PRELIMINARY SITE SELECTION – CHILEAN MARINE ENERGY RESOURCES

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Contact	Juan Paredes
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Author:

J Cruz, M D Thomson, E Stavroulia

Checked by:

R I Rawlinson-Smith

Approved by:

R I Rawlinson-Smith

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EXECUTIVE SUMMARY

The Inter-American Development Bank (IADB) commissioned Garrad Hassan and Partners (GH) to undertake a preliminary marine energy resource assessment study of the Chilean coast.

The GH approach comprised three stages:

a. site visit to Chile – engagement with the key Chilean entities;
b. review of marine energy resource and additional data;
c. publication of guidelines and project design recommendations.

Site Visit

During the site visit entities which expressed an interest in this field and have a key role in the future development of marine energy projects in Chile were approached. The list includes, among others:

- Comisión Nacional de Energía (CNE);
- Corporación de Fomento de la Producción (CORFO);
- Ministry of Public Works;
- Ministry of Defence (DIRECTEMAR and Subsecretaria Marina);
- Servicio Hidrográfico y Oceanográfico de la Armada del Chile (SHOA);
- Comisión Nacional del Medio Ambiente (CONAMA);
- Academic institutions.

The assessment focused on the wave and tidal stream energy resources and identified the most promising zones for marine renewable energy projects by creating a database which overlays the most relevant attributes and constraints, namely:

- Wave / tidal energy resource;
- Bathymetry;
- Access to the National electricity Grid;
- Seabed geology;
- Proximity to a commercial port (O&M base);
- Areas of economical interest (e.g. fisheries);
- Maritime concessions[1];
- Areas of scientific interest;
- Special areas of conservation;
- Onshore (shoreline) designated areas;
- Other relevant information (e.g. seismic risk, archaeological sites, etc.).

Two other constraints that are particularly restrictive when planning marine energy projects are the presence of underwater cables and military exercise areas. The former does not apply in Chile (source: CNE) and the location of the latter is not available in the public domain. The GH findings were passed on to DIRECTEMAR for analysis of the selected zones and identification of any possible constraint in this regard (including the assessment of an additional constraint: the presence of major maritime routes in the selected areas).

Wave Energy

[1] The analysis of the existing maritime concessions (short and long-term) and permits was made by using SIABC (Sistema Integrado Administación del Borde Costero) GIS database to assess the zones selected by GH (http://bc1.directemar.cl/siabc2/).

With regard to the preliminary selection of suitable zones for wave energy projects, six priority areas have been identified. All areas are suitable for offshore wave energy technologies, which provide the potential for utility-scale projects. These areas can house demonstration and pre-commercial projects, but it is recommended that from inception a large area is considered (e.g. 5 by 5 km) to allow the expansion of a given project. The installed capacity in a given area will depend on the type of technology. A guideline for wave energy farms can be established by considering Pelamis (a concept developed by Pelamis Wave Power Ltd, PWP), for which a wave farm rated at 30MW (40 Pelamis machines) would occupy a 0.6 by 2.1km area. Pelamis was chosen for representative proposes only, as it is one of the technologies which have reached full-scale that have published figures (namely the power matrix). Note that cost figures are not public for this or any of the other technologies mostly to the embryonic state of the industry. Note also the 30MW is the expected rating of the first commercial wave farm with this technology (e.g. expansion plans for the Portuguese project). A conservative estimate for the nominal energy yield associated with a single wave farm (using the published information) would amount to 80.94GWh/annum (assuming negligible interaction between devices). Wave energy technologies are not mature and thus large scale developments are not likely to occur in the near future – hence for representative purposes the estimates in the Table below considers a single Pelamis wave farm (rated at 30MW) in the 5km by 5km priority areas. The energy yield estimates presented take into account the above assumptions (80.94GWh/annum for a nominal wave climate of 55kW/m and 75% availability) and in the absence of spectral data for the local wave climates to query the device specific power matrix the preliminary assessment assumes a linear relationship between the average local wave energy resource and the nominal wave climate with regard to the influence of the resource in the energy yield.

It is important to consider a first wave farm as a means to demonstrate the potential of the country in terms of its indigenous wave energy resource. It is equally important to recognise initial projects will be associated with a sea space use of just 1km^2. When planning a wave energy strategy for Chile it is important to facilitate the development of such pilot projects without compromising their ability to expand – this can be applied to one site (pilot area or large dimensions) or to several sites, either by facilitating the licensing process or by designating a number of medium sized areas (e.g. 5km by 5km) where projects can be developed. The pilot area approach is being followed in several European countries.

Priority locations for the development of wave energy projects and estimated annual energy yield of a 30MW Pelamis wave farm (1km^2)

Region	O&M base	Average distance to nearest substation – cable routing (km)	Closest Electrical Grid - SIC	Average Local Wave Climate (kW/m)	Estimate of the energy yield for a 30 MW wave farm (GWh/annum)
V	Puerto Ventanas	6	220kV	37	54.55
V	Puerto San Antonio	16	66kV 110kV	37	54.55
VIII	Puerto San Vicente	13	66kV 220kV	44	64.75
VIII	Puerto de Coronel	10	66kV 220kV	44	64.75
X	Puerto de Corral	17	66kV 220kV	51	75.05
X	Puerto Montt	27	66kV 110kV 220kV	58	85.35

To conclude the summary related to wave energy, it is important to emphasise the key wave energy resource figures, which result from the exercise described in Appendix A. The average wave climate for the entire Chilean coast was estimated at 38.6kW/m, varying from 19.6kW/m (Arica) to 66kW/m (Diego Ramirez). Taking the straight line distance for the Chilean coastline (North to South) as 4270km, the raw offshore wave energy resource can be estimated at 164.9GW, showing that even if a small percentage of the resource is used the impact to the Chilean energy matrix would still be very significant.

Tidal Energy

The selection process to evaluate suitable zones for tidal stream energy projects is reliant on good tidal resource information. In this study the resource data has originated from a variety of limited sources. As a result, much of the underpinning analysis to characterise the resource could be subject to improvements if and when site data were to become available. The selection process quantified the attributes of various potential zones which were identified as suitable for both demonstration and commercial development. The table below shows a description of the three top zones evaluated by the selection process. An estimate for both the kinetic energy flux and annual energy yield for a 30MW farm, using a generic technology design, is provided. A 30MW farm has been used as a benchmark to demonstrate a site's commercial potential and typically would occupy 1km^2. There are significant issues with both the second and third zones evaluated. The Corcovado Gulf is estimated to have fairly low flows, and as a result the commercial development (1MW units) is unlikely, but specific site measurements are required to check the real flow conditions there. The Straits of Magallance is a problematic area due to the lack of grid, ports and possible energy users, as well as likely navigation problems. However on a resource basis the zone is attractive.

Priority locations for the development of tidal stream energy projects and estimated annual energy yield of a 30MW generic tidal farm

Zone	Water depth [m]	O&M base	Average distance to nearest substation - cable routing [km]	Closest Electrical Grid (SIC)	Local Tidal Resource[2] [kW/m^2]	Estimate of the energy yield for a 30 MW tidal farm[3] [GWh/annum]
Chacao (Region X)	30-100	Cabo Froward or Puerto Montt	0-10 ~60	110kV 220kV	3.8 - 5.2	101-152
Corcovado Gulf (Region X)	20-100	Cabo Froward or Puerto Montt	~30 ~95	66kV 110kV	0.72	19
Straits of Magallanes (Primera Angostura) (Region XII)	50 -70	Austral	none		3.6	99-126

The preliminary selection of suitable zones for tidal stream energy projects has identified one dominate area. The Chacao channel has unique geographical features that result in the formation of a large tidal elevation (head) difference between the Chilean Inland Sea (Aucud Gulf) and the Pacific Ocean. This head generates a substantial tidal current, typically flows of 4m/s are observed [3.11], and it has the potential for significant energy generation. The raw kinetic energy flux is estimated to be between 600 and 800MW, although the technically extractable resource will be a function of the spatial variation of the flow, the complex bathymetry and navigation conflicts and is likely to be 20-60% of the raw flux[4]. Further site specific studies would be required to evaluate the technically extractable resource.

Pilot projects

The final section of this report addresses the overview of similar projects in key markets. An overview of existing and planned test centres is made, along with a review of the engineering companies with suitable profile for a number of relevant activities, such as surveys, offshore electrical cable installation, device installation, etc.; the created list of companies includes Chilean based companies, which could assist in the engineering works. The indicative costs of measurement equipment and other components are also presented. Finally guidelines for a pre-Front End Engineering Design (FEED) study, to be developed under a Technical Cooperation Agreement (TCA) with the IADB, are given. Such guidelines outline the several work components that need to be covered when planning specific marine energy projects, in an integrated approach which addresses all technically relevant aspects. Project recommendations are also issued, taking into account the feedback from a further visit to Chile in February 2009 where CORFO, CNE, the Ministry of Public Works and the Ministry

[2] This is the depth averaged root mean cubed kinetic energy flux using a $1/7^{th}$ power law.

[3] The range in yield values results from different assumptions regard the spatial variation in flow and the design optimisation of the technology, see Section 4 and Appendix B.

[4] The raw kinetic energy flux is a good indicator of the resource, but it should be noted that the driving force behind the flow is 2m tidal elevation either side of the channel.

of Energy were again consulted. The key recommendations suggest that a potential way forward would be the creation of a Chilean Marine Energy Test Centre in one of the priority zones identified, with areas in Region X offering the best potential to share some of the infrastructure between a wave and a tidal test site.

1 INTRODUCTION

The Inter-American Development Bank (IADB) commissioned Garrad Hassan and Partners Ltd (GH) to conduct a preliminary site selection study to identify suitable locations for demonstration and utility scale projects utilising marine energy converters (wave and tidal).

The GH approach comprises three stages:

a. site visit to Chile – engagement with the key Chilean entities;
b. review of marine energy resource and additional data;
c. publication of guidelines and project design recommendations.

The objectives of a. include the identification of all public entities which must be involved in the definition of demonstration and / or utility scale projects that utilise marine energy converters in Chile. Potential end-users (private or partially private entities) and Chilean companies with expertise to conduct the necessary preliminary activities (e.g. bathymetry surveys, mooring and electrical cable installation) were also identified. Furthermore additional companies able to support the manufacture and assembly of such devices, along with R&D centres able to assist the technology developers, are also critical parts of a Chilean strategy towards wave and tidal energy. Finally an equally relevant component of this task is the identification of the external constraints that are associated with particular sections of the Chilean coast (e.g. environmental constraints, socio-economic impacts, etc.)

The main objective of b. was to review the existing sources of data, marine atlases, field data and previous resource assessment studies that have been carried out along the Chilean coast. To enable the selection of the most suitable zones for the development of marine energy projects in Chile the energy resource was coupled with both the feedback from the key meetings held during the visit to Chile and additional data (National electricity grid layout, commercial ports, bathymetry, environmentally protected areas, etc.) that defines the technical and non-technical constraints which condition the selection of the zones. Based on this pre-selection, an initial estimate of the electricity generation potential (in GWh/annum) was derived for each location. The compiled data is critical to identify data gaps and recommend further activities in the selected zones (e.g. site surveys; digitalisation of detailed nautical charts; use of existing wave data as reference in site specific long-term resource assessments to be carried out using the MCP (Measure, Correlate, Predict) approach, etc.)

Finally, in c. the findings of this study were compiled along with guidelines for a technical cooperation agreement (TCA) with the IADB which aims to overview the key actions required to create a national strategy towards the implementation of wave and tidal energy projects and define the main activities and components of the TCA, such as an initial cost and effort estimate, identification of companies with the professional profile required to conduct the key activities (e.g. bathymetry surveys, mooring and electrical cable installation, etc.), measurement equipment, logistical costs, execution timeframe for the studies, key milestones and deliverables to be expected, main risks and possible bottlenecks that could be encountered during this process and recommendations to alleviate the latter.

The motivation for this study is twofold: firstly, the development of a marine energy strategy for Chile and the subsequent demonstration (single units) and pre-commercial projects (first arrays) are directly inline with CORFO's objectives for the 2006-2010 period:

- Contribute to a large technological leap in Chile;
- Integrate the SME's in the development process;
- Promote the regional development by gathering investment and strengthening local clusters.

Secondly, Chile's marine energy resources are particularly attractive and could make a significant contribution to the Chilean energy matrix. Figures from CNE (2008) show that to meet the 2020 targets (and in the more optimistic scenario), 12.870GW and 1.181GW need to be added to the SIC and SING systems, respectively. This corresponds to an increase of 132% and 50% when compared to the 2008 values in these systems. Approved projects in SEIA (2007) account for 5.206GW, with 97.35% from conventional power plants (thermal plus large hydro), with most of the developments concentrated in Regions II, III, V and VIII.

A recent presentation from the Ministry of Energy (see http://www.cne.cl/f_seminario.html) shows a suggested a modification to the general law for electrical services which, if implemented, would be particularly well suited to the development of marine energy projects, as it enforces the development of renewable energy projects of the non-conventional type - ERNC (wind, marine, etc.). Such a modification to the law would force utilities to have in their energy mix a minimum of 5% of projects with these energy sources in the 2010-2014 period, with a further annual increase of 0.5% over 10 years to reach 10% in 2024 (2005 figures from CNE show that only 3.1% and 0.4% of the SIC and SING capacity is from this type of energy sources).

These actions from the Ministry of Energy aim to:

- Diversify the energy mix with additional renewable energy sources;
- Actively contribute to the increase in energy efficiency, sustainability and security of supply;
- Stimulate industrial R&D (including cooperation with international entities).

The objectives from CORFO and the Ministry of Energy are complementary, and are both well addressed by the development of policies and project guidelines for marine energy. This study outlines the priority zones for such developments, by considering the key attributes and constraints. The status of the technology is appropriate for a staged development, hence the immediate (2010) contribution is less likely to overcome the concern on the electricity demand and be more focused on the technology development side. However, for the 2014, 2020 and 2024 targets, and in particular if the initial steps to establish demonstration and pre-commercial projects in Chile are taken, the country could not only benefit from a significant technological advantage but also a significant contribution to its energy matrix, given the inherent marine energy resources. The final section of this report outlines the technical aspects that need to be addressed to further refine the preliminary selection, and provide a guideline for the site specific feasibility studies that would be necessary.

2 WAVE ENERGY: ZONE SELECTION

In this section the zone selection exercise conducted by GH to identify suitable areas for the development of wave energy projects in Chile is described and the key results presented. Due to the specific nature of wave energy and of the natural conditions of the Chilean coast, the initial range of options based merely on the wave energy resource is vast, and an objective ranking criteria that considers not only such attributes but also the key constraints needs to be defined.

In Section 2.1 the baseline methodology applied to rank and select the most interesting areas to develop initial wave energy projects in Chile is described, and examples of previous studies with similar objectives are given. The decisive factors, the constraint and the information data sets are defined, and the rationale behind the selection criteria is discussed.

In Section 2.2 the sources of data are presented, with emphasis on the key constraints and the several information layers that were created in the GH GIS database. Particular emphasis is given to the wave energy resource data, and a short introduction to the existing sources of data, the compilation that was done for this study and its usefulness as a reference data set for long-term resource estimates and / or offshore boundary conditions in future site-specific exercises is outlined.

Finally in Section 2.3 the results of the zone selection exercise are presented. The overall results of the ranking procedure and detailed plots for the areas of interest are given. The section is concluded with the calculation of a conservative estimate for the potential energy yield (in GWh/annum) for each of an initial project in the selected areas.

2.1 Methodology

2.1.1 Background

Experience in zone and site selection exercises is mostly focused in European countries, where project developers and local governments have and are promoting the development of wave energy conversion technologies. Project developers typically address site specific exercises from the start whereas local governments tend to initiate the selection process by searching for considerable larger areas (or zones), which may be used for demonstration, pre-commercial and commercial projects, promoting the development of innovation or technology clusters. The latter example is better adjusted to the objectives of this study.

