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Country Energy Efficiency and Renewable Energy
Demonstration Project for the Recovery of Lebanon

The National
Wind Atlas of Lebanon

25 January 2011

UNITED NATIONS
DEVELOPMENT GROUP

The National Wind Atlas of Lebanon

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for the United Nations Development Program (UNDP) -
CEDRO Project

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Note: The information contained within this document has been developed within a specific scope, and might be updated in the future.

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Republic of Lebanon
Ministry of Energy and Water
The Minister
January 10, 2011

Foreword

Over the last few years, there has been a growing debate on the need to have a national wind atlas for Lebanon. Experts and concerned parties were claiming that the only way to set a strategic and well structured path for the development of wind energy power plants starts with the development of this important document. In this regard, the Ministry of Energy and Water set this target in mind in the "Policy Paper of the Electricity Sector" published in June 2010. We believe that the development of wind energy in Lebanon plays a crucial role towards reaching the set target of 12% of renewable energy by 2020.

We are more than happy to publish the first version of the "National Wind Atlas for Lebanon" with the support of the United Nations Development Programme (UNDP) through the CEDRO project. The wind atlas has been developed by the reputable UK-based company Garrad and Hassan under the direct management of the CEDRO team. This project is financed by a grant from the Spanish Government through the Lebanon Recovery Fund (LRF). The Ministry of Energy and Water is keen to thank the Spanish Government for its continuous support to the development of energy efficiency and renewable energy in Lebanon.

We do firmly believe that the launching of the national wind atlas will create a growing momentum in Lebanon towards strengthening and developing the renewable energy sector in the country. The wind atlas study shows a promising potential for wind energy in Lebanon, reaching high levels of generation capacity.

The national wind atlas is a first step in a long journey, a journey that must be taken slowly but surely, towards clear and strategically well-defined objectives. The Ministry of Energy and Water has prepared the needed legal and administrative framework for the development of wind energy power plants in Lebanon. This will definitely open the door for the private sector to get involved in this promising sector. We hope that our country will see its first wind power plant soon.

The commitment of the Ministry of Energy and Water to energy efficiency and renewable energy stems from a deep belief in the importance of such measures and technologies in finding solutions for the electricity sector in Lebanon, and most importantly in finding new ways and opportunities to fight the threats that climate change is nowadays posing. The threats of climate change are increasing, leaving us with no option but to find alternative ways for mitigation and adaptation.

We would like to thank again the UNDP and the Spanish Government. The Ministry of Energy and Water highly appreciates and values the close collaboration with our local, regional, and international partners and friends in order to push forward the energy sector in Lebanon.

With the publishing of the national wind atlas, one major step is achieved. However, other challenges are arising ahead of us. It is only with wise determination and serious work that we can all cooperate to overcome all barriers and achieve the projects we are looking for. By doing so, we can really set our country Lebanon as a real positive model for the entire region to follow.

Gebran Bassil
Minister of Energy and Water

CONTENTS

1- INTRODUCTION

The United Nations Development Programme (the "Client") has requested that Garrad Hassan and Partners Ltd ("GH") provide consultancy services for the Republic of Lebanon ("Lebanon"). The Client has instructed GH to carry out mesoscale and microscale modelling for the entire Republic of Lebanon to produce a wind map with a resolution of 100 m. The results of this modelling work are reported here.

The specific deliverables required were redefined in a meeting between GH and the Client held in Beirut on 15 March 2010 and are defined in the GH document 104313/BT/01 Issue A dated 22 March 2010. The preliminary deliverables defined in that document were supplied to the Client in the document 104313/BT/02 Issue A dated 10 May 2010.

The Client also requested that GH consider the offshore wind energy potential for Lebanon. The deliverables to be provided as part of this work are outlined in GH proposal 104313/BP/02 Issue B and are reported here.

This document has been prepared pursuant to GH proposal documents 104313/BP/01 Issue A dated 17 November 2009, 104313/BT/01 Issue A dated 22 March 2010 and 104313/BP/02 Issue B dated 6 April 2010, and is subject to the terms and conditions contained therein.

2 - PHYSICAL CHARACTERISTICS OF LEBANON

2.1 - THE STUDY REGION

Lebanon is located on the eastern shores of the Mediterranean Sea. The country is located between Latitudes 33˚ 03’ 20” N and 34˚ 41’ 35” N and Longitudes 35˚ 06’ 15” E and 36˚ 37’ 21” E. Lebanon has an area of approximately 10,452 square kilometres [1], making it approximately 88 kilometres at its widest point and 32 kilometres at its narrowest, with an average length of 220 kilometres [2].

Lebanon is a mountainous country characterised by complex geography which is influenced by natural systems that extend beyond the boundaries of the country. There are two parallel ranges of mountains running north to south; the western mountain range known as the Lebanon Mountains which reach their highest point at Qurnat as Sawda' at 3,088 metres and the eastern range of Jabal Lubnan al Sharqi, commonly known as the Anti-Lebanon, with Mount Hermon at 2814 metres as their highest peak [3].

The Lebanon Mountains are part of a system that starts with the Nur Mountains in southern Turkey and end in the Sinai range [1]. The mountain range is separated from the Nusayriyah Mountains of Syria by the An Nahr al Kabir river to the north and the Al Qasimiyah River to the south, making the Lebanon Mountains approximately 160 kilometres in length. Another notable peak in the range is Jabal Sannin, located east of the capital, Beirut, at a height of approximately 2,650 metres [1].

Between the two mountain ranges there is a central plateau known as the Beqaa (or Biqa) Valley. This highland valley is approximately 177 kilometres in length and between 10 and 16 kilometres wide, at an average elevation of approximately 800 metres above sea level [1,3]. Geologically, the Beqaa Valley is at the midpoint of a geological depression that extends north to the western bend of the Nahr al Assi (or Orontes) river in Syria and south to Jordan through to the eastern arm of the Red Sea [1].

To the west of the Lebanon Mountains, a narrow coastal strip stretches along the shores of the Mediterranean. This region, known as the Sahil, has its widest point in the north near the city of Tripoli where it reaches a width of 6.5 kilometres. The coastline is generally characterised by rocky and abrupt topography with few natural harbours or estuaries [1]. The continental shelf of Lebanon extends less than 20 kilometres from the shoreline. The shelf is also characterised by an abrupt change in depth, which can reach 1500 metres [3]. Although Lebanon has many rivers and streams, they are not considered navigable, and no single river provides the sole source for irrigations [1]. Most of the rivers have their sources in springs located in the Lebanon Mountains.

The rivers of Lebanon can be characterised based on their orientations. The aforementioned An Nahr al Kabir and Al Qasimiyah rivers, to the north and south respectively, traverse the country on east west axis. Two further rivers of importance which both water the Beqaa Valley are orientated north-south; the Nahr al Assi which runs north into Syria and eventually reaches the Mediterranean in Turkey and the Litani which originally flows south but turns west after the southern region of the Beqaa valley to form the Al Qasimiyah river.

In general, smaller springs and streams act as tributaries of the principal rivers. However, the topography of the country results in steep gradients, making these streams and rivers fast moving which in turn leads to erosion of the land rather than resulting in water deposition [1].

The only permanent lake is Buhayrat al Qirawn (also known as Lac de Qaraaoun), located approximately 10 kilometres northeast of the town of Jezzin, while a seasonal lake which is fed by springs, appears near Yammunah on the eastern slopes of the Lebanon Mountains, approximately 40 kilometres southeast of Tripoli [1].

2.2 - CLIMATE OF LEBANON

Lebanon's climate is defined both by its position on the Mediterranean as well as its geography. The coastal regions of the country are characterised by a Mediterranean climate with hot, dry and humid summers, and mild, rainy winters [1].

The major period of precipitation occurs mainly in winter, generally in the months of December and January. Rainfall levels can vary substantially from one year to another.During Spring (and occasionally during Autumn), a hot wind called the Khamsin blows into Lebanon from North Africa. In the winter months, cold winds from Europe affect the northern regions of Lebanon. Thus, in general, the northern coastal regions are cooler and wetter while the southern regions are characterised by drier warmer climates [1].

In the Lebanon Mountains, the climate becomes more alpine. The increased altitude leads to colder winters and more precipitation, while heavy snow is more common and covers the highest peaks for most of the year. In the summer, temperatures during the day may reach similar levels as those seen in coastal areas, but the night time temperatures are markedly lower. As a result, although the mountain range is not far from the coast, the effect of the Mediterranean climate is tempered by the increase in altitude, producing wider daily variations in temperature.

The Beqaa Valley experiences less precipitation and humidity than the coastal regions, mainly due to the effect of the Lebanon Mountain range. However, due to its altitude, the valley also experiences a wide range of temperatures both on a diurnal as well as an annual basis [1].

The Beqaa Valley also experiences more snowfall than the Lebanon Mountains at equivalent altitudes [1].

The Anti-Lebanon Mountain range experiences high levels of precipitation, mainly in the form of snow, while temperatures are lower than the neighbouring Beqaa Valley.

3 - MEASURED WIND DATA

3.1 - DESCRIPTION OF MEASURED DATA SUPPLIED

In the derivation of a national wind speed map it is desirable to calibrate the outputs of the wind flow models against actual ground based wind measurements recorded at locations within the model boundaries. Wind measurements collected at meteorological stations operated by the local national meteorological service can often be suitable for this purpose.

Lebanon has a nationwide network of meteorological stations operated by Météo Liban (ML). ML has supplied GH with basic information and monthly wind data from 17 meteorological stations located throughout the country which are available for the wind map analysis [4]. Additionally hourly, wind data from a subset of 5 meteorological stations has been supplied [5].

A summary of the meteorological stations, including an indication of the stations where hourly data is available, is presented below:

Station	Easting [m]1	Northing [m]1	Altitude [m]	Data supplied3
Beirut International	729850	3744602	12	
Airport	730546	3748546	27	Jan 1999 – Dec 2007
Beirut Gulf	768760	3747699	Not supplied	Feb 1999 – Feb 2010
Tripoli	756216	3744470	5	Jan 1999 – Feb 2010
Sour2	780976	3793722	5	Nov 1999 – Jan 2010
El Koulaiaat / Akkar	776448	3750672	40	Jan 2008 – Jan 2010
Al Abdeh2	774278	3823977	1916	Jan 1999 – Dec 2009
Al Arz Les Cèdres2	706366	3682611	1524	Jan 1999 – Jul 2008
Daher el Baidar	717436	3709937	978	Nov 1999 – Jan 2010
Bayssour2	775180	3830929	920	Jan 2002 – Jan 2010
Zahleh Houch el	736790	3738849	905	Jan 1999 – Mar 2010
Oumara	738724	3714557	855	Jan 1999 – Apr 2008
Rayak Amara2	759727	3764325	1710	Sept 2007 – Jan 2010
El Quaraoun	813182	3811943	700	Jan 2009 – Jan 2010
Faqra	749026	3715206	760	Apr 2008 – Feb 2010
Hermel	740292	3693657	10	Mar 2009 – Feb 2010
Marjayoun	764898	3815825	955	Sept 2000 – Dec
Zahrani				2004
Jezzin				Not supplied

Notes:
1. Co-ordinate system is UTM Zone 36S, WGS84 datum
2. Additional hourly wind data supplied
3. These dates indicate the data period for the monthly wind speed data

A map of the Lebanon showing the locations of the ML meteorological stations is presented in Figure 3.1.

In addition to the data supplied from ML meteorological stations, the Client has supplied wind data measured at 5 meteorological stations situated within Syria near to the Lebanese border [6]. The locations of these masts are indicated in Figure 3.1. These data are summarised in the table below.

Station	Easting [m]1	Northing [m]1	Altitude [m]	Data supplied2
Sindiana 1	846431	3821094	515	April 2004 – January 2010
Sindiana 2	815168	3846851	545	April 2004 – March 2010
Qatina	814744	3845406	505	July 2005 – December 2007
Jandar	831205	3842425	750	June 2005 – December 2009
Hasia	849564	3805855	960	Not supplied

Notes:
4. Co-ordinate system is UTM Zone 36S, WGS84 datum
5. Ten minute data

GH has reviewed all the data supplied to identify potential sources of consistent, long term reference data in the country that can be used as wind map calibration points, as discussed in the sections overleaf.

3.2 MONITORING EQUIPMENT

3.2.1 Météo Liban Meteorological Stations

Limited information has been provided regarding the equipment used to measure wind data at the ML meteorological stations.

It is noted that all the ML meteorological stations have a height of 10 m. The wind flow at 10 m above ground level is subject to significant effects from small local terrain features. As a result this is generally considered to be too low to give a reliable indication of the wind speed at typical turbine hub heights.

It is understood from the information provided that most of the stations are “Auria E” type systems, from France. Auria E is a data acquisition system manufactured by Degreane and commonly used by Météo-France (MF). When deployed by MF, this data logger is typically used in combination with a Degreane DEOLIA 96 combined anemometer and wind vane unit. GH has experience with these instruments in France and considers them suitable for use at a meteorological station.

It is understood from the information provided that Beirut International Airport and Tripoli meteorological stations are “Milos” type systems with Vaisala instruments. GH has limited experience with Milos data logging systems, however Vaisala anemometers and wind vanes are well known by GH and are considered suitable for use at a meteorological station.

GH staff have visited Beirut Gulf Meteorological Station. As specified in the information provided, the station was found to consist of a 10 m meteorological mast equipped with a DEOLIA 96 combined anemometer and wind vane unit, as shown in Figure 3.2. The equipment was considered to be reasonably well configured. However, the exposure of the mast is considered relatively poor, with numerous tall buildings and trees close to the mast location, as can be seen in Figure 3.3. The poor exposure is likely to have influenced the wind data recorded at the mast.

Furthermore, without information regarding the date of construction of surrounding buildings and obstacles, it is possible that they were constructed during the measurement campaign, which would constitute a change in the exposure of the station.

Assuming that the wind monitoring masts at the other ML stations are configured similarly to the mast at Beirut Golf Meteorological Station, GH considers it likely that all of the ML meteorological stations detailed in the table are equipped with wind monitoring masts suitable for use at a meteorological station.

However it should be stressed that GH has not been able to inspect any of the meteorological stations other than ML Beirut Gulf. GH therefore cannot confirm the exposure or consistency of any of the masts and it is possible that some of the masts are adversely affected by local obstacles, which significantly elevates the uncertainty in the use of the data.

3.2.2 Syrian Meteorological Stations

Documentation provided with the supplied data [6] indicate, that all five measurement masts are 40 m in height and feature anemometers installed at 40 m and 10 m above ground level and a wind vane at 40 m. This information is generally supported by a photograph of a meteorological station contained in the supplied documentation and is consistent with the information found in the measured data files.

Inspection of the aforementioned photograph does not enable the type of measurement equipment installed at these masts or specific details of the mounting arrangements to be ascertained. However from other supplied photographs that indicate that they were taken at the location of the Jandar and Sindiana 1 masts it can be seen that these two masts are located in well exposed regions away from the influence of buildings or trees.

No maintenance records or calibration certificates for the instrumentation installed at the considered masts have been supplied so it has not been possible to ascertain the consistency of the instrumentation. Additionally the data supplied is not in the raw form as output by the logger, so it cannot be confirmed that the anemometer calibrations have been correctly applied. In light of this and the lack of information regarding the appropriate calibrations, GH has assumed that the calibrations are correctly applied and the data has been analysed without any further adjustment.

The lack of information regarding the equipment, anemometer calibration and mounting arrangements at any of the masts is considered to significantly elevate the uncertainty in considering the data recorded at all the Syrian masts.

Again it must be stressed that GH staff have not visited these meteorological stations, so GH cannot confirm that the details described for these meteorological stations are correct, which significantly elevates the uncertainty in the use of this data.

