historically, the NEA had 18 meteorological stations in the Supsa River basin with different observation programmes. Table 2 shows the meteorological stations and their metadata. Meteorological data are collected for atmospheric air and soil temperatures, precipitation, snow cover, wind speed and direction, humidity, cloudiness, pressure and other meteorological elements and events. Currently, there is one rain gauge and one automatic meteorological post located in the Supsa River basin.

Table 2

#	Station Name	Station Type[64]	Region	District	River Basin	Elevation	Latitude	Longitude	Observation Period		Digital Data	
									Start Year	End Year	Start Year	End Year
1	Anaseuli	MS	Guria	Ozurgeti	Supsa, Natanebi	158	41°55’	041°59’	1948	1992	1955	1992[65]
2	Anaseuli	MP	Guria	Ozurgeti	Supsa, Natanebi	158	41°59’	041°55’	1993	2005	-	-
3	Gomi	MP	Guria	Ozurgeti	Supsa, Natanebi	295	41°54’	042°06’	1928	1991	1961	1991
4	Natanebi	MP	Guria	Ozurgeti	Supsa, Natanebi	10	41°55’	041°50’	1948	2005	1948	2005[66]
5	Qveda Bakhvi	RAIN	Guria	Ozurgeti	Supsa, Natanebi	200	41°58’	042°05’	1948	1988	1961	1988
6	Vakijvari	MP	Guria	Ozurgeti	Supsa, Natanebi	400	41°56’	042°08’	1952	1991	1952	1991
7	Bakhmaro	MS	Guria	Chokha-tauri	Supsa	1926	41°51’	042°19’	1922	2011	1936	2011
8	Chokha-tauri	MS	Guria	Chokha-tauri	Supsa	136	42°01’	042°14’	1936	2006	1936	2006
9	Chokha-tauri	RAIN	Guria	Chokha-tauri	Supsa	136	42°01’	042°14’	2007	Active	2008	Until now
10	Chokha-tauri	AWS	Guria	Chokha-tauri	Supsa	136	42°01’	042°14’	2014	Active	2014	Until now

64. **MS – Meteorological Station**
Measured Parameters: Air and soil temperature, precipitation (rain, snow), cloud cover (amount, form, height), humidity (relative, water vapor pressure, saturation deficit, dew point temperature), wind (speed, direction), air pressure (station, sea-level, tendency), weather phenomena
Till 1935: 3 observations per day (17UTC-03UTC-09UTC).
1936-1965: 4 observations per day (21UTC-03UTC-09UTC-15UTC).
Since 1966: 8 observations per day (18UTC-21UTC-00UTC-03UTC-06UTC-09UTC-12UTC-15UTC).
MP – Meteorological Post
Measured Parameters: Maximum and minimum air temperature, precipitation (rain, snow), weather phenomena
2 observations per day (03UTC-15UTC).
RAIN – Rain Gauge Post
Measured Parameters: Precipitation (rain, snow), weather phenomena
2 observations per day (03UTC-15UTC).
AWS – Automatic Meteorological Station
Measured Parameters: Air temperature, precipitation, humidity (relative, dew point temperature), wind (speed, direction), air pressure (station, sea-level, tendency)
24 observations per day (each 1 hour).

65. Missing Data: 1963-1965

66. Missing Data: 1995-2001

11	Khidistavi	RAIN	Guria	Chokha-tauri	Supsa	142	41°59’	042°14’	1954	1992	1954	1992
12	Khidma-ghala	RAIN	Guria	Lanch-khuti	Supsa	10	42°02’	041°48’	1954	1992	1954	1992
13	Lanchkhuti	MS	Guria	Lanch-khuti	Supsa	10	42°06’	042°02’	1914	2000	1955	2000
14	Lanchkhuti	MP	Guria	Lanch-khuti	Supsa	10	42°06’	042°02’	2001	2006	2001	2006
15	Nabeghlavi	RAIN	Guria	Lanch-khuti	Supsa	475	41°57’	042°22’	1948	1992	1948	1992
16	Nigoiti	RAIN	Guria	Lanch-khuti	Supsa	14	42°06’	042°07’	1946	1988	1947	1988
17	Supsa	MP	Guria	Lanch-khuti	Supsa	7	42°04’	041°48’	1958	1969	1958	1969
18	Zoti	RAIN	Guria	Chokha-tauri	Supsa	1270	41°54’	042°21’	1942	1981	1942	1981

The Supsa River belongs to the type of Black Sea rivers which are characterised by floods and flash floods throughout the year. During the year, the number of floods varies from between 15-27 on average. Heavy flooding is mainly in the autumn while spring floods begin in mid-March to late May. The duration of the peak levels is five to ten days. The main hydrological characteristics of the Supsa River are given in Table 3.

Table 3

Characteristic	Calculation Points										
	1,337,6 m height	Village of Zemosurebi	300 m height	259.8 m height	Town of Chokhatauri	To the Gubazeuli River confluence	Below the Gubazeuli River confluence	Below The Bakhvistskali River confluence	To the Bakhvistskali River confluence	Village of Khidmaghala	Confluence
Basin area, km^2	54.0	186	254	277	316	360	722	842	959	1100	1130
Basin mean height, m	2,090	1,670	1,300	1,270	1,250	1,100	1,200	1,050	1,095	970	970
Average annual runoff, m^3/s	2.56	8.52	11.2	12.1	13.8	15.3	31.1	35.2	40.5	44.8	46.0
Maximum annual runoff, m^3/s	-	-	-	-	135	-	-	-	-	514	

The historical hydrological observational records that exist for the Supsa River basin are digitised. Historically, the NEA had four stations on the Supsa River. Presently, there is only one automatic station, but the data are often not quality controlled. Table 4 gives the list of hydrological stations and the metadata.

Table 4

River	Hydrological Station	F, km²	Latitude	Longitude	Water Level and Discharge (cm, m³/s)
Supsa	V. Zemo-Surebi	186	41 58	42 27	1935, 37, 38
Supsa	T. Chokhatauri	316	42° 00¢ 35.68 ²	42° 14¢ 21.29²	1932--35, 40-48, 50-2011
Supsa	St. Supsa	1100	42 02	41 49	1915-17, 19-34, 37-39
Supsa	V. Khidmaghala	1100	42 02	41 48	1940-50, 54-92

Peak Discharges

The different return period floods are necessary in order to model the response of the Supsa catchment and the sub-catchments. To calculate the different return period floods, more than 40 years of peak discharge data are available for the Supsa Chokhatauri hydrological station.

Table 5

Year	Peak Discharge, m³/sec	Event Date
1941	220	7.10
1942	98.9	3.04
1943		
1944	75.0	22.09
1945	161	8.06
1946	120	15; 28. 10
1947		
1948	113	10.04
1949	-	
1950	136	23.10
1951	166	13.11
1952	134	29.11
1953	128	23.11
1954	84.0	3.05
1955	246	3.11
1956	146	23.07
1957	72.0	17; 19.12
1958	67.0	25.10
1959	132	23.11
1960	65.8	2.12
1961	61.0	1.12
1962	154	9.10

1963	112	24.11
1964	111	5.10
1965	119	9.11
1966	41.5	5.07
1967	290	2.12
1968	100	12.09
1969	99.0	29.10
1970	98.0	9,30.10
1971	94.1	9.10
1972	64.6	4.11
1973	98.1	22.06
1974	67.2	20.04
1975	59.8	4.04
1976	104	27.09
1977	139	18.08
1978	177	9.04
1979	104	2.12
1980	96.2	19.09
1981	81.7	4.11
1982	149	1.04
1983	97.6	30.12
1984	92.3	26.11
1985	71.0	20.01
1986	35.2	16.04
1987	134	15.08
1988	63.7	31.01
1989	71.5	20.10;18.11
1990	76.0	18.12
1991	129	7.07

Kintrishi River

Catchment Topography

The Kintrishi River originates on the north-western slope of the Meskheti Range near Mount Khino (2,599 m) at 2,320 m and joins the Black Sea close to Kobuleti. The length of the river is 45 km, the average slope is 52‰, the catchment area is 291 km^2 and the average height is 835 m. The river network is quite dense, consisting of small rivers with a total length of 653 km. Relatively large tributaries are as follows: Magalakhevisghele (12 km) and Kinkisha (15 km). The average density of the river network is 2.24 km/km^2.

The Kintrishi River basin occupies part of the mountains and foothills of the Adjara-Imereti ridge between the Natanebi and Atchkva Rivers in the north and the Adjaristskali, Chakvistskali and Dekhva Rivers in the south. The basin has a longitudinal direction from east to west. Its average width is 10-11 km, and the length is 32.33 km. There are high mountains at about 2,600-1,000 m high along the watershed ridge, mountains of the Adjara-Imereti ridge in the north and a mountain system at a height of 2,250-1,150 m in the south. The relief of the basin is mainly crossed with mountainous and multi-flowing-branched valleys. The terrain is slightly mountainous (50-100 m) only near the confluence at a distance of 5-6 km.

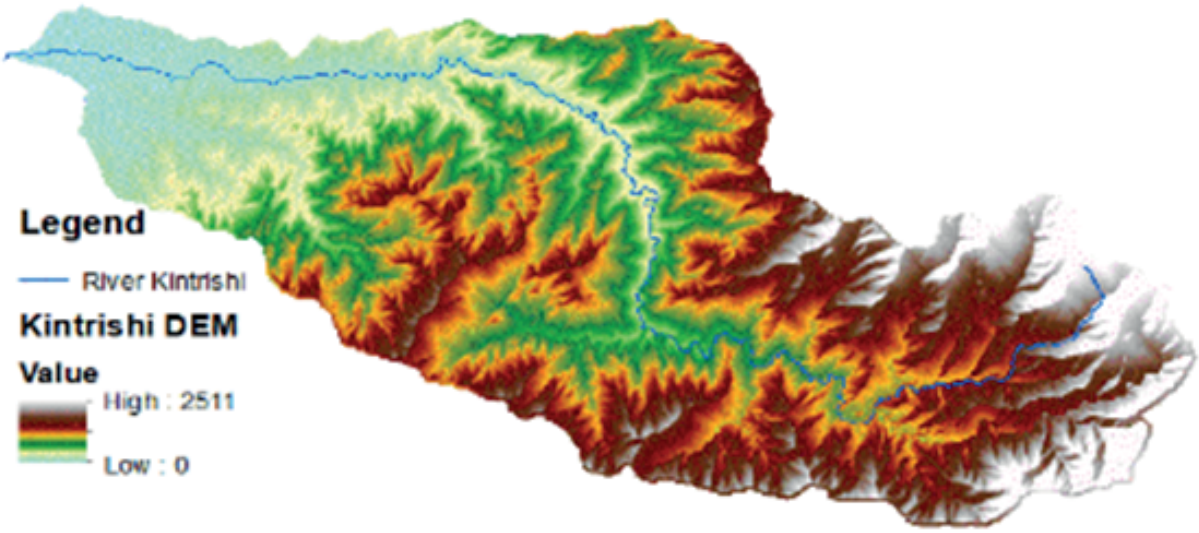


Figure 5. DEM of the Kintrishi Catchment

Field Investigation

The Kintrishi River valley is mainly V-shaped from the village of Khutsubani to the confluence of the trapezoid. The bottom width of the V-shaped valley is mainly 10-50 m and rarely 80-120 m (near the village of Zemokhino). The width of the riverbed in the trapezoidal part of the valley is 0.4-1.0 km. The slopes of the valley merge with the surrounding ridges which are strongly crossed by lateral tributaries and have a concave shape. The slope inclination is 20-40° and 8-10° in the trapezoidal part of the valleys. The slopes to the village of Zedaboslebi are covered with mixed forest. The area below the confluence features a deciduous forest. Terraces are found from the village of Dzakhati to the confluence. Their width at the beginning is 50-200 m, and 200-800 m at the confluence. The height of the terraces is 3-12 m, and their loamy surfaces are straight and transversely inclined (1-30). The terraces are covered with arable land, gardens and tea and citrus plantations.

The width of the floodplain in the downstream is 20-80 m, the height is 0.5-1.2 m, and it is covered with pebbles and stones. It is flat and covered with a layer of water up to 0.7-2.0 m during floods. The riverbed is meandrous and branches below the village of Khutsubani up to the confluence. The width of the Kintrishi River varies from 1 m to 80 m at the confluence while mostly at a width of 20 m. The

depth varies from 0.2 m (east of the village of Zemokheti) to 3 m (near the village of Chakhati) but is mostly 1.2 m deep. The flow speed changes from 0.7 metres/second (near the town of Kobuleti) to 1.8 metres/second (near the village of Kokhi) while mostly showing a speed of 1.0 metre/second. The channel of the Kintrishi River upstream is covered with boulder-pebbles and stones, and with pebbles and gravel downstream. The riverbanks of the mountainous part of the catchment up to the village of Kokhi merge with the slopes of the valley. Downstream before the confluence, their height varies from 0.5-1.2 m, they are 3-12 m within the boundaries of the floodplain and reach 3-12 m in the part where the terraces are located. The beaches are moderately developed, mainly with pebbles and gravel, and rarely with loam.

A topographical survey in the Kintrishi River catchment was carried out during the field investigation. Different sized bridges were identified on the Kintrishi River and its one main tributary, the Kinkisha. Cross sections were made in 45 sections and eight different sized bridges were found on the Kintrishi River while 26 cross sections and five bridges were found on the Kinkisha River.

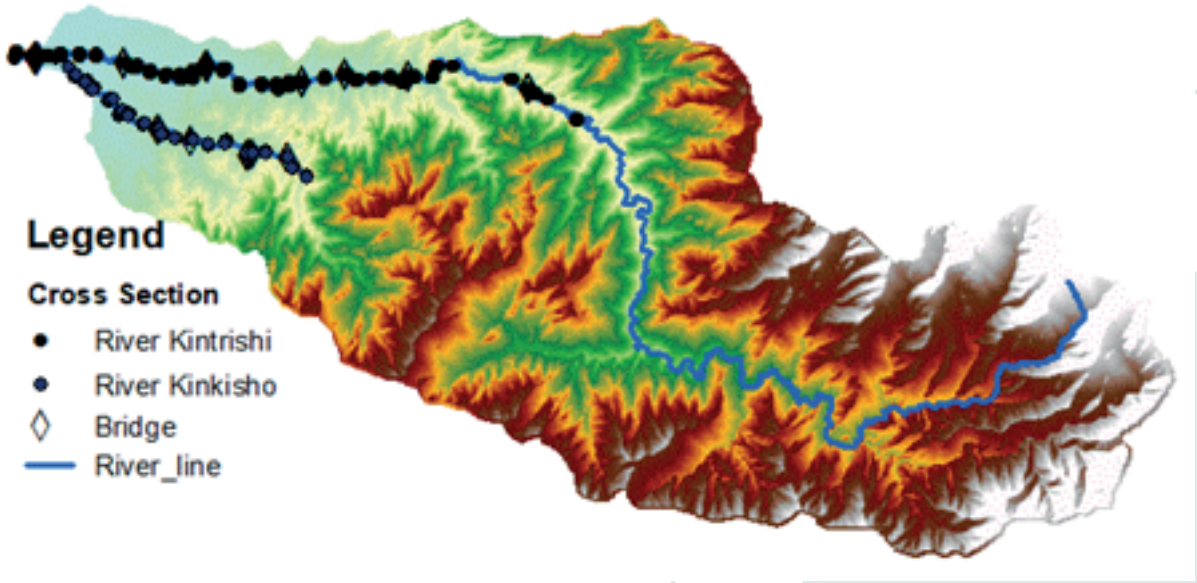


Figure 6. Topographical Survey of the Kintrishi Catchment

Land-use

Land-use data comprise one of the data sets which is used to set the runoff parameters to estimate the roughness for the sub-catchments when undertaking hydrological modelling. It is key to determining what percentage of the precipitation falling on the ground will be converted to runoff. Most of the catchment area of the Kintrishi river (70% of the whole area) is covered with dense forest, deciduous-coniferous upstream and deciduous below the village of Zedaboslebi. There are arable lands, gardens, tea plantations and tung-tree downstream of the river.