One of the European countries where a significant amount of site and zone selection studies have been developed is Portugal. The Wave Energy Centre has conducted a study[5] to identify the most suitable areas for development of wave energy projects at a utility-scale, using a non-quantitative approach, i.e. several information layers were compiled in a GIS database but no quantitative ranking was implemented, and thus recommendations are limited. A major limitation is linked with the absence of information regarding access to the National electricity grid, which is minimised due to the country's specific conditions (i.e. the major cities in Portugal, and thus the backbone of the electricity grid, are located close to the shore). Such qualitative approaches are, by definition, less objective and harder to justify and implement in larger countries such as Chile.

[5] Potential and Strategy for the Development of Wave Energy in Portugal, WavEC, 2004 (http://www.wavec.org/client/files/Summary_DGGE_ingl.pdf).

For this study a quantitative approach was envisaged from the start, and similar examples can be found in the literature. One of these reflects a study also applied to the Portuguese coastline[6]. The authors created a GIS database and defined the study area by removing from the initial scoping area the most limiting constraints (i.e. the decisive factors) such as bathymetry (e.g. shallow sites are associated with lower energy levels), environmentally protected areas or militarily exercise areas. The result is a reduced area (the 'mask') where the projects can be developed and thus where the analysis can be conducted.

The technical constraints are then defined; in this particular study the constraint layers included:

- Distance to coastline;
- Distance to ports;
- Distance to National electricity grid;
- Seabed geology;
- Wave energy resource.

All the criteria above are objective with the exception of the first one (Distance to coastline), as it is unclear which situation is more beneficial to a project. From the technical point of view the priority is to minimise the distance to shore to minimise the costs related to the access to electricity grid and the response time for any planned or unplanned O&M. However such objective categories are handled explicitly in the second and third criteria. Furthermore, from the non-technical point of view it can be more beneficial to the project to maximise the distance to shore, to minimise the impacts associated with its development (in particular the socio-economic and the environmental ones). Given this ambiguity this criterion was excluded from the GH study, as it is considered that the distance to port and distance to grid criteria cover the relevant technical aspects.

The next step is related to the reclassification of the masked area. Here the above mentioned criteria are applied to the area of interest by defining the objective function associated with each one. For example, the objective function associated with any of the above distance criteria is to search for the locations that minimise such distance, and the objective function associated with the wave energy resource is to search for the locations that maximise the resource levels. In the Nobre et al. (2009) study the seabed geology attribute was reclassified to reflect the type of seabed (sand being the best suited). The masked area was therefore reclassified from 0 to 100, with 100 being given to the grid point which maximises the objective function and 0 being the grid point that it is the farthest away from such objective.

Once the constraints are defined and the masked area is reclassified according to the selected criteria, weights needs to be attributed to each of the criteria to obtain a final ranking of the area. This step corresponds to the main subjective component of the process and may lead to different conclusions, according to the sensitivity of the selection process to each constraint. As the reclassification procedure used a scale from 0 to 100, percentages can be attributed to each weight and the final percentage rating will result from the weighted sum of the individual contribution associated with each attribute. In this study the wave energy resource was the attribute the largest weight, although there are several ways to include the influence of the resource (see Section 2.1.2).

Finally, once the area of interest is ranked, it is possible to zoom in the best suited sites and make objective conclusions regarding the preliminary sites. It is important at this stage to introduce information layers in the database, to assess non-technical constraints or any zone or site specific constraints that may condition the development of projects in the candidate

[6] 'Geospatial multicriteria analysis for wave energy conversion system deployment', Nobre et al. (2009), Renewable Energy, Vol. 34, pp. 97-111.

areas. This level of complexity was not included in the Nobre et al. study. The final result of this study is presented in Figure 2.1.

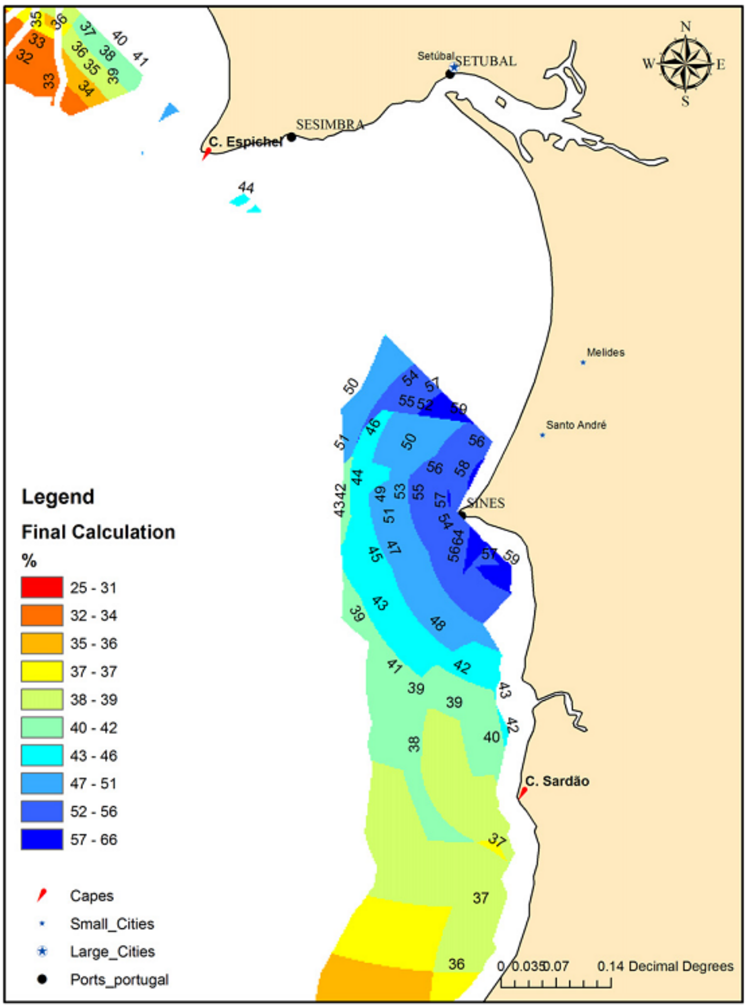

Figure 2-1 Example of a site selection exercise using a quantitative approach (Nobre et al., 2009)

2.1.2 Application to Chile

The above described objective methodology was implemented by GH to the Chilean coastline. The initial study area is vast, making the definition of the mask particularly relevant. The approach aims to obtain a quantitative indication of the location of the most suitable zones for the development of wave energy projects in Chile.

When applying the methodology to Chile, the following fundamental decisive factors were identified:

- Bathymetry

  The analysis was limited to the area between the 50m and the 200m depth contours. Such range of depths is the most indicated for the vast majority of the current nearshore and offshore wave energy technologies, which are the most likely to be applied in utility scale projects in the near future. To select suitable sites shoreline technologies require site specific studies which are outside the scope of this study.

Additionally, and after the meeting with CONAMA, GH was advised that any project to be installed at a shallower site would require a more detailed environmental licensing process (benthos protection).

- Special Areas of Conversation (AMCPs)

  The several environmentally protected marine areas were excluded from the final study area.

- Limit study area to SIC and SING electrical grid systems

  After discussion with CNE, exclude the XI and XII regions (Aysen and Magallanes electrical grid systems), that account for less than 1% of the installed / grid capacity.

- Sheltered areas

  Sheltered areas where excluded from the study area. This applies mostly to the inland seas in Region X (note that from the above Regions XI and XII were already excluded from the analysis).

After defining the study area using the decisive factors recommended above, four major parameters were identified for the classification of potential zones:

- Distance to the National electricity grid (100 – shortest distance)
- Distance to Ports (100 – shortest distance)
- Wave energy resource (kW/m) (100 – highest resource)
- Seabed geology (sediment chart) (100 – deepest sediment layer)

Maps for each of the above categories were created, reclassifying the study area from 0 to 100 (with the latter being the grid point that maximises the objective function). Weights were then attributed to each category, following:

- Distance to the National electricity grid – 25%
- Distance to Ports – 25%
- Wave energy resource (kW/m) – 40%
- Seabed geology (sediment chart) – 10%

Other categories could include:

- Distance to shore - project specific, as it is not clear which should be the objective function e.g. shortest distance better for economical reasons, longest distance possible better for environmental aspects; thus it is less suitable for a preliminary zone selection exercise).
- Evaluate the resource seasonally and the spectral parameters separately (H_s, T_e) - evaluation of the seasonal resource may be beneficial as the annual average may camouflage a large seasonal variation. The wave climates in the Southern hemisphere (and in particular in Chile) are less influenced by such variations than Northern hemispheres wave climates, according to the available studies[7]. The use of not only

[7] See, e.g., Monárdez et al. (2008), Evaluation of the Potential of Wave Energy in Chile, Proc. of the ASME 27th International Offshore Mechanics and Arctic Engineering Conference, Estoril, Portugal.

the resource levels (in kW/m of wave front) but also the key spectral parameters (namely the significant wave height and the wave energy period) as individual constraints could be used at a second stage to check the suitability of the wave energy resource to a particular device and to define the access limits for the O&M vessels. However the former is not applicable at this stage and the latter is a secondary effect with regard to the distance to ports and thus can be left for a site specific exercise.

- Access to the spectral parameters describing the wave resource (H_s, T_e) would also allow a more detailed assessment of the output of a given wave energy converter, via the device specific power matrix. A preliminary assessment was made, by relating the local wave climate with the nominal wave climate behind the derivation of the power matrix of one of the most advanced wave energy technologies to obtain a estimate of the average yearly energy yield of a representative wave farm (see Section 2.3).

With the study area ranked, the regions with the best average scoring can be looked at in detail, by including several information layers to assess additional constraints that may condition the development of wave energy projects. The GH GIS database has the following additional layers, which were used when plotting detailed maps of the highest ranked regions to conduct an informed decision of the preliminary location of the best zones:

- Fishing concessions (Areas de Manejo Bentonico);
- Sites of special scientific interest;
- Onshore protected areas;
- Wetlands;
- Archaeological sites;
- Zones of contaminated ground;
- Other areas of economical interest (e.g. tourism, denomination of origin).

Other suitable layers at all three levels (decisive factor, constraint and information) were identified, but were not included in the GH database due to the limited access to such data. In particular: information on military exercise areas and major maritime routes was formally requested (by both the IADB and GH) to DIRECTEMAR. Access to such information was denied but DIRECTEMAR agreed to review the conclusions of this study prior to publication of the final report. Thus the influence of the below mentioned constraints is limited to a final check once the zones have been selected (as additional information):

- Maritime concessions
- Military exercise areas
- Major maritime routes
- Port entrance routes

With regard to the maritime concessions, GH used the SIABC (Sistema Integrado de Administacion del Borde Costero) database (http://bc1.directemar.cl/siabc2/) to assess if short or long term concessions (or permits) have been granted in the areas of interest. The selected zones show no significant conflicts. A similar conclusion was reached by searching for conflicting projects in the SEIA database (Sistema de Evaluación de Impacto Ambiental: www.e-seia.cl), although several plans for port expansion were found (namely in Regions VIII and X), which deserve special attention when considering the implementation of the recommendations of this study.

The results from the ranking exercise, including global plots with the classification according to each of the four constraints, are presented in Section 2.3. Detailed plots for the most promising areas are also presented, overlaying the additional information layers to select several zones (5 by 5km) that show the best potential for the development of wave energy projects. A preliminary assessment of the electricity generation capability associated with each of the areas is also given.

Recommendations for further studies include the assessment of two key items for refinement of the selected zones:

- Digitalisation of the most updated nautical charts for the areas of interest;
- Detailed seabed geology information (potentially via site surveys).

2.2 Sources of data

In this section the sources of data for the decisive factors, constraints and information layers specified in Section 2.1 are presented. Particular emphasis is given to the wave data set, given the importance attributed to the wave energy resource in the selection process (40% weight). Long-term wave data also allows the possibility of conducting long-term site specific resource assessments using hindcasts (numerical estimates), satellite measurements or buoy data as reference, and applying the MCP (Measure, Correlate, Predict) methodology using short-term site specific data to derive a site-reference relationship. Potential sources of reference data for such detailed studies are overviewed in this section.

Firstly, Table 2-1 presents the sources of the data implemented in the decisive factors, constraints and information layers used in the selection of the preliminary zones for wave energy projects. The vast majority of these data sets were obtained following the meetings between GH, the IADB and key Chilean official entities, to maximise the accuracy of the data used in the study. The exceptions were the bathymetry, the seabed geology information (obtained from the National Geophysical Data Centre, USA) and the wave resource.

With regard to the wave resource, Baird & Associates Ltd. (a Canadian coastal engineering consultancy) have compiled a database of offshore wave data under the Olas del Pacífico project. Such database includes Chile's coastline. SHOA's involvement in the project is not clear, although some references[5] mention the use of over 20 data points from SHOA's wave buoy measurements as a validation tool. In the project website (www.olasdelpacifico.com) all data points for the Chilean coast rely on outputs from the WaveWatchIII model (NOAA's open-source wave model) or satellite estimates form the TOPEX mission (NASA), and thus it is not possible to confirm which (if any) of SHOA's wave measurement buoys were used in the validation of the data sets. SHOA, after being queried by GH and the IADB in a meeting held in Valparaíso on the 11th September 2008, did not confirm the use of its data in this project.

Baird & Associates Ltd have also presented results from an earlier version of the same model[6]. The project described used the WaveWatchII model, and results were compiled in the Olas Chile II project. Deepwater long-term estimates of the resource were presented, along with rough offshore to nearshore transition model (based on linear wave theory), for several locations along the Chilean coast. These results were used by GH as a first estimate for the exercise described in Section 2.1.2 in version A of this report.

From inception GH intended to use SHOA's wave data as the reference in this exercise. With the assistance of the IADB, GH approached SHOA to acquire the summary spectral statistics from wave buoy measurements for 12 locations offshore Chile (all the available) to refine and enhance the quality of the wave resource constraint layer which was used for the selection of the most suitable zones for wave energy projects. In issue B of this report (final version) GH has refined the outputs of the WaveWatchIII model in the 12 locations of the SHOA measurement buoys in order to derive long-term (10 year) estimates. The procedure and key statistics, inc. monthly and annual variation, are described in Appendix A. Such dataset has been be used as the wave energy resource layer.

Future zone or site specific long-term wave resource estimates will require suitable data sets to act as local data sources, should short-term measurement campaigns be conducted and the MCP (Measure, Correlate, Predict) methodology applied. In such methodology the data listed in Appendix A can be used as reference, in order to allow the extrapolation of a short-term measurement campaign and obtain long-term site specific estimates. The most common sensors that are used for local wave measurements are surface following buoys or bottom-mounted acoustic profilers. Other alternatives for long-term reference data include several commercially available databases and the raw outputs of wave models such as WAM or WaveWatchIII, the GH outputs listed in Appendix A and the SHOA data. In all cases the application of a suitable transformation model such as SWAN (a offshore to nearshore wave propagation model) or equivalent to obtain the site specific conditions is desirable, although it is recognised that for depths bigger than 50m this is not a decisive factor given that the deepwater conditions apply for $d > \lambda /2$, where λ is the dominant wavelength (hence the recommendation to rely on the data listed in Appendix A and conduct a MCP exercise where appropriate).

Table 2-1 Sources of Data for the wave energy zone selection exercise

Data Set	Source
Bathymetry	GEBCO database[8]
Special area of conservation (AMCPs)	CONAMA
National electricity grid layout	CNE
Ports	Ministry of Public Works
Wave energy resource (kW/m)	NOAA's WaveWatchIII model and measured wave data (supplied by SHOA)
Seabed geology (sediment chart)	NGDC
Fishing concessions (Areas de Manejo Bentonico)	SUBPESCAS
Sites of special scientific interest	CNE GIS database[9]
Onshore protected areas	
Wetlands	
Archaeological sites	
Zones of contaminated ground	
Other areas of economical interest (e.g. tourism, denomination of origin)	

2.3 Results

Having compiled a database with the relevant constraints and information layers, the methodology described in Section 2.1.2 was applied to the study area defined by the several decisive factors.