3.3 MEASURED WIND DATA

ML has supplied monthly mean wind speed data from each meteorological station for the periods presented in the table shown in Section 3.1. GH has used these data to derive information about long term annual and seasonal mean wind speeds at the meteorological stations. The hourly mean wind speed and direction data supplied for the sub-set of meteorological stations has also been considered and used to derive some information regarding the diurnal variation of the mean wind speed.

It is noted that the hourly wind speed data and some of the monthly mean wind speed data provided appear to have been rounded to the nearest 1 m/s. Additionally the hourly wind direction data has been rounded to the nearest 10 degree bin. These rounding procedures are considered coarse, especially given the low mean wind speeds at most of the meteorological stations, and further limit detailed investigation of the data.

GH has however performed a basic quality checking procedure on the mean wind speed data in an attempt to identify records which were grossly affected by equipment malfunction or other anomalies.

No data coverage information was available for the stations [7]. As a result the level of checking which could be undertaken for the stations for which wind speed data was available in monthly format only was limited to the identification and removal of obvious outliers.

The following periods were identified as having unrealistically high monthly mean wind speeds and were excluded from the analysis:

- Beirut International Airport: November – December 2005;
- Daher el Baidar: January – March 2008.

At the Zahleh Houch el Oumara and Sour meteorological stations a significant increase in monthly mean wind speeds was observed from January 2009 onwards, which was not consistent with wind speed trends observed at the other surrounding stations. At both of these stations there is a period of missing data prior to the apparent increase in wind speeds. GH therefore considers it most likely that the increase in wind speeds is due to a reconfiguration or relocation of the meteorological mast, rather than a genuine meteorological effect. For wind measurements to be valid, it is important that the consistency of measurements at any mast is maintained. GH therefore considers it appropriate to exclude the following data from the analysis:

- Zahleh Houch el Oumara: January 2009 - present;
- Sour: January 2009 - present.

Although significant differences were observed on a monthly basis between stations that are located very close to each other or in apparently similar geographical areas, the low resolution of the available wind speed data and the lack of any data coverage information prevented GH from establishing any more sophisticated quality checking. For the purposes of this analysis GH has therefore had to assume that all remaining data are valid. It is noted that there is considerable uncertainty in this assumption.

A similar quality checking procedure to that applied to the monthly data was carried out for the hourly wind speed and direction data. In addition, GH has undertaken a comparison of the monthly data supplied and the hourly data supplied for the same station. In order to avoid the introduction of bias due to a low number of observations within any given month, those months with less than 90 % data coverage have been excluded from the analysis. The mean wind speed values derived from this process were compared to the monthly values for the same measurement period at the same mast. As these datasets were derived from the same raw measurements, very close agreement between the values should be expected.

However, the level of agreement between these datasets was relatively poor, although overall trends are similar.For all masts, creating significant uncertainty over how these data were derived. Due to this, and concerns regarding the format of the hourly data supplied, GH does not consider the hourly data provided by ML to be suitable for defining the mean wind speeds across Lebanon. However due to the lack of suitable alternatives the hourly wind speed measurements have still been considered when defining the wind speed distribution and for examining the diurnal variation in the wind speeds.

Furthermore, when considering the hourly wind speed data supplied for the El Abde mast, very large periods were observed where the measurement equipment appeared to be subject to a malfunction. These records were excluded from the analysis. The data remaining after this process was not sufficient to carry out a sensible comparison with the monthly values. However, as both datasets were recorded using the same equipment, it must be assumed that the supplied monthly data is invalid also. As a result of this conclusion the El Abde mast has been removed from all further analysis.

GH has calculated the long-term annual and monthly mean wind speeds for each ML meteorological station for the valid data available. In order to avoid the introduction of bias into the annual mean wind speed estimate from seasonally uneven data coverage, the following procedure was followed:

- The mean wind speed for each month was determined from the average of all valid data recorded in that month over the period. This was taken as the monthly mean thereby assuming that the valid data are representative of any missing data.
- The mean of the monthly means was taken to determine the annual mean (“mean of means”) to eliminate the effect of seasonal bias in the data.

The annual mean wind speed is only considered to be valid for measurement periods representing a period of 1 year or more.
The results of the analysis of the monthly mean wind speed data from the ML meteorological stations are presented in Table 3.1.

The 10 minute mean wind data recorded at each of the Syrian meteorological stations has also been subject to a quality checking procedure. As mentioned in Section 3.3.2, the equipment used to measure this data is unknown. Additionally this data has been measured at locations that lie outside Lebanon and so cannot be considered to be fully representative of the wind regime within Lebanon. However, as these measurement masts feature anemometers installed at both 40 m and 10 m heights, and the supplied data has been averaged over 10 minute periods, this data is considered to add value to the analysis carried out. Due to this, the Syrian data has been considered in all the subsequent aspects of the analysis presented here.

The final mean of monthly mean wind speeds for the measurements supplied for each of the Syrian meteorological stations are presented for both 40 m and 10 m above ground level in Table 3.2.

4 WIND REGIME OF LEBANON

GH has undertaken correlations of monthly mean wind speeds between the ML meteorological stations located around Lebanon, in an attempt to establish a basic understanding of the dominant wind regimes in the country. When undertaking such correlations, GH would typically expect masts located close to each other, or in locations that are geographically similar, to correlate reasonably well.

In a small number of cases, pairs of Lebanese meteorological stations located close to each other correlated reasonably well on a monthly basis. However in the majority of cases the standard of correlation was poor, with significant scatter. GH observed no consistent trends in the correlations that would suggest wind regimes driven by proximity to the coast, altitude or relative location north or south in the country. Therefore GH was unable to draw any reliable conclusions as to the dominant wind mechanisms in the country.

The poor correlations and resulting inability to draw conclusions may be due to any of a number of potential factors:

- The low resolution of some of the monthly mean wind speed data and lack of data coverage information creates significant uncertainty in the wind speed data used in the correlations;
- GH has not inspected any of the meteorological stations other than Beirut Golf and it is possible that some of the stations, particularly those in urban areas, are adversely affected by nearby obstacles such as buildings or trees;
- Lebanon has large areas of complex, mountainous terrain. Correlations for locations situated in complex terrain are typically less reliable as masts tend to be affected by localised terrain-induced wind regimes;

Given the above factors regarding complex terrain and possible poor exposure of the masts, the low height of all the measurements could be responsible for the low quality correlations.

4.1 Seasonal and annual variability

Despite being unable to determine any regional wind regimes within the Lebanon, GH has examined the available wind data for the whole country in an attempt to define the seasonal and annual variability in windiness.

The seasonal windiness of each month of the year has been estimated by normalising the monthly wind speed time series at each meteorological station, and then averaging all of the occurrences of that month within the entire national data set.

Due to the annual variability in wind speeds, there is significant uncertainty associated with any assumption that a short period of measurements is representative of the long-term. The above procedure was therefore refined to only include meteorological stations with an extensive period of data which appears to be unaffected by gross inconsistency issues. This allows the estimate of the seasonal variation in windiness to be more representative of the long-term historical period. Given the available data, GH considers it most appropriate to define the long-term seasonal variation in windiness based on Beirut International Airport, Beirut Golf, Tripoli, Sour, El Koulaiaat / Akkar, Al Abdeh, Al Arz Les Cèdres, Daher el Baidar, Bayssour, Zahleh Houch el Oumara and Rayak Amara meteorological stations only.

The predicted long-term monthly variation of windiness in Lebanon is presented below:

Month	**Windiness [٪]**
January	104.4
February	113.2
March	110.0
April	109.8
May	102.8
June	102.0
July	103.4
August	93.4
September	91.1
October	86.2
November	86.9
December	97.1
Annual	100.0

It can be seen that, on average, February to April is the windiest period of the year and that October and November are the least windy months of the year.

In the data provided by ML, the meteorological stations with the longest data sets have a long-term period of approximately 11 years. GH generally recommends that at least 30 years of data are used to generate a robust estimate of the inter-annual variability of wind speed [6]. Due to this GH has attempted to obtain further historical data for the ML meteorological stations from the publicly available NOAA National Climate Data Centre database [7].

However, poor agreement was observed between NOAA monthly mean wind speed data for Lebanese meteorological stations and the corresponding data supplied directly by ML. Given the available data, GH does not consider it appropriate to calculate the inter-annual variability.

In all other countries surrounding the Mediterranean Sea, GH assumes an inter-annual variability of wind speed of 6 %. This is considered a reasonable starting assumption for the Republic of Lebanon.

4.2 Diurnal variability

GH has examined the hourly data available within Lebanon in an attempt to define the diurnal variability of the wind regime.

It is again noted that the available data is recorded at 10 m above ground level. When analysing data in other parts of the world GH has observed that the diurnal wind speed variation at 10 m may be very different, even the complete opposite, of the variation observed at typical turbine hub heights. This effect occurs due to differing atmospheric stability causing different wind shear between day and night. The presence of this effect cannot be investigated here due to the lack of measurements above 10 m height.

Due to the limitations of the available hourly data both as mentioned here and in Section 3.3, the uncertainty associated with the analysis is very high. GH considers it appropriate to make the following general qualitative statements:

- On average the wind speed is higher during the day than at night;
- The difference between the wind speeds observed at night and during the day is reduced both for the winter months and with increased altitude.

5 WIND MAP OF LEBANON

5.1 Wind Speed Map

The variation in wind speed has been predicted for Lebanon using the MC2 ("Mesoscale Compressible Community") computational model as developed by Environment Canada. In this application, MC2 has been run at 5 km resolution in EOLE Mode in which a finite number of climate states are defined according to a global database of geostrophic weather statistics based on public domain reanalysis hindcast data. The NCEP/NCAR ReAnalysis dataset has been used for this purpose. In this mode of operation, a number of simplifying assumptions are made relating to atmospheric stratification to allow a much faster convergence for the sake of computational efficiency. In addition, certain thermally driven atmospheric phenomena such as katabatic and anabatic flows are neglected in the modelling, again to allow computational efficiency gains. Each climate state is simulated individually until a converged state has been reached for each. Following the simulations for each of the standard climate states, the results are weighted by frequency of occurrence [10].

The results from the mesoscale modelling have been used to initiate the MS-Micro linear wind flow model. This model has then been used to predict the wind regime at heights of 80 m and 50 m above ground level across Lebanon at a resolution of 100 m.

Throughout the modelling process, the digital terrain map, which is a crucial input to the wind flow modelling, has been based on SRTM terrain data [11]. Due to the modelling resolutions used here, GH considers these terrain maps to provide a suitable level of accuracy. In order to define the terrain roughness within the flow modelling, the GenGeo database, which provides land use data at a resolution of approximately 1 km has been utilised [12].

Calibration of the wind map has been undertaken considering all suitable available measurements as described in Section 3.

As all the measured data available within Lebanon are produced using single anemometers mounted on masts of 10 m height, no indication of the vertical variation of wind speed, or wind shear, is available. Instead, modelling results have been applied to inform the shear values for each mast location. GH has taken the step of applying the shear value derived from the microscale model between heights of 50 m and 80 m at each mast location. The shear value is then applied to the measured wind speed at 10 m height to scale it to the considered heights of 50 m and 80 m. The data output from the modelling process at 10 m above ground level is not considered to be valid due to the dominance of local terrain features which necessarily cannot be included within the model.

The measured data available for the Syrian meteorological stations are produced using two anemometers mounted at heights of 40 m and 10 m above ground level. Due to this, GH has calculated a shear value using the long-term mean wind speed measured at the two measurement heights for each of the measurement masts for which data is available.

The shear values derived from these approaches are displayed in the table overleaf.

Station	Shear applied
Beirut International Airport	0.17
Beirut Golf	0.17
Tripoli	0.24
Sour	0.24
El Koulaiaat / Akkar	0.21
Al Arz Les Cèdres	0.30
Daher el Baidar	0.32
Bayssour	0.20
Zahleh Houch el Oumara	0.31
Rayak Amara	0.29
El Quaraoun	0.27
Faqra	0.25
Hermel	0.28
Marjayoun	No data supplied
Zahrani	0.24
Jezzin	No data supplied
Sindiana 11	0.11
Sindiana 21	0.16
Qatina1	0.15
Jandar1	0.11

Notes:
1. Syrian meteorological stations

These shear values are generally considered to be broadly within the range of possible values. However, due to the lack of measurements to validate these values, they are subject to extremely high uncertainty.

The wind maps produced by applying the methodology described above at 50 m and 80 m above ground level are displayed in Figures 5.1 and 5.2. These wind maps should be considered to represent a central estimate. A discussion of the high levels of uncertainty in these maps combined with a sensitivity analysis is given in Section 5.4.

5.2 Power Density Map

Power density maps have been produced at 100 m resolution for Lebanon at heights of 80 m and 50 m above ground level as shown in Figures 5.3 and 5.4, respectively. For each grid point a wind speed distribution representative of the modelled region has been scaled to the predicted wind speed and used to calculate the power density by applying the standard formula below:

$$PD = \sum_{v=0}^{50} F(v) \tfrac{1}{2} \rho v^{3}$$

Where: PD = power density [W/m2]
v = wind speed bin [m/s]
ρ = air density [kg/m3], based on historical data from nearby meteorological stations and standard lapse rate assumptions
F(v) = frequency of occurrence for each wind speed bin

Clearly, as the power density values are derived from the wind speed values, any uncertainty in the wind speed values is inherent and amplified in the power density maps; this is discussed further in Section 5.4.

Furthermore, the definition of the wind speed distribution used in this calculation is critical to the resulting power density values. The distributions derived from all the available ML hourly wind speed data and the Syrian meteorological stations have been considered for this purpose. From consideration of these distributions, GH has made the pragmatic assumption that wind speeds in Lebanon are distributed according to a Weibull distribution with a “k” shape parameter of 1.8. As a guide, to illustrate the sensitivity in this calculation, if a k value of 1.6 or 2.0 is assumed, the power density values would change by approximately +20 % or -12 % respectively.

5.3 Indicative Annual Energy Output

In order to provide an indication of the approximate amount of energy that could be generated by a single turbine installed at a given location, the indicative annual energy output for each power density band displayed in the supplied power density maps (Figures 5.3 to 5.4) has been calculated. As no specific turbine model has been specified at this stage, the figures displayed relate to a generic 1.5 MW turbine model with an 80 m hub height. This turbine does not represent any commercially available turbine but provides the reader with a useful indication of the energy yield that could be expected for a single turbine installed at any specific location. For reference, the generic power curve applied here is shown in Table 5.1.

It must be noted that the values of annual energy output displayed do not include any consideration of wake modelling as this is dependent on the exact location and turbine layout for any proposed development. Due to this, the figures relate to a single turbine only.

The output for a single turbine within a larger wind farm development is likely to be lower than the values below.

Power Density (W/m2)	Annual Energy Output (GWh/yr)
650	2.7
600	2.6
550	2.5
500	2.5
450	2.4
400	2.3
350	2.2
300	2.1
250	1.9
200	1.7
150	1.4
100	1.1
50	0.6
0	0.0

The annual energy output calculation includes standard GH loss assumptions and an estimate of the high wind hysteresis loss expected for each power density band.

The table overleaf lists the high level standard losses included in the Annual Energy Output calculation.