Figure 7. Land-use Map of the Kintrishi River Basin

Soil Type and Geology

Paper-based digitised soil type and geological maps are available. Some data have been provided by the National Agency of Public Registry and the Ministry of Environmental Protection and Agriculture. Due to the influence of climatic-relief and geological conditions, there are different types of soils in the study's river basins. Peat bog and meadow sandy soils as well as podzoly and swampy varieties of alluvial soils are developed on weakly fragmented surfaces on a significant part of the Kolkheti lowland in the conditions of abundant atmospheric precipitation and redundant surface runoff. Large areas in the elevated portions of the plains are occupied by bleached sub-tropical podzols. Podzolic forest and loamy soils are common in the upper part of the Kintrishi River basin and red soils are found in the middle and downstream areas. The figure below shows the soil types in the Kintrishi catchment.

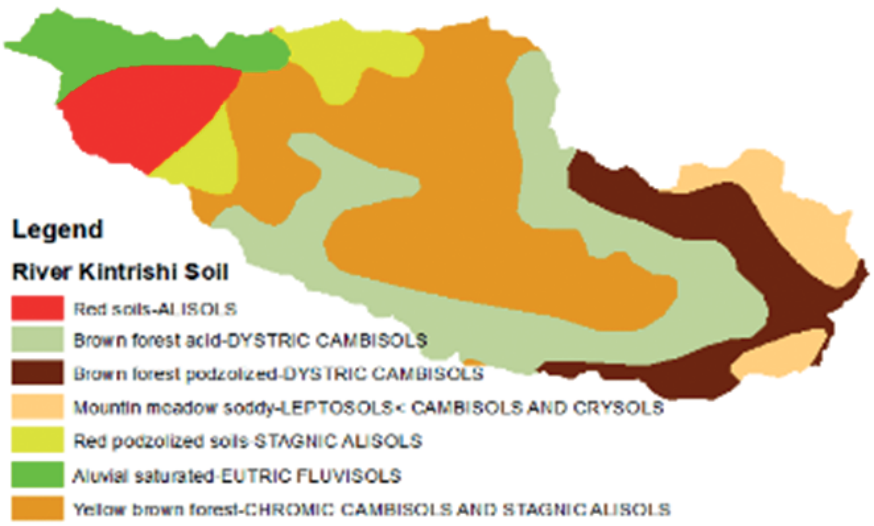


Figure 8. Soil Type Map of the Kintrishi River Basin

Table 6 shows the soil types, depth, and hydrological group of the Kintrishi River catchment.

Table 6

#	Soil Name	Soil Depth cm	Soil Hydrological Group
1	Eutric fluvisols – Alluvial Saturated	60-80	A
2	Dystric cambisols – Brown Forest Acid	50-70	A
3	Dystric cambisols – Brown Forest Podzolized	50-70	A
4	Leptosols and histosols – Mountain Meadow Soddy	30-40	A
5	Stagnic alisols – Red Podzolized Soils	80-100	B
6	Alisols – Red Soils	120-150	A
7	Chromic cambisols and stagnic alisols–Yellow Brown Forest	100-120	A

Tuffogens, andesites and basalts are found in the upper reaches of the Kintrishi River from the source to the village of Zedaboslebi. The rest of the basin features tertiary rocks covered with alluvial, deluvial and alluvial sediments.

Meteorological and Hydrological Data Sets

Systematic and frequent hydro-meteorological observations over a long period of time are vital for the full modelling and representation of the hydro-meteorological response of a catchment and can provide evidence of how the climate has changed over the period of record.

The historical hydrological and meteorological observational records that exist for the Kintrishi basin are digitised. Historically, the NEA had eight meteorological stations in the Kintrishi River basin with different observation programmes. Table 7 shows the meteorological stations and their metadata. Meteorological data are collected for atmospheric air and soil temperatures, precipitation, snow cover, wind speed and direction, humidity, cloudiness, pressure and other meteorological elements and events. Currently, there is one rain gauge and one automatic meteorological post located in the Supsa River basin.

Table 7

#	Station Name	Station Type	Region	District	River Basin	Elevation	Latitude	Longitude	Observation Period		Digital Data	
									Start Year	End Year	Start Year	End Year
1	Chaqvi	MS	Adjara	Kobuleti	Kintrishi	30	41°44’	041°44’	1897	2006	1936	2006
2	Chaqvistavi	RAIN	Adjara	Kobuleti	Kintrishi	315	41°41’	041°50’	1947	1992	1947	1992
3	Dagva	MP	Adjara	Kobuleti	Kintrishi	200	41°45’	041°48’	1942	1992	1942	1992
4	Kokhi	MP	Adjara	Kobuleti	Kintrishi	112	41°48’	041°55’	1943	2003	1943	1992
5	Mtsvane Kontskhi	MP	Adjara	Kobuleti	Kintrishi	94	41°42’	041°43’	1966	1992	1966	1992
6	Kobuleti	MS	Adjara	Kobuleti	Kintrishi	5	41°52’	041°47’	1897	2011	1955	2011
7	Kobuleti	MP	Adjara	Kobuleti	Kintrishi	5	41°52’	041°47’	2011	Active	2011	Until now
8	Kobuleti	AWS	Adjara	Kobuleti	Kintrishi	5	41°52’	041°47’	2010	Active	2010	Until now

The Kintrishi River is characterised by flash floods throughout the year with a short period between floods (15-25 days) mainly observed in July-August. Mostly, the flash floods occur during September-November. In late summer and autumn, floods caused by heavy rain rise the river level by 2.5-3.3 m. The average height is 1.3-1.7 m, and the duration is one to two days. Other dangerous hydro-meteorological events are not observed on the river.

The Kintrishi River is fed from mixed sources. The average annual flow of the river at the village of Kokhi varies from 7.55 metres^3/second to 15.2 metres^3/second. The water-level of the river is shallow in winter and summer. The winter runoff is 16.6% of the annual runoff, the summer runoff is 18.1%, the spring runoff is 34-36% and the autumn runoff is 28.32%. The river’s water is clean, transparent, and suitable for drinking. River water is not used for agricultural purposes.

The main hydrological characteristics of the Kintrishi River are given in Table 8.

Table 8

Characteristic	Calculation Points							
	770.0 m height	600.0 m height	Village of Zara-bosleli	Village of Kokhi	To the Kintrishi River confluence	Below the Kintri-shi River confluence	Town of Kobuleti	Confluence
Basin area, km^2	56.8	72.8	95.4	191	209	246	251	291
Basin mean height, m	1,670	1,470	1,420	1,120	1,020	940	940	835
Average annual runoff, m^3/s	4.25	5.17	6.72	12.3	13.2	15.0	15.3	17.3
Maximal annual runoff, m^3/s	-	-	-	444	-	-	-	-

The historical hydrological observational records that exist for the Kintrishi basin are digitised. Historically, the NEA had two stations on the Kintrishi River. Presently, there is only one automatic station, and the data are often not quality controlled. Table 9 gives the list of hydrological stations and the metadata.

Table 9

River	Hydrological Station	F, km^2	Latitude	Longitude	Water Level and Discharge (cm, m^3/s)
Kintrishi	V. Kokhi	191	41 48	41 54	1930-33 1940-91
Kintrishi	T. Kobuleti	251	41 48	41 47	1930-35

Peak Discharge

The different return period floods are necessary to model the response of the Kintrishi catchment and sub-catchments. About 50 years of peak discharge data for the Kintrishi Kokhi hydrological station are available for calculating the different return period floods.

Table 10

Year	Peak Discharge, m^3/sec	Event Date
1942	125	15.09
1943	130	16.09
1944	94.8	15.07
1945	93.9	19.08
1946	149	6.10
1947	267	30.10
1948	267	20.09
1949	287	5.10
1950	128	3.08
1951	169	28.10
1952	175	9.05
1953	107	20.10; 23.11
1954	107	22.07; 21.08
1955	72.5	31.03
1956	97.7	21.11
1957	81.0	3.07
1958	53.2	9.03-25.10 (3)
1959	68.5	12;14.1
1960	57.6	21.06
1961	78.0	22.09
1962	328	12.09
1963	84.0	2.08
1964	137	6.10
1965	72.0	31.12
1966	69.6	5.07
1967	147	2.12
1968	68.6	1.07
1969	164	24.06
1970	74.9	9.10
1971	179	19.08
1972	67.0	4.11
1973	67.6	22.06
1974	53.5	3.09
1975	106	12.08

1976	104	17.10
1977	130	18.08
1978	158	1.11
1979	194	1.08
1980	95.5	4.10
1981	81.0	24.11
1982	185	1.04
1983	121	25.08
1984	64.0	14.10
1985	227	20.10
1986	236	6.11
1987	224	10.08
1988	131	19.08
1989	158	14.09
1990	111	14.09
1991	444	7.07

Natanebi River

Catchment Topography

The Natanebi river originates on the northern slope of the Adjara-Imereti (Meskheti) ridge at an altitude of 2,560 m and joins the Black Sea at the village of Shekvetili. The length of the river is 60 km, the catchment area is 657 km^2 and the average height of the basin is 830 m. The river has a well-developed river net, especially on its left side and its upper reaches. There is a total of 727 rivers in the Natanebi River basin with a total length of 1,052 km and an average density of the river network of 1.6 km/km^2. Its main tributaries are the rivers: Bzhuzha (length 32 km), Skurdubi (length 13 km), Orapo (length 11 km) and Choloki (length 24 km).

The river basin is located in the western part of the southern highlands and is bordered on the north by the Supsa River and from the south by the Kintrishi River basin. The Natanebi River basin is asymmetrical in shape, its length is 63 km, and its maximum width is 22 km. The upstream of the Natanebi River on the north-western slope of the Adjara-Imereti Range is mountainous and characterised by the mountain's lowlands and deep valleys cut by the numerous tributaries. The slopes of the ridge are steep and merge with the river valleys at 400-600 m above sea-level. Steep slopes cause a rapid flow of the river and related events. The river flows in the hilly cave of the Natanebi foothills relief downstream of the village of Vakijvari. From the north, it is bordered by the southern slope of the Nasakirali mountain system and to the south by the mid-height watershed ridge of the Kintrishi and Achkva Rivers. The height of the eastern part of the cave is 350-400 m while the coastal plain is 20-0 m. The river flows in the flat and swampy Kolkheti lowland below the hilly cave of the Natanebi foothills.

The river valley changes shape from the source to the confluence. The shape from the source to the village of Vakijvari is V-like with a 20-40 m wide bottom. In this section, the inclination of the slopes varies from 20° to 30° and rarely reaches 50° (2.5 km upwards from the village of Korisbude). The shape is trapezoidal from the village of Vakijvari to the train station in the village of Meria. The width of its bottom varies from 250m (1.5 km below the village of Vakijvari) to 1.5 m (near the village of Zedauchkhubi). The slope of the valley is relatively less steep (10-12°) and is indistinctly shaped and represents a wide straight valley from the train station in the village of Meria to the confluence.

The terraces are well defined in the middle and lower reaches on both sides of the river with 200-400 m wide and 2.5-5 m high steps. The surface of the terraces is levelled clay covered with pastures and gardens. The floodplain on both banks of the river is found in the area of the village of Korisbude to the confluence. Its width varies from 40 m (2.5 km below the village of Korisbude) to 500 m (near the village of Kakhuri); the average width is 60-70 m, and the floodplain height is 0.5-0.8 m. The floodplain is rough and covered with sand-pebbles and is devoid of vegetation. During the high-water level, it is covered with a 0.2-2.0 m water layer.

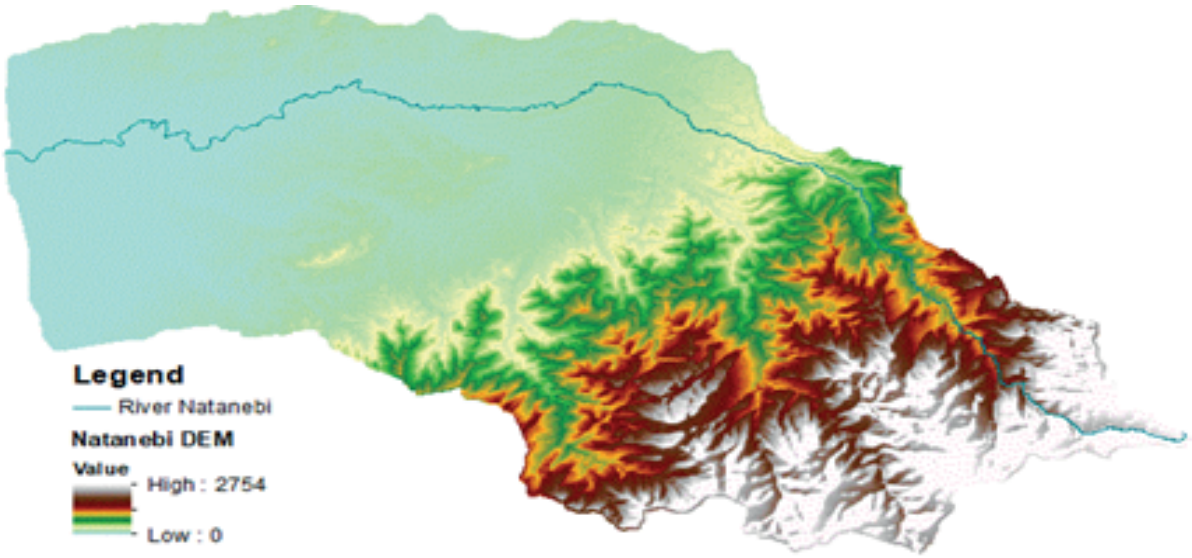


Figure 9. DEM of the Kintrishi Catchment

Field Investigation

The width of the Natanebi River varies from 1-2 m (at the source) to 60-70 m (at the confluence), the average width to the village of Vakisjvari is 5 m and 20 m up to the confluence. The depth varies from 0.2-0.7 m in mountainous areas to 1.5-2.0 m in the lowlands and the flow velocity in the mountainous part is 1-1.5 metres/second and up to 0.4-0.6 metres/second in the lowlands.

The riverbed from the source to the village of Vakijvari is moderately meandering and unbranched and is characterised by a rapid flow. The riverbed is branched and meandering from the village of Vakijvari on the way out to the lowlands with a radius of 100-200 m, forming mainly 50-300-metre-long islands.

The bottom of the river is homogeneous with pebble-sand upstream and sandy pebbles in other sections. The banks within the floodplain are low (0.2-0.8 m) and of boulder-pebble nature. The slopes in the upper reaches of the river are mostly covered with dense forests while the banks are clayey in the lowlands. The steps of the plateaus are of a uniform height of 2-3 m (right bank) and 4-11 m (left bank).

A topographical survey was carried out in the Natanebi River catchment during the field investigation. Different sized brides were identified on the Natanebi River and its four tributaries: the Skurdubi, Atchistskali, Bzhuzha and Akidakva. Cross sections were made in 105 sections and 15 different sized bridges and gas pipes were revealed on the Natanebi River. Further, 33 cross sections and five bridges were identified on the Skurdubi River, 30 cross sections and five bridges were identified on the Atchistskali River, 39 cross sections and five bridges were identified on the Bzhuzha River and 20 cross sections, and four bridges were found on the Akidakva River.