[8] IOC, IHO and BODC (2003), 'Centenary Edition of the GEBCO Digital Atlas', CD-ROM edition, published on behalf of the Intergovernmental Oceanographic Commission, International Hydrographic Organisation and British Oceanographic Data Centre.

[9] The assistance of CNE (in particular Cristian Santana and Carolina Gómez) is acknowledged.

In this section several maps present the overall classification and reclassification scoring for each of the constraints (allowing an assessment per constraint). Detailed maps zoom in the zones with the best overall scoring and show additional information layers which may influence the final decision regarding the suitability of a given zone to receive a wave energy project. Finally, preliminary (and conservative) estimates for the energy yield (in GWh/annum) of 5 by 5km areas within the selected zones are presented. Such areas are large enough for demonstration, pre-commercial and commercial projects to be developed.

Each of the following figures in this section presents a result that reflects a scale from 0 to 100. With regard to the constraints the maximum result may be outside the study area; their relative influence in the overall classification is characterised by the different weights outlined in Section 2.1.2.

Figure 2.2 presents the overall ranking (colour scale) along with some of the key constrains (location of ports and layout of the National electricity grid). The application area defined by the decisive factors, namely the area between the 50 and the 200m depth contours, is also marked in the map. In general, and given the predominance that was allocated to the wave energy resource, Southern sites are favoured with regard to Northern sites. Furthermore, the area between the 50 and the 200m depth contours is smaller and very close to shore for Regions I to IV. Coupling these considerations with the additional constraints, detailed maps for Regions V, VIII, IX and X were created to incorporate the several information layers, in order to recommend zones within the above mentioned regions (Figures 2-7 to 2-9). Firstly, Figures 2-3 to 2-6 show the reclassification maps for the entire study area in each of the relevant constraints: distance to the electricity grid, distance to port, seabed geology and wave energy resource, allowing the non-weighted assessment of the influence associated with each individual constraint.

The first detailed map illustrates that the most interesting areas in Region V are located in the vicinity of Puerto Ventanas (northbound) and Puerto San Antonio (southbound) – see Figure 2-7. The area between Puerto Ventanas and Valparaíso is likely to be strongly conditioned by the maritime traffic in and out of both ports, and thus should not be considered a priority. Puerto Ventanas is a private port of public use whereas Puerto San Antonio is a state-owned port; thus the latter might be better suited if a wave energy project is to be supported by the Chilean government. In addition, Puerto San Antonio is considerably larger than Puerto Ventanas, and the 2005 data from the Ministry of Public Works shows a usage factor of 37% (thus potential for alternative uses). Such availability and its inherent characteristics (namely the marine area) ensure its suitability to operate as a O&M base for future wave energy projects. The area south of Puerto San Antonio within the 50 to 200m depth contour area is subject to offshore wave climates of 34 to 38kW/m; these are the lower wave energy resource level for the zones identified in this preliminary study, but are still well suited for demonstration and pre-commercial projects. A potential onshore limitation (conflict of use) for auxiliary works in areas south of Puerto de San Antonio is related to the classification of such area as a zone of denomination of origin.

In Regions VIII and IV (Figure 2-8) the area south of Puerto Coronel is less interesting due to the increasing distance to a suitable O&M base (areas close to Puerto de Corral are handled in the analysis of the detailed map for Region X). The most promising zones in the region are in between Puerto San Vicente and Terminal Escuadrón, and north of Puerto San Vicente (VIII region). The former is likely to be conditioned by maritime traffic, but presents the highest overall scoring given the coupling of the wave energy resource, distance to grid and distance to port. The wave resource estimates are higher than in the previous case for Region V (spanning between 43 and 47kW/m), but the fact that both ports are small should be considered when planning its use as a O&M base. As in the areas pointed for region V there is no immediate conflict with, e.g. large fishing concessions, but some onshore constraints apply as the surrounding onshore areas are zones of contaminated ground.

Finally, Figure 2-9 shows a detailed map of the scoring and information layers for Region X. As mentioned previously, the wave climate in Southern Chile is more energetic and thus the potential for electricity generation is higher. A first suitable area is located offshore Puerto de Corral: the wave energy resource is high, distance to the 66kV and 220kV SIC grid lines is short and there are no significant shoreline limitations (small fishing concessions being the major concern). However one negative aspect is the size of Puerto de Corral, which could limit its ability to serve as a suitable O&M base for projects involving several wave energy converters. Although there is no explicit minimum requirement in terms of area and there are only a few precedents, a O&M base should allow the safe manoeuvring and access to the wave energy converter(s). The size of the harbour is equally conditioned but the type of technology and project (demonstration or pre-commercial). An example can be found in the facilities used by Pelamis Wave Power Ltd in Portugal: while the assembly of the machines was done in a relatively small shipyard in Peniche (350m quay; www.enp.pt), the permanent O&M base for the Agucadoura project (3 Pelamis units initially, potentially expandable to a further 27) was set up in Leixões (www.apdl.pt), which has a wetted area of 120ha. The potential expansion of Puerto de Corral (should the project require) is beyond the scope of this study.

The inland sea near the Canal de Chacao was excluded from the study area as this is a sheltered area, i.e. not exposed to the swell waves which carry the vast majority of the wave energy. However Puerto Montt is the largest port in the region and the best equipped to house a O&M base, but its use for wave energy projects is conditioned, among other factors, by the maritime traffic in the Canal de Chacao. Furthermore, this is an area of interest for tidal projects (see Section 3), and thus a logistical interest in sharing the onshore infrastructure (namely the control room and substation) for the two sites (wave and tidal) may exist. The other ports and peers in the region (namely those operated by Empresa Portuaria Cabo Froward) are less suited, given their current application and size. Such limitation makes the sites south of Puerto San José de Calbuco less attractive (for a first series of projects), although it is recognized that overall scoring is high, mostly due to the wave energy resource levels.

To conclude, Table 2-2 outlines the priority locations that have been identified for initial wave energy projects under the preliminary zone selection exercise described in this section. The exact location of such areas is subject to a final check from DIRECTEMAR (for the reasons outlined in Section 2.1.2), but no restrictions were found in the SIABC online database (absence of permits, short or long-term concessions for ocean use in the selected areas). In Figures 2-7 to 2-9 areas of 5km by 5km within the 50 to 200m depth contour zone have been marked for representative purposes, although it should be noted that larger areas would be well suited for phased developments, allowing the long-term planning of a strategy for wave energy developments in Chile. Such large pilot areas are being planned in other countries, namely the UK, Portugal and Spain, under similar development strategies. Such staged development is coherent with the current status of the technology and would allow a deeper involvement of the Chilean government (and the other entities involved in renewable energy projects, such as the IADB) in the promotion and development of wave energy conversion technologies in Chile.

The installed capacity in a given area will depend on the type of technology. A guideline can be established by considering Pelamis (a concept developed by Pelamis Wave Power Ltd, PWP), for which a wave farm rated at 30MW (40 Pelamis machines) would occupy a 0.6 by 2.1km area. Pelamis was chosen for representative proposes only, as it is one of the technologies which have reached full-scale that have published figures (namely the power matrix). Note that cost figures are not public for this or any of the other technologies mostly to the embryonic state of the industry. Note also the 30MW is the expected rating of the first commercial wave farm with this technology (e.g. expansion plans for the Portuguese project). The nominal wave climate for a Pelamis machine (55kW/m) is stated in the PWP brochure[10]. A representative capacity factor (estimated at 30.8%, corresponding to the nominal capacity factor[6] times a 75% availability level), a conservative estimate for the nominal energy yield associated with a single wave farm would amount to 80.94GWh/annum (assuming negligible interaction between devices). Wave energy technologies are not mature (note that the first worldwide wave farm, corresponding to three Pelamis machines, was installed in Portugal in September 2008) and thus large scale developments are not likely to occur in the near future – hence for representative purposes Table 2-2 considers a single Pelamis wave farm (rated at 30MW) in the 5km by 5km priority areas.

The energy yield estimates presented in Table 2-2 take into account the above assumptions (80.94GWh/annum for a nominal wave climate of 55kW/m and 75% availability) and in the absence of spectral data for the local wave climates to query the device specific power matrix the preliminary assessment assumes a linear relationship between the average local wave energy resource with regard to the nominal wave climate.

It is important to consider a first wave farm as an objective to demonstrate the potential of the country in terms of its indigenous wave energy resource. It is equally important to recognise that the estimates in Table 2-2 are associated with a sea space use of just 1km^2. When planning a wave energy strategy for Chile it is pivotal to facilitate the development of such pilot projects without compromising their ability to expand – this can be applied to one site (pilot area or large dimensions) or to several sites, either by facilitating the licensing process or by designating a number of medium sized areas (e.g. 5km by 5km) where projects can be developed.

A final note to the key wave energy resource figures, which result from the exercise described in Appendix A. The average wave climate for the entire Chilean coast was estimated at 38.6kW/m, varying from 19.6kW/m (Arica) to 66kW/m (Diego Ramirez). Taking the straight line distance for the Chilean coastline (North to South) as 4270km, the raw offshore wave energy resource can be estimated at 164.9GW, showing that even if a small percentage of the resource is used the impact to the Chilean energy matrix would still be very significant.

Table 2-2 Priority locations for the development of wave energy projects and estimated annual energy yield of a 30MW Pelamis wave farm (1km^2)

Region	O&M base	Average distance to nearest substation – cable routing (km)	Closest Electrical Grid - SIC	Average Local Wave Climate (kW/m)	Estimate of the energy yield for a 30 MW wave farm (GWh/annum)
V	Puerto Ventanas	6	220kV	36	52.98

[10] Available in www.pelamiswave.com; nominal energy yield per machine is quoted to be 2.7 GWh/annum for a wave climate of 55kW/m (capacity factor of 41%).

V	Puerto San Antonio	16	66kV 110kV	36	52.98
VIII	Puerto San Vicente	13	66kV 220kV	45	66.22
VIII	Puerto de Coronel	10	66kV 220kV	45	66.22
X	Puerto de Corral	17	66kV 220kV	50	73.58
X	Puerto Montt	27	66kV 110kV 220kV	52	76.53