Wake effect	100.0%
Availability	96.0 %
Electrical efficiency	97.0 %
Turbine performance[1]	98.6 %
Environmental[2]	99.0 %
Curtailment	100.0%
Total Loss Applied	**90.9%**

Notes:

1. High wind hysteresis loss is not included in this figure as it has been calculated for each power density band.
2. This loss accounts for performance degradation due to dirt accretion and blade degradation

5.4 Consideration of Uncertainty

There is considerable uncertainty in the wind maps supplied here.Although GH's extensive experience, skill and care has been applied throughout the work presented here, the wind mapping results presented here are subject to high uncertainty due to:

- low resolution of monthly wind data provided;
- poor agreement between the hourly and monthly data provided for specific masts;
- absence of data coverage information for each month;
- lack of detailed information for each station;
- low height of the measurements;
- there only being one measurement height for the ML meteorological stations, preventing any measured estimate of wind shear within Lebanon;
- large extrapolation distance from 10 m to heights of 50 m and 80 m and corresponding uncertainty in the modelled shear assumed;
- grid resolution (5 km and 100 m);
- the inherent uncertainties in wind modelling over large distances.

The microscale modelling uses an increased grid resolution of 100 m. This enables the terrain and hence the wind flow to be modelled at a higher resolution. In order to best interpret the microscale modelling results, the following points must be noted:

- The mesoscale modelling output is utilised as input data and consequently the uncertainty in the mesoscale modelling is inherent in the microscale wind speed predictions;
- As no preferable alternative is available, the GenGeo database is used for the definition of surface roughness. This is a lower resolution than the microscale grid;

- The wind speed will be over-predicted near the peaks of hills with slopes of greater than 17 degrees. This may be seen in the wind speed predictions around the peaks of mountains although it is noted that these areas in particular are unlikely to be suitable for wind power development due to their inaccessibility.

As shown in the formulation of the power density shown in Section 5.2, any uncertainty in wind speed predictions is greatly amplified in the power density predictions together with the uncertainty in defining the wind speed distribution used in this calculation which is also discussed in Section 5.2.

Due to the high uncertainty in the modelling process it is not considered appropriate to formally and rigorously quantify the uncertainty in the wind speed predictions. GH recommends that the presented results are used for early feasibility purposes and to assist in the design of wind measurement campaigns at prospective sites only.

In order to illustrate the impact of the uncertainty in the wind maps supplied, wind speed maps have also been produced for scenarios of plus and minus 10 % change in wind speed when compared with the central estimate presented in Figures 5.1 and 5.2 for 80 m and 50 m respectively. These scenarios are shown in Figures 5.5 to 5.8.

Correspondingly, to highlight the sensitivity of the power density to changes in wind speed, power density maps have been produced for the plus and minus 10 % cases and are shown in Figures 5.9 to 5.12.

It is noted that the sensitivity cases mentioned above of plus and minus 10 % on wind speed do not represent the range of uncertainty in the modelling results presented here; these cases merely illustrate how the deliverables may change if a relatively small perturbation is introduced. Without higher quality measured data it is not possible to meaningfully define the bounds of uncertainty in the maps produced.

Additional wind speed measurements compliant with IEC recommendations [13], made at heights comparable to those at which the maps are presented, and at a number of heights, in numerous locations around Lebanon would provide more reliable predictions of the wind speed at the wind map heights. Measurements made in this way could be used to better calibrate the current wind map and so reduce the uncertainty in the wind speed values displayed, as well as retaining value for use in more detailed analysis for potential wind farm sites in the immediate vicinity of the new measurements.

6 POTENTIAL WIND POWER CAPACITY

GH has utilised the wind map derived here along with consideration of other constraints on wind power development to derive a figure for the potential installed wind capacity for Lebanon.

The constraints information used was provided to GH by the Client [14] and considers the following factors:

- Areas of high population density;
- Areas of high political instability;
- Military sites;
- Commercial interests (e.g. mining, fisheries etc…);
- Civilian aviation sites;
- Areas in close proximity to radar or telecommunication sites;
- National parks;
- Conservation areas e.g. Cedar forests;
- Historic sites;
- Sites of religious significance.

Migratory bird flight routes and sensitive animal habitats could not be considered here as the Client is currently in the process of investigating this information [15].

Proximity to transmission lines and roads has not been included in this constraints list as the aim of this calculation was to derive the potential installed wind power capacity and not the currently practicable wind power capacity. So although some areas may currently be uneconomical for wind power development due to distance from the necessary infrastructure, this situation may change in the future.

In addition to the constraints listed above, GH has also considered a maximum terrain slope at which it is economically reasonable to install a wind turbine. The value assumed for this aspect of the analysis is 14 degrees. Due to the significant areas of complex terrain in Lebanon, the selection of this maximum slope has a significant impact on the potential wind power capacity derived.

In order to calculate the potential wind power capacity, a number of high-level assumptions are required. The values that GH has assumed are considered to be reasonable universal assumptions and are listed here:

- A wind speed of greater than 6.5 m/s at 80 m above ground level has been considered necessary for a viable wind farm;
- An installation density of 8 MW/km2.

It must be noted that GH has pragmatically applied these assumptions in order to produce the value displayed below, however the actual value may vary due to a wide range of factors.
Based on the described assumptions above the potential onshore wind power capacity of Lebanon is 6.1 GW.

To illustrate the sensitivity of this capacity to the key inputs, if GH considers the perturbation analysis described in Section 5.4, the impact of reducing all wind speeds by 10 % would result in a potential wind power capacity of 2.5 GW. If all wind speeds were increased by 10 %, the potential capacity would be 12.0 GW.

Furthermore, if the maximum slope constant is altered to be 8 degrees, the potential capacity would be reduced to 3.8 GW. If this reduced maximum slope is combined with the minus 10 % perturbation case the resulting potential capacity is reduced to 1.5 GW.

7 OFFSHORE WIND MAP OF LEBANON

The variation in wind speed for the offshore region for a distance of up to 20 km from the coast of Lebanon has been predicted by following the same modelling methodology as applied onshore, (see Section 5.1). The final wind map for this region has been derived for 80 m and 50 m above ground level and is shown in Figures 7.1 and 7.2 respectively.

It is generally considered that an ocean depth of up to 50 m is feasible for the installation of wind turbines with currently available bottom-mounted technologies, although this depth limit may vary to some extent due to factors such as sea bed soil conditions. Therefore the areas for possible offshore wind development within the Exclusive Economic Zone (EEZ) of Lebanon are limited to a small area close to the coast. The maximum distance from the coast for which a sea depth of less than 50 m is observed is approximately 10 km. Due to this, the supplied wind map covers considerably more than the region that is available for offshore wind power development.

Power Density maps are also provided for the same modelling region as the offshore wind map. These represent 80 m and 50 m above mean sea level as shown in Figures 7.3 and 7.4, respectively. The power density values have been calculated using the same methodology as for the onshore maps as described in Section 5.2.

In addition to the uncertainties described in Section 5.4, producing a wind map offshore, and particularly in the coastal region, is subject to additional uncertainty arising from the following:

- A lack of suitable offshore wind measurements with which to validate the modelling output;
- The presence of complex, local and thermally driven diurnal onshore and offshore breezes.

As no offshore wind speed measurements are available to assess the applicability of the offshore wind speed predictions, GH has considered two independent sources of Earth Observation (EO) wind speed data. The datasets considered are quickSCAT and ERS. For more detailed information on how these datasets were derived please refer to Appendix 1. These datasets provide an indication of the wind speed across an area at approximately 10 m above the sea surface and are themselves subject to significant uncertainties. Additionally data points are only available for locations that lie a significant distance from the shore.

The locations where the EO data is available and can be used to compare with the modelling results produced here are shown in Figures 7.5 and 7.6 for the quickSCAT and ERS datasets respectively. Wind flow modelling has been carried out across this entire area to facilitate this comparison; however these results are not presented here.

There are high uncertainties with the comparison between the modelling results and the EO data due to the following:

- The algorithms used to convert the wave observations to wind speed are subject to large assumptions;

- The locations where the EO data are available at a large distance from the wind mapping area.

No close agreement was observed between the EO datasets and the modelling results. This is not unexpected, due to the high uncertainties in both the modelling and the EO data.

GH considers that due to the limitations of EO data, the high uncertainty in the modelling results and the lack of close agreement between the predictions and measurements, the offshore wind map is subject to additional uncertainty than the results presented for the onshore wind map. Necessarily these offshore wind mapping results must be treated with extreme caution.

GH strongly recommends that wind measurements are installed at any site proposed for offshore wind power development to properly establish the wind resource available.

8 DELIVERABLES

In addition to the figures contained in this report, the wind speed maps derived using the methodology described in Sections 5 and 7 have been supplied to the Client. These deliverables have been supplied to the Client in a number of file formats as detailed below:

- An *.emf image file containing a high resolution figure of the considered wind map;
- A *.shp file containing the coordinates and predicted wind speed for each result point within the study region. This file type can be viewed in GIS software such as ArcGIS;
- A *.kmz file enabling the considered wind map to be overlaid over the freely available GoogleEarth software.

The wind mapping deliverables described above have been presented to the Client for all the central estimate wind and power density maps both onshore and offshore and at heights of 80 m and 50 m. This amounts to a total of 8 different datasets to be displayed in the three file formats.

In addition to the deliverables outlined above a *.kmz file containing wind roses derived from every node of the mesoscale grid has been supplied. These wind roses can be overlaid over the freely available GoogleEarth software, enabling the Client to observe an indication of the wind direction for points across Lebanon.

The above deliverables can be found in the accompanying CD attached at the end of the report.

9 SUMMARY

The results of the modelling work undertaken here are presented in Figures 5.1 to 7.4. This work is summarised below:

- Both mesoscale and microscale wind flow modelling has been carried out to determine the wind speed variation at heights of 50 m and 80 m for Lebanon at a final resolution of 100 m. Measured data supplied by Météo Liban and for meteorological stations located in Syria, as described in Section 3, have been considered in the production of these wind maps, the central estimates of which are presented in Figures 5.1 and 5.2.

- The same wind flow modelling methodology was carried out to determine the wind speed variation at heights of 50 m and 80 m for the offshore region lying within 20 km of the Lebanese coastline. Consideration of all applicable offshore observations has been undertaken in order to assess the applicability of the modelling results to the offshore region. The central estimate wind maps are presented in Figures 7.1 and 7.2.

- The wind speed outputs described above have been converted to Power Density as described in Section 5.2. The central estimate values from this work are presented in Figures 5.3 and 5.4 for the onshore maps and Figures 7.3 and 7.4 for the offshore maps.

- There is considerable uncertainty in all the displayed wind mapping results. This uncertainty arises despite the application GH's extensive experience, skill and care. This uncertainty arises from a number of sources such as:

    - low resolution of monthly wind data provided;
    - poor agreement between the hourly and monthly data provided for specific masts;
    - absence of data coverage information for each month;
    - lack of detailed information for each station;
    - low height of the measurements;
    - there only being one measurement height for the ML meteorological stations, preventing any measured estimate of wind shear within Lebanon;
    - large extrapolation distance from 10 m to heights of 50 m and 80 m and corresponding uncertainty in the modelled shear assumed;
    - grid resolution (5 km and 100 m);
    - the inherent uncertainties in wind modelling over large distances.
- Due to the high uncertainty in the shear values applied to the available wind speed measurements and the high uncertainty in the measurements themselves it is considered that the observed wind speed values may vary significantly from the displayed central estimate. Due to this, Figures 5.5 to 5.8 display wind speeds from upwards and downwards perturbations which represent a 10 % variation from the central estimates for both 80 m and 50 m above ground level. The Power Density values derived from the wind speed perturbation scenarios are shown in Figures 5.9 to 5.12. It is noted that the sensitivity cases of plus and minus 10 % of

wind speed do not represent the range of uncertainty with the modelling results presented here; these cases merely illustrate how the deliverables may change if a relatively small perturbation is introduced. Without higher quality measured data it is not possible to meaningfully define the bounds of uncertainty in the maps produced.

- Section 5.3 describes a simple methodology that can be applied by users of the wind map to obtain a quick initial indication of the annual energy output that could be expected from a single turbine installed at a location within Lebanon.

- It is noted that the limitations of the modelling techniques applied, as outlined in Section 5.4, and also in Section 7 for the offshore work, must be taken into account when considering the results presented here.

- The potential installed onshore wind power capacity for Lebanon has been calculated as 6.1 GW based on the wind speed at 80 m above ground level, a number of high level assumptions and constraint data supplied by the Client. Details of how this figure was derived are included in Section 6. It is noted that there is significant sensitivity to the inputs applied in this calculation. To illustrate this if the downward wind speed perturbation is applied and the maximum practical terrain slope for turbine construction is reduced to 8^o the figure quoted above is reduced to 1.5 GW.

- It is not considered appropriate to quantify the high uncertainties inherent within the results presented here. Consequently, GH recommends that the presented results are used for strategic or feasibility purposes and to assist in the design of wind measurement campaigns at prospective sites only.

- Additional wind measurements at multiple heights approaching those of typical turbine hub heights are recommended in order to reduce the uncertainty in any future wind resource assessments carried out in Lebanon.

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13. IEC 614001-12-, “Wind turbines - Part 121-: Power performance measurements of electricity producing wind turbines, Annex G”, 2005.
14. Email from Hassan Harajli, UNDP Lebanon, to Joel Manning, GH, 30th March 2010.
15. Email from Hassan Harajli, UNDP Lebanon, to Joel Manning, GH, 5th October 2010.

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LIST OF FIGURES

	Beirut Airport	Beirut Golf	Tripoli	Sour	Klaiaat Akkar	Abdé	Les Cèdres	Dahr-el-Baidar
January	3.4	3.0	1.9	3.3	7.2	2.4	4.4	6.0
February	3.7	3.3	2.4	3.4	6.1	2.9	4.6	6.1
March	3.5	3.0	2.3	3.2	5.1	3.0	4.2	6.1
April	3.1	3.1	2.4	3.1	4.5	2.9	4.5	5.9
May	3.2	3.0	2.2	2.9	3.5	2.5	4.1	5.5
June	3.2	3.0	2.1	3.0	3.3	2.6	3.5	5.3
July	3.4	3.1	2.3	3.1	4.2	2.7	3.3	5.8
August	3.0	2.7	2.0	2.8	2.5	2.4	3.1	5.5
September	2.8	2.5	1.9	2.9	2.8	2.3	3.3	5.0
October	3.0	2.3	1.6	2.6	1.8	2.3	3.9	4.3
November	2.7	2.2	1.6	2.8	3.9	2.5	3.7	4.3
December	3.6	2.5	1.8	2.9	5.4	2.4	4.0	4.9
Data period (years)	8.8	11.1	11.2	8.8	1.6	11.0	9.6	7.4
Long-term mean wind speed	3.2	2.8	2.0	3.0	4.2	2.6	3.9	5.4

Table 3.1 Monthly and long-term wind speeds at 10 m above ground level derived from Météo Liban meteorological stations measurements (continued).

	Bayssour	Zahlé	Rayak	Qaraoun	Faqra	Hermel	Marjayoun	Zahrani
January	4.2	2.6	3.3	4.0	2.7	3.2	5.9	4.0
February	4.0	2.7	3.7	4.2	3.2	3.2	8.1	4.6
March	4.0	2.7	3.8	4.2	2.9	3.5	7.3	4.3
April	3.6	2.9	4.1	4.0	2.5	3.4	-1	4.1
May	3.3	2.7	3.7	3.8	2.4	3.3	-1	4.2
June	3.2	2.9	3.8	3.6	1.8	3.1	8.9	3.7
July	3.0	2.9	3.7	3.6	1.7	3.8	9.1	3.7
August	2.6	2.6	3.5	3.4	1.6	2.8	-1	3.6
September	3.0	2.4	3.4	3.5	1.8	2.8	-1	3.7
October	3.2	2.0	3.0	3.7	2.4	2.5	7.4	3.9
November	3.4	1.9	3.1	3.7	2.6	2.1	6.8	4.0
December	3.6	2.5	3.6	4.0	3.1	2.9	6.4	4.1
Data period (years)	7.7	9.5	9.3	2.1	1.1	1.4	0.7	4.3
Long-term mean wind speed	3.4	2.6	3.6	3.8	2.4	3.1	-2	4.0

Notes:
1. No data available for this month.
2. No long-term wind speed indicated as the data is available for less than 1 year.