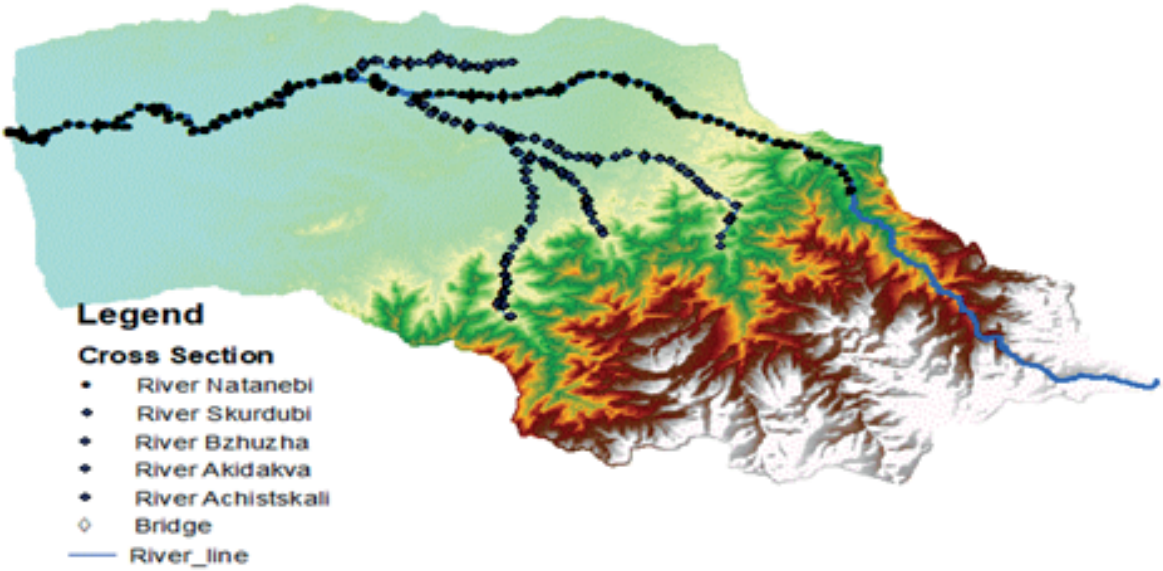


Figure 10. Topographical Survey of the Natanebi Catchment

Land-use

The vegetation of the Natanebi River basin is characterised by vertical zonation. Alpine vegetation on the mountain-meadow is located on the mountainous part above 2,000 meters. Mixed forest is widespread below 2,000 meters. The basin area is covered with arable land and tea plantations as well as sparse shrub below the village of Vakijvari before the confluence of the river. The total forested area of the catchment does not exceed 50-60% of its total area.

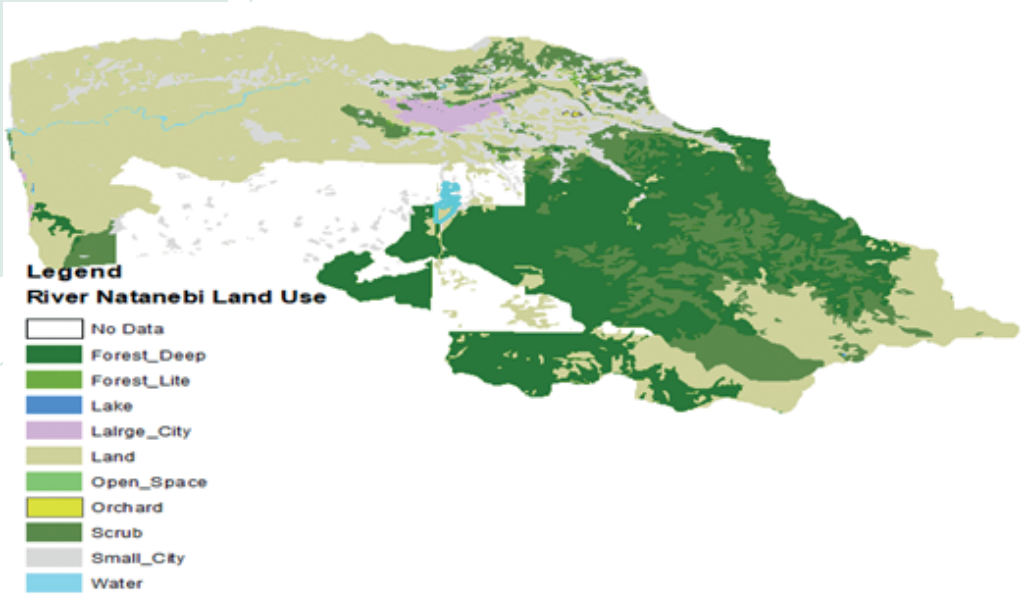


Figure 11. Land-use Map of the Natanebi River Basin

Soil Type and Geology

Paper-based digitised soil type and geological maps are available. Some data have been provided by the National Agency of Public Registry and the Ministry of Environmental Protection and Agriculture. Due to the influence of climatic-relief and geological conditions, there are different types of soils in the study of river basins. Peat bog and meadow sandy soils as well as podzolic and swampy varieties of alluvial soils are developed on weakly fragmented surfaces on a significant part of the Kolkheti lowland in the conditions of abundant atmospheric precipitation and redundant surface runoff. Large parts in the elevated areas of the plains are covered with bleached sub-tropical podzols. There are alluvial red alisols and cumbisols in the coastal zone of the Natanebi catchment. The figure shows the soil types of the Natanebi catchment.

Figure 12. Soil Type Map of the Natanebi River Basin

Table 11 gives the soil types, depth, and a hydrological group of the Natanebi catchment.

Table 11

#	Soil Name	Soil Depth cm	Soil Hydrological Group
1	Dystric fluvisols – Alluvial Acid	60-80	A
2	Dystric cambisols – Brown Forest Acid	50-70	A
3	Leptosols and histosols – Mountain Meadow Soddy Peat	50	A
4	Rendzic leptosols – Raw Hummus Calcareous	50-80	A
5	Stagnic alisols – Red Podzolized Soils	80-100	A
6	Alisols – Red Soils	120-150	A
7	Gleysols – Silty Bog	120-150	A/D
8	Gleysols – Subtropical Gley Podzols	70-80	B
9	Chromic cambisols and stagnic alisols–Yellow Brown Forest	100-120	A
10	Chromic and ferralic cambisols – Yellow Soils	100-120	B

Meteorological and Hydrological Data Sets

Systematic and frequent hydro-meteorological observations over a long period are vital for the full modelling and representation of the hydro-meteorological response of a catchment and can provide evidence of how the climate has changed throughout the record.

The historical hydrological and meteorological observational records that exist for the Natanebi basin are digitised. Historically, the NEA had six meteorological stations on the Natanebi River with different observation programmes. Table 12 is giving the meteorological stations and their meta-data. Meteorological data are collected for atmospheric air and soil temperatures, precipitation, snow cover, wind speed and direction, humidity, cloudiness, pressure and other meteorological elements and events. Currently, there is one rain gauge and one automatic meteorological post located in the Supsa River basin.

Table 12

#	Station Name	Station Type	Region	District	River Basin	Elevation	Latitude	Longitude	Observation Period		Digital Data	
									Start Year	End Year	Start Year	End Year
1	Anaseuli	MS	Guria	Ozurgeti	Natanebi	158	41°55’	041°59’	1948	1992	1955	1992
2	Anaseuli	MP	Guria	Ozurgeti	Natanebi	158	41°59’	041°55’	1993	2005	-	-
3	Gomi	MP	Guria	Ozurgeti	Natanebi	295	41°54’	042°06’	1928	1991	1961	1991
4	Natanebi	MP	Guria	Ozurgeti	Natanebi	10	41°55’	041°50’	1948	2005	1948	2005
5	Qveda Bakhvi	RAIN	Guria	Ozurgeti	Natanebi	200	41°58’	042°05’	1948	1988	1961	1988
6	Vakijvari	MP	Guria	Ozurgeti	Natanebi	400	41°56’	042°08’	1952	1991	1952	1991

The Natanebi River is characterised by strong and intense floods throughout the year. Spring floods, which last from March to May, are formed in the upper reaches of the river at 1,000-1,500 m and are accompanied by rain-induced flash flooding. During snowy periods, high water levels is observed throughout the river basin in April and May. There are four to 14 flash floods in autumn. The river’s average height before the flood is 0.8-0.9 m above normal level. Flash floods are also quite frequent in winter and occur between three and 13 times with a height 1-3 m. Flash floods are relatively rare in spring and summer (two to ten times); nevertheless, they are particularly strong in summer, and the water-level reaches 5-6 m close to the village of Natanebi. The shallow water period in between the floods (15-25 days) is mainly observed in July-August.

Table 13

Characteristic	Calculation Points						
	1380,0 m height	Village of Qorisubani	Village of Vakijvari	TO the Bzhuzha River confluence	Below The Bzhuzha River confluence	Village of Natanebi	Confluence
Basin area, km^2	34.4	54.0	70.0	128	381	469	657
Basin mean height, m	2,110	1,970	1,720	1,110	1,100	880	830
Average annual runoff, m^3/s	2.12	3.41	4.63	7.14	21.0	24.2	33.5
Maximal annual runoff, m^3/s	-	-	-	-	-	708	-

The historical hydrological observational records that exist for the Kintrishi basin are digitized. Historically, the NEA had three stations on the Natanebi River. Presently, there is only one automatic station, and the data are often not quality controlled. Table 14 gives the list of hydrological stations and the metadata.

Table 14

River	Hydrological Station	F, km^2	Latitude	Longitude	Water Level and Discharge (cm, m^3/s)
Natanebi	V. Korisbude	54.0	41 52	42 12	1943-49
Natanebi	V. Vakijvari	70.0	41 56	42 08	1942-49
Natanebi	V. Natanebi	469	41 55	41 49	1930-47, 49-91

Peak Discharges

The different return period floods are necessary to model the response of the Natanebi catchment and the sub-catchments. More than 50 years of peak discharge data for the Natanebi V. Natanebi hydrological station is available in order to calculate the different return period floods.

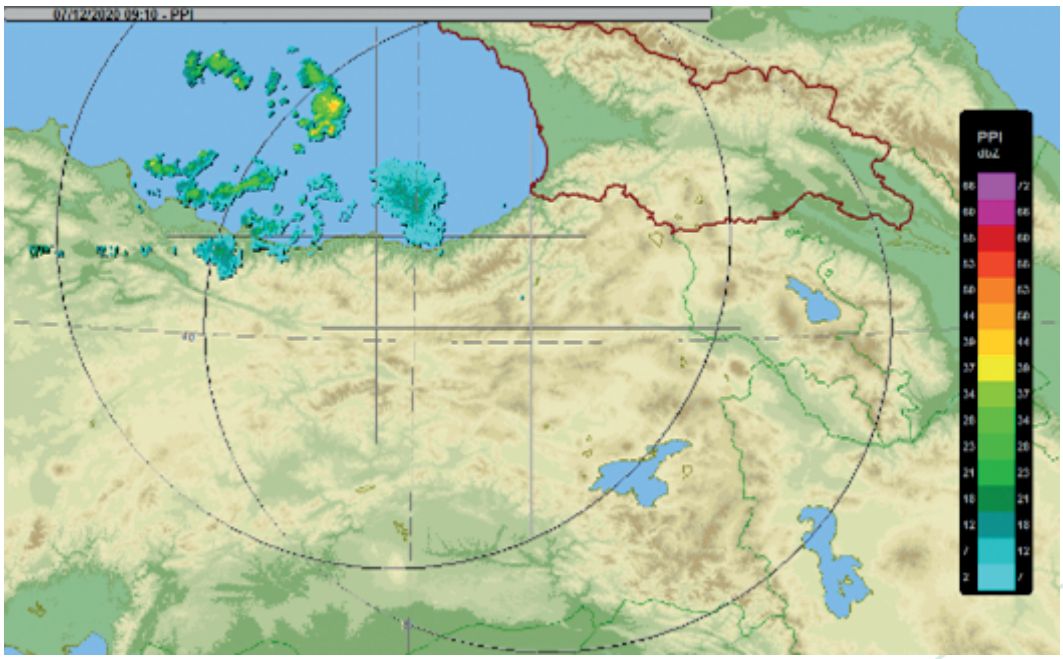
Table 15

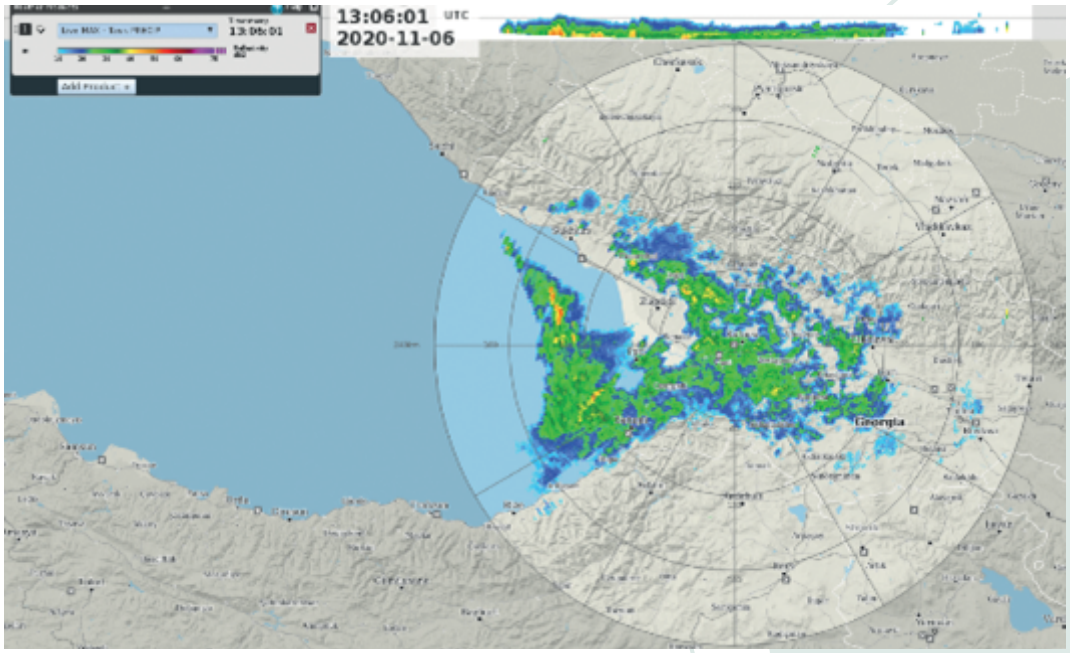
Year	Peak Discharge, m^3/sec	Event Date
1938	133	12.03
1939		
1940	141	25.10
1941		
1942	244	15.09
1943	177	16.09
1944	392	16.09
1945	132	23.10
1946	89.0	3.07
1947	112	7.09
1948		
1949	350	6.10
1950	263	9.10
1951	330	28.10
1952	322	25.09
1953	313	23.11
1954	322	3.10
1955	318	3.11
1956	272	2.11

1957	204	3.07; 27.10
1958	167	20.03
1959	392	12.10
1960	305	6.07
1961	257	22.09
1962	392	9.10
1963	310	22.09
1964	306	5.10
1965	263	14.10
1966	480	6.07
1967	282	12.03
1968	247	12.09
1969	276	24.06
1970	226	9.10
1971	708	19.08
1972	315	4.11
1973	291	22.06
1974	272	26.11
1975	205	12.08
1976	347	3.07
1977	527	18.08
1978	404	9.04
1979	300	5.06
1980	455	19.09
1981	363	24.11
1982	283	1.04
1983	406	29.12
1984	339	13.11
1985	348	1.10
1986	215	18.06
1987	520	10.08
1988	364	22.01
1989	310	14.09
1990	390	14.09
1991	701	7.07

Weather Forecast

Presently, three different locations vis-à-vis radar data are available in the investigated area. Two of them belong to the National Meteorological Service of Turkey and one is located in the western part of Georgia in Kutaisi.