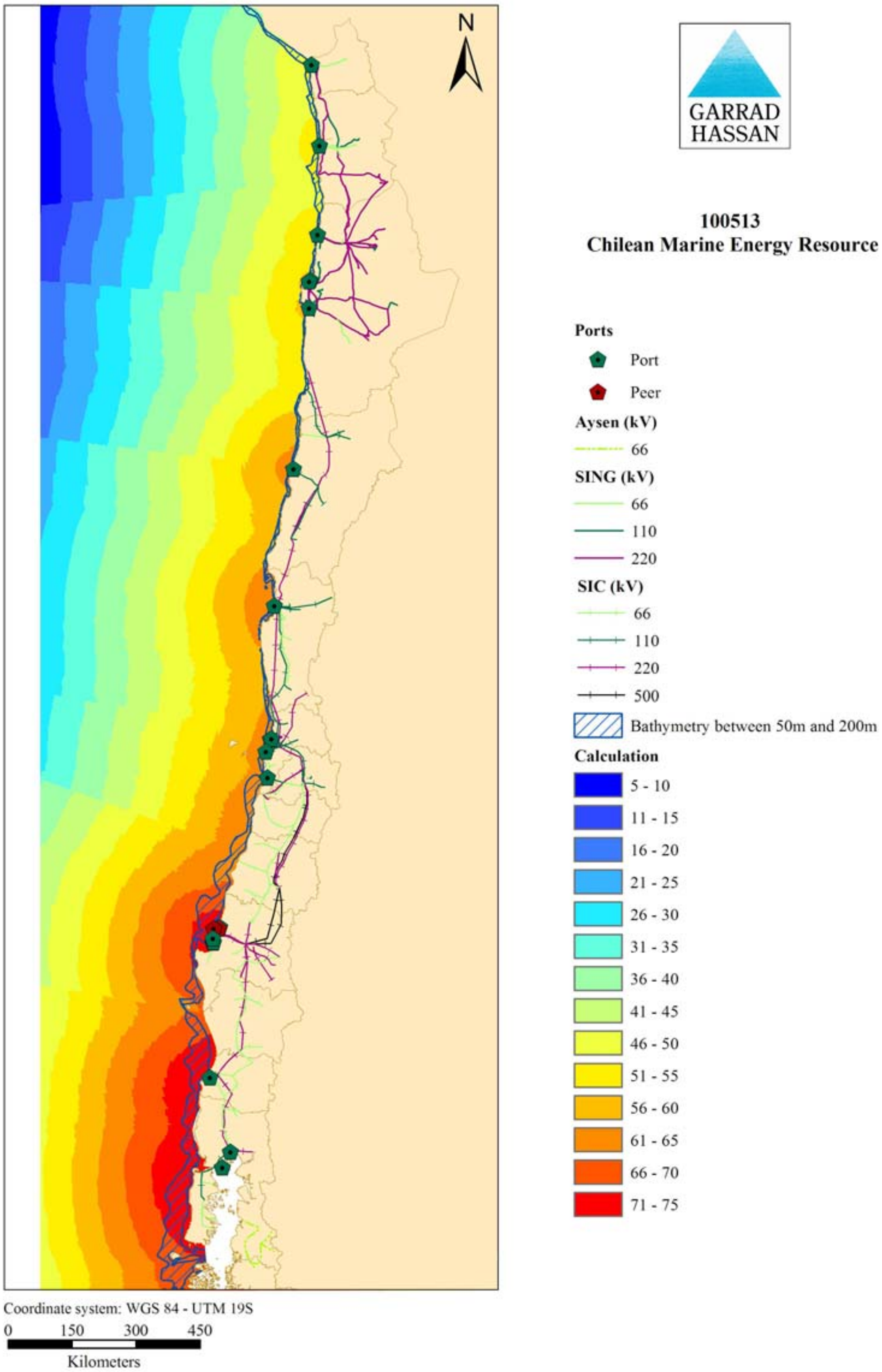

Figure 2-2 Overall classification – weighted average

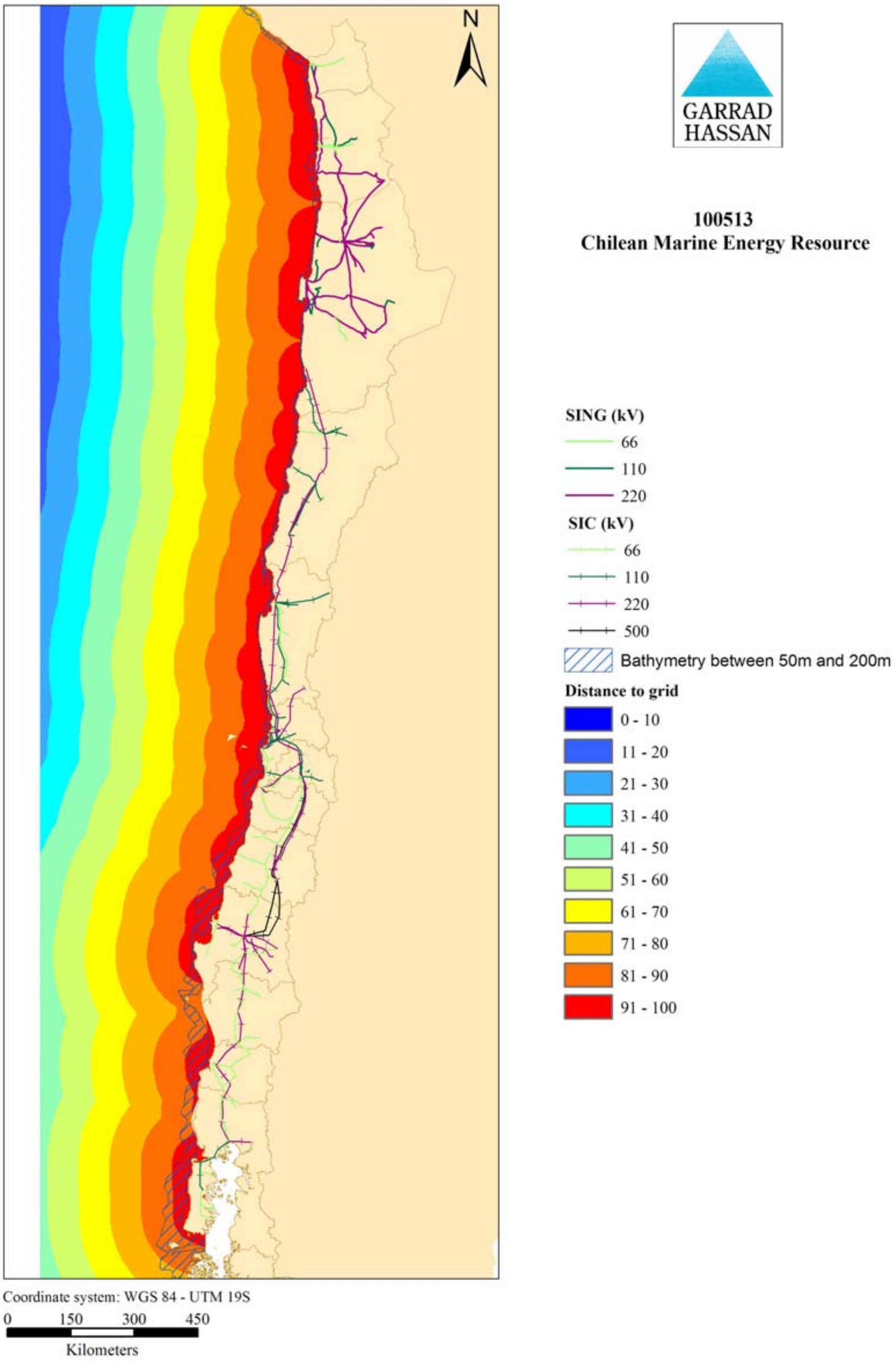

Figure 2-3 Reclassification of distance to electricity grid

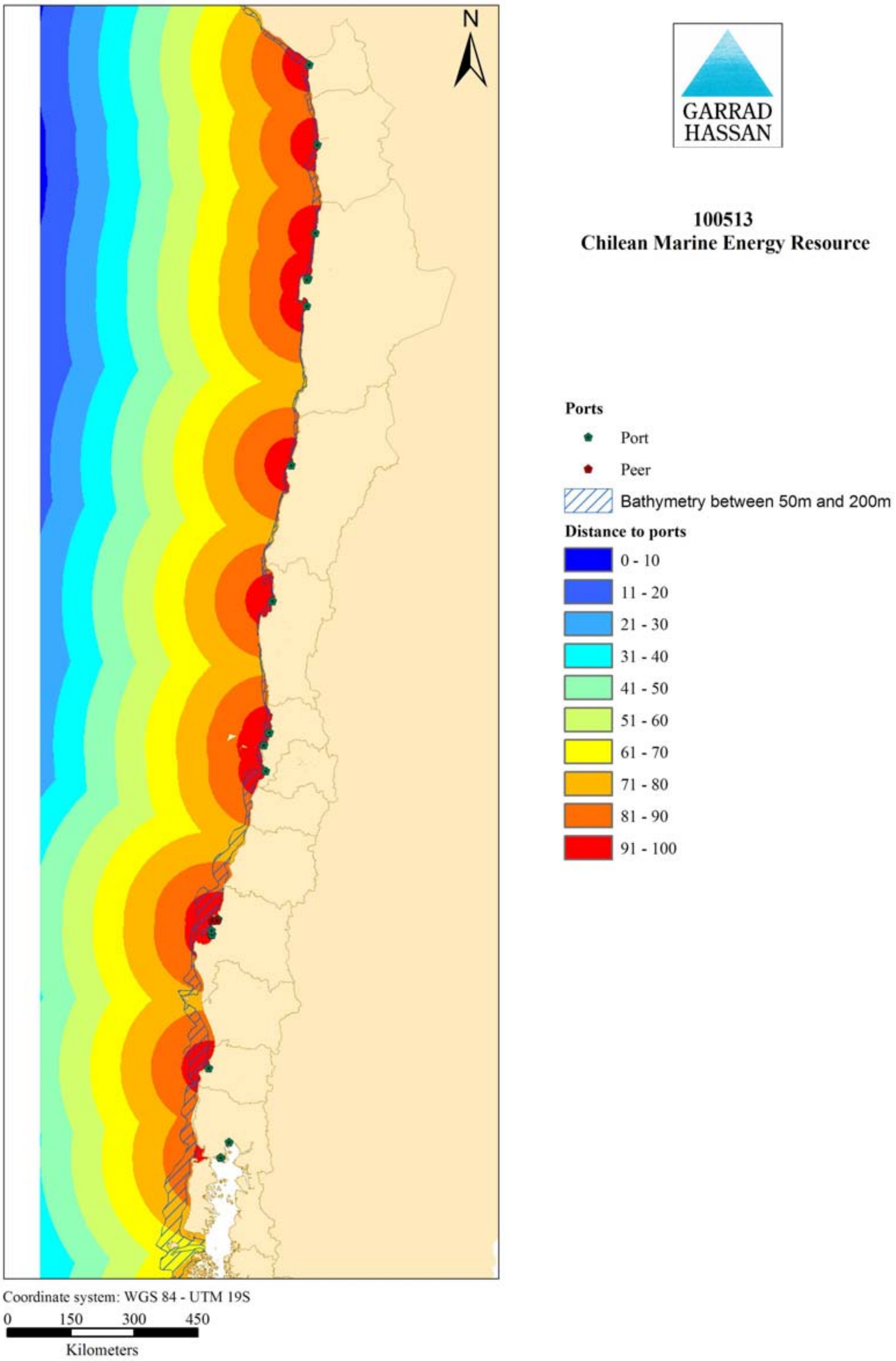

Figure 2-4 Reclassification of distance to port

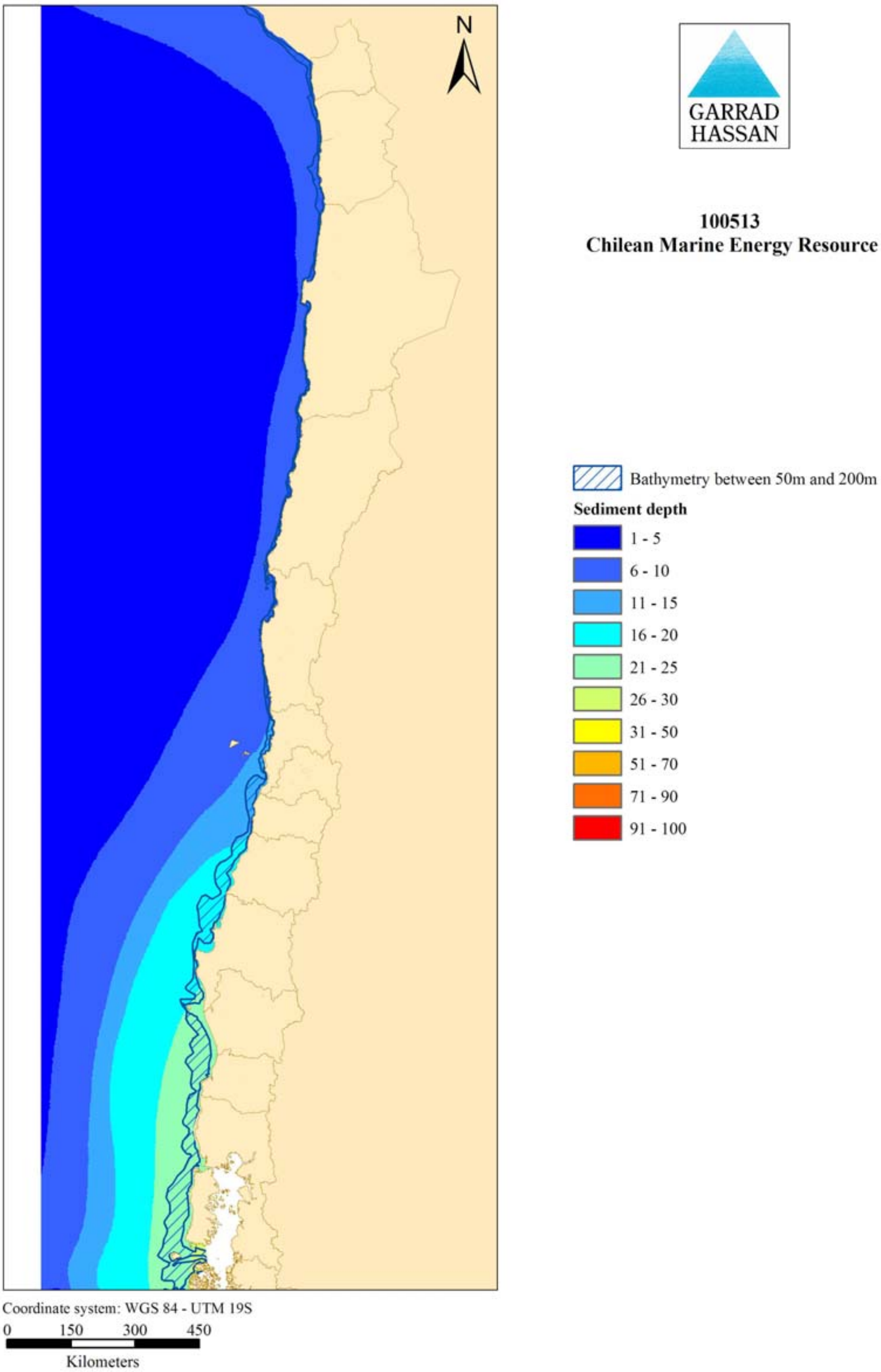

Figure 2-5 Reclassification of seabed sediment thickness (geology)

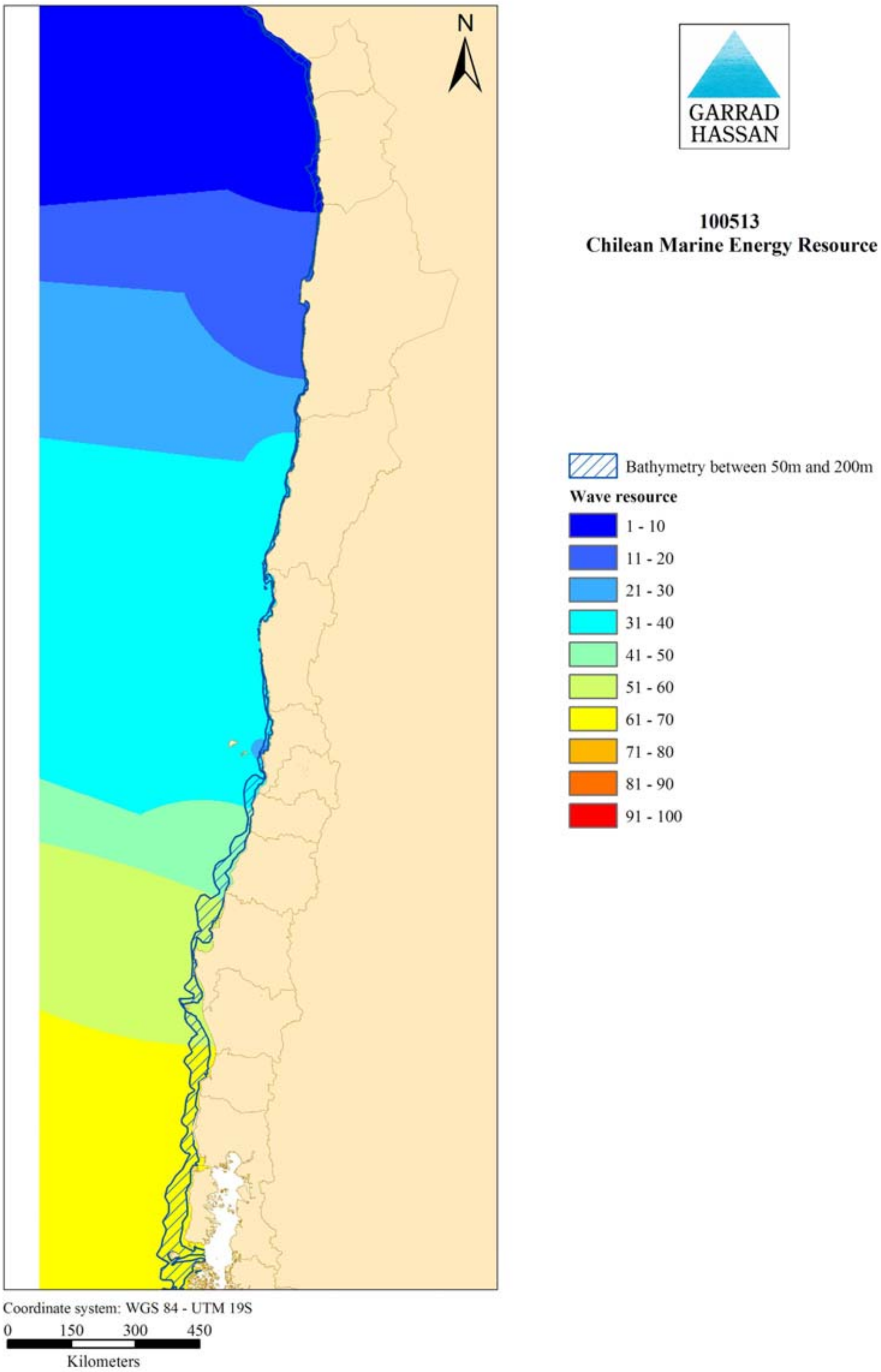

Figure 2-6 Reclassification of wave power

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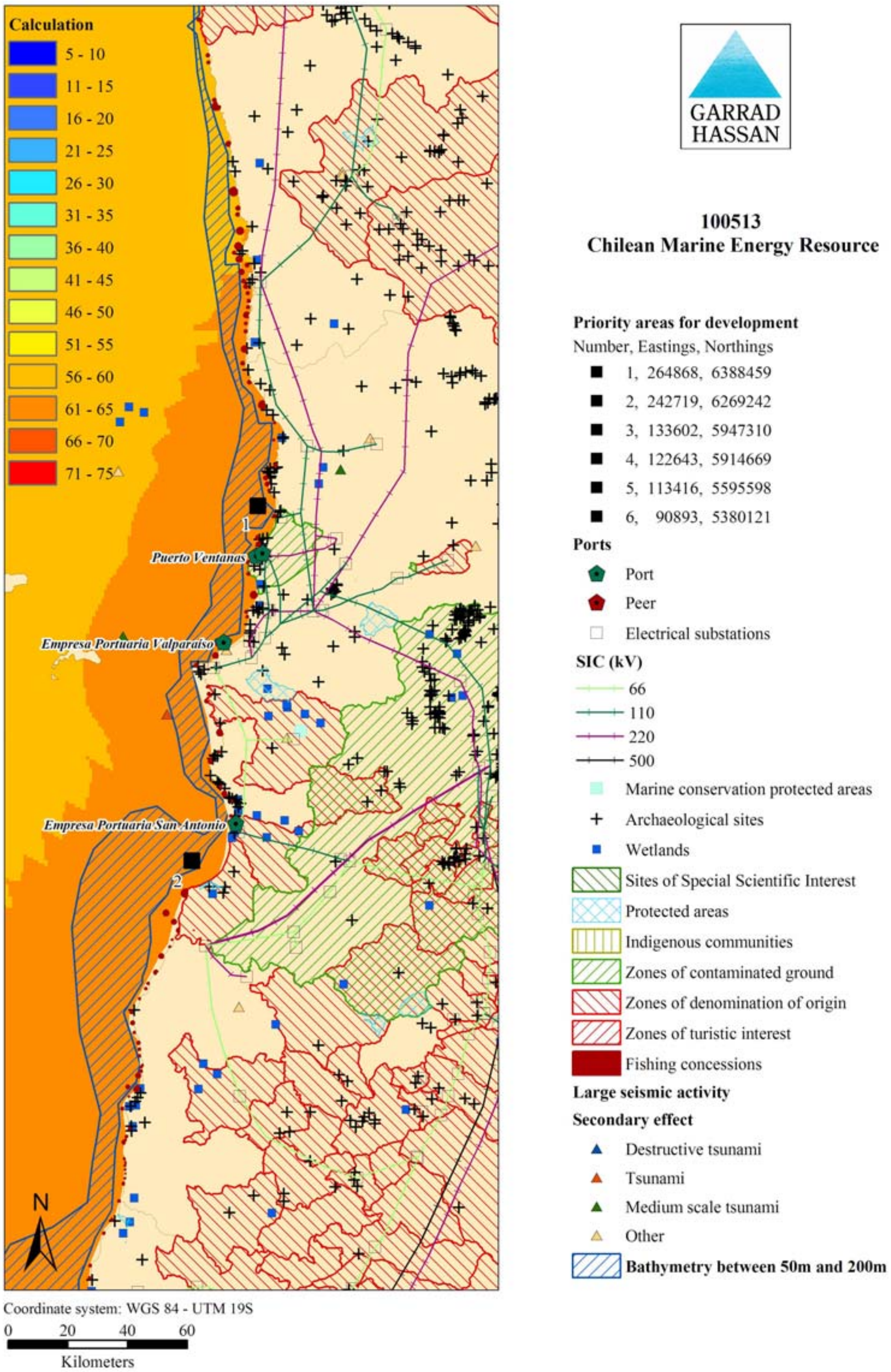