Table 3.1 Monthly and long-term wind speeds at 10 m above ground level derived from Météo Liban meteorological stations measurements (concluded).

	Sindiana 1	Sindiana 2	Qatina	Jandar
Data period (years)	5.4	2.0	2.0	4.2
Long-term mean wind speed at 10 m height	6.7	6.1	6.1	4.6
Long-term mean wind speed at 40 m height	7.7	7.6	7.5	5.3

Table 3.2 Long-term mean wind speeds at 40 m and 10 m above ground level derived from the Syrian meteorological station measurements

Hub height wind speed [m/s]	Electrical power [kW]
3	0
4	20
5	100
6	230
7	390
8	600
9	850
10	1130
11	1330
12	1430
13	1490
14	1500
15	1500
16	1500
17	1500
18	1500
19	1500
20	1500
Hub height	80 m
Air Density	1.1 kg/m3
Cut out ten minute mean wind speed	20 m/s
Restart ten minute mean wind speed	18 m/s

Table 5.1 Performance data for the Generic wind turbine applied in the annual energy production calculation.

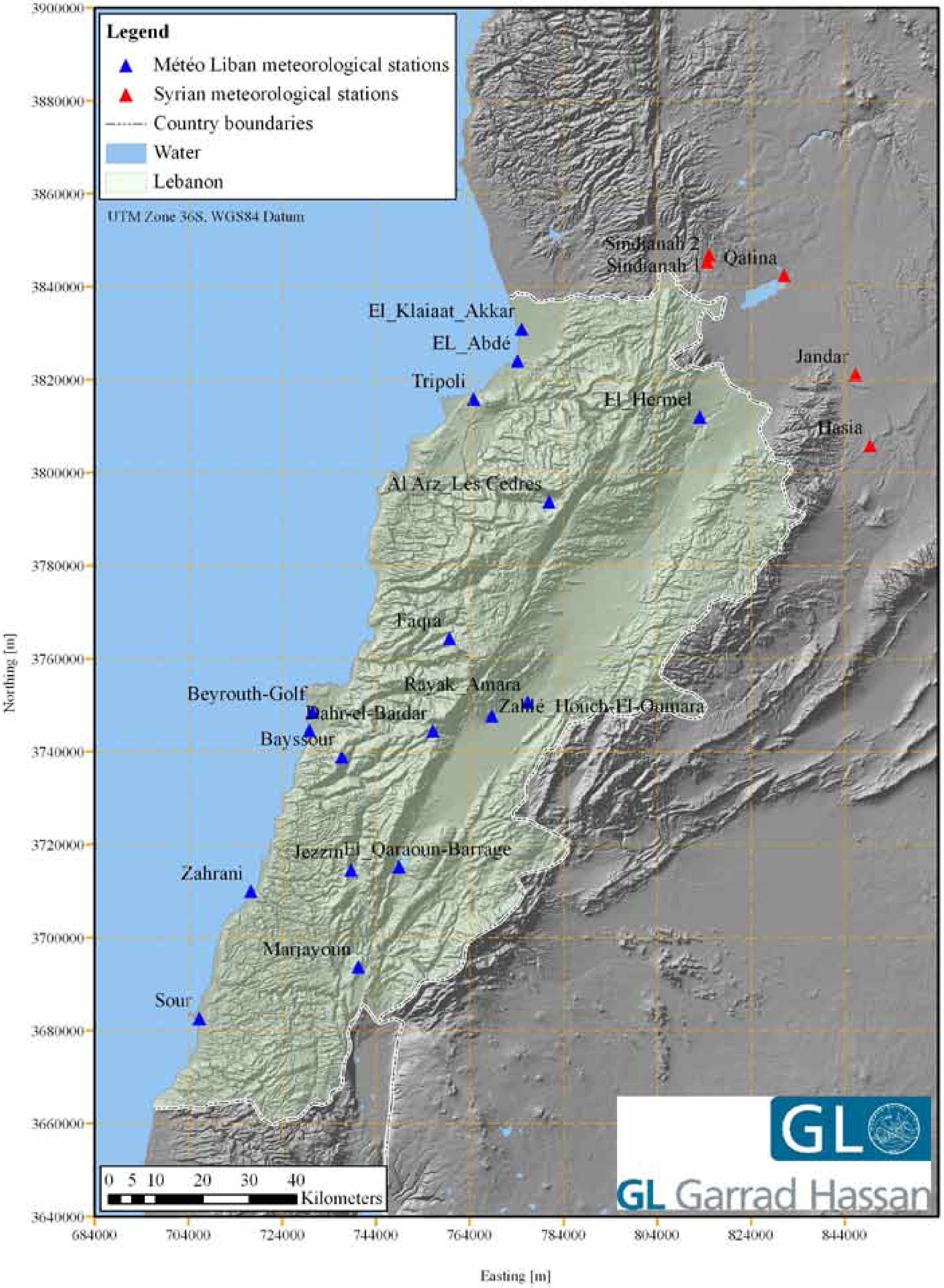

Figure 3.1 Map of the Republic of Lebanon indicating the location of the meteorological stations used in the production of the presented wind map.

Figure 3.2 View of the Beirut Golf Meteorological Station and instrumentation.

Figure 3.3 Panoramic view of from the location of the Beirut Golf Course Meteorological Station.

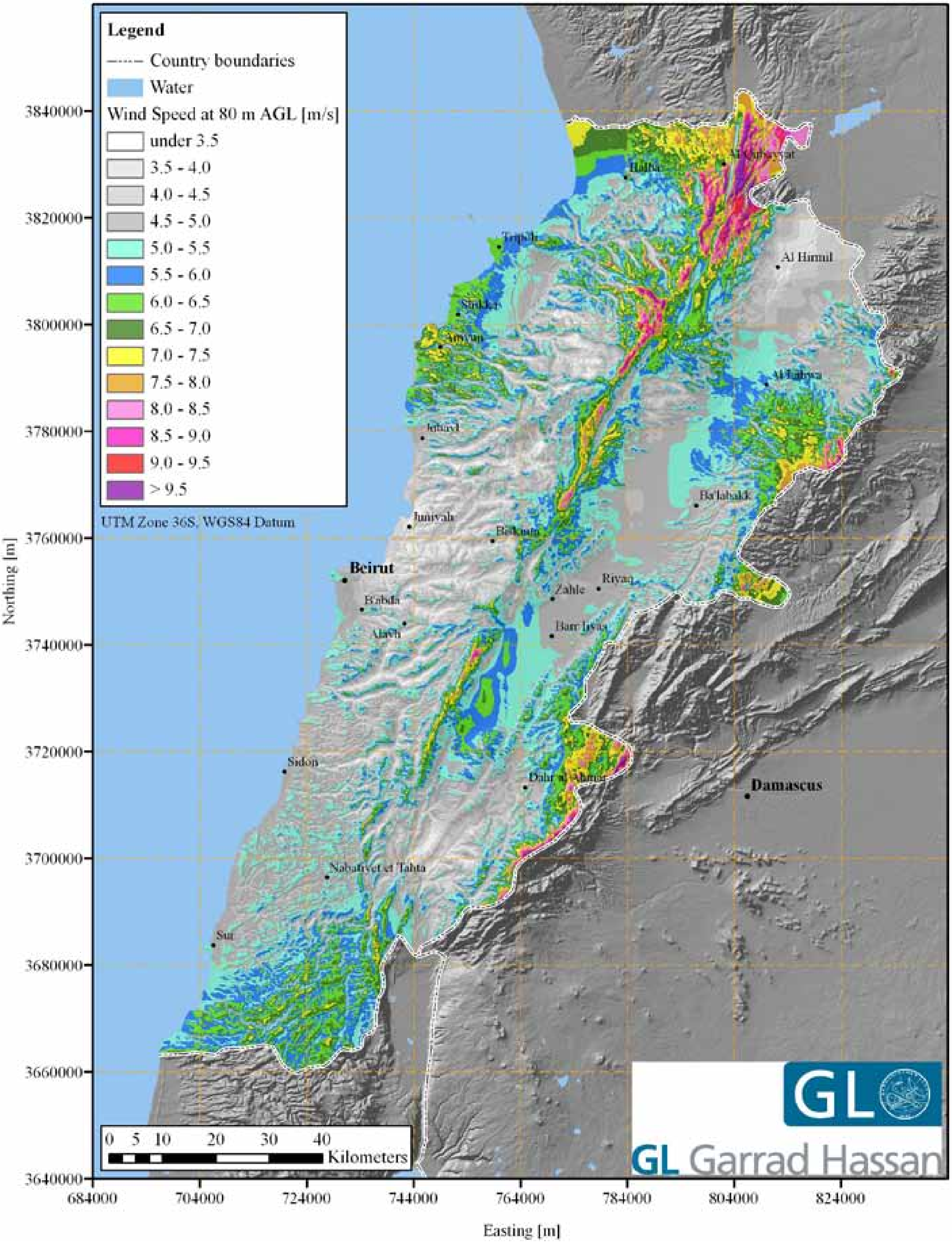

Figure 5.1 Central estimate wind map of the Republic of Lebanon at 80 m above ground.

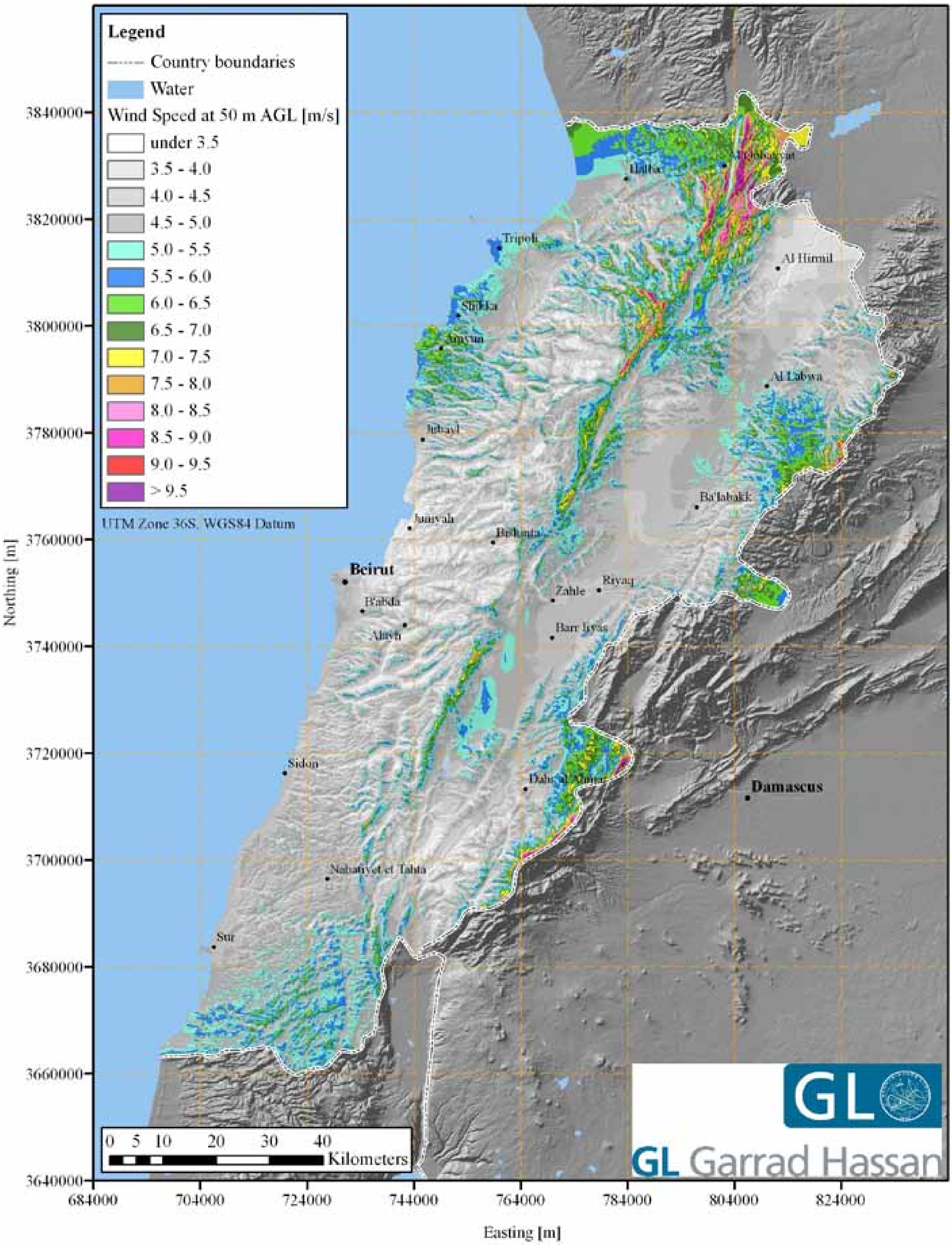

Figure 5.2 Central estimate wind map of the Republic of Lebanon at 50 m above ground level.

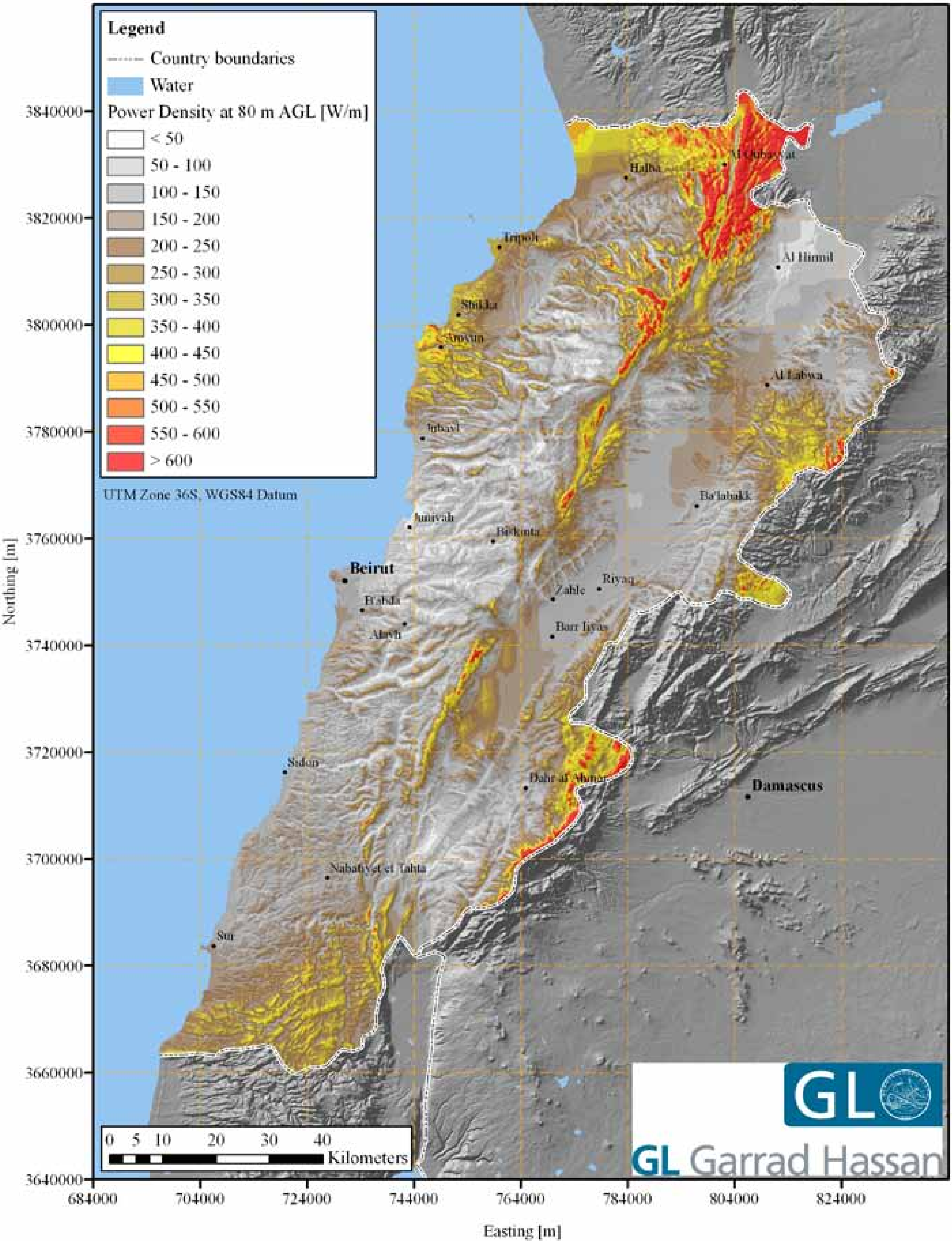

Figure 5.3 Central estimate Power Density map of the Republic of Lebanon at 80 m above ground level.