The main system for the national weather forecasting service is a standard application of SYNERGIE (deployed at two workstations) developed by Météo France International. The SYNERGIE is a tool for accessing and integrating meteorological data – for example, outputs from the ARPEGE model, SYNOP data and AWS data from Georgia and data from WMO GTS.

ARPEGE – the forecast resolution is T539L60C2.4; i.e., 15 km horizontal resolution over Europe and an increasing vertical resolution closer to the tropopause. The model is launched four times a day, every six hours, at set times of 00:00, 06:00, 12:00 and 18:00 UTC. The variable forecast periods are: 96 hours, 48 hours, 72 hours, and 30 hours.

Since 2013, the WRF model has been running within the NHMS by the Administration of Hydro-meteorological Forecast Models Adaptation and Implementation (created in 2013). The predicted meteorological fields are given for 84 hours ahead (every three hours for the first and the second day and every six hours for the third and the fourth day), http://www.wrf odel.org/index.php.

Georgia is not a member of EUMETSAT but receives data directly from EUMETSAT satellites by EUMETCast. The satellite data are used in forecasting and warning services. The polar satellites are used as well. Some satellite data (for example, the land-use data from Sentinel-1) are used for glacier observation (Paul et al, 2007; Haeberli et al, 2007).

11.2 Annex II

Questionnaire for the Description of Past Flood Events

A separate questionnaire is filled out for each past flood event which has occurred in each settlement.

	Settlement		
	Municipality		
1	**FLOOD INFORMATION**		
1.1	**Time frame**		
1.1.1	Date and hour of commencement of the flood event.		
1.1.2	Duration of the flood event.		
1.1.3	The number of times an event of a similar size has occurred at this location (number).		
1.1.4	The number of years elapsed between floods of a similar size at this location (number).		
1.2	**FLOOD DESCRIPTION**		
1.2.1	Source of flooding (one or more options can be selected).	☐ Fluvial flooding ☐ Pluvial flooding ☐ Sea-water flooding	☐ Groundwater flooding ☐ Artificial water-bearing infrastructure flooding
1.2.2	Mechanism of flooding (one or more options can be selected).	☐ Natural exceedance ☐ Defence exceedance ☐ Defence or infrastructural failure	☐ Blockage / restriction ☐ Other
1.2.3	Characteristics of flooding (one or more options can be selected).	☐ Flash flood ☐ Snowmelt flood ☐ Another rapid onset ☐ Medium onset flood ☐ Slow onset flood	☐ Debris-flow ☐ High velocity flow ☐ Deep flood ☐ Other characteristics, or no special characteristics
1.2.4	Other flood description		

1.3	FLOOD EXTENT INFORMATION		
1.3.1	Type or description of inundated land (one or more options can be selected).	☐ Coordinate files (kmz, kml, shapefile) ☐ Text description ☐ Map	☐ Other ☐ No data available
1.3.2	Description of inundated land,		
1.3.3	Area of inundated land (sq. km),		
1.3.4	Official documents for the past flood event,		
1.3.5	Other settlements affected by the past flood event,		

11.3 Annex III

11.3.1 HEC-RAS

The US Army Corps of Engineers River Analysis System (HEC-RAS) was first released in 1995 and it is an open-source modelling software that is widely used for hydraulic modelling applications. HEC-RAS is an integrated system of software designed for interactive use in a multi-tasking environment. The system comprises a graphical user interface (GUI), separate analysis components, data storage and management capabilities, graphics, and reporting facilities. The HEC-RAS system contains the following river analysis components for:

- Steady flow water surface profile computations.
- One-dimensional and/or two-dimensional unsteady flow simulation.
- Quasi unsteady or fully unsteady flow movable boundary sediment transport computations.
- Water quality analysis.

A key element is that all four components use a common geometric data representation and common geometric and hydraulic computation routines. In addition to the four river analysis components, the system contains several hydraulic design features that can be invoked once the water surface profiles are computed.

HEC-RAS is designed to perform one-dimensional and two-dimensional hydraulic calculations for a full network of natural and constructed channels, overbank/floodplain areas or levee protected areas.

The current version of HEC-RAS is 6.0.1 This new version of HEC-RAS was recently released in Beta mode, and it provides the following new features:

- Spatial precipitation (gridded and point gage options).
- Spatial infiltration; wind forces for 1D and 2D modelling.
- A new shallow water solution scheme and turbulence modelling.
- 1D finite volume solution algorithme.
- Pump stations for 2D areas.
- Bridge modelling inside of 2D areas.
- Structure layout in HEC-RAS Mapper.
- A new 3D viewer for terrain and model results.
- Calibration tools inside of HEC-RAS Mapper for 1D and 2D regions.

11.3.2 Overview of the 1D Engine

The physical laws which govern the flow of water in a stream are:

- The principle of conservation of mass (continuity), and
- The principle of conservation of momentum.

These laws are expressed mathematically in the form of partial differential equations.

The most successful and accepted procedure for solving the one-dimensional unsteady flow equations is the four-point implicit scheme, also known as the box scheme. Under this scheme, space derivatives and function values are evaluated at an interior point. For each river, a system of simultaneous equations results. The simultaneous solution is an important aspect of this scheme because it allows information from the entire reach to influence the solution at any one point. Consequently, the time-step can be significantly larger than with explicit numerical schemes.

The HEC-RAS unsteady flow engine combines the properties of the left and right overbank into a single flow compartment called the floodplain.

Hydraulic properties for the floodplain are computed by combining the left and right overbank elevation vs. area, conveyance, and storage into a single set of relationships for the floodplain portion of the cross-section. The reach length used for the floodplain area is computed by taking the arithmetic average of the left and right overbank reach lengths.

The average floodplain reach length is used in both the continuity and momentum equations to compute their respective terms for a combined floodplain compartment (left and right overbank combined together).

11.3.3 Overview of the 2D Engine

The Navier-Stokes equations describe the motion of fluids in three dimensions. In the context of channel and flood modelling, further simplifications are imposed. One simplified set of equations is the shallow water (SW) equations. Incompressible flow, uniform density and hydrostatic pressure are assumed, and the equations are Reynolds averaged so that turbulent motion is approximated using eddy viscosity. It is also assumed that the vertical length scale is much smaller than the horizontal length scales.

As a consequence, the vertical velocity is small and the pressure is hydrostatic, leading to the differential form of the SW equations derived in subsequent sections. In some shallow flows the barotropic pressure gradient (gravity) term and the bottom friction terms are the dominant terms in the momentum equations and unsteady, advection and viscous terms can be disregarded. The momentum equation then becomes the two-dimensional form of the diffusion wave approximation. Combining this equation with mass conservation yields a one equation model known as the diffusive wave approximation of shallow water (DSW) equations. Furthermore, in order to improve computation time, a sub-grid bathymetry approach can be used. The idea behind this approach is to use a relatively coarse computational grid and finer scale information about the underlying topography. The mass conservation equation is discretised using a finite volume technique. The fine grid details are factored out as parameters representing multiple integrals over volumes and face areas. As a result, the transport of fluid mass accounts for the fine scale topography inside of each discrete cell. Since this idea relates only to the mass equation, it can be used independently of the version of the momentum equation. In the sections below, sub-grid bathymetry equations are derived in the context of both full shallow water (SW) equations and diffusive wave approximation of shallow water equations (DSW).

Modern advances in the field of airborne remote sensing can provide very high-resolution topographic data. In many cases, the data are too dense to be feasibly used directly as a grid for the numerical model. This presents a dilemma in which a relatively coarse computational grid must be used to produce a fluid simulation, but the fine topographic features should be incorporated into the computation. The solution to this problem that HEC-RAS uses is the sub-grid bathymetry approach. The computational grid cells contain some extra information such as the hydraulic radius, volume and the cross-sectional area that can be pre-computed from the fine bathymetry. The high-resolution details are lost but enough information is available so that the coarser numerical method can account for the fine bathymetry through mass conservation. For many applications this method is appropriate because the free water surface is smoother than the bathymetry so a coarser grid can effectively be used to compute the spatial variability in a free surface elevation.

11.3.4 Overview of the Linking Method

The 1D and 2D domains link can be carried out in HEC-RAS through different means, depending on the particular location and the purpose of the linking:

- Standard Link: where one or more 2D grid cells are linked to the end of a 1D river branch. This type of link is useful for connecting a detailed 2D mesh into a broader 1D network. The standard link is explicit.
- Lateral Link: a lateral link allows a string of 2D grid cells to be laterally linked to a given reach in 1D, either a section of a branch or an entire branch. Flow through the lateral link is calculated using the weir equation. This type of link is particularly useful for simulating overflow from a river channel onto a flood plain. For lateral links, flow from the river model goes via a lateral structure which is then applied in a 2D domain. A structure is required to calculate the flow between the 1D and the 2D domains.

11.3.5 Pre-processing Interface

11.3.5.1 Overall Software Structure

11.3.5.1.1 User Interface

The HEC-RAS user interface is compact and easy to navigate. The main modelling interfaces can be accessed in the top menu as well as all the different result-output options. Additionally, the selected file for each specific plan is visible in the lower menu so the user knows what files are being used as input for each scenario (plan).

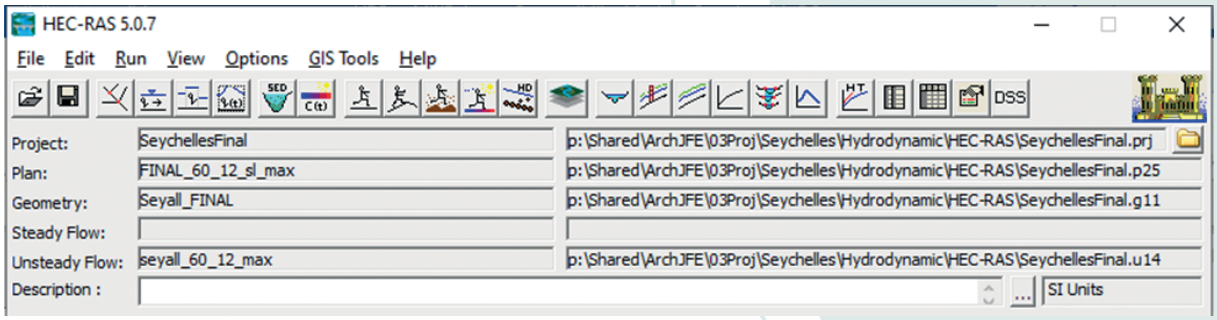


Figure 0-1. Main HEC-RAS Interface

11.3.5.2 Data Editors

As will be described further below, HEC-RAS data can be structured with the HEC database (DSS). However, data management and data input use HEC-RAS formats in some cases. The data editors would vary depending on the type of file, geometry, or flow files. This will be described in detail below. The data editors in HEC-RAS are easy to use but sometimes data formats are very specific.

11.3.5.3 File Structure

The file structure of any HEC-RAS project depends on the type of files. The following should be noted:

- Project files (*.prj).
- Geometry files (*.gXX).
- Steady flow files (*.fXX).
- Unsteady flow files (*.uXX).
- Plan files (*.pXX).

Additionally, geometry and plan files that have a 2D component have an additional HDF file associated with the new 2D and DEM files.

The file name for each file does not correspond to the file name given within the software but file names are assigned in sequence (01, 02, …, 99). Unfortunately, there is a limit in the number of files per type. This means that it is not possible to have 100 (or more) unsteady flow files or 100 geometry files in the same project. While this can seem to be a fair number, but this quantity is not enough in some hydraulic modelling exercises. Further, the software does not warn the user about this issue but only crashes when trying to save the 100th file. In this case, a new project has to be created for additional files.

11.3.5.4 File/Database Formats

As noted above, there is a standard HEC database and boundary condition files can be linked to an external DSS database. No other database format is accepted in HEC-RAS.

11.3.5.5 Data Exchange (Time Series and Spatial Data)

HEC-RAS boundary conditions can be linked to a (external) DSS database for time series data. HEC-RAS results (time-series) can also be exported to a DSS.

Spatial data can be imported into HEC-RAS through the RASMapper. This tool is flexible, and most data formats are allowed and imported. All spatial data are converted to an HDF format in HEC-RAS.

11.3.6 River Geometry

11.3.6.1 Schematisation (Reaches vs Chainage)

The schematisation of rivers and reaches in HEC-RAS can be undertaken directly in the software by digitising or importing a GIS (shape) file. This can currently be undertaken in RASMapper. This could also be undertaken manually in the geometry editor if the point information (x and y) is

pasted in the reach editor. It can be confusing vis-à-vis the activities which can be undertaken in either editor.

Both HEC-RAS and MIKE 11 have different ways of managing reaches and junctions. A new reach is created every time a junction is created in HEC-RAS while a reach keeps its integrity in MIKE even if it has tributaries coming in.

A chainage of 0 in HEC-RAS indicates the most downstream location of a river whereas it is the other way around in MIKE. A chainage of 0 is the most upstream computational point of a river.

11.3.6.2 Delineation and Editing Tools

River branches and reaches can be delineated both in RASMapper and in the geometry editor. The delineation tools are user-friendly.

11.3.6.3 Cross-section Management, Editing and Processing

Cross-section data can be inserted manually in HEC-RAS using the cross-section editor (Figure 02) tool within the geometry editor, specifying first the chainage (river station). Additionally, the data of the cross-sections can be altered graphically (something that cannot be done in MIKE).

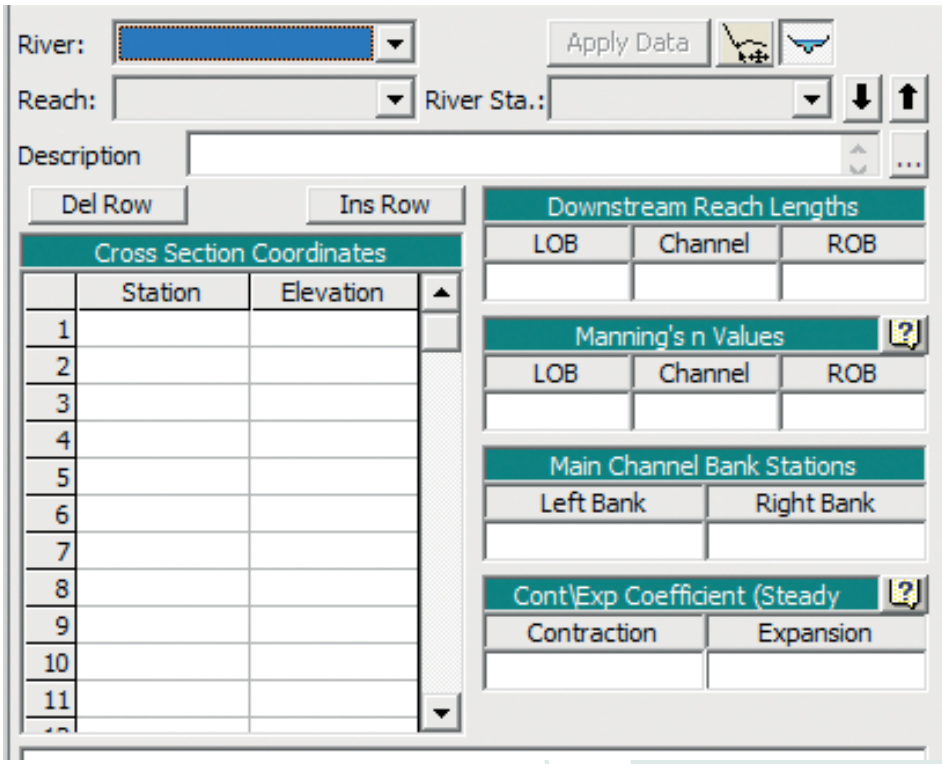


Figure 0-2. Cross-section Editor

The data of the cross-section is pre-computed for unsteady simulations. These data can be observed in the HTab parameters tool within the geometry editor. The number of calculation points can be adjusted as well as the spacing between these points.