Figure 2-7 Detailed analysis map: Region V

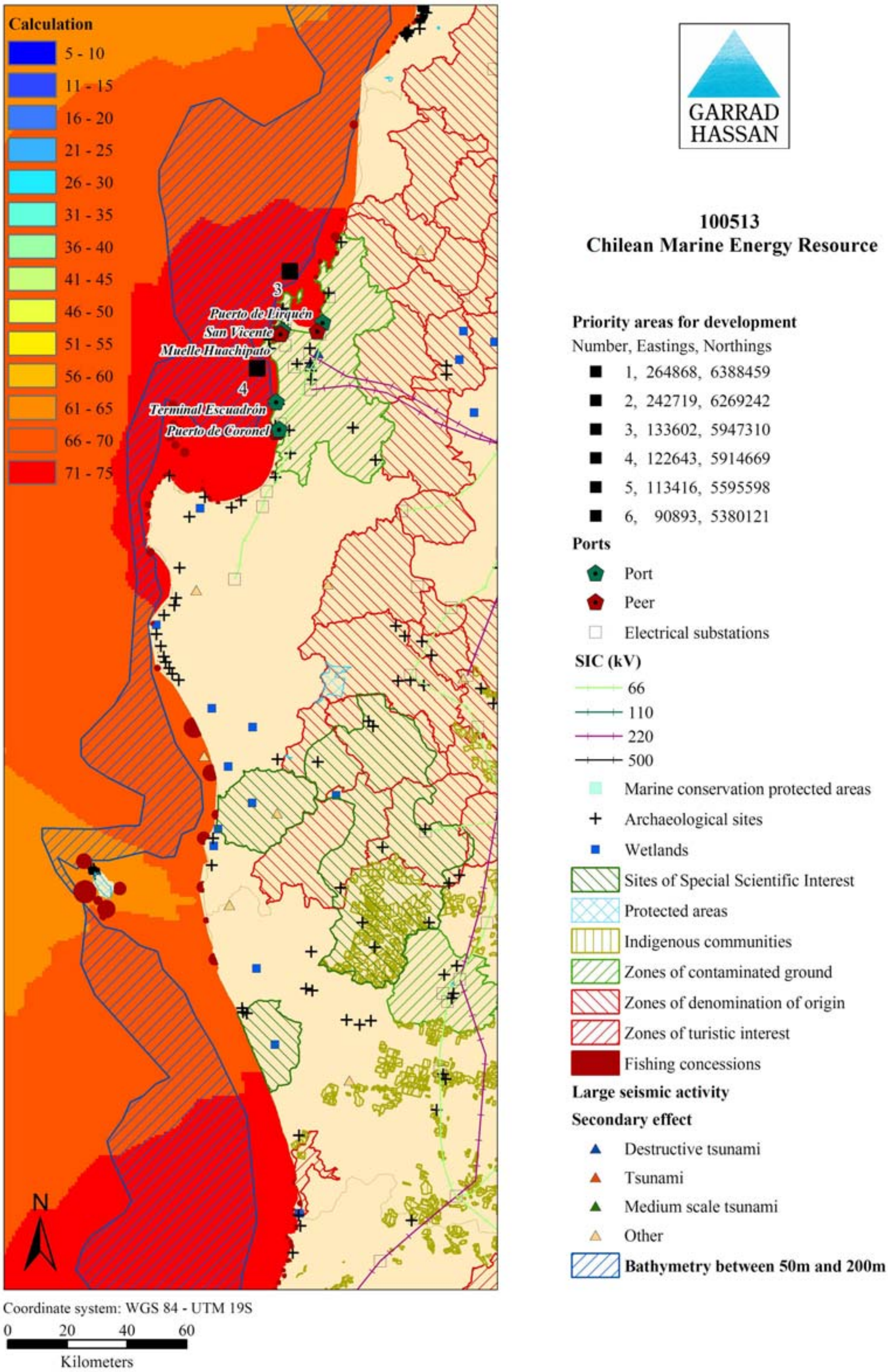

Figure 2-8 Detailed analysis map: Regions VIII and IX

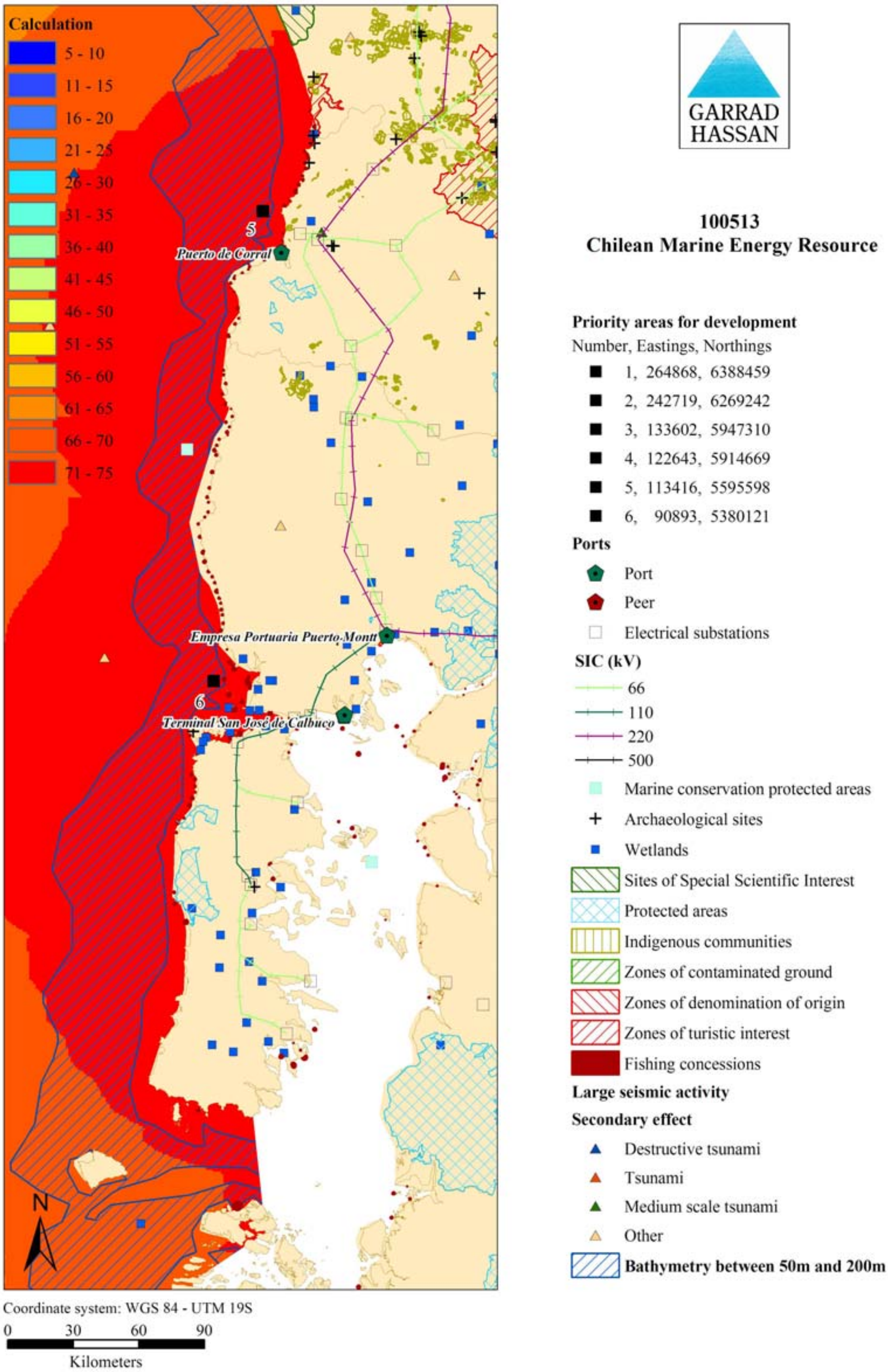

Figure 2-9 Detailed analysis map: Region X

3 TIDAL ENERGY ZONE SELECTION

This section reports the selection of suitable areas (or zones) for the development of tidal stream energy projects in Chile. The nature of the tidal resource is quite different to that of offshore wind and wave. It is generated by a combination of global tidal forcing, regional and local geography and, as such, the resource (tidal races/stream/currents) tends to be very specific to a particular location. Hence the starting point of a zone selection exercise is the identification of these specific locations from which the most suitable areas can be selected. It should be noted that the objectives of this study are to evaluate areas of resource that are suitable for demonstration, pre-commercial and commercial projects. As a result the areas investigated are generally much larger than those analysed by project developers conducting a site selection exercise.

The method adopted to evaluate some of the most promising areas for a potential test centre/ commercial farm is outlined in Section 3.1. Outlined in this section are: The approach to identify areas of suitable tidal stream energy resource; the constraint mapping method required to differentiate the selected areas; and the method to estimate an annual energy yield are outlined.

In Section 3.2 the various information data sources are listed, with some brief discussion on the impacts key information has on the selection process. As outlined in Section 2.2 key information data sets were created in a GH GIS database.

Section 3.3 presents and discusses the results of the zone selection exercise. The section is concluded with the calculation of a conservative estimate for the potential energy yield (in GWh/annum) for each of the three selected areas.

3.1 Methodology

3.1.1 Resource assessment in Chile

Historically most areas of good tidal stream resource have been identified by mariners and recorded on national hydrographic charts for navigational safety purposes. However, the information about these tidal races can be limited (spatially and temporally). In some areas coast lines have been numerically modelled by oceanographer using regional numerical models coupled with finer resolution local bathymetry information to predict local flow accelerations (e.g. The UK Marine Energy Atlas [3.1]). The results of such models enable potential tidal races to be identified and, more critically, quantified when little recorded measurement data exists. Although, it should be noted these models are in the main validated with tidal gauge (height) measurements rather than the less available current measurements. The complex nature of the tidal resource means that in situ measurements are essential for any robust annual energy yield. However, basic information, such as max and mean current speed (or more commonly mean spring and neap peak currents) can be used as indicators of the strength of the resource.

The extensive coastline of Chile and the complex navigation routes in the southern parts has prompted the development of a fairly sophisticate competence in maritime activity. SHOA (the hydrographic office in charge of maritime charts for Chile) operates at international standard protocol and over the last couple of decades has been active in the developing the knowledge of local tidal races. As a result SHOA's hydrographic charts do include some information about tidal stream velocities. However, a complete set of charts for the whole of Chile was not readily available for review and measured data was only available at cost. Instead a literature review coupled with the SHOA tide tables were assessed, along with some reports kindly provided by CNE. Details are provided in Section 3.2.

The UK is generally accepted as the country that is presently leading the development of tidal energy technologies and project developments. In 2004 a review of the UK tidal stream resource was conducted [3.2] and this report use the more commonly available mean spring peak current (Vmsp[11]) parameter as the indicator for the strength of the resource. Generally a Vmsp greater than 2.5m/s is considered to yield a feasible commercial site. Other indicators of the strength of a tidal race are: mean flow; peak flow; tidal range; and the magnitude of the M2 constituent (lunar variation) of the tidal harmonic. But caution is needed when using these values as they can vary dramatically depending of the local driving geography. There are many websites which outline the fundamentals of tidal stream energy, a few of which are listed below:

- http://www.carbontrust.co.uk/technology/technologyaccelerator/ME_guide.htm
- http://www.darvill.clara.net/altenerg/tidal.htm
- http://www.berr.gov.uk/whatwedo/energy/sources/renewables/news-events/press-materials/background/tidal/page24345.html
- http://www.aquaret.com

3.1.2 Constraints mapping and zone selection

Having identified the areas with suitable tidal resource, the mapping of various constraints is required in order to differentiate the selected areas. Attributes that act to reduce the attractiveness of a potential development of a possible tidal stream energy site are complied in a GIS database. Through the GIS information multiple constraints can be visualised, enabling identification and assessment of limiting constraints, such as bathymetry, environmentally protected areas or militarily exercise areas (i.e. the zones where projects may not get planning consent). The technical constraints and the method by which are used in this study are described below and are further defined in Appendix B:

- Tidal resource areas where the peak flow[12] exceeds 3m/s are considered excellent, areas where the flow >2m/s are good and flows >1.8m/s are considered for investigation.
- Bathymetry:
  - Geology/seabed conditions are generally specific to a tidal site and detailed survey work is required when conducting site selection. Presently device developers are looking at various technology options depending on the seabed conditions (e.g. gravity bases where drilling or pilling is not an option) and thus for this study it is assumed that seabed geology is not a limiting factor. However, the inclination of bed could limit device installation (apart from a monopile type concept), so to evaluate the seabed steepness (depending on the concept although 10deg is considered a max), depth contours are reviewed when available.
  - At present no tidal stream technology device developers are investigating operating in depths beyond 100m and the preference is for depths of between 30 – 80 m. However due to limited resolution of the depth data assessment

[11] Vmsp is the mean spring peak flow speed, Vmnp is the mean neap peak flow speed.
[12] The peak flow is used here instead of the Vmsp as the majority of information only contains reference to peak and mean flows. This is explained further in Section 4.3.1.

scoring is based on the weather the majority of the site has a depth greater or less than 100m. An addition consideration (but not considered a constraint) is that CONAMA required a more detailed environmental licensing process beyond the 50m water mark (benthos protection).

- Distance to national electricity grid connection – proximity to the SIC and SING is deemed of major importance by CNE. However, the zones identified in the southern regions i.e. Region XI (Aysen) and Region XII (Magallanes) are not excluded on the base that there are possible alternative options such as remote data centres (like the one proposed by Google [3.3].
- Distance to shore: generally tidal races are located close enough to the shore and thus in this study the distance to shore is not included. It is however, an important factor in the micro-siting process where the increased cable costs must be balanced with a reduce quality of resource closer to shore.
- Distance from ports has been banded by circles of multiples of 25km radius from the various public (or private, but with possible public access) ports. Higher scoring is given to areas closer to ports.
- Concession: fishing concessions were the only concession type that was reviewed. The greater the number (or surface area covered by the concession) the lower the scoring.
- Environmentally protected areas are known as Special Areas of Conversation (AMCPs). In this study the areas within an AMCP were not automatically excluded on the grounds that each case should be judged on an individual basis. Additional environmental information layers have been included in the detailed maps to allow identification of any potential constraints for the development of tidal energy projects. The GH GIS database includes; Sites of special scientific interest; Onshore protected areas; Wetlands; Archaeological sites; Zones of contaminated ground; Other areas of economical interest (e.g. tourism, denomination of origin).
- Other user groups – detailed information regarding navigation routes and issues were not readily available[13]. It is assumed that smaller vessels can co-exist with a submerged array of device and if necessary shipping lanes could be altered. However, a common sense review of the navigation disruption was included in the assessment.
- Military exclusion zones[13] – no information supplied and thus was not included in the assessment.