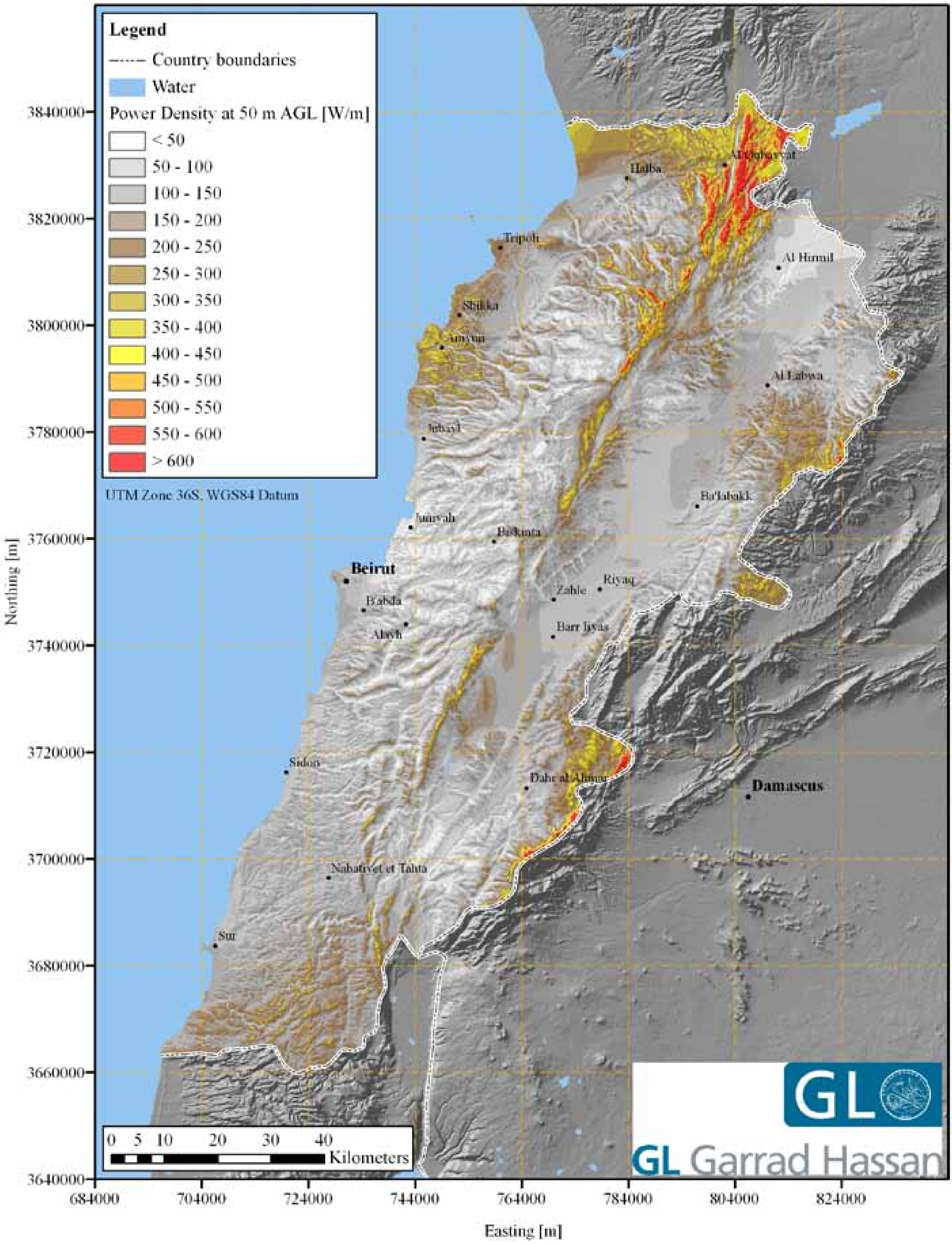

Figure 5.4 Central estimate Power Density map of the Republic of Lebanon at 50 m above ground level.

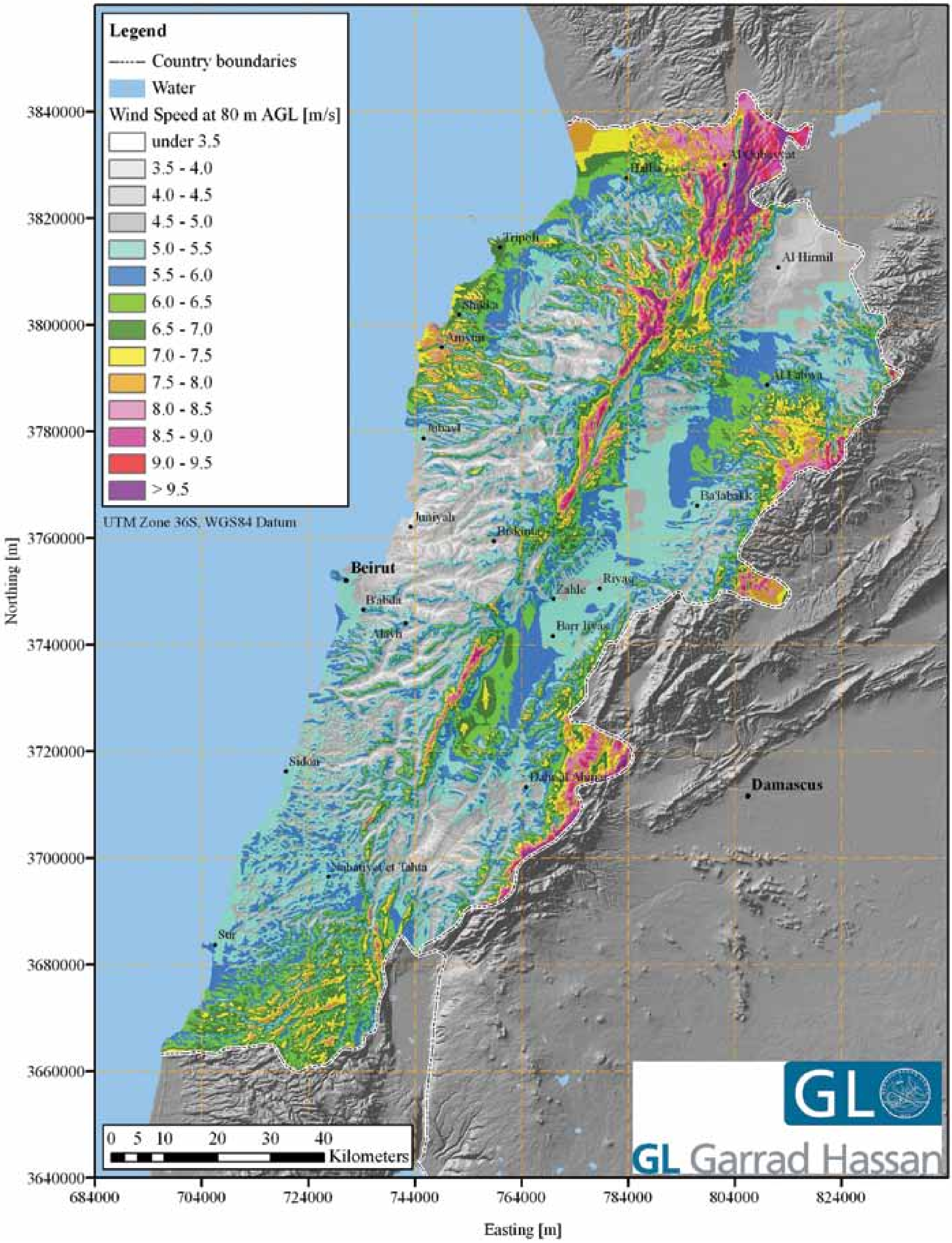

Figure 5.5 Upwards sensitivity (central estimate plus 10 %) wind map of the Republic of Lebanon at 80 m above ground level.

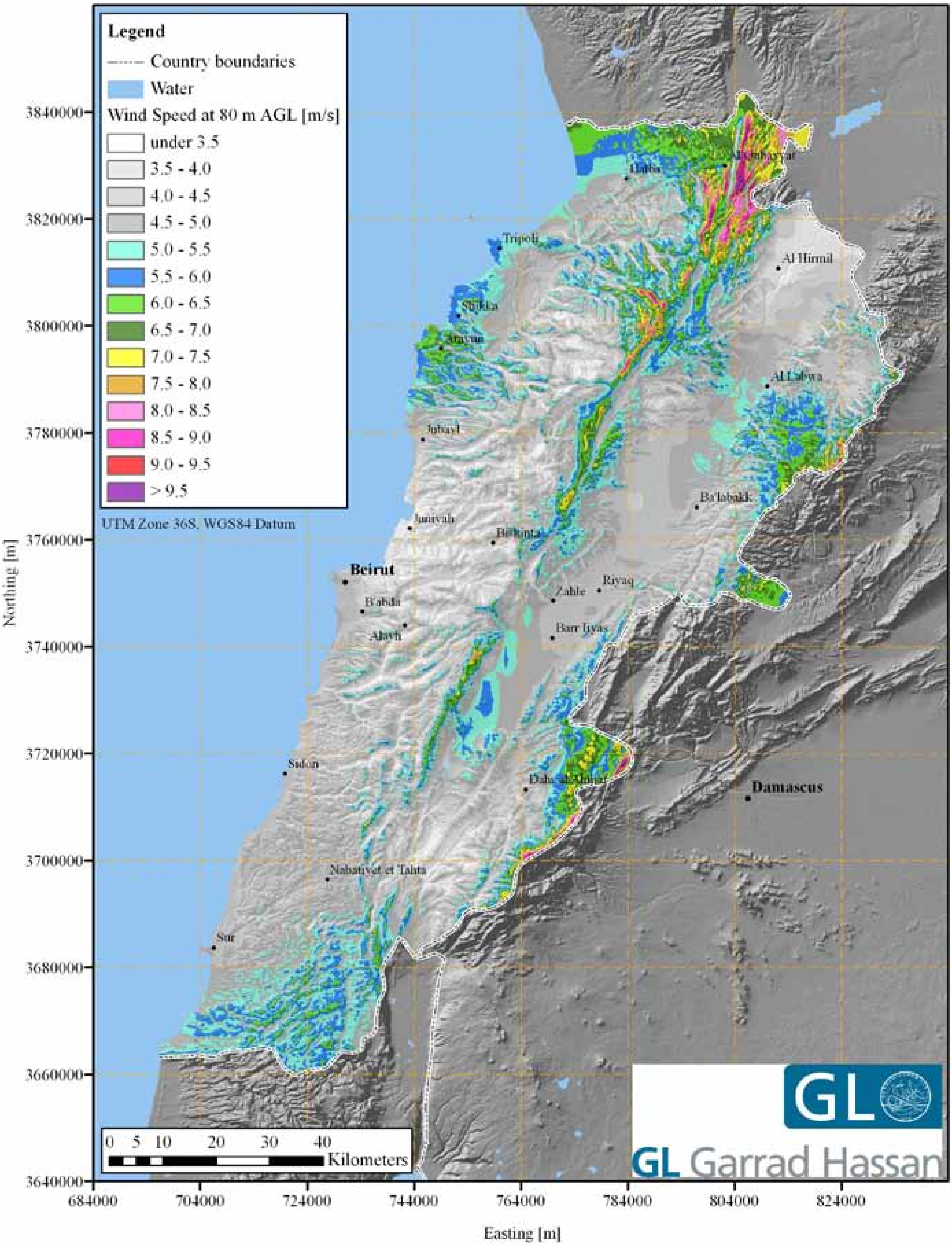

Figure 5.6 Downwards sensitivity (central estimate minus 10 %) wind map of the Republic of Lebanon at 80 m above ground level.

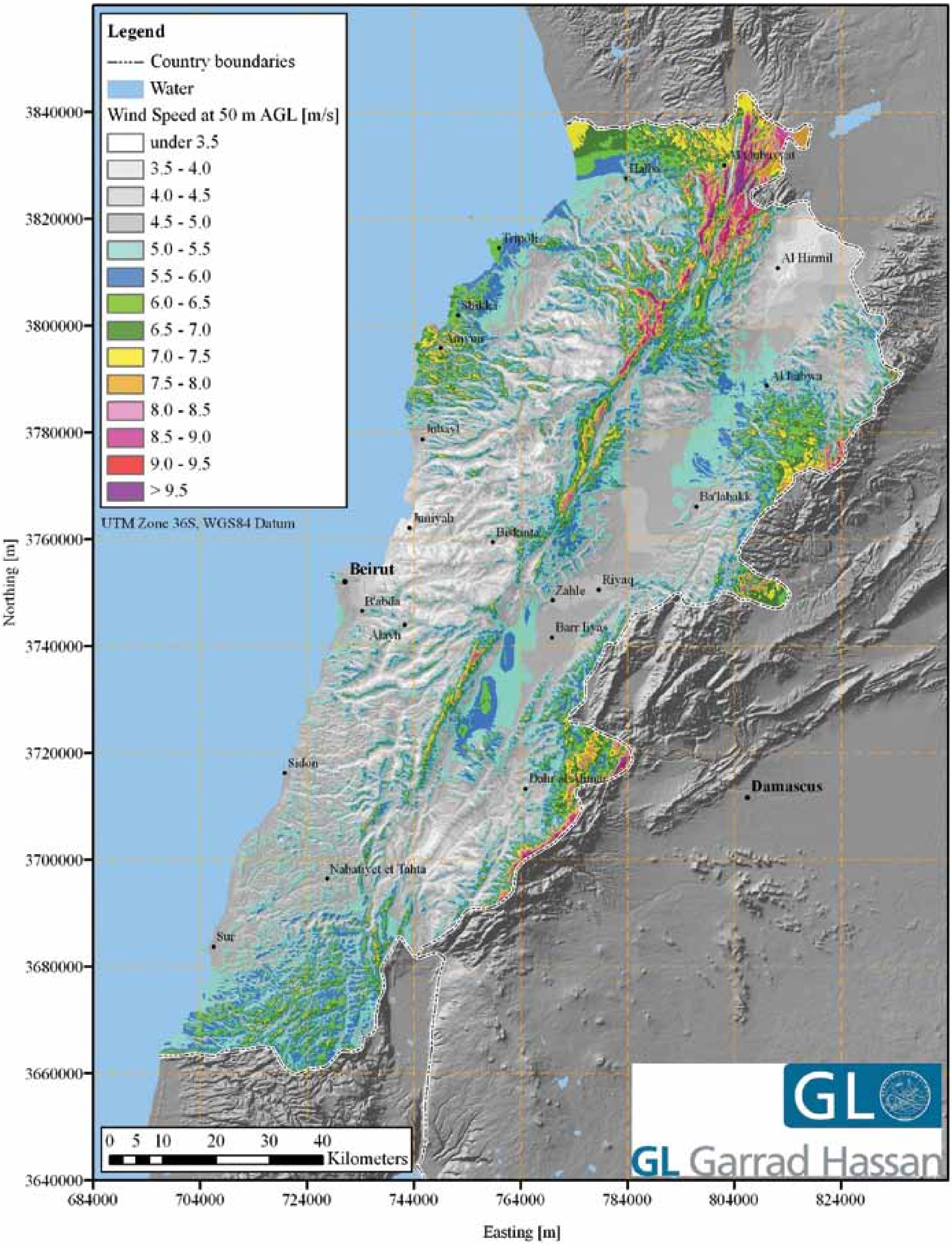

Figure 5.7 Upwards sensitivity (central estimate plus 10 %) wind map of the Republic of Lebanon at 50 m above ground level.