11.3.6.4 DEM Processing and XS Extraction

As noted above, spatial data can be imported into from a variety of formats such as asc, geotiff and dem. The data can also be imported into HEC-RAS even if the DEM data are in another projection. They will be converted into the projection stated in RASMapper. Several DEMs can be imported and combined into a single one, giving preferences to specific DEMs when they overlap. However, it is not possible to manually modify the DEM within HEC-RAS at the moment, although this is a feature that is expected in the new version of HEC-RAS to be released.

There are tools in RASMapper for both delineating and extracting DEM into the cross-sections. These tools are at BETA status at the moment, but some testing has found these tools to be working appropriately.

11.3.6.5 Import/Export

Cross-sections can be imported using the following options:

- GIS format.
- USACE survey data format.
- HEC-RAS format (using information from other geometry files from HEC-RAS).
- HEC-2 format.
- UNET geometry format.
- HEC stream alignment.
- MIKE 11 cross sections.
- CSV format.
- GML format.

The possibility of importing MIKE 11 models into HEC-RAS is important to note. Additionally, the CSV format is a very useful capability, although the format specified for this is not very user-friendly because the user has to specify the chainage of each of the cross-sections to be imported.

Further, there are possibilities for creating the whole HEC-RAS model (branches and cross-sections) through the HEC-GeoRAS module of ArcGIS.

The geometry files from HEC-RAS (1D) can be exported into a RAS format to be used in other HEC-RAS files. Additionally, this can be exported into a GIS format through RASMapper. There is also an add-on to export HEC-RAS geometry files into MIKE 11, although this is not widely available and works only for the older versions of HEC-RAS.

11.3.6.6 List all Structure Types

The structures that are allowed in HEC-RAS at this stage are:

- Bridge and culverts.
- Inline structures.
- Lateral structures.
- Pumping stations.
- Storage areas.

There are several formulations available for the modelling of each of these structures. There is a limit in the number of points that can be used (999), especially for lateral structures. This is especially important for the coupling of 1D and 2D models because more than one structure may have to be used to represent the link between the 1D and the 2D models in the case of long lateral structures.

11.3.7 2D Domains

There is no separate module within HEC-RAS for 2D modelling and the same editors used for 1D can be used for 2D.

11.3.7.1 Model Definition

2D domains can be directly specified in the same geometry editor as the one for the 1D geometry or in RASMapper. The definition of 2D domains is straightforward and the user has to digitise the area to be included in the domain as well as the grid size.

The DEM used is the same as the one described in section 11.3.6.4 and several DEMs can be used to define the elevation within the grid. Additionally, an elevation profile is defined in every grid point in HEC-RAS, using all of the information within that specific grid cell.

11.3.7.2 Domain Alteration

The 2D domain can be altered through the use of break-lines. The spacing in the break-lines can be defined and then inserted into the 2D domain for a re-computation of the grid. Each cell can face no more than six other cells, otherwise there is a computational error.

11.3.7.3 Structures in 2D

There is a very limited number of structures that can be included in HEC-RAS in a 2D domain at the moment. This is undertaken through the use of '2D/SA Area Connectors' and only culverts and lateral structures can currently be used. This is expected to be improved in the next HEC-RAS version.

11.3.7.4 Importing/Exporting

There are no features to import or export 2D models from HEC-RAS into or from any other software. The DEM used in the model can be exported into GIS software directly (HDF file).

11.3.8 Boundary Conditions

11.3.8.1 Boundary Definitions

The definition of boundary conditions in HEC-RAS depends on the dimensionality of the model.

1D MODULE

For 1D models, the boundary is defined in the steady or unsteady flow editor (depending on the selected flow regime). The upstream and downstream ends of the model are automatically selected for boundary definition while the user can add river stations (chainage) in between these two.

2D MODULE

In a 2D module, the user has to specify the location of the boundary unless this is a precipitation boundary condition, that at the moment is specified for the whole 2D domain.

11.3.8.2 Boundary Types Supported

The following boundary types are supported in HEC-RAS.

1D MODULE

For the upstream river station, the following boundary conditions are available:

- Stage hydrograph.
- Flow hydrograph.
- Stage/flow hydrograph.

These can be defined as a time-series within the flow editor (for unsteady flow) or by specifying a connection to a DSS database.

For the downstream river station, the following boundary conditions are available:

- Stage hydrograph.
- Flow hydrograph.
- Stage/flow hydrograph.
- Rating curve.
- Normal depth.

The following boundary conditions are available for those additional boundary conditions applied in between the upstream and the downstream as automatically selected stations:

- Lateral inflow hydrograph.
- Uniform lateral inflow.
- Groundwater interflow.
- Internal boundary stage and flow hydrograph.

2D MODULE

For the 2D module, the boundary conditions available would depend on the location of the boundary condition.

For boundary conditions placed outside of the domain, the following boundary condition is available:

- Flow hydrograph.

For the boundary conditions placed outside of the domain, the following boundary conditions are available:

- Flow hydrograph.
- Stage hydrograph.
- Rating curve.
- Normal depth.

Additionally, the following boundary condition is available if no boundary condition is defined for a domain:

- Precipitation.

As per the 1D domain, the boundary conditions can be defined either by inserting the time-series into the editor or by connecting the boundary condition to a DSS database.

11.3.9 Hydraulic Parameters

11.3.9.1 Resistance Definition

In HEC-RAS, the Manning approach (n values) or the roughness height (k values) can be used to define the resistance/roughness in the model. The approach to define this differs depending on the dimensionality of the model.

1D MODULE

In a 1D model, the Manning coefficient can be defined either in each cross-section or in the table for Manning n or k values. This can be defined per regions (left bank, channel, and right bank) or horizontally and vertically changing.

2D MODULE

In a 2D model, Only the Manning n approach is available. This can be specified directly for the whole domain when selecting the domain features or it can be defined using an imported grid file via RAS-Mapper.

11.3.10 Initial Conditions

Initial conditions for HEC-RAS models are specified directly using the first value in the time-series of the flow editor. However, these values can be altered in the initial conditions tab within the unsteady flow editor.

11.3.11 Numerical Scheme Control

There are several parameters that can be adjusted for the computational scheme in HEC-RAS depending on the type of model to be used: namely, 1D, 2D or 1D-2D.

1D MODULE

There is a choice for the numerical solution within the 1D module, the Skyline/Gaussian matrix solver or Pardiso. In addition to that, there are different unsteady flow options that can be adjusted in the unsteady flow simulation editor (Figure 03).

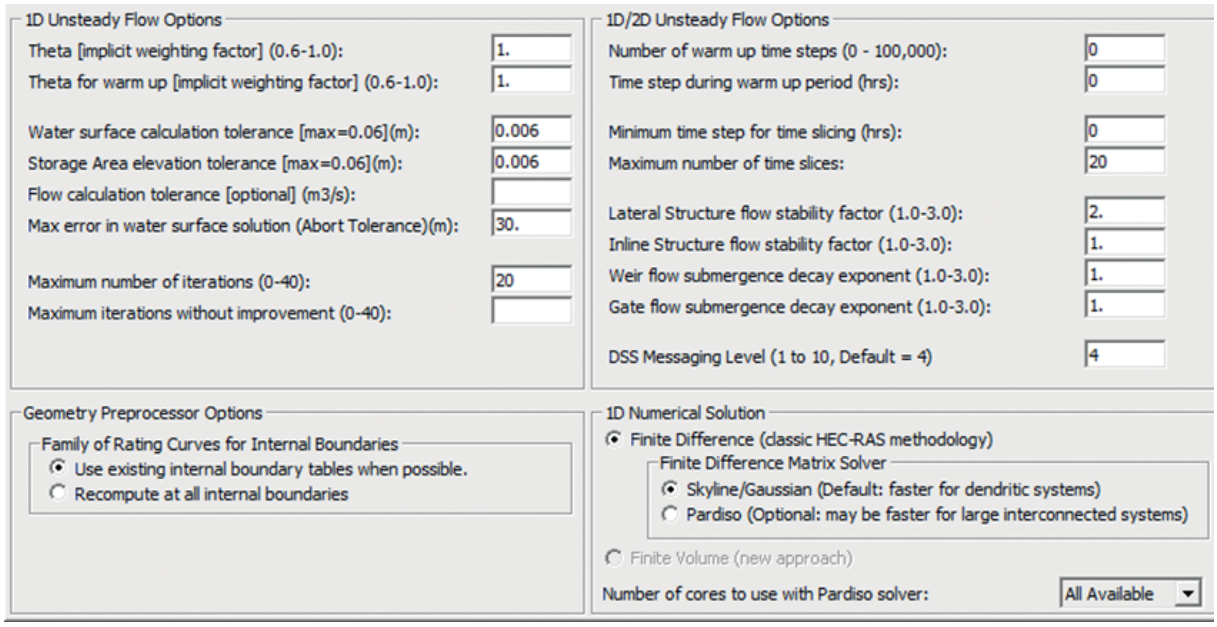


Figure 0-3. Unsteady Flow Calculation Options

2D MODULE

HEC-RAS allows the user to choose between two 2D equation options; namely, the diffusion wave equation and the full momentum equation. The diffusion wave equation is the default option, and it allows for faster run times. The diffusion wave equation is a simplified version of the full momentum equation, although many situations can be accurately modelled with the 2D diffusion wave equation.

In addition to that, the following parameters can be adjusted regarding the numerical scheme (Figure 04).

	Parameter
1	Theta (0.6-1.0):
2	Theta Warmup (0.6-1.0):
3	Water Surface Tolerance [max=0.06](m)
4	Volume Tolerance (m)
5	Maximum Iterations
6	Equation Set
7	Initial Conditions Time (hrs)
8	Initial Conditions Ramp Up Fraction (0-1)
9	Number of Time Slices (Integer Value)
10	Eddy Viscosity Transverse Mixing Coefficient
11	Boundary Condition Volume Check
12	Latitude for Coriolis (-90 to 90)

Figure 0-4. 2D Modelling Calculation Options

1D-2D MODULE

There are several options for calculation flow for 1D-2D models (Figure 05).

Maximum iterations between 1D and 2D (0=off, 1 to 20):	0
Water surface tolerance (m):	0.003
Flow Tolerance (%)	0.1
Minimum flow tolerance (m3/s):	0.03

Figure 0-5. 1D-2D Calculation Options

11.3.12 Hydrology

11.3.12.1 Hydrological Models Supported

HEC-RAS models can be linked to HEC-HMS models as specified in the boundary conditions definition outlined above.

11.3.12.2 Catchment Connections

The catchment connection is undertaken through the unsteady flow editor for the pre-specified boundary conditions.

11.3.13 Model Running Processes

11.3.13.1 Computational Scheme and Engines

11.3.13.1.1 Engines (Steady State, Quasi SS, Full HD, Hydrological Routing)

While a 1D model in HEC-RAS can be run in a steady or an unsteady mode, a 1D-2D and a 2D model can only be run in an unsteady mode. The sediment transport module in HEC-RAS is run in a quasi-steady mode. There are no hydrological routing capabilities in HEC-RAS.

11.3.13.2 Typical Time-steps and Run-times

The typical time-steps in HEC-RAS depend on the complexity of the model for both the 1D and the 2D. The computational time-steps would depend on the Courant number and the user can select the adaptive time-step in order to ensure that a Courant number under 1 is always satisfied during the calculations.

11.3.13.3 Stability

1D steady models are very stable whereas unsteady 1D models, especially when steep gradients are present, can be more unstable. 2D models in HEC-RAS are also very stable but an incorrect time-step may produce results that overestimate water depths if the time-step was too high. 1D-2D models also tend to be unstable, especially due to instabilities in the lateral structure.

11.3.14 Model Coupling

The coupling of 1D and 2D models in HEC-RAS is automatically generated within the geometry editor. This coupling, as explained above, can be standard (only connecting the river branch and the 2D grid) or through a lateral structure. If the lateral structure option is selected, the user can adjust the way in which this linking method is undertaken.

11.3.15 Post-processing Interface

There are several ways for exploring results in HEC-RAS. 1D results can be explored using the cross-sections or longitudinal profiles. 3D profiles are available as well as the resulting data for each cross-section. If the floodplain mapping option is selected in the unsteady flow simulation editor, the model will also calculate the floodplain extent for the 1D model, and this will be visible through RASMapper.

2D results can be mainly explored through RASMapper and these results can be exported into GIS format files. Additionally, the flow through structures can be explored for both 1D and 2D models.

11.3.16 Calibration

11.3.16.1 Auto-calibration

There are no auto-calibration features in HEC-RAS.

11.3.16.2 Qualitative and Quantitative Assessments of Model Fit

There are no auto-calibration features in HEC-RAS.

11.3.17 Acquisition Cost

There is no acquisition cost for HEC-RAS as it is open-source software.

11.3.18 Updates and Maintenance Cost

The current version of HEC-RAS is 5.0.7. A new version of HEC-RAS (5.1) was expected last summer, and the new release date is unknown at the moment. This upcoming version is supposed to provide the following new features:

- Spatial precipitation (gridded and point gage options).
- Spatial infiltration; wind forces for 1D and 2D modelling.
- A new shallow water solution scheme and turbulence modelling.
- 1D finite volume solution algorithme.
- Pump stations for 2D areas.
- Bridge modelling inside of 2D areas.
- Structure layout in HEC-RAS Mapper.
- A new 3D viewer for terrain and model results.
- Calibration tools inside of HEC-RAS Mapper for 1D and 2D regions.

There is no annual update or maintenance cost for HEC-RAS as it is open-source software.

11.3.19 Customer Support

There are several private companies that can provide customer support for HEC-RAS. The cost for this support varies.

11.3.20 Forecasting Add-on

11.3.20.1 Model Hot-starting

HEC-RAS has possibilities for using a hot-start file as initial conditions. The process for producing and using a hot start is not very intuitive.

11.3.20.2 Data Assimilation

There is no direct assimilation option in HEC-RAS. This can be accomplished, however, through the use of a forecasting platform such as Delft-FEWS

11.3.21 Delft-FEWS Support

There is a model adapter for HEC-RAS in Delft-FEWS (Figure 06). This model adapter has been developed by Deltares and there is some limited support thereto. Nonetheless, this adapter is well documented and updated on the Delft-FEWS website.