Each of the above attribute used in this study, was weighted by the follow amounts:

- Tidal resource - 35%
- Depth limit - 10% (although quite critical this weighting is kept low due to the uncertainties regarding the depth variations at sites)
- Distance to national electricity grid connection - 20%
- Distance from ports - 20%
- Fishing concession - 5%
- Navigation -5%
- Environmentally protected areas -5%

[13] As mentioned in Section 3, influence of the constraints below is limited to a final check once the zones have been selected (as additional information):

- Maritime concessions
- Military exercise areas
- Major maritime routes
- Port entrance routes

In the absence of a standard protocol for the zone selection of a demonstration site with the potential for utility scale projects, the specific weightings are based on experience gain from the industry.

By combining the effect of all attributes each area can be ranked relative to each other.

3.1.3 Annual energy calculation methodology

There are two established ways to estimate the potential resource: the "flux" method and the "farm" method. The farm method needs detailed information of the devices to be used and more information on the temporal and spatial variation of the resource (further details are listed below), where as the "flux" method uses a single flow parameter (root mean cubed velocity), some characteristic dimensions of the flow cross sectional area, coupled with an extraction parameter. This extraction parameter (coined the Significant Impact Factor) is introduced to limit the total amount of mean annual power that can should be extracted from a tidal flow as not to cause a significant impact on the up and down stream environment. For the UK assessment the value used was 20%. However, subsequent assessment have increased the potential value to 50% and even higher than 100% for specific sites. As a starting point the value of 20% is used, however, for certain tidal races (e.g. Chacao channel) the driving force and hence energy source is very significant on the flood tide when a ~2 m head difference between the pacific and the Chilean Inland Sea exists.

To avoid the uncertainties associated with the flux method in evaluating the technically extractable resource, it more useful conduct an annual energy yield calculation using the farm method. 30MW is often used as a benchmark for the first commercially feasible farm[14].

To conduct a detailed annual energy yield calculation the following details are required:

- Flow distribution (usually at or near the surface) or harmonic description
- Detailed bathymetry
- Flow profile through water column (boundary layer)
- Assume spatial variation (side effects/ side profile)
- Device power curve (water to wire)
- Device hub height setting
- Packing density (lateral and longitudinal limits i.e. blockage and wake effects)
- Limit of extraction / extraction constraints
- Electrical efficiency
- Availability

For the 30MW farm assessment the following assumptions are made:

- A flow distribution can either be used directly from measured data or constructed using a simplified harmonic model (based on Vmsp and Vmnp). From the distribution the root mean cubed speed is found (Vrmc).
- Spatial consistency is assumed: the same mean flow is assumed over the site. For the Chacao channel three varying assumptions have been used (see Appendix B&D)
- A 1/7th power law depth profile is assumed
- Hub height is assumed to be mid water depth
- The overall efficiency for a farm is assumed to be 31.3% and includes:
  - Rotor to wire 35%
  - Grid losses at 95%

[14] The Carbon Trust's MEC cost estimation methodology uses 30MW as the benchmark see http://www.carbontrust.co.uk/technology/technologyaccelerator/mec_cost_estimation_methodology.htm

    - Farm availability at 94%
- The selection of the optimum rotor size for a particular site is driven by cost of energy modelling. It is not the intension in this study to optimise here, however, to provide an indication of the variation the following design options are used (see analysis in Appendix B):
    - Fixed rotor diameter (19.5m and 22m[15])
    - Fixed rated velocity as 71% of the Vmsp[16]
- The annual mean power and energy yield is then evaluated using the following equations:

$$P_{mean} = \eta_{overall} \tfrac{1}{2} \rho \frac{\pi D^2}{4} V_{rmc}^3$$

$$Annual\ Energy = P_{mean} * 24 * 365 * No.devices$$

Where ρ is the density of sea water and a value of 1020 kg/m^3 has been used.

The area devices operating in arrays take up is of function of the technology type (i.e. if it is seabed mounted or floating) and the ambient turbulence intensities at the site. Typical packing densities are between 25-30 units per km^2, i.e. a 30MW farm occupies an area of 1km^2.

3.2 Source of data

In this section the sources of data for the resource assessment and some bathymetry data are outlined below. Table 2-1 in Section 2 presents the sources of the data of the various constraint attributes.

3.2.1 SHOA presentation

SHOA have an extensive knowledge of the coast around Chile and have recently identified some areas of interest and might have some potential for marine energy projects [3.4]. SHOA have conducted many measurement campaigns (oceanographic cruises) and have actively monitoring station within the Chilean Inland Sea. The figure below shows a slide from the SHOA presentation of the different measurements (Oceanographic works/hydrographic, Permanent Stations of Tide) taken within the Chilean Inland Sea.

[15] The selection of rotor diameters is based on scaling up the MCT SeaGen rotor, setting the capacity factor at 0.4 and 0.6 respectively. The higher capacity factor is justified on inspection of the flow probability distribution - see Appendix B.

[16] There is greater uncertainty associated with this method for two reasons: firstly the 71% is rather arbitrary (it was used in many of the early UK resource assessments) and should be a function of the flow probability distribution. And secondly the Vmsp of a site is typically not defined.

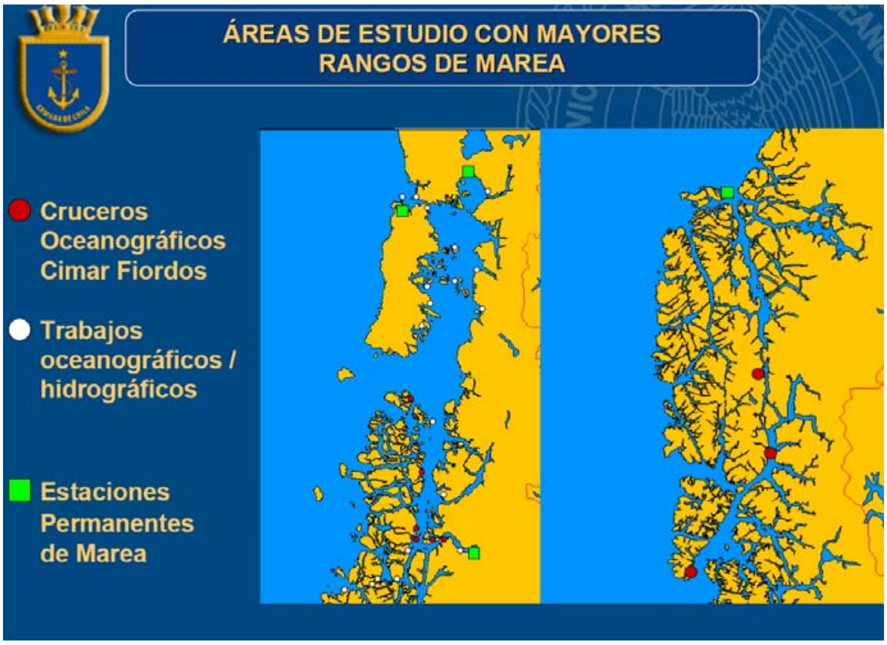

Figure 3-1 SHOA presentation – measurements in the Chilean Inland Sea

The permanent stations are primarily equipped to measure offshore oceanographic conditions to detect tsunamis. Some of the results from the CIMAR cruise have been used in this study, but the time series measurements obtain were not freely available for inclusion in this study.

Estadísticas de corrientes medidas en sitios localizados entre la X y XII regiones.

LOCALIDAD	FECHAS		Profundidad. [m]	Magnitud [nudos]		Magnitud [m/s]	
	Inicio	Term.		Máx.	Media	Máx.	Media
CANAL GABRIEL	250386	250486	6	4.13	0.40	2.12	0.20
PASO SUMMER 1	180488	230588	5	0.46	0.08	0.24	0.04
PASO SUMMER 2	180488	230588	5	1.37	0.10	0.70	0.05
CANAL GRAY 1	180488	230588	5	1.08	0.10	0.56	0.05
CANAL GRAY 2	180488	230588	6	0.85	0.05	0.44	0.03
ROCA ANSON	260988	311088	5	2.95	0.23	1.52	0.12
CANAL CHACAO	081288	110189	8	2.57	0.38	1.32	0.19
CANAL CANACUS	241089	131189	5	0.33	0.02	0.17	0.01
CANAL CANACUS (2)	241089	131189	5	0.33	0.02	0.17	0.01
BEAGLE (BRAZO SURWESTE)	090798	260798	68	0.92	0.07	0.47	0.04

Figure 3-2 SHOA presentation – tidal measurements

Figure 3.2 shows some survey measurement results at various locations in Chile. The current magnitudes are not impressive and there is large discrepancy with the typical values used for Chacao channel of 4m/s. However, they do indicate that the focus on of the resource assessment should be on the Chilean Inland Sea and the Southern Straits. SHOA further present some possible areas for tidal stream energy projects (shown in the figure below).

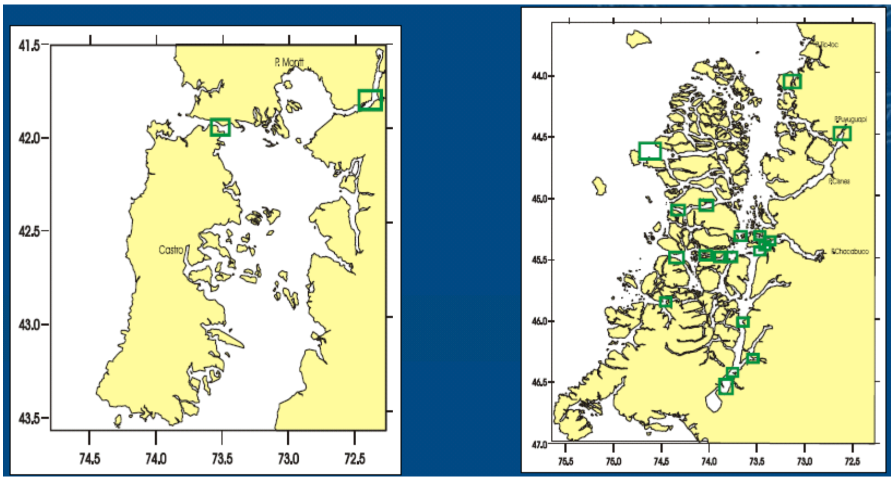

Figure 3-3 SHOA presentation – potential tidal areas

The SHOA presentation also highlighted strong currents in the southern channel of the Straits of Magallanes. This strait connects the south Atlantic ocean with the Pacific and the constraining geography is likely to generate strong currents. The figure below shows a slide from SHOA's presentation where flows of up to 5.8 knots occur (and are tabulated in the SHOA tide tables [3.18]).

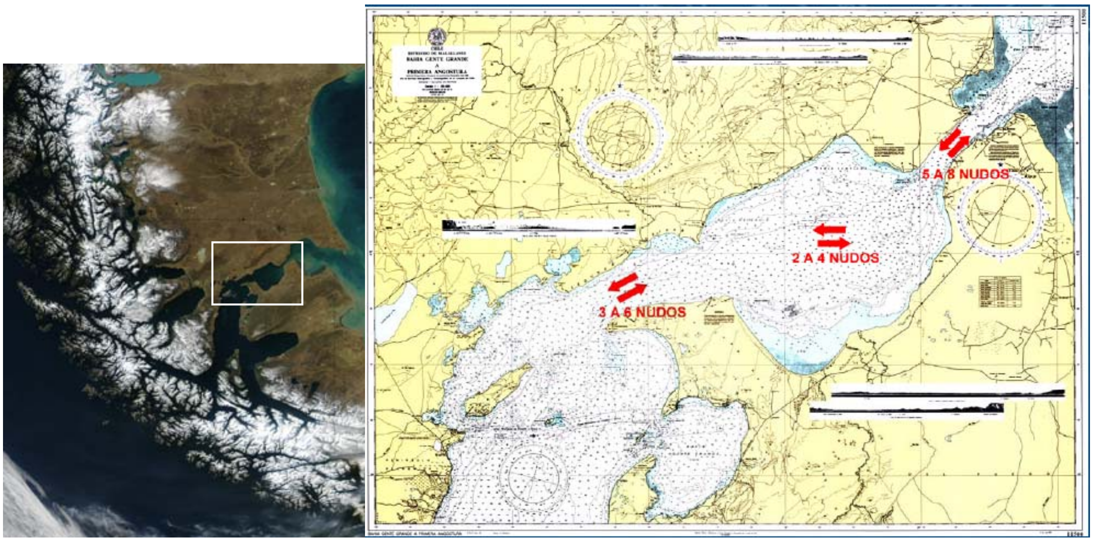

Figure 3-4 Potential tidal resource in Southern Chile

3.2.2 SHOA tide tables

The SHOA tide table [3.18] contain a comprehensive annual characterisation of tidal elevations throughout Chile. In addition the timing of eight tidal currents are included. However, only two of the eight have a current magnitudes associated with them. Some further information on the peak flows are also presented.

3.2.3 SHOA charts

Via the SHOA website [3.5] some basic hydrographic charts are available for free use. These charts have been used to review the bathymetry at some locations. Comparing the bathymetry data from the National Geophysical Data Centre, USA shows significant variation from the SHOA web maps.

3.2.4 Published literature

The list below states a brief overview and reference for all the published literature used in the resource assessment or supplied bathymetry data.

Mejillones Bay

- Upwelling shadows at Mejillones Bay (northern Chilean coast), a remote sensing in situ analysis, Víctor H. Marín1, Luisa E. Delgado1 & Rubén Escribano, Invest. Mar., Valparaíso, 31(2): 47-55, 2003 [3.6]

Satellite (NOAA's AVHRR upwelling shadows images) and measurement data coupled with numerical modelling of the oceangraphic currents in the bay.

Valparaiso to Topocalma Point

- A simulation of the Chilean Coastal Current and associated topographic upwelling near Valparaíso, Chile, Christopher M. Aiken a,b,_, Manuel I. Castillo a, Sergio A. Navarrete a, Continental Shelf Research 28 (2008) 2371– 2381 [3.7]

Numerical modelling of the surface wind driven currents around central Chile.

Concepción Bay

- The Influence of Winds and Tides in the Formation of Circulation Layers in a Bay, a Case Study: Concepcio´n Bay, Chile, M. B. Sobarzoa, D. Figueroab and D. R. Arcosc , Estuarine, Coastal and Shelf Science (1997) 45, 729–736 [3.8]

Review of wind driven currents in the bay.

Concepción to Valdivia

- Oceanographic observations in Chilean coastal waters between Valdivia and Concepciòn Larry P. Atkinson,1 Arnoldo Valle-Levinson,1 Dante Figueroa,2 Ricardo De Pol-Holz,2 Victor A. Gallardo,2 Wolfgang Schneider,2 Jose L. Blanco,1 and Mike Schmidt3 JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107, NO. C7, 10.1029/2001JC000991, 2002 [3.9]

Satellite and measurement data coupled with numerical modelling of the oceangraphic currents from Valdivia to Concepciòn.

Chilean Inland Sea

- Barotropic tides of the Chilean Inland Sea and their sensitivity to basin geometry, C. M. Aiken, JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, C08024, doi:10.1029/2007JC004593, 2008 [3.10]

This paper describes the numerical modelling of the flows within the Chilean Inland Sea. The paper describes the model set up, validation and illustrates and discusses some of the results.

Chacao channel

- Observations of cross-channel structure of flow in an energetic tidal channel, Mario Caceres (Servicio Hidrografico y Oceanografico de la Armada, Valparaiso, Chile), Arnoldo Valle-Levinson and Larry Atkinson, JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. C4, 3114, doi:10.1029/2001JC000968, 2003 [3.11]

This paper presents detailed and interesting information of current measurements in the Chacao channel. The paper demonstrates the complexity of the channel bathymetry and flow.