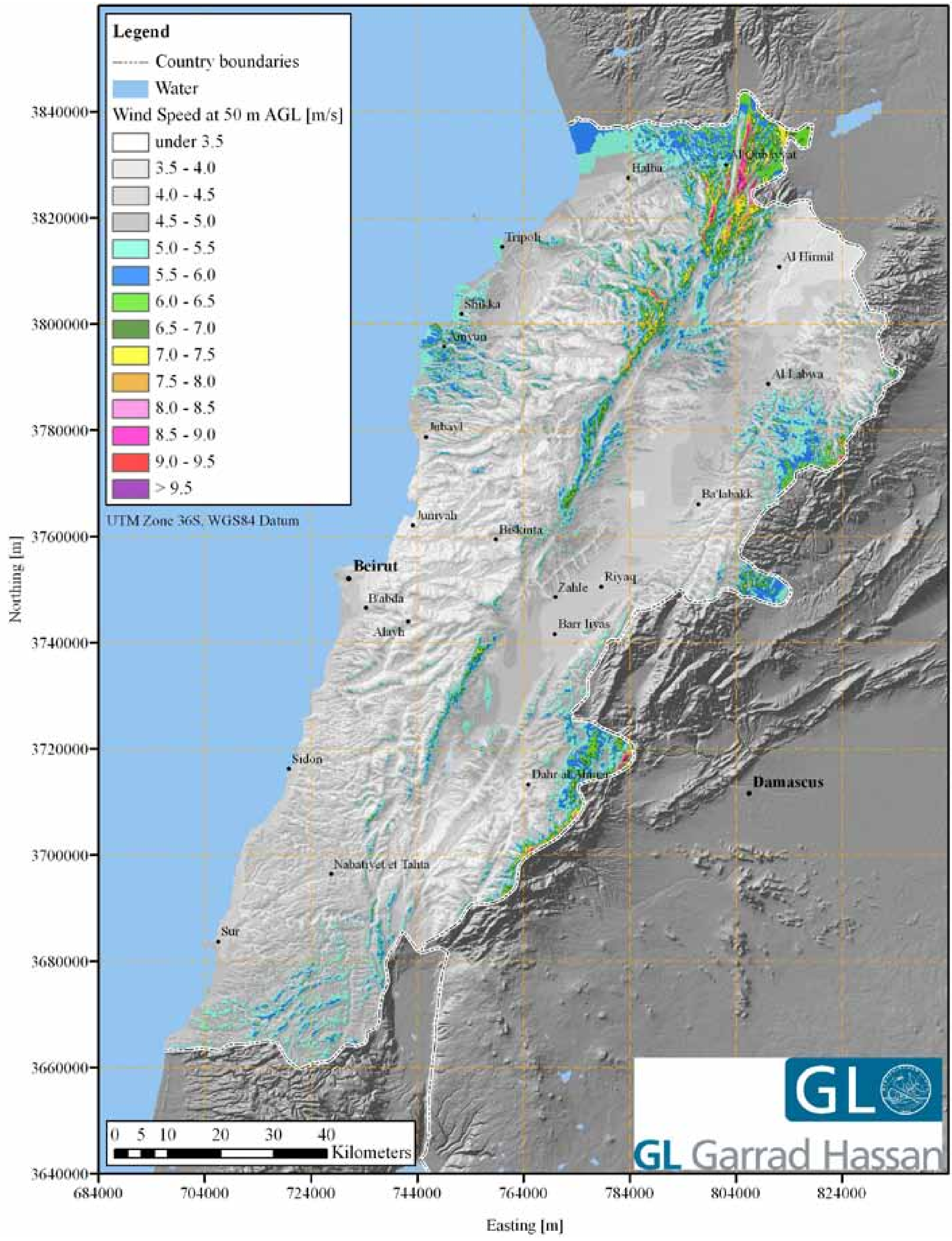

Figure 5.8 Downwards sensitivity (central estimate minus 10 %) wind map of the Republic of Lebanon at 50 m above ground level.

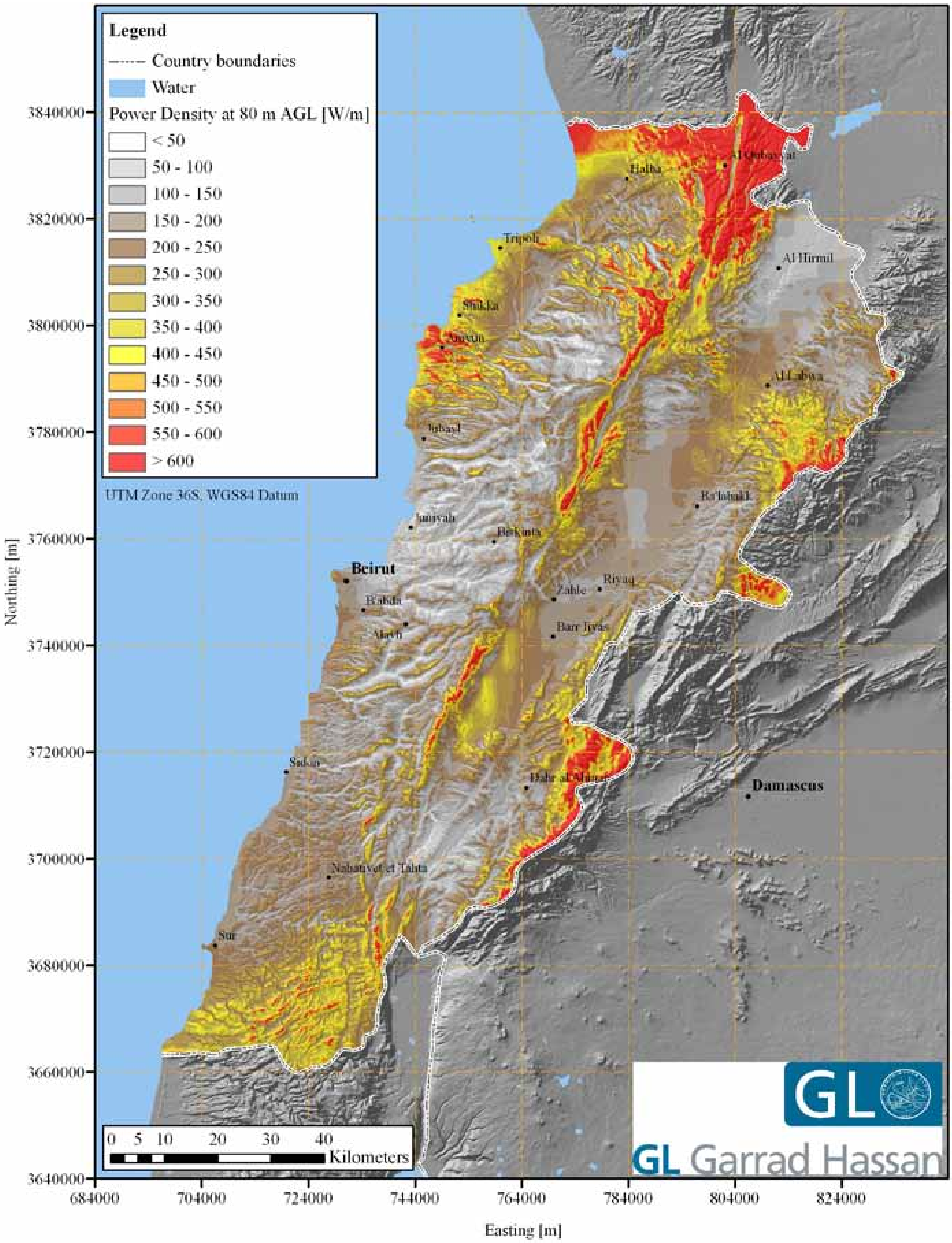

Figure 5.9 Upwards sensitivity Power Density map (derived from central estimate wind speed plus 10 %) of the Republic of Lebanon at 80 m above ground level.

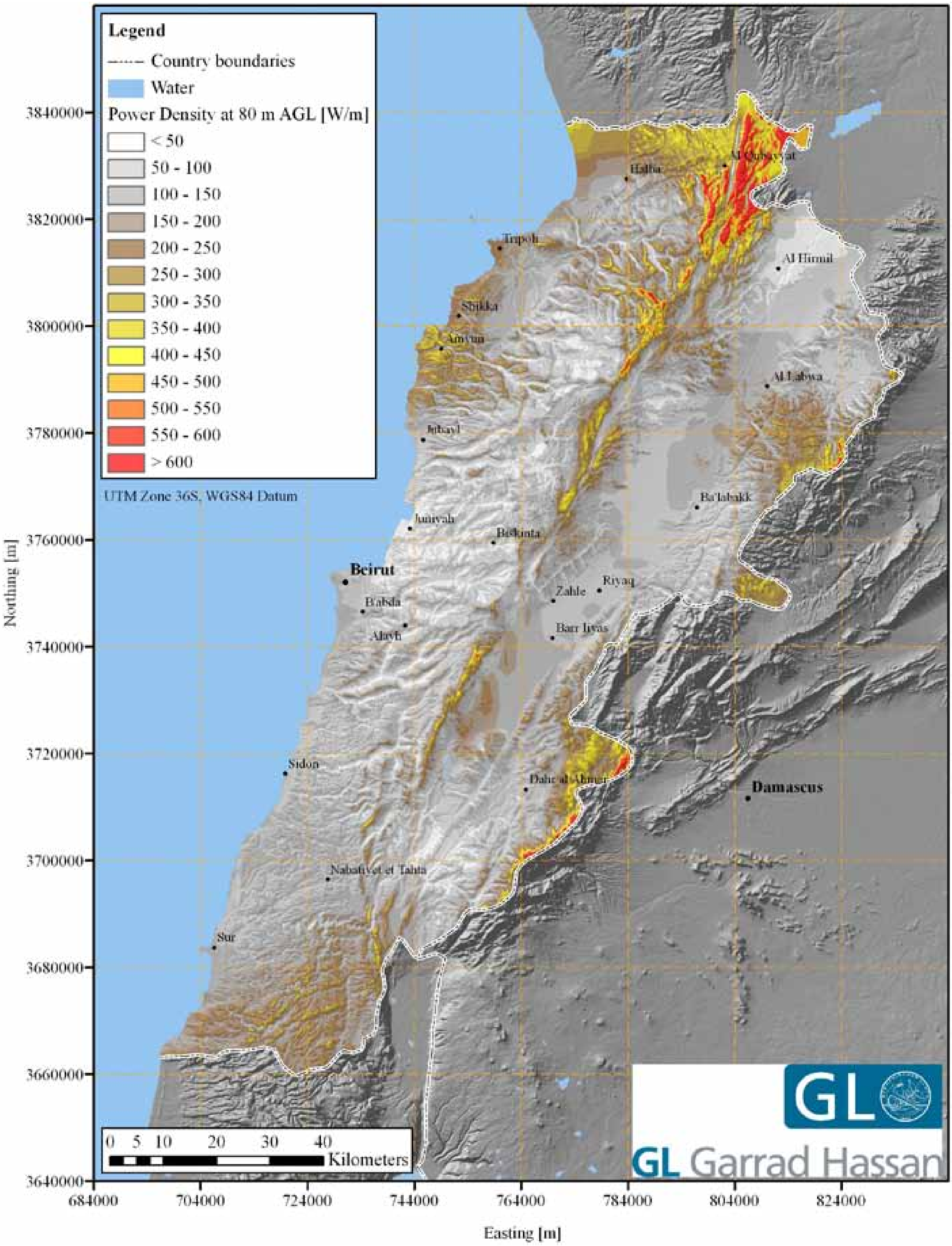

Figure 5.10 Downwards sensitivity wind map (derived from central estimate wind speed minus 10 %) of the Republic of Lebanon at 80 m above ground level.

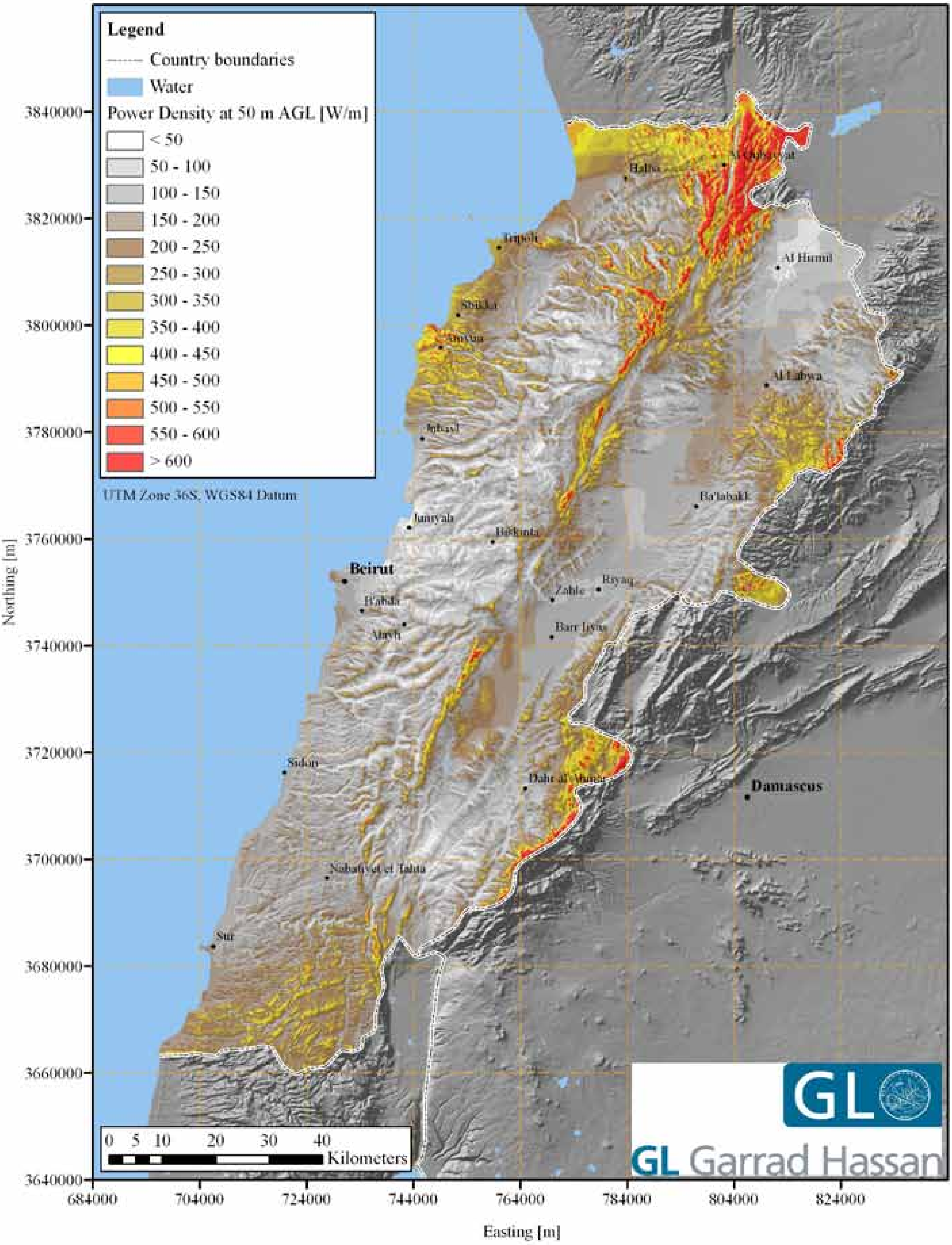

Figure 5.11 Upwards sensitivity Power Density map (derived from central estimate wind speed plus 10 %) of the Republic of Lebanon at 50 m above ground level.