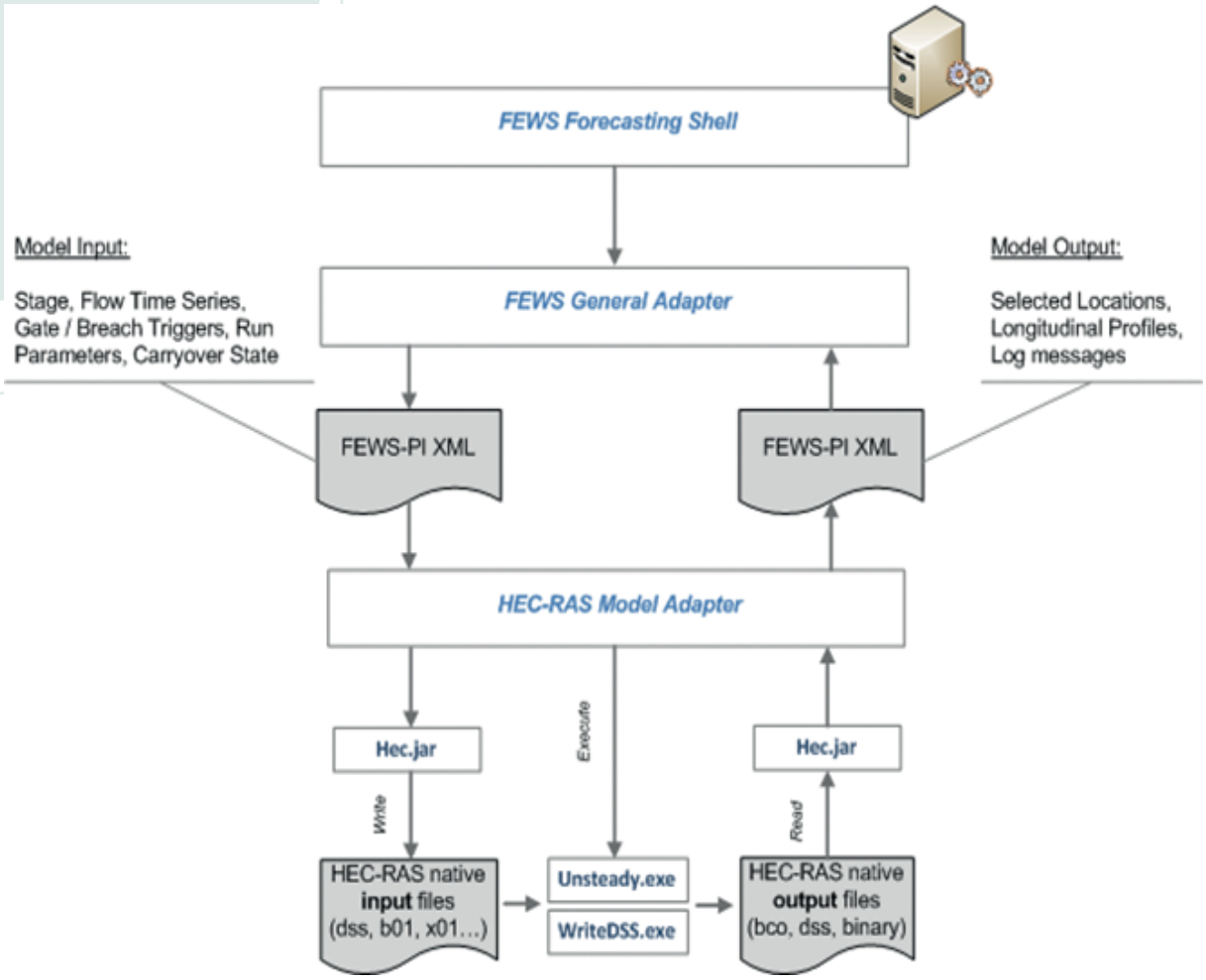


Figure 0-6. HEC-RAS adapter for Delft-FEWS

11.3.22 MIKE FLOOD

MIKE FLOOD dynamically links two independent software packages: MIKE 11 (1D) and MIKE 21 (2D) developed by the Danish Hydraulic Institute (DHI).

While HEC-RAS is a whole package and the 1D, 2D and 1D-2D modules are all within the same interface, different interfaces and different components are available in the case of MIKE.

- MIKE ZERO: main interface for all the modules and for time-series and results processing.
- MIKE 11: the 1D module.
- MIKE 21: the 2D structural grid module.
- MIKE 21 FM: the 2D Flexible Mesh (FM) module.
- MIKE FLOOD: the module for linking 1D (either MIKE 11 or MIKE URBAN) and the 2D (either MIKE 21 or MIKE 21 FM) models.
- MIKE RIVER HYDRO: recently developed 1D interface.

11.3.22.1 Overview of the 1D Engine

The MIKE 11 hydrodynamic module (HD) uses an implicit finite difference scheme for the computation of unsteady flows in rivers and estuaries. The module can describe sub-critical as well as super critical flow conditions through a numerical scheme which adapts according to the local flow conditions (in time and space). Advanced computational modules are included for description of flow over hydraulic structures, including possibilities to describe structural operation. The formulations can be applied to looped networks and quasi two-dimensional flow simulation on flood plains. The computational scheme is applicable for vertically homogeneous flow conditions extending from steep river flows to tidal influenced estuaries.

11.3.22.2 Overview of the 2D Engine

The hydrodynamic model in the MIKE 21 Flow Model (MIKE 21 HD) is a general numerical modelling system for the simulation of water levels and flows in estuaries, bays, and coastal areas. It simulates unsteady two-dimensional flows in one-layer (vertically homogeneous) fluids and has been applied in a large number of studies. The "classic" version of MIKE 21 uses a rectangular grid and solves the shallow water equations by means of a finite difference scheme. It is capable of handling flooding and drying, spatially varying surface roughness, eddy viscosity, Coriolis forces and wind friction. MIKE 21 flexible meshes (unstructured, MIKE 21 FM) are also available.

11.3.22.3 Overview of the Linking Method

The coupling of the different models is made through different linkage options. Five different types of links are presently available in MIKE FLOOD:

1. STANDARD LINK

This is the standard linkage in MIKE FLOOD where one or more MIKE 21 cells/elements are linked to the end of a MIKE 11 river branch. This type of link is useful for connecting a detailed MIKE 21 grid/mesh into a broader MIKE 11 network or to connect an internal structure (with an extent of more than a grid cell) or feature inside a MIKE 21 grid/mesh. The standard link is explicit.

2. LATERAL LINK

A lateral link allows a string of MIKE 21 cells/elements to be laterally linked to a given reach in MIKE 11, either a section of a branch or an entire branch. Flow through the lateral link is calculated using a structure equation. This type of link is particularly useful for simulating overflow from a river channel onto a flood plain. For lateral links, flow from the river model goes via a lateral boundary which is then applied in MIKE 21. A structure is required to calculate the flow between MIKE 11 and MIKE 21. This structure is typically a weir that represents overtopping of a riverbank or levee. The geometry of the structure can be determined from cross-section bank markers, MIKE 21 topographical levels, a combination of the highest of each or from an external file.

3. STRUCTURE LINK

The structure link takes the flow terms from a structure in MIKE 11 and inserts them directly into the momentum equations of MIKE 21 (rectangular MIKE 21 version only). This is fully implicit so

it should not affect time-step considerations in MIKE 21. The structure link is useful for simulating structures within a MIKE 21 model. The link consists of a three-point MIKE 11 branch (upstream cross-section, structure, downstream cross-section) whose flow terms are applied to a MIKE 21 cell or group of cells.

4. SIDE STRUCTURE LINK

The side structure link is designed to model interaction between the river model and the overland flow model through side structures as defined in MIKE 11. Side structures can be defined in MIKE 11 for almost all structure types available and then are typically applied in MIKE 11 to define the local lateral abstraction (or source) of water from the main river course in applications where either fixed hydraulic structure is present to convey water from the main river course to a neighbour area or a channel-system or where a local breach of embankment occurred during a historical event. The side structure link is explicit and implemented in the computational engine equivalent to the standard link option

5. ZERO FLOW LINKS (XFLOW=0 AND YFLOW=0)

A MIKE 21 cell specified as a zero-flow link in the x direction will have zero flow passing across the right side of the cell. Similarly, a zero-flow link in the y direction will have zero flow passing across the top of the cell. The zero-flow links were developed to complement the lateral flow links. To ensure that flood plain flow in MIKE 21 does not travel directly across a river to the opposite side of the flood plain without passing through MIKE 11, zero flow links are inserted to block MIKE 21 flows. An alternative to using the zero-flow links is to apply land cells which, depending upon grid resolution, may not be appropriate.

11.3.22.4 Pre-processing Interface

The pre-processing interface of MIKE FLOOD is easy to use. It has GIS facilities and importing data is well documented. The creation of the necessary input files and the input and processing of data are positively considered. As noted above, the following modules have to be considered in order to analyse the pre-processing interface in detail.

11.3.22.5 Overall Software Structure

11.3.22.5.1 User Interface

The MIKE software user interface can be a bit complex depending on the type of module and it takes some effort to become familiar with all of the different products and modules. Nonetheless, the layout in each of the modules is easy to navigate, especially for the 2D and 1D-2D ones, and it will flag anything missing or wrong (auto-validation of the model).

11.3.22.5.2 MIKE ZERO

The MIKE ZERO interface it is the general one in MIKE software, and it provides the tools to access all of the other modules listed below. There are also several tools within the MIKE ZERO interface that are very useful from a modelling point of view.

The time-series and grid (structural) generation, editing and importing also takes place within MIKE ZERO.

11.3.22.5.3 MIKE 11

MIKE 11 is the 1D module within MIKE (ZERO). The MIKE simulation file (Figure 07) is the main file to consider within the MIKE 11 module. The required files for any 1D simulation can be included, edited, or accessed through the simulation file interface. Within this file, the user selects the simulation type, the simulation period, and the result output option.

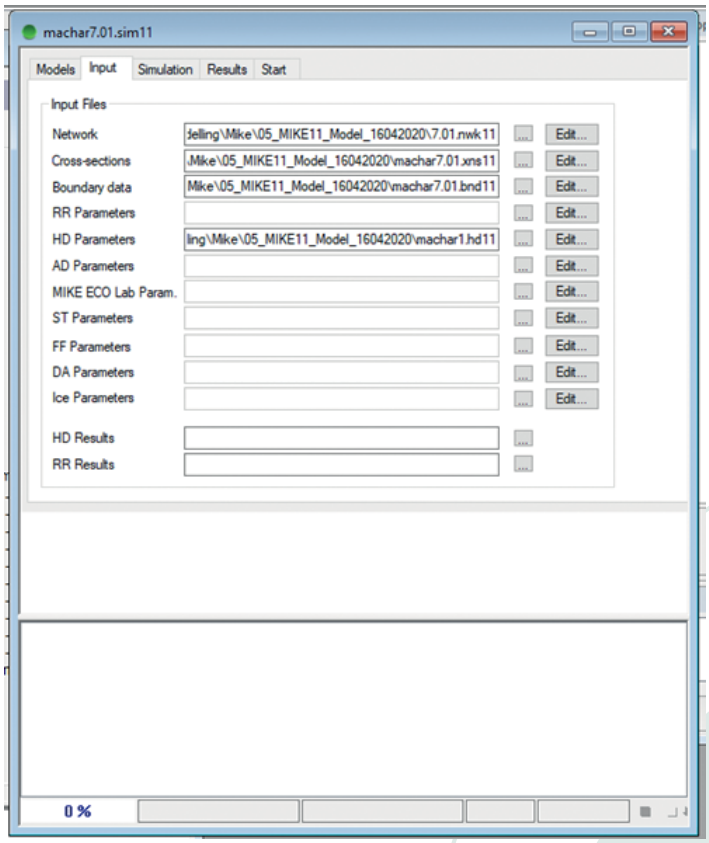


Figure 0-7. MIKE 11 Interface

11.3.22.5.4 MIKE 21 and MIKE 21 FM

MIKE 21 flow modelling (Figure 08) and MIKE 21 FM flow modelling (Figure 09) interfaces are compact and all of the required steps and model definitions are available within the same interface.

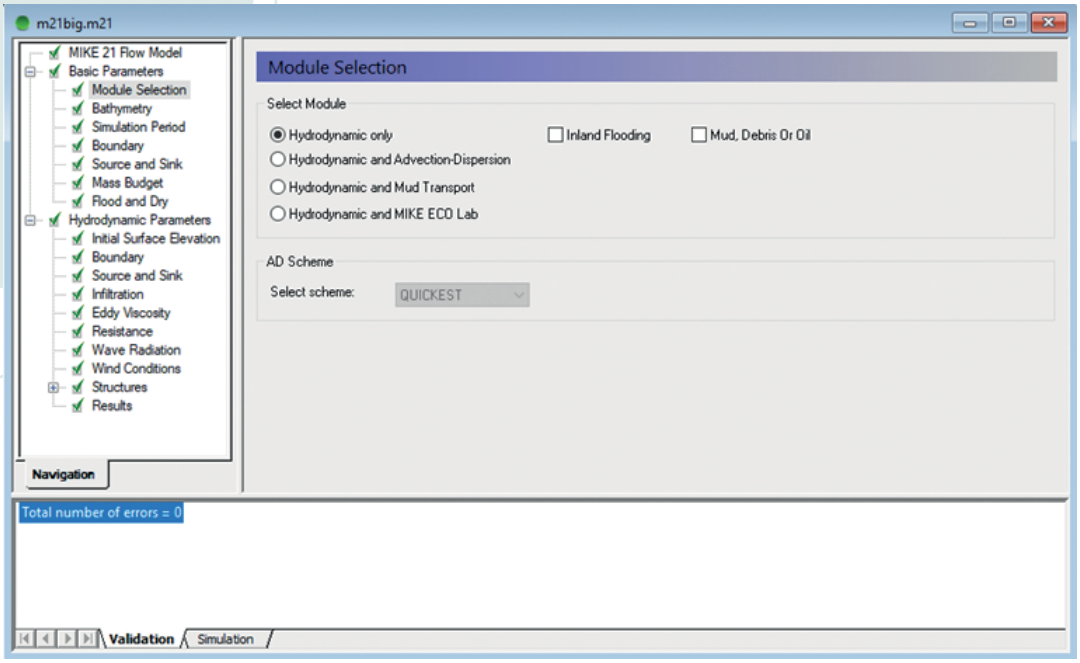


Figure 0-8. MIKE 21 Flow Modelling Interface

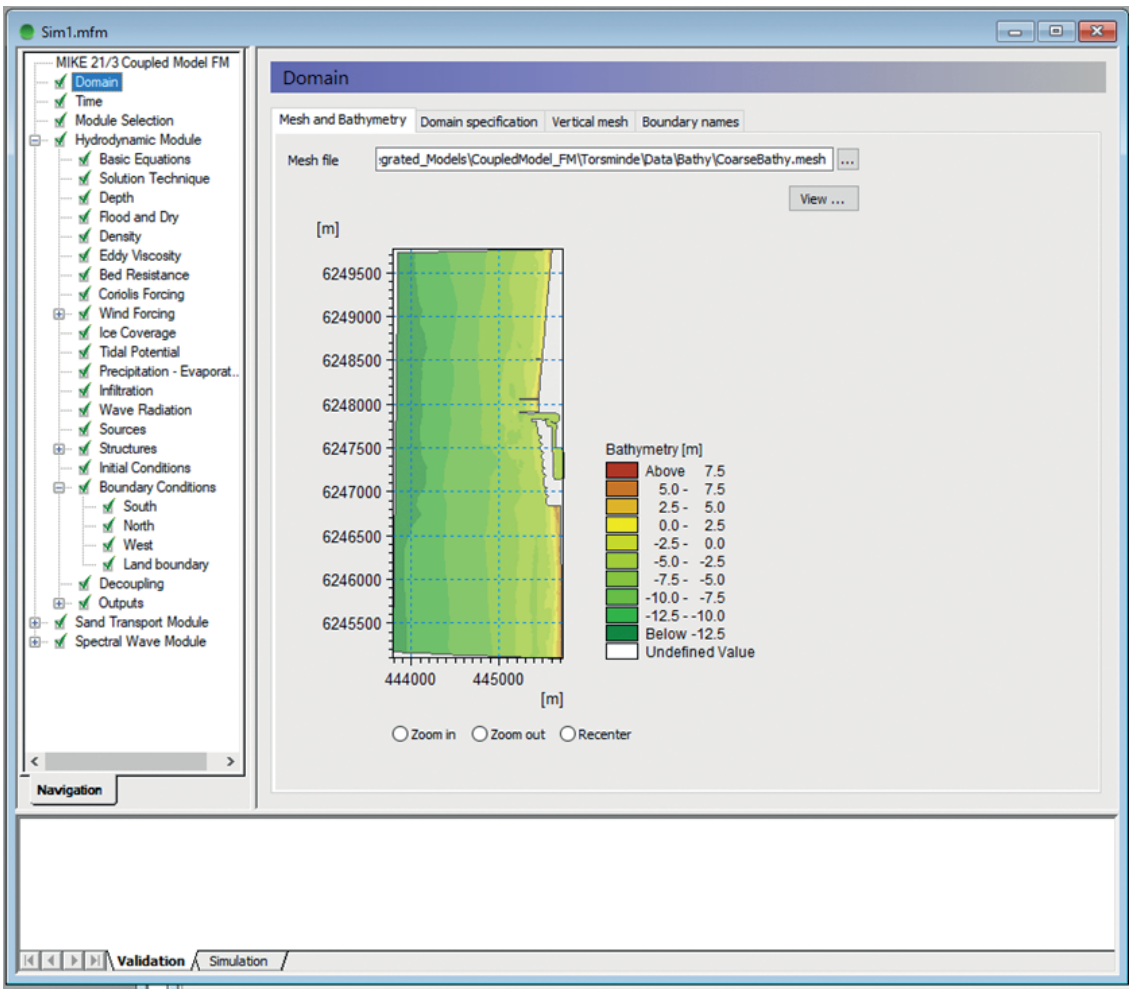


Figure 0-9. MIKE 21 FM (Flexible Mesh) Flow Modelling Interface

11.3.22.5.5 MIKE FLOOD

The MIKE FLOOD interface (Figure 010) follows a similar approach to the ones for MIKE 21 and MIKE 21 FM. All of the required data and information are within the same window interface.