- CNE report : Estudios Básicos e Ingeniería de Detalles, Construcción Terminal Portuario Canal de Chacao, X Región, Informe de Corrientes, Consultor GHD S.A., Marzo 2007 [3.12]

Report detailing various flow conditions at points around the mouth of the Chacao channel.

- Presentation: Manejo Portuario y Navegación, Aplicación de Radares Marinos HF, Exponaval 2008, Valparaíso, 4 de diciembre de 2008 [3.13]

A slide showing some radar measurements made within the Chacao channel.

Darwin channel

- VARIABILIDAD LONGITUDINAL DEL FLUJO EN CANALES CON INFLUENCIA BATIMÉTRICA Y TOPOGRÁFICA, Mario Cáceres1, Arnoldo Valle-Levinson2, Juan Fierro1, Mónica Bello1 & Manuel Castillo1, Crucero CIMAR 8 Fiordos SHOA [3.14]

Typical flow speeds and bathymetry in three channels given.

AYSÉN estuary

- 2.4 VARIABILIDAD TRANSVERSAL DEL FLUJO Y DE LA DENSIDAD, EN LA BOCA DEL SENO AYSÉN, Mario Cáceres 1, Arnoldo Valle-Levinson 2,, Juan Fierro 1, Claudia Valenzuela 1 y Manuel Castillo 1, Crucero CIMAR 7 SHOA [3.15]

Some typical flow speeds in the channel given.

Moraleda channel

- CARACTERIZACIÓN DEL RÉGIMEN DE MAREAS Y CORRIENTES A LO LARGO DEL CANAL MORALEDA (43o 54’ S - 45o 17’ S), CHARACTERIZATION OF THE TIDAL REGIME AND CURRENTS ALONG THE CHANNEL MORALEDA (43O 54’ S - 45O 17’ S), JUAN FIERRO C.*, MAURICIO BRAVO R.*, MANUEL CASTILLO S.**, Cienc. Tecnol. Mar, 23: 3-14, 2000 [3.16]

Some typical flow speeds in the channel given.

Puerto Edén, Punta Beresford and Caleta Patria

- PROPAGACIÓN DE LA ONDA DE MAREA EN CANALES ADYACENTES A CAMPOS DE HIELO SUR, TIDE WAVE PROPAGATION IN CHANNELS ADYACENT TO SOUTH ICE FIELDS, JUAN FIERRO C.,, MANUEL CASTILLO S., ,CLAUDIA VALENZUELA C. Cienc. Tecnol. MParr,o 2pa6g (a1c)i:ó 5n- 1d4e ,l a2 0o0n3da de marea en los canales adyacentes a Campos de Hielo Sur 5 [3.17]

Analysis of tidal elevations, no flow speeds given.

3.2.5 Numerical model data

The paper *Barotropic tides of the Chilean Inland Sea and their sensitivity to basin geometry* [3.10] describes a numerical model used to predict the tidal flows within the Chilean Inland Sea. The results of this modelling indicate where strong tidal flows maybe found within the Chilean Inland Sea. During the site visit contact was made with the author (Chris Aiken[17]) and subsequently the numerical model results of the tidal currents flows and elevation were kindly supplied. This information will be referred to as source [3.19] from hereafter. The

[17] Chris Aiken undertook the numerical modelling of Chilean Inland Sea whilst at Centro de Investigación en Ecosistemas de la Patagonia, Coyhaique. He now works at Pontificia Universidad Catolica de Chile, based in Valparaiso.

modelling software used was the Regional Ocean Modelling System (ROMS[18]) code which is a highly regarded community based development used internationally by academic oceanographers.

The figure below highlights the measured data points used for model validation (this is done using both tidal elevation and tidal current data) and further description is provided in [3.10]. It should be noted that the numerical model does not have particularly good correlation with observations in the Chacao channel, but elsewhere correlation is stated as good.

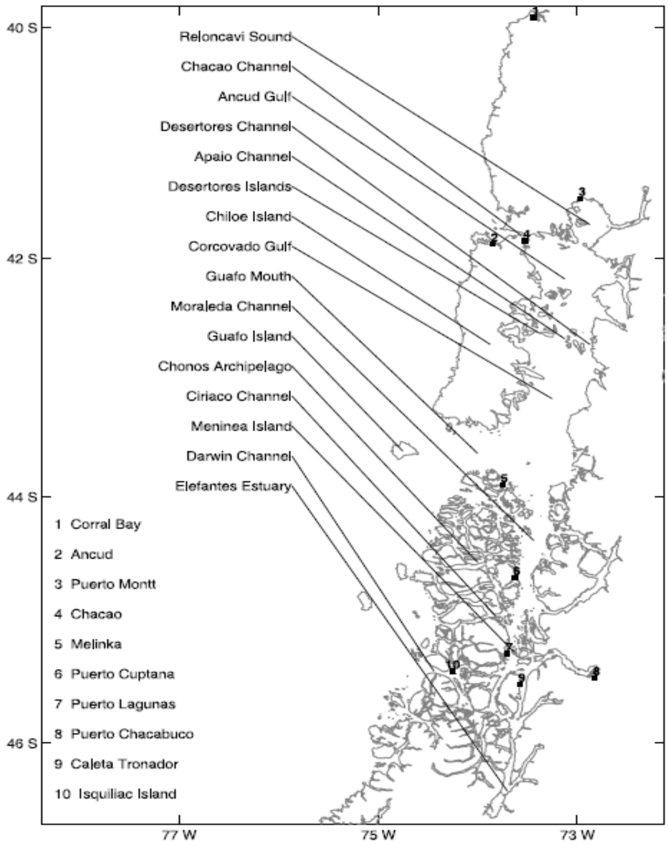

Figure 1. Major features of the Chilean Inland Sea. Locations where tidal observations were compared to the model are indicated by the numbered boxes.

Figure 3-5 Model area of the Chilean Inland Sea (source: [3.10])

The geography of the Chilean Inland Sea is the result of previous glacial action which formed a deep central channel reaching from the Guafo Mouth up to Puerto Montt and comprising of numerous and complex islands, channels and fjords. The Pacific tidal wave enters the Chilean Inland Sea through a 50 km opening at Guafo Mouth and increases from a range of 2m to up to 7m in Reloncavi Sound [3.10] (see figure above). The dramatic increase in tidal range is probably due to tidal resonance [3.11]. The action of large tidal ranges coupled with narrow channels and inlets leads to the formation of accelerated flows and tidal races. In addition the resulting difference in water elevation between the Inland sea and the Pacific Ocean generates very high flow through the Chacao channel. The figure below shows up to a 2m head difference either end of the Chacao channel (this is further validated with site data – see Appenddix D) which equates to a significant amount of power (~13GW[19]).

[18] ROMS website.

[19] The number indicates the order of magnitude of the driving force through the channel and is calculated by the equation *Power = density*head*gravity*flow rate* assuming an cross-sectional area of 80x2000m and a flow speed of 4m/s.

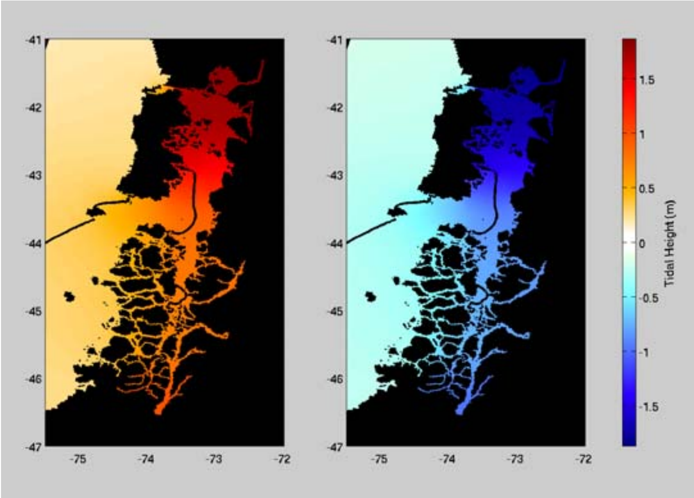

Figure 3-6 Concurrent water level elevations in the Chilean Inland Sea (source: [3.19])

Figure 3.7 below shows that there are several locations where the peak currents exceed 1.8m/s making them of potential interest.

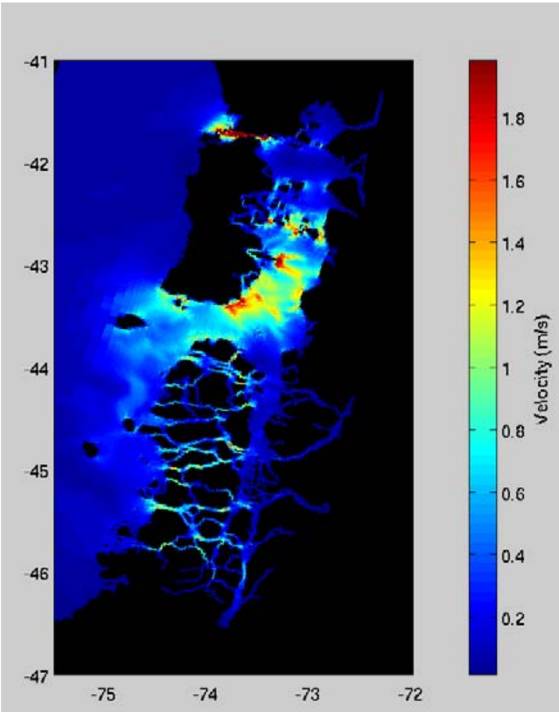

Figure 3-7 Potential tidal resource (peak spring currents) in the Chilean Inland Sea (source: [3.19])

3.3 Results

3.3.1 Resource

The literature review found no tidal races along the central and northern Chilean coast. Given the relatively small tidal range along the most of central and northern coast this would be expected. In contrast the geography in southern Chile is favourable for the generation of tidal races. In particular the Chilean Inland Sea is of sufficient form and size as to allow tidal amplification to occur creating a larger than normal tidal elevation and when coupled constraining geography, such narrow channels, high flows can results. The phenomena of the Chacao channel is a result of the large difference in tidal elevation between the Pacific

Ocean and Aucud Gulf (top of the Chilean Inland Sea). A driving head of 2m generates very high current flows making the Chacao channel a highly unique site.

The results of the numerical modelling conducted by Chris Aiken [3.19] together with the results of the literature review and analysis of the SHOA tide tables have identified a number of key zones with the potential to have a feasible tidal stream energy resource. The table below describes these areas and quantifies their resource potential.

Table 3-1 Identified areas of good tidal resource

List potential zones:	Coordinates	Site size Width km	Site size Length Km	Peak flow (m/s)	Source
Chacao channel	41 45.5S 73 60.5W	2- 5	10	3.5 - 5	[3.11] [3.12] [3.20]
Apaio channel	42 40S 73 08.2W	2	2	~1.8	[3.19]
Corcovado Gulf	43 00S 73 17.04W	4	10	~2	[3.12] [3.19]
Gusto mouth Chiloe SE pinnacle	43 23S 73 36W	5	25	~1.8	[3.19]
Darwin channel	45 24S 74 17W	~0.5	~2	2	[3.14]
Angostura Inglesa	48 57.8S 74 25.5W	<1	1-2	1.9	[3.18]
Gabriel channel	54 07S 70 55W	0.5-1.5	25	2.1	[3.18]
Primera Angostura (Straits of Magallanes)	52 34S 69 40W	3	14	~4	[3.18]

There are many interconnecting sea channels populating the south of Chile which could offer the potential for localised tidal streams with good or excellent resource. This is particularly applicable to the Southern part of the Chilean Inland Sea - see Figure 3.7, (e.g. Pulluche channel approximate coordinates 45 46.0 S 74 19.5 W). SHOA highlight a potential site at Estuario Reloncavı (approximate coordinates 41 42.4 S 72 28.5 W), however, no resource data could be found and on inspection the majority of the channel depth exceeds 100m.

Without reviewing all the relevant hydrographical (SHOA) charts and gaining a more comprehensive resource data set, it is not feasible to identify and hence include these areas in this study. However, it is likely that due to the in-depth knowledge of SHOA the main areas of resource have been identified.

Of the potential zones only two really exhibit a commercially feasibly resource (Chacao and the Straits of Magallanes). However, due to the uncertainty associated with the peak flow values, all areas are included in this study.

3.3.2 Review of constraints

3.3.2.1 Depth limits

The Chilean Inland Sea and southern straits have been formed from previous glacial action and thus tend to have rather steep and deep channels. The maximum design operating depths that the majority of technology developers are designing to, or are expecting to design to, is one hundred meters. However, for the earlier stage technology (first farms) a depth limit of between 30-50m is expected. Further work is needed to prove the installation, retrieve and recover methods, prior to deep water installation.

Table 3-2 Typical depths at the identified areas

Zone	Depth range (m)
Chacao channel	31-100
Apaio channel	100
Corcovado Gulf	20-100
Gusto mouth Chiloe SE pinnacle	20-100
Darwin channel	100
Angostura Inglesa	100[20]
Gabriel channel	100
Primera Angostura (Straits of Magallanes)	50 -70

3.3.2.2 Electrical interconnection and subsea cable route

The figure below shows the extent of the SIC grid into the south of Chile. The SIC does extend on to the island of Chiloe via a 100kV and then 66kV line, however, the 220kV SIC finishes at Puerto Montt. As shown in Figure 3.8 below there is no SIC or SING in the south.

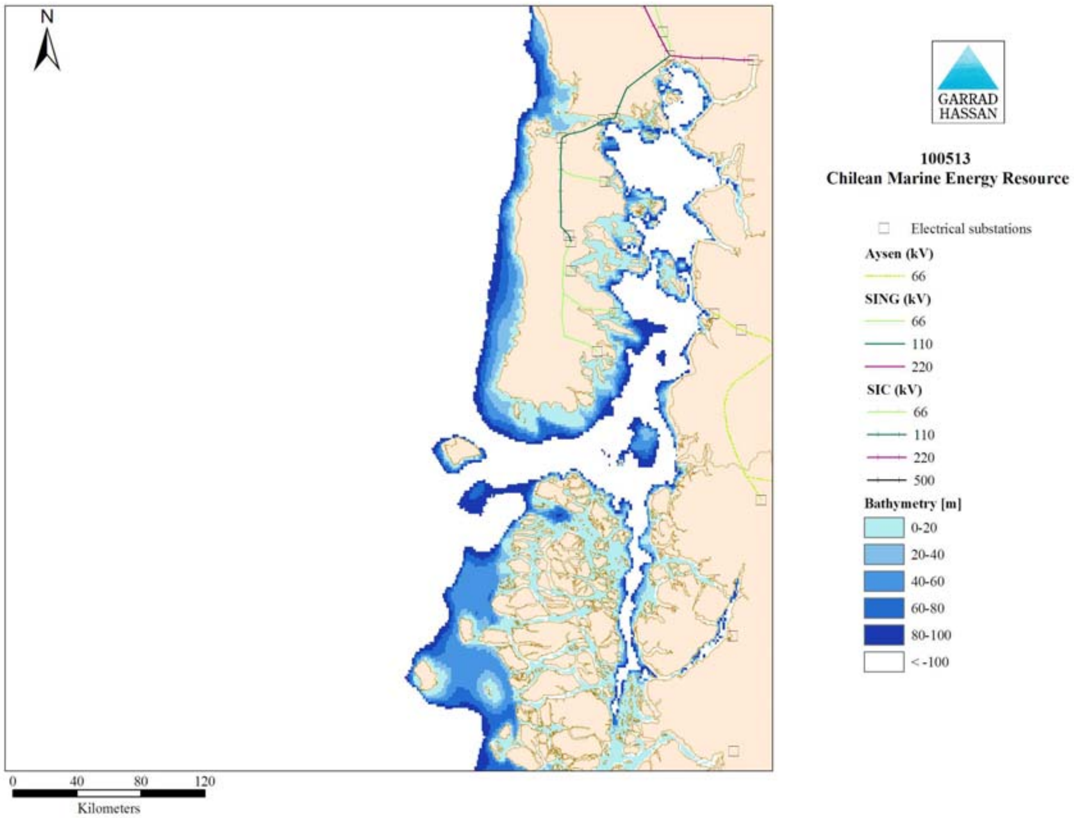

Figure 3-8 Electrical grid in Region X and XI.