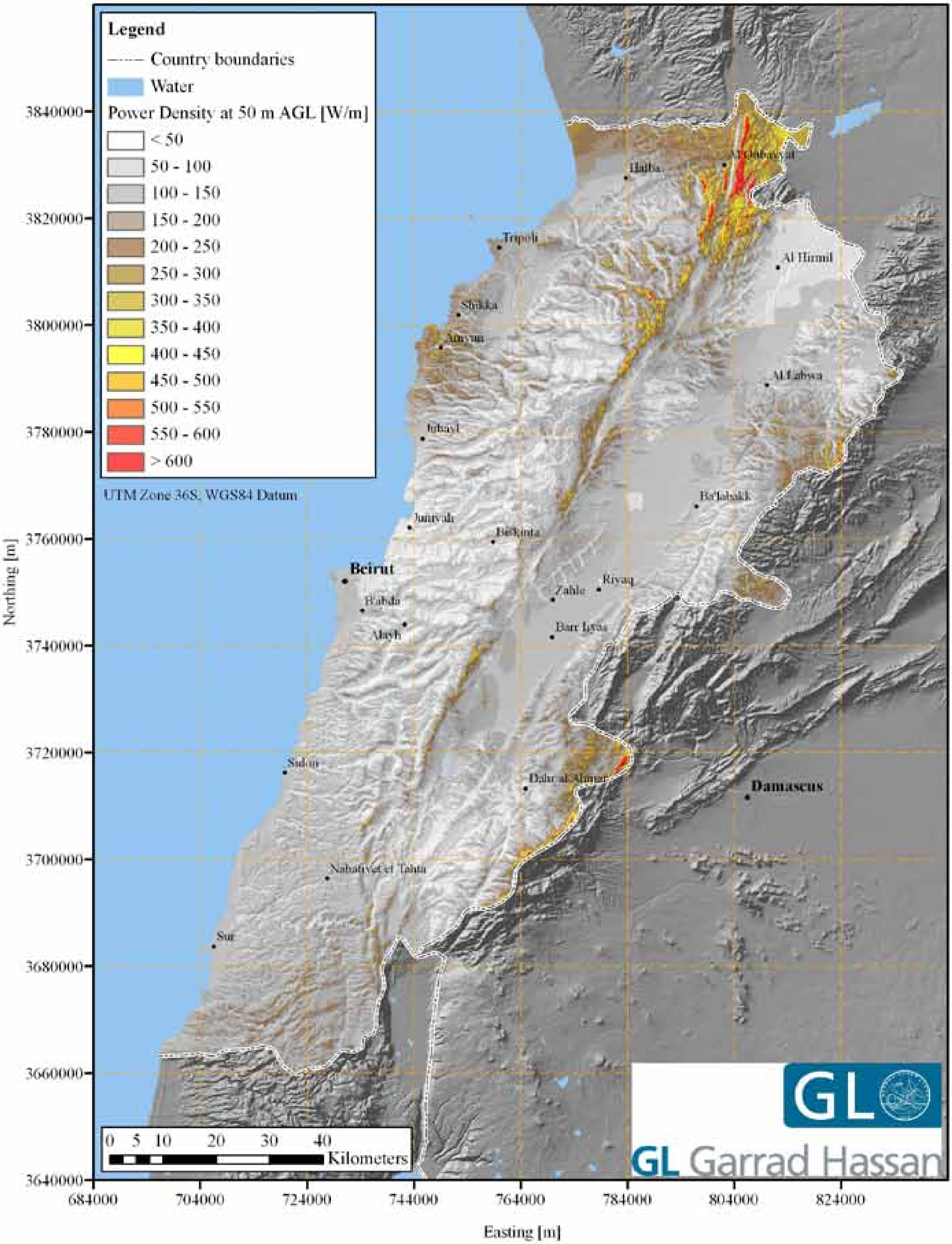

Figure 5.12 Downwards sensitivity wind map (derived from central estimate wind speed minus 10 %) of the Republic of Lebanon at 50 m above ground level.

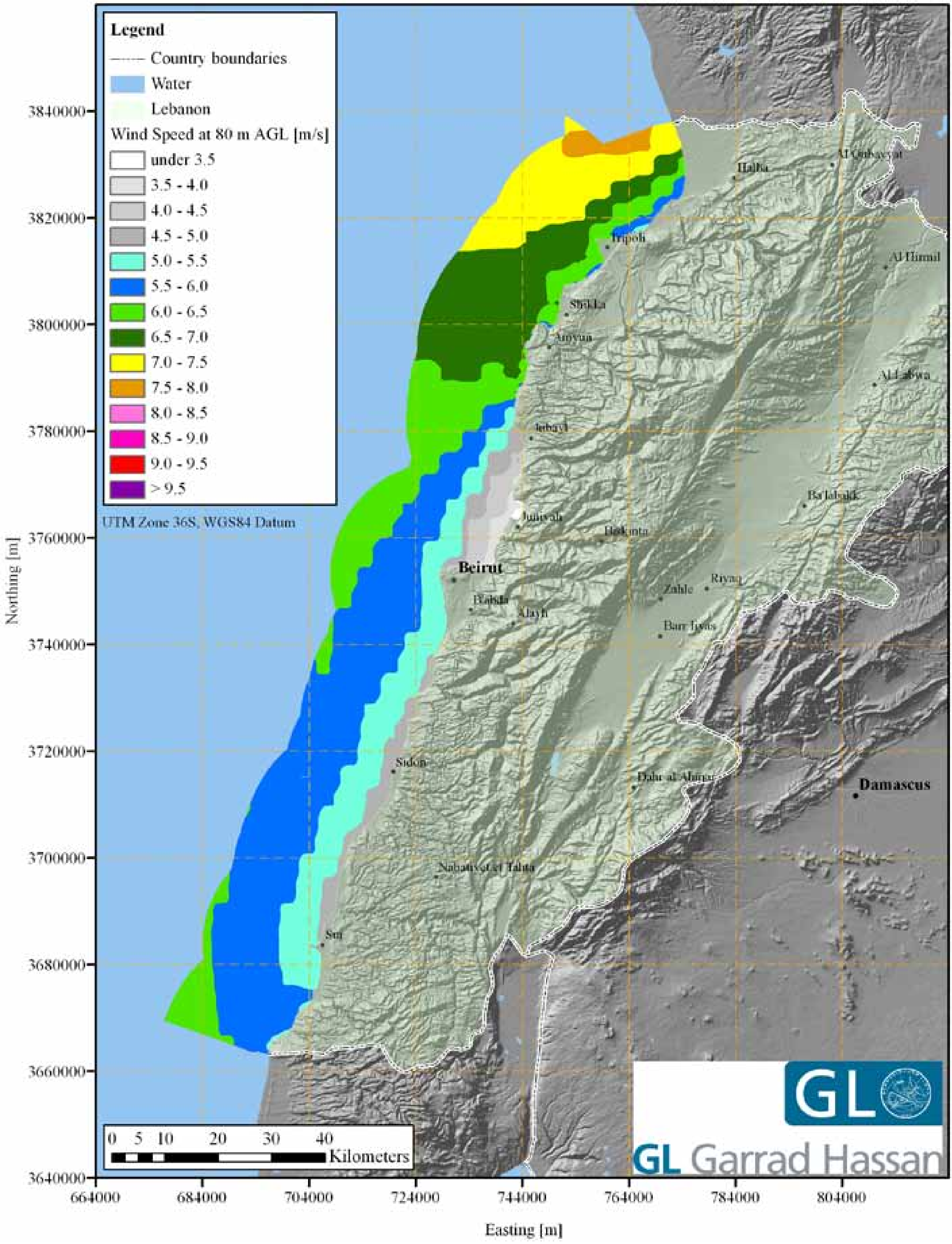

Figure 7.1 Central estimate Offshore wind map of the region lying up to 20 km from the coast of the Republic of Lebanon at 80 m above ground level..

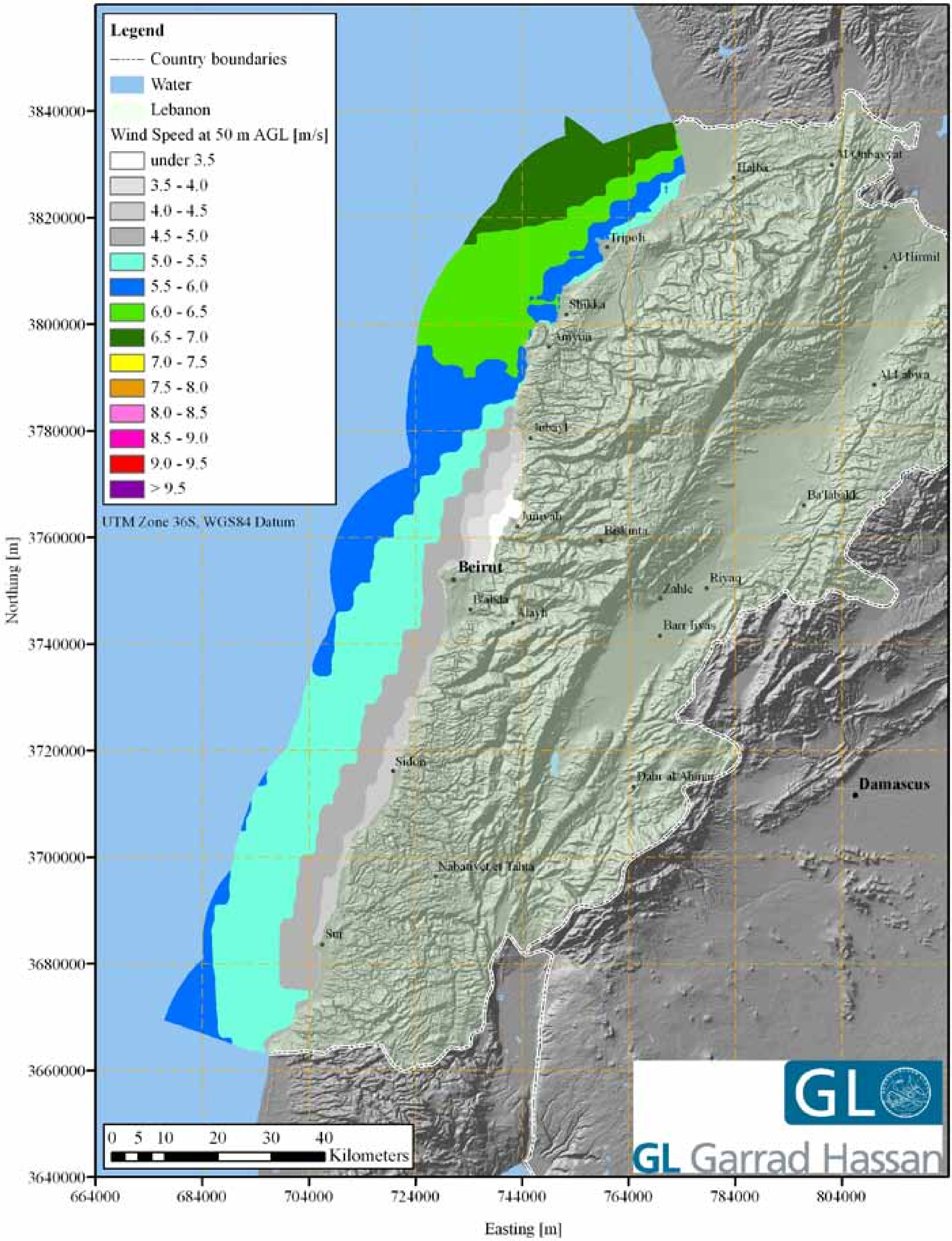

Figure 7.2 Central estimate Offshore wind map of the region lying up to 20 km from the coast of the Republic of Lebanon at 50 m above ground level.

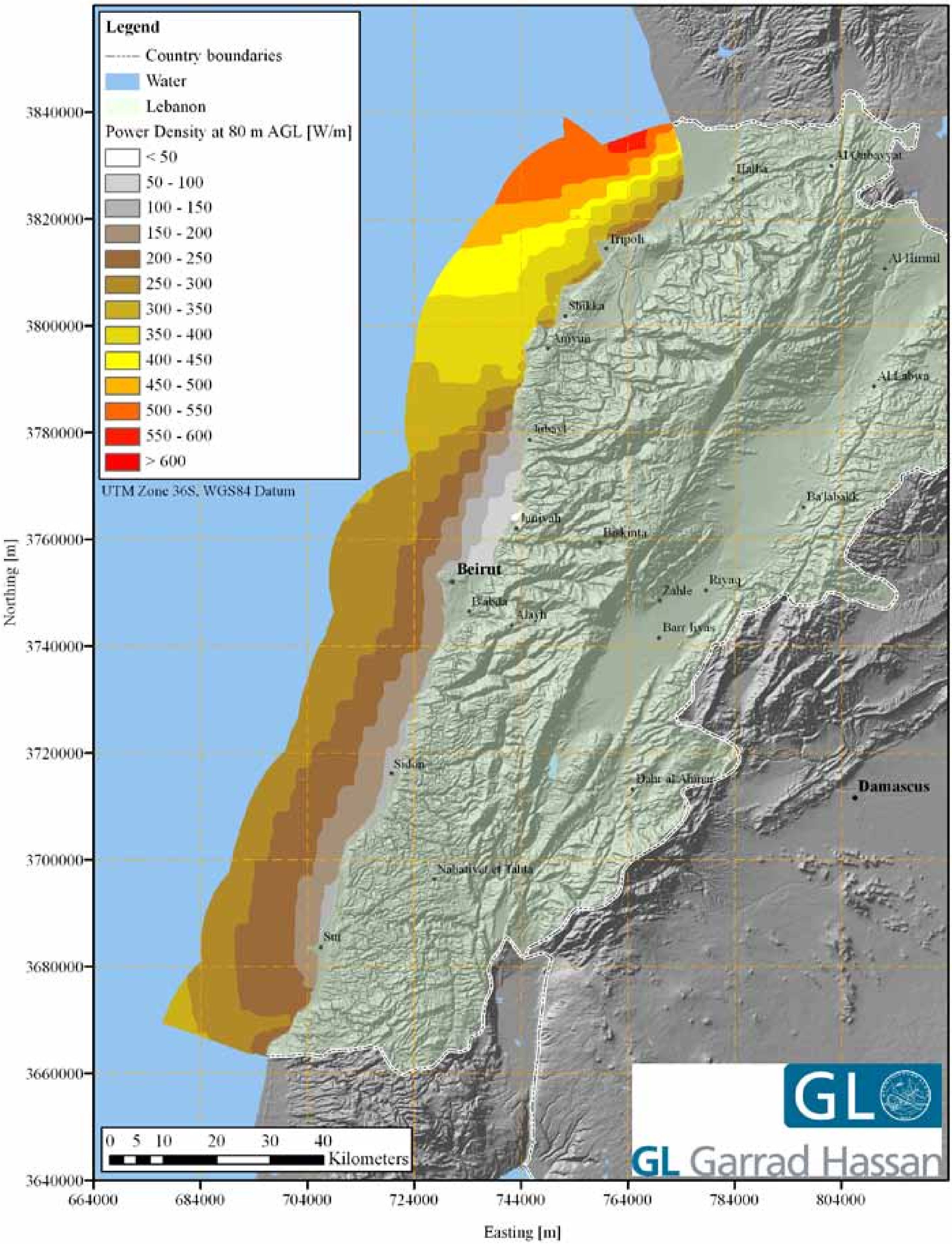

Figure 7.3 Central estimate Offshore power density map of the region lying up to 20 km from the coast of the Republic of Lebanon at 80 m above ground level.