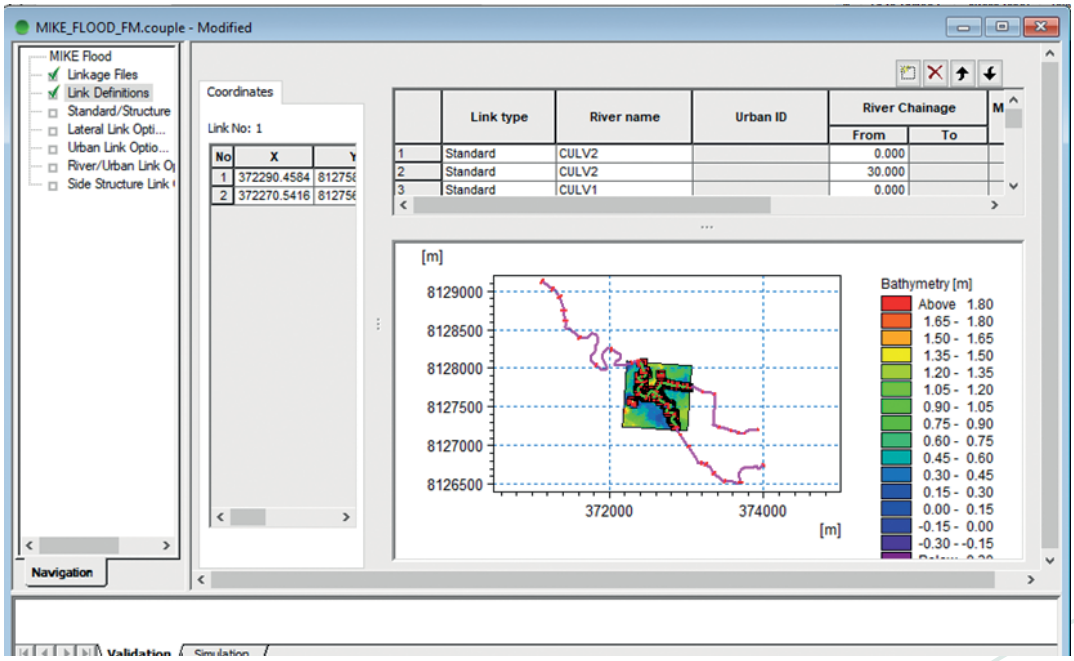


Figure 0-10. MIKE FLOOD Interface

11.3.22.5.6 Data Editors

The data editors in MIKE are very intuitive and several tools are available in order to process data, including a very useful calculation tool.

11.3.22.5.7 File Structure

The file structure of any MIKE project, as in HEC-RAS, depends on the type of files. The following should be noted:

- MIKE 11.
- Simulations files (*.sim11).
- Network files (*.nwk11).
- Cross-section files (*.xns11).
- Boundary condition files (*.bnd11).
- Hydrodynamic parameters files (*.hd11).
- MIKE 21 (*.m21).
- MIKE 21 FM (*.m21fm).
- MIKE FLOOD (*.couple).

11.3.22.5.8 File/Database Formats

The time-series and files in MIKE are also defined depending on their dimensionality:

- DFS0: time-series, no dimensionality.
- DFS1: 1 dimensional file for profiles.
- DFS2: 2 dimensional files for 2D grids.
- DFS3: 3 dimensional files for 3D grids.
- DFSu: unstructured grids.
- Mesh: mesh files.

In this case, the file name for each file corresponds to the file name given within the software, ensuring that the inspection of the files is easy.

There is no database associated with MIKE models.

11.3.22.5.9 Data Exchange (Time-series and Spatial Data)

There are several tools for importing data into MIKE:

- Time-series: they can be imported through the DFS0 tool, providing they are in the same format. Additionally, data can be easily copied and pasted into the data editor. Every time-series is defined within MIKE, stating the kind of data and the units.
- Topographic data can be imported into MIKE through the MIKE Zero toolbox, providing it is in an ASC ArcGIS format.

Regarding the data export capabilities, both time-series and DFS2 files (topography) can be exported into text and ASC files, respectively, through the MIKE Zero toolbox. Time-series can also be exported through the data editor.

11.3.22.6 River Geometry

11.3.22.6.1 Schematisation (Reaches vs Chainage)

The schematisation of rivers and reaches in MIKE 11 can be undertaken directly in the software by digitising or importing a GIS (shape) file via the network editor. This can also be undertaken through MIKE HYDRO RIVER. It can be confusing as to which activities can be undertaken in either editor.

Within the network editor, the user also has to specify the structures and the connections to other software (MIKE SHE).

11.3.22.6.2 Delineation and Editing Tools

The river branches and reaches can be delineated in the network editor. The delineation tools are user-friendly, although some problems may be found when moving river points due to the grid approach (moving points to a grid corner).

11.3.22.6.3 Cross-section Management, Editing and Processing

Cross-section data can be inserted manually in MIKE using the cross-section editor (Figure 011) tool within the geometry editor.

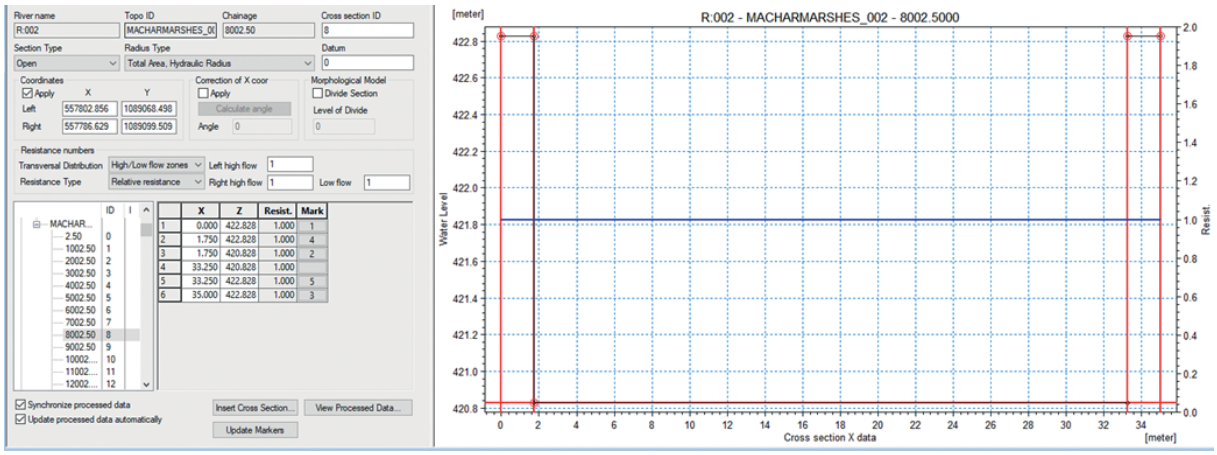


Figure 0-11. Cross-section Editor

The processed data are automatically available in the cross-section editor, including information about the area, radius, resistance, and conveyance. These data can be modified. Additionally, there are tools to modify values for all or selected cross-sections.

Once the network file and the cross-section file are selected into a simulation file, they are connected and the location of the cross-sections in the network can be observed.

11.3.22.6.4 DEM Processing and XS Extraction

Within MIKO HYDRO RIVER there are tools for creating cross-sections at pre-specified spacing and extracting DEM information into the cross-sections. This DEM is created within MIKE HYDRO RIVER with the following formats allowed:

- ESRI ASCII.
- GeoTIFF.
- ArcInfo Binary Grid.
- DFS2.

11.3.22.6.5 Import/Export

Cross-sections can be imported into MIKE using the following options:

- Text file: a text file with the following format has to be used to import cross-sections into MIKE (Figure 012).

```
MacharMarshes_001
R:001
2.500
COORDINATES
    2      546136.672      974033.999      546086.245      974050.313
FLOW DIRECTION
0
DATUM
0.00
RADIUS TYPE
2
DIVIDE X-Section
0
SECTION ID
0
INTERPOLATED
0
ANGLE
0.00
PROFILE   6
     0.000   401.362   1.000     <#1>     0     0.00     0
     2.650   401.362   1.000     <#8>     0     0.00     0
     2.650   399.362   1.000     <#2>     0     0.00     0
    50.350   399.362   1.000     <#0>     0     0.00     0
    50.350   401.362   1.000     <#16>     0     0.00     0
    53.000   401.362   1.000     <#4>     0     0.00     0
******************************
```

Figure 0-12. Text Format for Cross-section Import

- HEC-RAS: it is possible to import HEC-RAS models into MIKE using an add-on developed by DHI. This add-on works with old HEC-RAS versions.

11.3.22.6.6 List of All Structure Types

The structures that are allowed in MIKE at this stage are:

- Weirs.
- Culverts.
- Bridges.
- Pumps.
- Control and regulating structures.
- Dam break structures.
- User defined structures.

As in the HEC-RAS case, there are several formulations available for the modelling of each of these structures. For dam-breaching scenarios, no reservoir structures or options are available in MIKE and, therefore, this has to be defined in a different way for assessing a dam-breaching scenario in MIKE. The structures are located in the network editor.

11.3.22.7 2D Domains

Two different modules are available for the definition and simulation of 2D models: namely, MIKE 21 and MIKE 21 FM.

11.3.22.7.1 Model Definition

MIKE 21

The MIKE 21 model domain is defined as a DFS2 file. This gridded domain is a regular structured grid that can be imported into MIKE from an ASC ArcGIS format file or directly created in MIKE using tools available and text data files (in *.xyz format).

MIKE 21 FM

The MIKE 21 FM domain and input grid has to be prepared using the mesh generator tool available in MIKE ZERO. As compared to HEC-RAS, the process for preparing this grid is slightly more complicated.

6.8.22.7.2 Domain Alteration

MIKE 21 domains cannot be altered unless the grid size is adjusted while MIKE 21 FM domains can be altered through the use of the mesh generator. In both cases, the DEM associated with the grid files can be manually adjusted in MIKE by opening the data in the grid editor.

6.8.22.7.3 Structures in 2D

The following structures are available directly in the 2D models for MIKE 21 and MIKE 21 FM directly.

MIKE 21

The following structures are available:

- Weirs.
- Culverts.
- Dikes.

MIKE 21 FM

The following structures are available:

- Weirs.
- Culverts.
- Gates.
- Dikes.
- Piers.
- Turbines.

The instability of the models is reduced once the structures are introduced directly into the 2D domain.

11.3.22.7.4 Importing/Exporting

There are no features to import or export 2D models from MIKE into or from any other software. The DEM and the gridded domain used in the MIKE 21 model can be exported into GIS software through MIKE ZERO tools. The MIKE 21 FM grid cannot be exported directly.

11.3.22.8 Boundary Conditions

11.3.22.8.1 Boundary Definitions

The definition of boundary conditions in MIKE also depends on the dimensionality of the model.

11.3.22.8.2 1D Module – MIKE 11

As in HEC-RAS, the user has to define the boundary conditions for open chainages, and this is undertaken in the boundary conditions editor. In fact, the user can include all of the open chainages directly using an available function in the network editor.

11.3.22.8.3 2D Module – MIKE 21 and MIKE 21 FM

In MIKE 21 and MIKE21 FM, the software will automatically detect the open boundaries. The user can also select additional boundaries or automatically alter the ones selected through the definition of the computational points within the grid that are open boundaries.

11.3.22.8.4 Boundary Types Supported

The following boundary types are supported in MIKE.

1D MODULE

The user can select among open boundaries (for the upstream and the downstream ends of the models), point sources, distributed sources, global structures, and closed sources. The main relevant boundaries for river modelling would be open boundaries, point boundaries and distributed boundaries.

For open boundary conditions, the following are available:

- Inflow.
- Bottom level.
- Q/h relationship.
- Sediment supply.
- Sediment transport.
- Water level.

These can be defined as a time-series (DFS0 format) in the time-series editor or as constant values.

For additional boundary conditions applied in between the automatically selected upstream and downstream stations, the point sources and distributed sources options are available. The point sources will apply the boundary condition in a single location while the distributed one will apply the boundary

condition evenly across the selected river stretch. The following boundary condition types are available for these two options:

- Inflow.
- Sediment transport.

The global type of boundary condition should also be noted. There are several options within this boundary condition type; the resistance type is most relevant one. This can be used to apply a temporal change in the resistance for the whole modelled river section.

2D Module

In MIKE 21 the following boundary conditions are available:

- Flux.
- Level.

In MIKE 21 FM the following conditions are available:

- Land.
- Velocity.
- Flux.
- Discharge.
- Free outflow.
- Flather condition.

11.3.22.9 Hydraulic Parameters

11.3.22.9.1 Resistance Definition

In MIKE, the approach to define the resistance differs depending on the dimensionality of the model.

1D MODULE

In a 1D model, the Manning coefficient can be defined either in each cross-section (absolute or relative) or in the table within the hydrodynamic parameters. The choices are:

- Manning (n or M).
- Chezy (C).
- Darcy-Weisbach (k).

This can be defined per regions (left bank, channel, and right bank) within the hydrodynamic parameters or horizontally within the cross-section editor.

2D MODULE

In a 2D model, the following options are available:

- Manning (only M).
- Chezy (C).
- Wave induced bed resistance.

Manning M is equivalent to Manning 1/n. The resistance can be specified as a constant value for the whole domain or as a grid (DFS2) file.

11.3.22.9.2 Initial Conditions

Initial conditions for MIKE models have to be specified. In the 1D module, this can be undertaken within the hydrodynamic parameter editor and the values can be global or per cross-sections; they can also be specified to be automatically calculated in the simulation file. In the case of 2D models, these conditions should be specified in the initial conditions tab and constant or grid values (DFS2) can be selected.

11.3.22.9.3 Numerical Scheme Control

There are several parameters that can be adjusted for the computational scheme in MIKE depending on the type of model to be used, 1D or 2D.

1D MODULE

The wave approximation for the 1D module can be selected in the hydrodynamic parameter file and the choices available are:

- High Order Fully Dynamic.
- Fully Dynamic.
- Diffusive Wave.
- Kinematic Wave.

These options can be selected globally for the whole model or just for certain river cross-sections (chainage).

In addition, there are several hydrodynamic parameters that can be adjusted during the simulation (Figure 013).

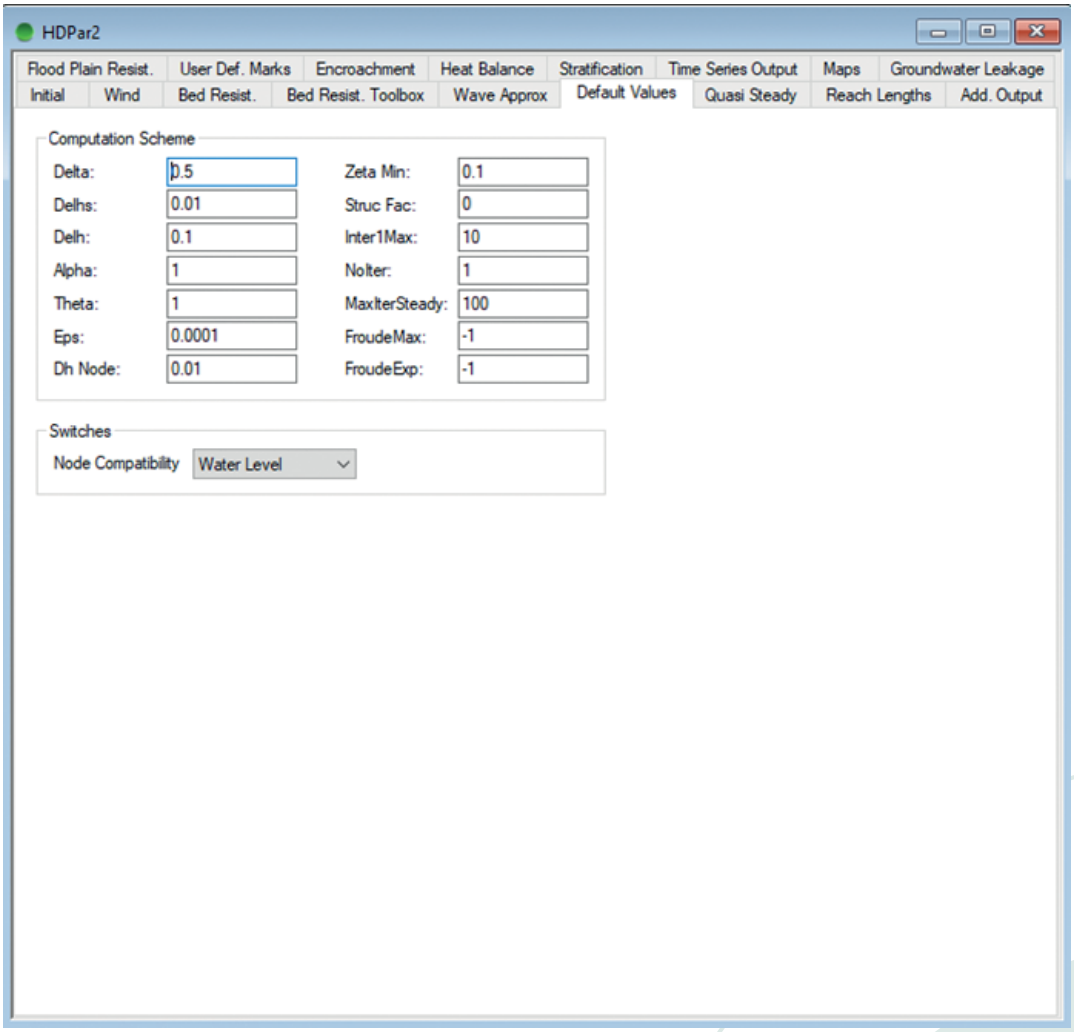


Figure 0-13. Unsteady Flow Calculation Options

2D Module

The user can select between the Unstationary formulation or the Quasi-stationary calculation engines in MIKE 21 FM.

11.3.22.10 Hydrology

11.3.22.10.1 Hydrological Models Supported

MIKE 11 models can be linked to MIKE NAM hydrological models using the boundary condition editor and selecting the MIKE NAM model within the simulation file.

11.3.22.10.2 Catchment Connections

The catchment connection is undertaken through the unsteady flow editor for the pre-specified boundary conditions.

11.3.22.11 Model Running Processes

11.3.22.11.1 Computational Scheme and Engines

Engines (Steady State, Quasi SS, Full HD, Hydrological Routing)

While a 1D model can be run in a quasi-steady or an unsteady mode in MIKE, a 1D-2D and a 2D model can only be run in an unsteady model. There are no hydrological routing capabilities in HEC-RAS.

Typical Time-steps and Run-times

The typical time-steps in MIKE depend on the complexity of the model for both the 1D and the 2D. The computational time-steps would depend on the Courant number and the user can select the adaptive time-step in order to ensure that a Courant number under 1 is always satisfied during the calculations.

Runtimes are slightly faster in MIKE than in HEC-RAS based on an analysis undertaken with the same grid sizes (for 2D models).

Stability

1D steady models are very stable whereas 1D unsteady models, as in HEC-RAS, can be unstable, especially when steep gradients are present. 2D models in MIKE are not very stable with several 'blow-ups' occurring if drastic changes are present in the DEM.

11.3.22.12 Model Coupling

A MIKE FLOOD interface has to be used in order to couple a MIKE 11 (1D) and a MIKE 21 (2D, either MIKE 21 or MIKE 21 FM) model. The models to be linked and the full linking processes and options can be specified in this interface. The linking options outlined above in section 11.3.22.3 are available.

11.3.22.13 Post-processing Interface

There are several ways of exploring the results in MIKE. 1D results can be explored using MIKE VIEWER with information about the water level and discharge in computational nodes or longitudinal profiles. If MIKE GIS is also available, the results for the floodplain mapping can also be observed.

2D results can mainly be explored through the grid editor and they can be exported into GIS. The MIKE ZERO toolbox can be used to extract results in points or profiles, allowing several statistics options.

11.3.22.14 Calibration

11.3.22.14.1 Auto-calibration

There are no auto-calibration features in MIKE, although assimilation options are available.

11.3.22.14.2 Qualitative and Quantitative Assessments of Model Fit

There are no auto-calibration features in MIKE.

11.3.22.15 Acquisition Cost

The acquisition cost for MIKE FLOOD is $XXXXX as follows:

MIKE FLOOD 2D Inland Flexible Mesh UL (MARINE PP + MIKE 21 HD): $XXXXX

MIKE FLOOD 1D River UL (MIKE 11 HD): $XXXXX.

11.3.22.16 Updates and Maintenance Cost

The annual maintenance cost for MIKE FLOOD is $XXXXX.

11.3.22.17 Customer Support

Customer support is provided with MIKE FLOOD if the annual license is maintained, involving an annual cost.

11.3.22.18 Forecasting Add-on

11.3.22.18.1 Model hot-starting

MIKE 11 has direct hot-start application options, and the model can be selected to start with a hot-start in the simulation file (initial conditions options). The creation of this hot start is also fairly simple as it is the results of a normal simulation.

11.3.22.18.2 Data Assimilation

There is a direct assimilation option in MIKE 11, and this can also be accomplished through the use of a forecasting platform such as Delft-FEWS.

11.3.22.19 Delft-FEWS Support

There is a model adapter for MIKE 11 in Delft-FEWS. This model adapter has been developed by DHI but there is limited support thereto. Nonetheless, it should be noted that this adapter is well documented and updated on the Delft-FEWS website.

11.3.23 Hydraulic Modelling Comparison

A comparison for the two modelling software packages is outlined in the tables below.

Numerical Modelling Capabilities	HEC-RAS	MIKE
Linking methods available	Direct link. Lateral link.	Standard link. Lateral link. Structure link. Side-structure link. Zero link.
List all structure types	Bridge, culvert, dam, gate, pump, siphon, weir, user defined.	
2D domains	Unstructured grid.	2D Cartesian and flexible grid.
Discretisation	Finite difference.	Finite difference.
Domain alteration	Possible with break-lines.	Possible in MIKE 21 FM.
Structures in 1D	Bridge and culverts, inline structures, lateral structures, pumping stations, storage areas.	Weirs, culverts, bridges, pumps, control and regulating structures, dam break structures, user defined structures.
Structures in 2D	Culverts, lateral structures.	Culverts, lateral structures.
Importing/exporting	Limited.	Limited.
Boundary conditions		
1D Module	Stage hydrograph, flow hydrograph, stage/flow hydrograph, rating curve, normal depth, lateral inflow hydrograph, uniform lateral inflow, groundwater interflow, internal boundary stage and flow hydrograph.	Inflow, bottom level, Q/h relationship, sediment supply, sediment transport, water level, inflow, sediment transport.
2D Module	Flow hydrograph, stage hydrograph, rating curve, normal depth, precipitation.	Land, velocity, flux, discharge, free outflow, flather condition (MIKE 21 FM) flux, level (MIKE 21).
Hydraulic parameters		
Resistance definition		
1D Module	Manning 'n' or k values.	Manning (n or M), Chezy (C), Darcy-Weisbach (k).
2D Module	Manning 'n.'	Manning (only M), Chezy (C), wave induced bed resistance.
Initial conditions	Automatic although editable.	In hydrodynamic file.

Numerical scheme control		
1D Module	**Skyline/Gaussian or the Pardiso matrix solvers.**	**High order fully dynamic, fully dynamic, diffusive wave, kinematic wave.**
2D Module	**Diffusion wave equation or the full momentum equation.**	**Unstationary formulation or the quasi-stationary formulation.**
1D-2D Module	**Calculation flow options available.**	**Calculation flow options available.**
Hydrology	**HEC-HMS.**	**NAM, unit hydrograph, SMAP, FEH, DRiFit.**
Model running processes		
Engines (steady state, quasi-SS, full HD, hydrological routing)	**Steady and unsteady.**	**Quasi-steady or unsteady mode.**
Post-processing interface		
Calibration	**Not available.**	**Available.**
Auto calibration	**Not available.**	**Available.**
Qualitative and quantitative assessments of model fit	**Not available.**	**Available.**
Acquisition cost	**No associated cost.**	**Cost involved.**
Updates and maintenance cost	**No associated cost.**	**Cost involved.**
Customer support	**Available.**	**Available.**
Forecasting add-on		
Model hot-starting	**Available but difficult to use.**	**Available.**
Data assimilation	**Not available.**	**Available.**
Delft-FEWS support	**Adapter and support available.**	**Adapter available but no support.**

11.4 Annex IV

Type of Channel and Description	Minimum	Normal	Maximum
A. *Natural Streams*			
1. Main Channels			
a. Clean, straight, full, no rifts or deep pools	0.025	0.030	0.033
b. Same as above, but more stones and weeds	0.030	0.035	0.040
c. Clean, winding, some pools, and shoals 0.030	0.033	0.040	0.045
d. Same as above, but some weeds and stones	0.035	0.045	0.050
e. Same as above, lower stages, more ineffective slopes, and sections	0.040	0.048	0.055
f. Same as "d" but more stones	0.045	0.050	0.060
g. Sluggish reaches, weedy, deep pools	0.050	0.070	0.080
h. Very weedy reaches, deep pools, or floodway with heavy stands of timber and brush	0.070	0.100	0.150
2. Flood Plains			
a. Pasture no brush			
1. Short grass	0.025	0.030	0.035
2. High grass	0.030	0.035	0.050
b. Cultivated areas			
1. No crop	0.020	0.030	0.040
2. Mature row crops	0.025	0.035	0.045
3. Mature field crops	0.030	0.040	0.050
c. Brush			
1. Scattered brush, heavy weeds	0.035	0.050	0.070
2. Light brush and trees, in winter	0.035	0.050	0.060
3. Light brush and trees, in summer	0.040	0.060	0.080
4. Medium to dense brush, in winter	0.045	0.070	0.110
5. Medium to dense brush, in summer	0.070	0.100	0.160
d. Trees			
1. Cleared land with tree stumps, no sprouts	0.030	0.040	0.050
2. Same as above, but heavy sprouts	0.050	0.060	0.080
3. Heavy stand of timber, few down trees, little undergrowth, flow below branches	0.080	0.100	0.120
4. Same as above, but with flow into branches	0.100	0.120	0.160
5. Dense willows, summer, straight	0.110	0.150	0.200
3. Mountain Streams, No Vegetation in Channel, Banks Usually Steep with Trees and Brush on Banks Submerged			
a. Bottom: gravels, cobbles, and few boulders	0.030	0.040	0.050
b. Bottom: cobbles with large boulders	0.040	0.050	0.070

Type of Channel and Description	Minimum	Normal	Maximum
B. *Lined or Built-Up Channels*			
1. Concrete			
a. Trowel finish	0.011	0.013	0.015
b. Float Finish	0.013	0.015	0.016
c. Finished, with gravel bottom	0.015	0.017	0.020
d. Unfinished	0.014	0.017	0.020
e. Gunite, good section	0.016	0.019	0.023
f. Gunite, wavy section	0.018	0.022	0.025
g. On good, excavated rock	0.017	0.020	
h. On irregular excavated rock	0.022	0.027	
2. Concrete Bottom Float Finished with Sides of:			
a. Dressed stone in mortar	0.015	0.017	0.020
b. Random stone in mortar	0.017	0.020	0.024
c. Cement rubble masonry, plastered	0.016	0.020	0.024
d. Cement rubble masonry	0.020	0.025	0.030
e. Dry rubble on riprap	0.020	0.030	0.035
3. Gravel Bottom with Sides of:			
a. Formed concrete	0.017	0.020	0.025
b. Random stone in mortar	0.020	0.023	0.026
c. Dry rubble or riprap	0.023	0.033	0.036
4. Brick			
a. Glazed	0.011	0.013	0.015
b. In cement mortar	0.012	0.015	0.018
5. Metal			
a. Smooth steel surfaces	0.011	0.012	0.014
b. Corrugated metal	0.021	0.025	0.030
6. Asphalt			
a. Smooth	0.013	0.013	
b. Rough	0.016	0.016	
7. Vegetal Lining	0.030		0.500

Type of Channel and Description	Minimum	Normal	Maximum
C. *Excavated or Dredged Channels*			
1. Earth, Straight and Uniform			
a. Clean, recently completed	0.016	0.018	0.020
b. Clean, after weathering	0.018	0.022	0.025
c. Gravel, uniform section, clean	0.022	0.025	0.030
d. With short grass, few weeds	0.022	0.027	0.033
2. Earth, Winding and Sluggish			
a. No vegetation	0.023	0.025	0.030
b. Grass, some weeds	0.025	0.030	0.033
c. Dense weeds or aquatic plants in deep channels	0.030	0.035	0.040
d. Earth bottom and rubble side	0.028	0.030	0.035
e. Stony bottom and weedy banks	0.025	0.035	0.040
f. Cobble bottom and clean sides	0.030	0.040	0.050
3. Dragline-excavated or Dredged			
a. No vegetation	0.025	0.028	0.033
b. Light brush on banks	0.035	0.050	0.060
3. Rock Cuts			
a. Smooth and uniform	0.025	0.035	0.040
b. Jagged and irregular	0.035	0.040	0.050
4. Channels not Maintained, Weeds and Brush			
a. Clean bottom, brush on sides	0.040	0.050	0.080
b. Same as above, highest stage of flow	0.045	0.070	0.110
c. Dense weeds, high as flow depth	0.050	0.080	0.120
d. Dense brush, high stage	0.080	0.100	0.140