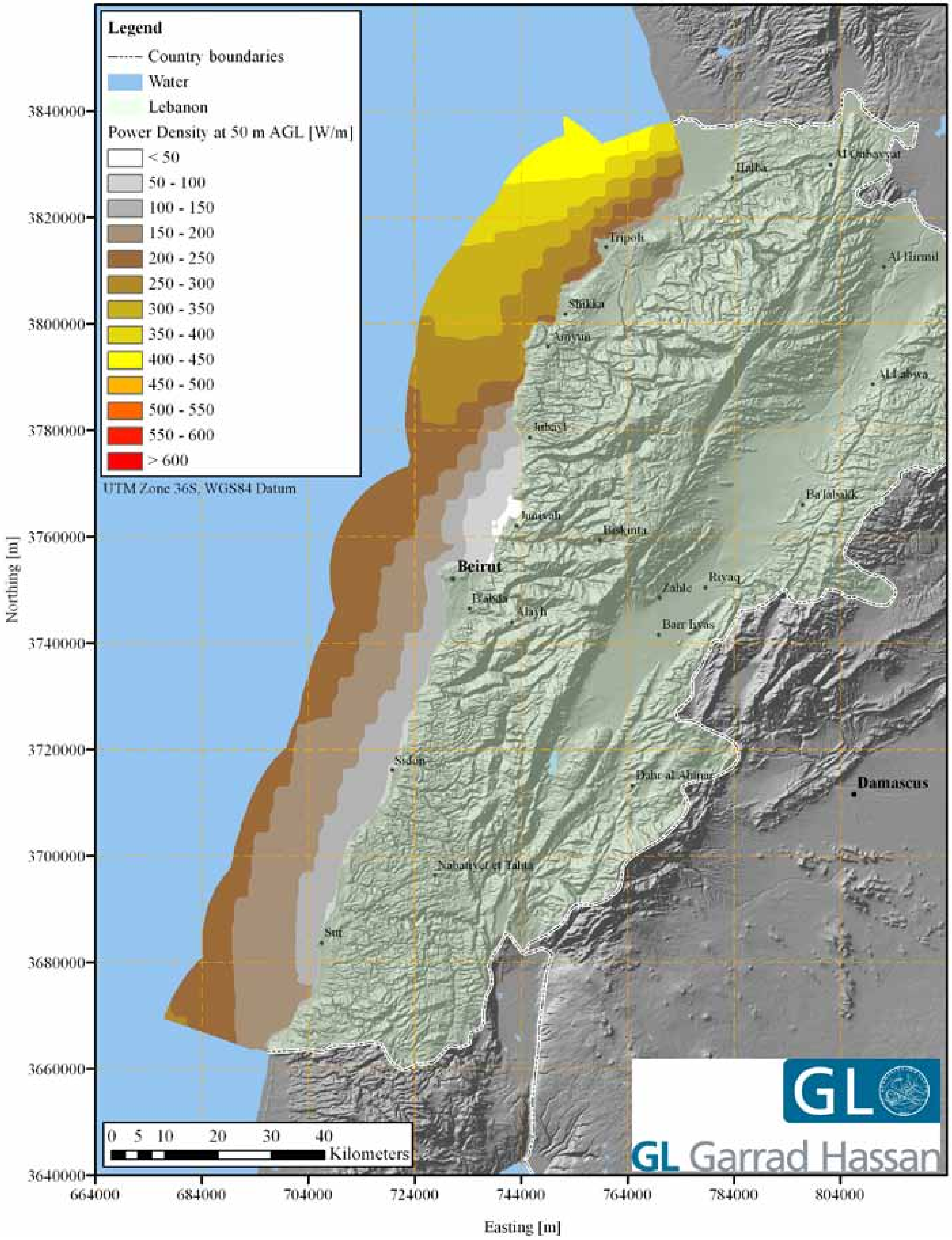

Figure 7.4 Central estimate Offshore power density map of the region lying up to 20 km from the coast of the Republic of Lebanon at 50 m above ground level.

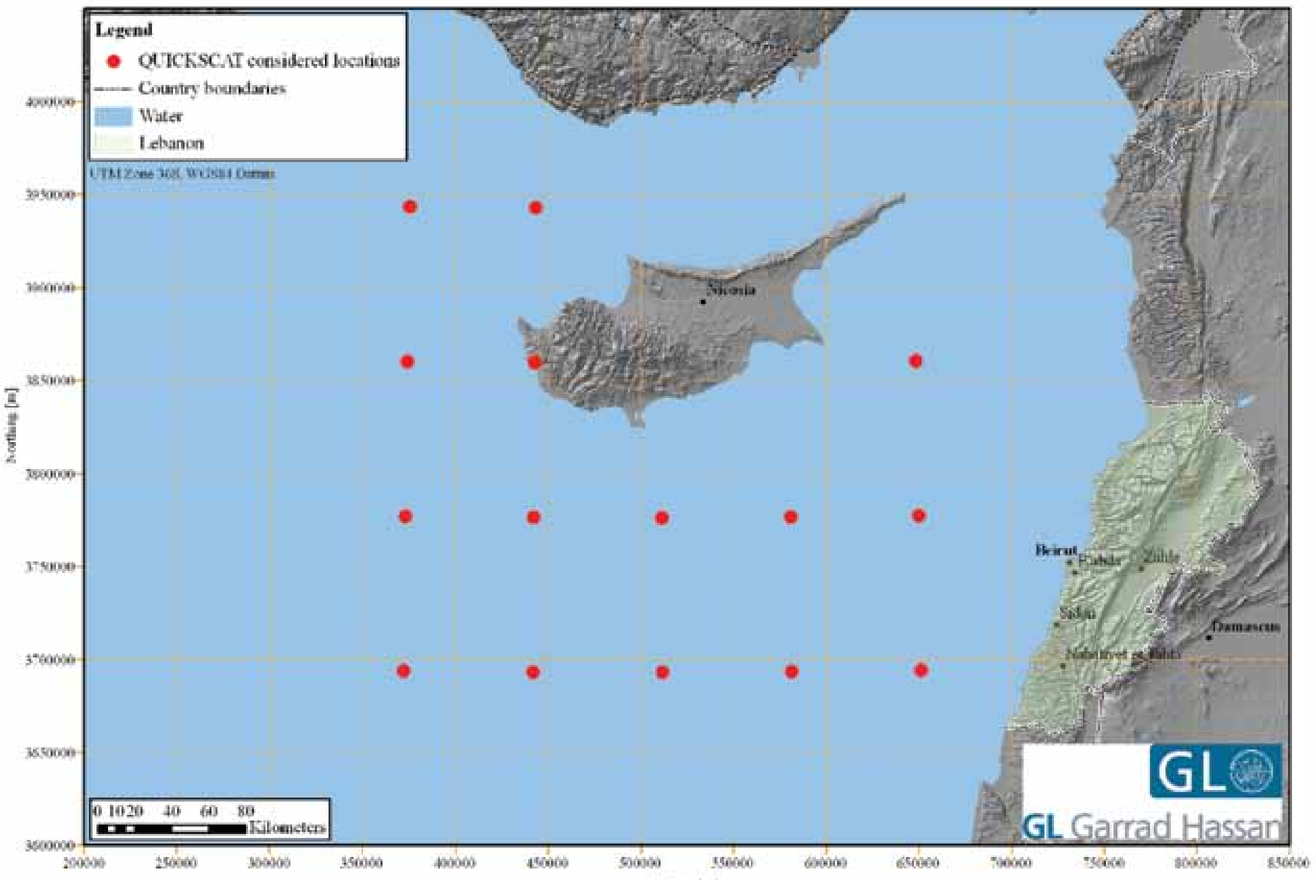

Figure 7.5 QuickSCAT EO data locations available for consideration.

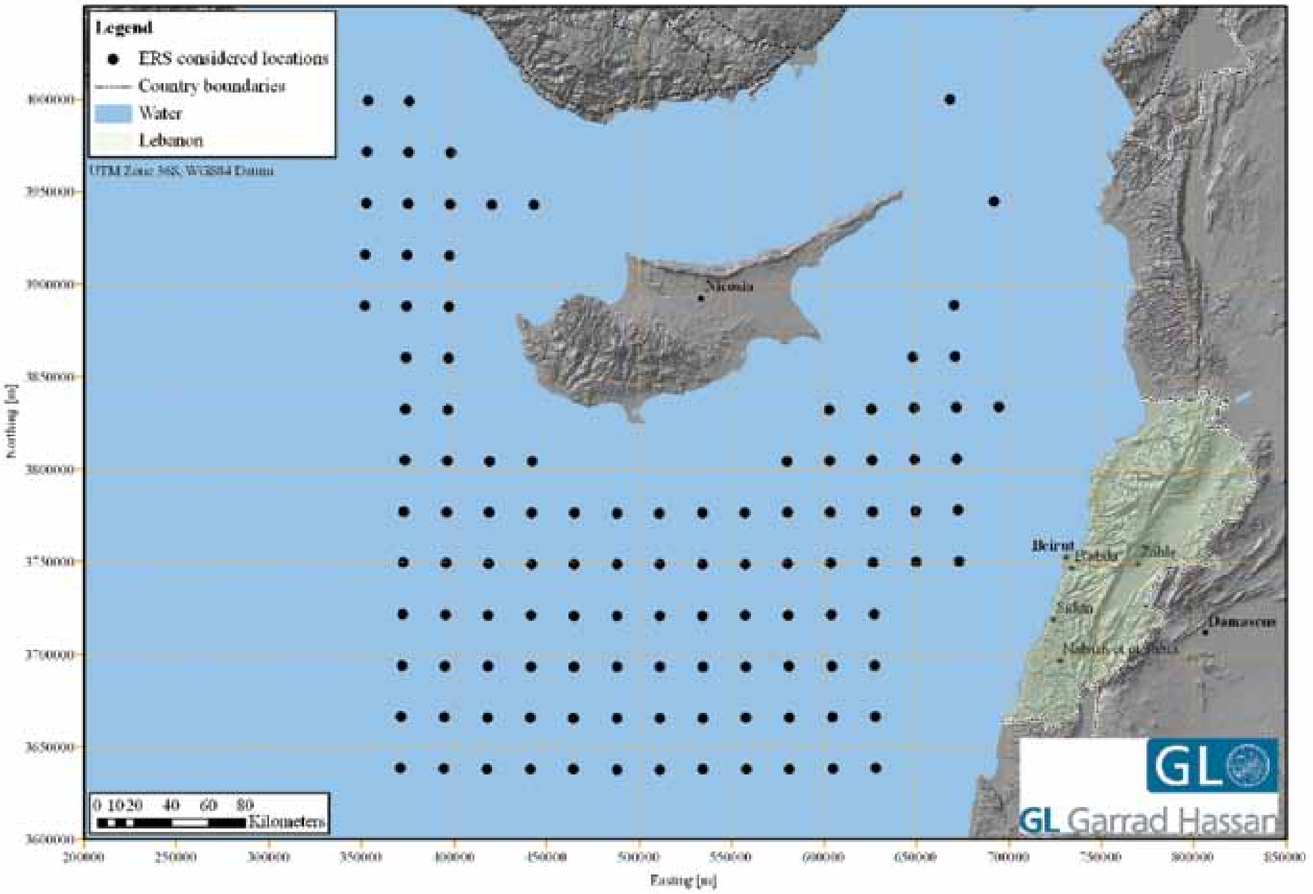

Figure 7.6 ERS EO data locations available for consideration.

APPENDIX 1

Earth Observation data

quikSCAT

The quikSCAT satellite was launched by NASA in 1999, equipped with a SeaWinds Scatterometer instrument able to measure wind speeds with a target accuracy of +/- 2 m/s. The objectives of the mission are to provide rapid access to measured data to enable improved weather forecasting near coastlines, and improve storm tracking [1].

The wind speed data product maintained by GH were obtained from KNMI [2]. The data were processed by KNMI to provide wind speed and direction at a spatial resolution of 100km and data that may have been contaminated by land were removed. Detailed information on the processing algorithm and QA approach applied by KNMI can be found in [3].

The width of the band over which the SeaWinds instrument operates (known as the swath) is 1800km. This relatively large swath width, along with the orbital path of the satellite, ensures that wind speed and direction data is generally available twice daily in most locations. This high coverage is a clear advantage of this dataset, although the low resolution limits the value that can be derived when assess spatial variation of wind resource.

ERS 1 / ERS 2

The ERS-1 satellite was launched in July 1991, and was equipped with, amongst other sensors, a Scatterometer designed to measure wind speed to a target accuracy of +/- 2 m/s. The swath width is 500km for the ERS-1 Scatterometer, considerably smaller than the quikSCAT instrument. Wind vectors are resolved to a nominal resolution of 50km, although measurements are taken every 25km within the Swath [4]. ERS-2 was launched as the successor to ERS-1 in April 1995 and was equipped with an identical wind Scatterometer. Data from both these satellites have been combined to give a near continuous record from 1991 to 1999. More information on the ERS mission can be found in [5].
Given the swath width of ERS-1 and 2 and their repeat cycle of 35 days, the temporal continuity of measurements at any one location is degraded when compared to the quikSCAT campaign. The ERS data yields an approximate average of 1 measurement every 314- days at any given location.

The wind speed data product maintained by GH was obtained from KNMI [2]. The data was processed by KNMI to provide wind speed and direction at a spatial resolution of 25 km, and data that may have been contaminated by land was removed. Detailed information on the processing algorithm and QA approach applied by KNMI can be found in [3].
The intermittency of the ERS 1 / ERS 2 data for any one location means that even aggregated data over many years would fail to adequately capture the characteristics of the wind climate in an absolute sense. As such this dataset cannot be used for wind mapping in an absolute sense but may be used to assess the relative spatial variation of wind resource.

Satellite	Instrument	Time Period	Measurement Coverage	Measurement Resolution
quikSCAT	Scatterometer	2000 - 2004	High	Low (100 km)
ERS 1 / ERS 2	Scatterometer	1991 - 1999	Medium	Medium (50 km)

References

1. http://winds.jpl.nasa.gov/missions/quikscat, accessed March 2008.
2. http://www.knmi.nl/scatterometer/, accessed March 2008.
3. http://www.knmi.nl/scatterometer/publications/pdf/ERS_Product_Manual.pdf, accessed March 2008.
4. Aage C, Allan TD, Carter DJT, Lindgren G, Olagnon M. Oceans from Space: A textbook for Offshore Engineers and Naval Architects. Ifremer Repéres Océans 16. September 1998.
5. http://earth.esa.int/ers/, accessed March 2008.