[20] Little information could be found about this channel, so given the nearby water depth an upper limit of 100m was used.

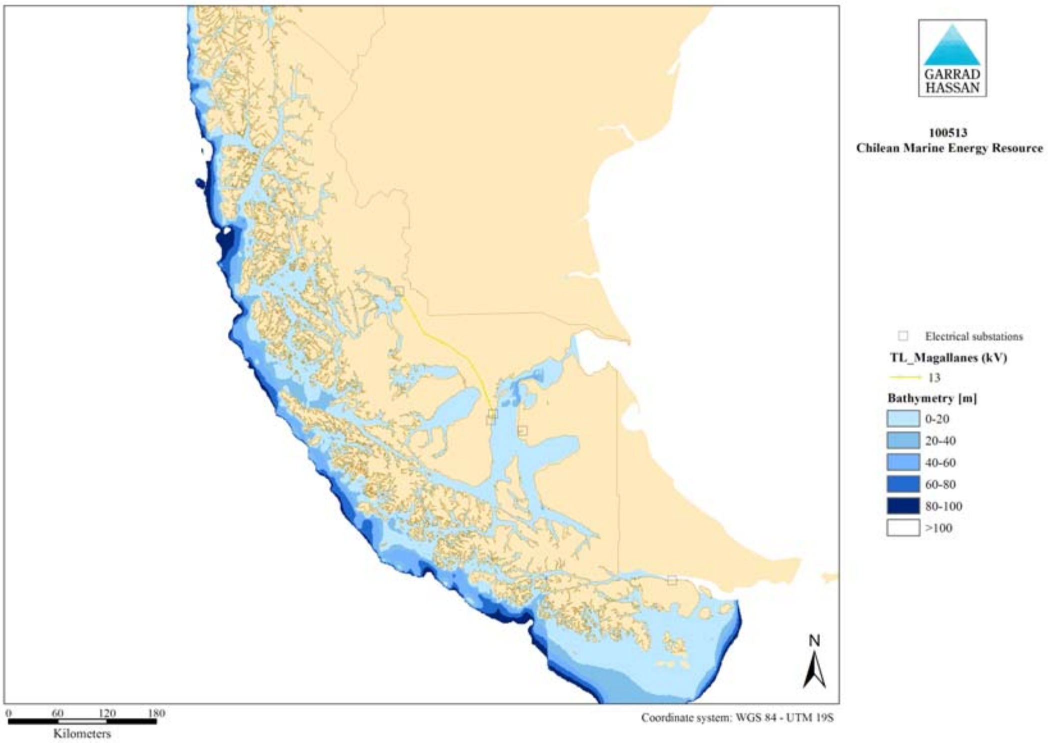

Figure 3-9 Electrical grid in Region XII

The table below lists the estimated distance to electrical grid connections.

Table 3-3 Location Typical depths at the identified areas

Zone	Distance to grid connection
Chacao channel	0-10km to 110kV, ~ 60km to 220kV
Apaio channel	~60 to 110kV
Corcovado Gulf	~30km to 66 kV + 65km to 110kV line
Gusto mouth Chiloe SE pinnacle	35km to 66 kV + ~130km to 110kV.
Darwin channel	Na
Angostura Inglesa	Na
Gabriel channel	Na
Primera Angostura (Straits of Magallanes)	Na

3.3.2.3 Distance to nearest ports

The distance of the area to the various public or private with public access ports in shown the figures below:

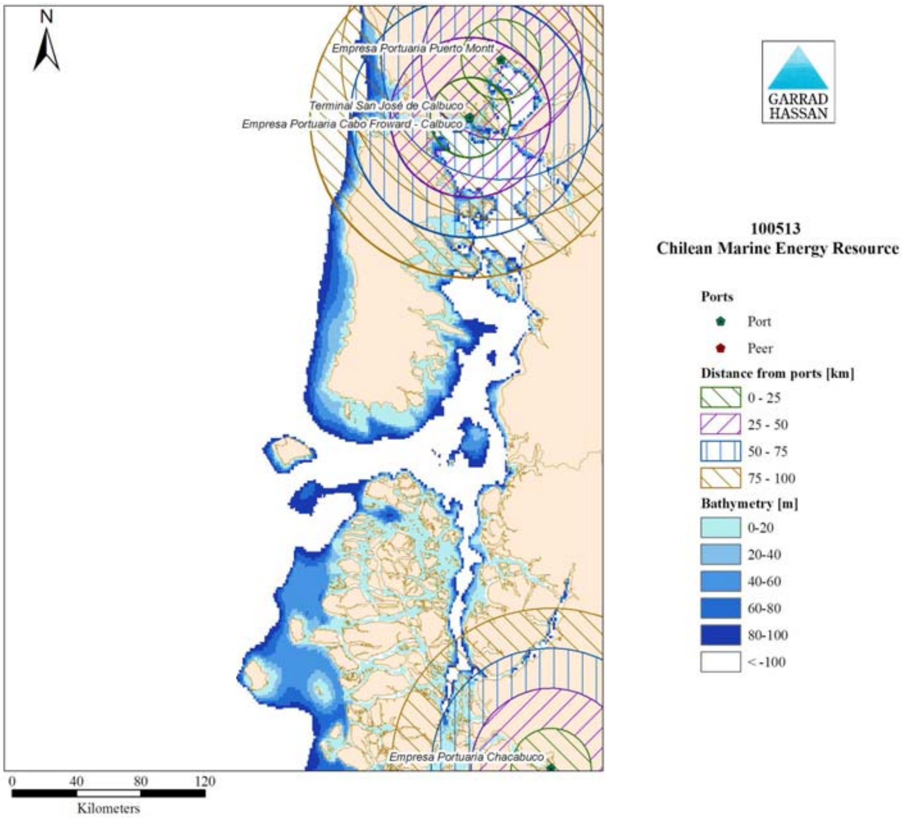

Figure 3-10 Port proximities in Region X and XI

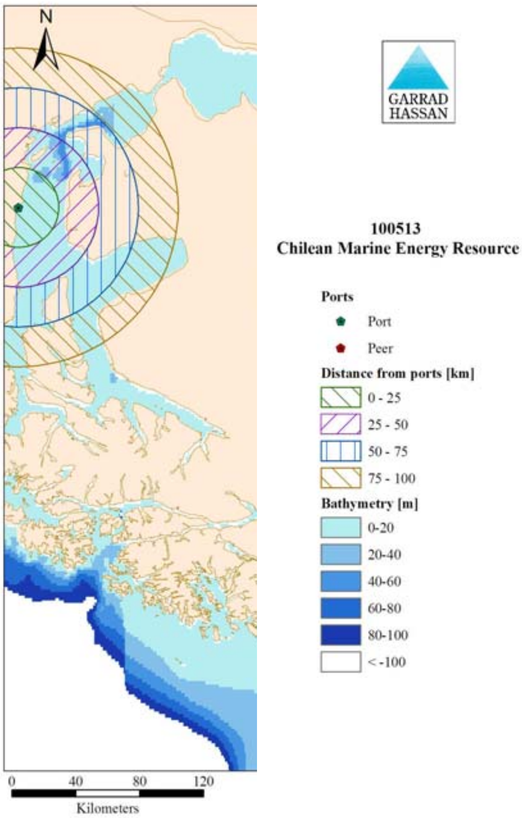

Figure 3-11 Port proximities in Region XII

The table below lists the banded distance from the nearest port for the indentified areas.

Table 3-4 Distance to the nearest port for the identified areas

Zone	Distance to nearest port (km)
Chacao channel	0-25 to Cabo Froward ~ 80 to Puerto Montt
Apaio channel	75-100 to Cabo Froward
Corcovado Gulf	100+
Gusto mouth Chiloe SE pinnacle	100+
Darwin channel	100+
Angostura Inglesa	25-50 to Chacabuco
Gabriel channel	75-100 to Austral
Primera Angostura (Straits of Magallanes)	100+

3.3.2.4 Conflicts with other user-groups

Fishing concessions were assumed to be the primary concession of interest due to the possible direct conflict of interest. The figure below shows the location of the fishing concession in and around the Chilean Inland Sea. There are no fishing concessions in the other areas of interest.

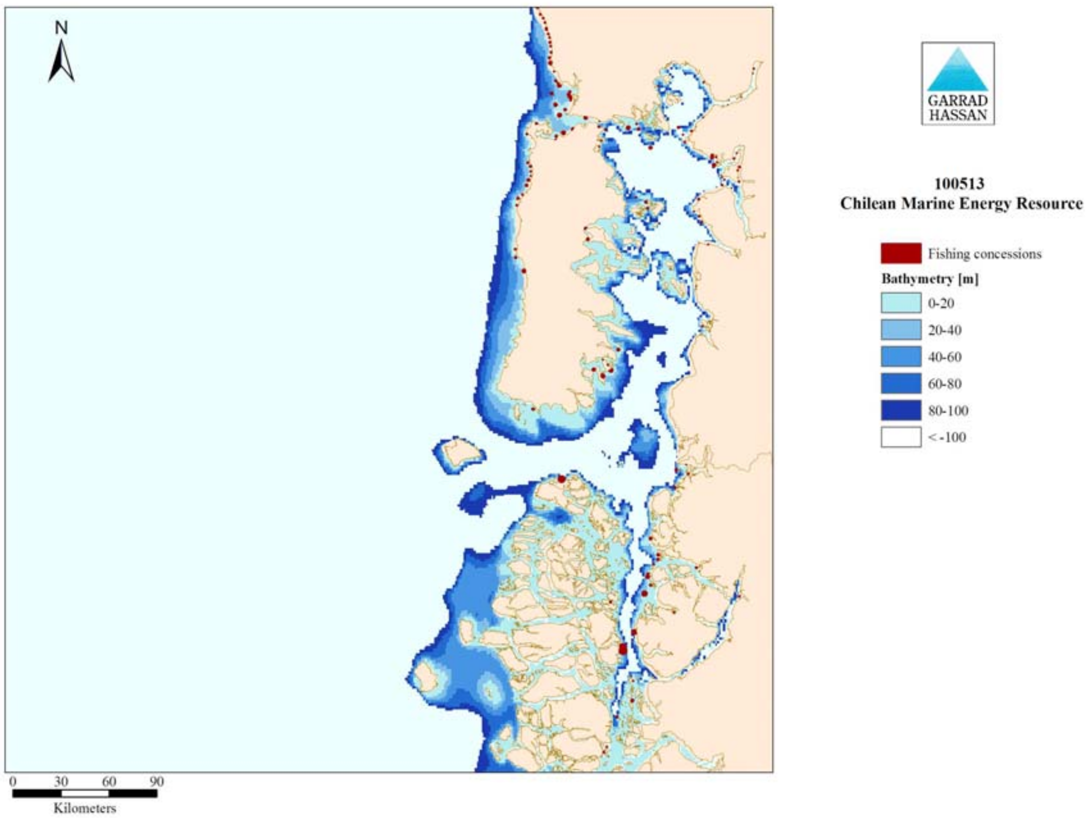

Figure 3-12 Fishing concession in and around the Chilean Inland Sea

The table below lists the fishing concessions within the selected areas as well as some assessment as to the possible conflict with maritime traffic.

Table 3-5 Fishing and navigation issues at the identified areas

Zone	Fishing concession	Navigation issues
Chacao	Three concession in location area (SUBPESCAS ID 462, 349, 444; see Table 3-6)	Chacao ferry crossing, fishing vessels,
Apaio channel	None[21]	Possible shipping conflict
Corcovado Gulf	None	
Gusto mouth Chiloe SE pinnacle	None	
Darwin channel	None	
Angostura Inglesa	None	
Gabriel channel	None	
Primera Angostura (Straits of Magallanes)	None	Significant shipping route. Ferry crossing.

Table 3-6 Fishing concession details

Name	Lenqui-Punta Santa Teresa	Bahia Pargua	Punta Remolinos - Punta Soledad
ID	462	349	444
SECTOR	Lenqui-Punta Santa Teresa	Pargua	Punta Remolinos - Punta Soledad
REGION	X	X	X
DECR_SUPRE	677/15,10,03 – 14	714/07.12.00	663/13,10,03
SUP_HA	325	11	95
DECR_DESTI	138/10,08,05	155/20,12,01	80/18,08,04
DIARIO_OFI	22,10,03 -	01.02.01	17.10.03
FUENTE	Subpesca	Subpesca	Subpesca

3.3.2.5 Ecological sensitivity

Figures 3.13 and 3.14 show that a large percentage of the network of channels in the southern Chilean Inland Sea and large parts of Region XII are protected areas.

For the purpose of this study only environmental factor incorporated into the scoring assessment is whether a zone is very close or within a protected AMCP area, see Table 3-7.

[21] There is a fishing concession 8km from this site (ID 512), but the size of the concession is small at 14ha.

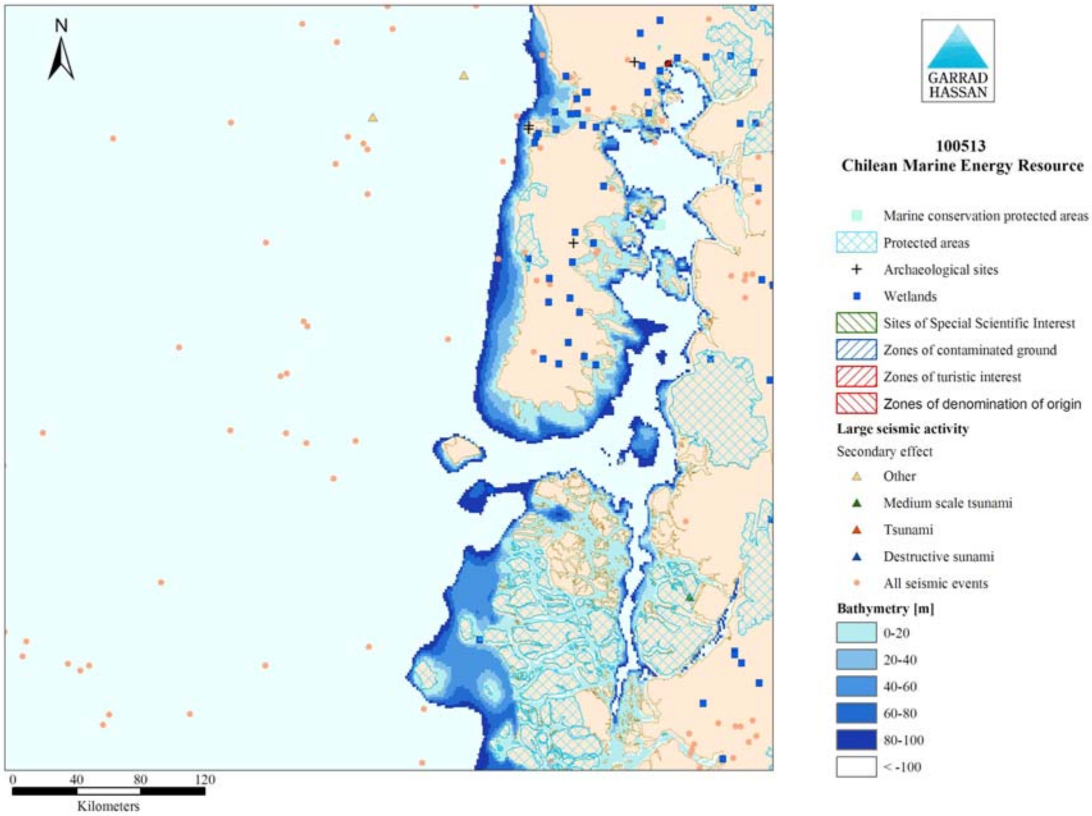

Figure 3-13 Environmental issues in and around the Chilean Inland Sea

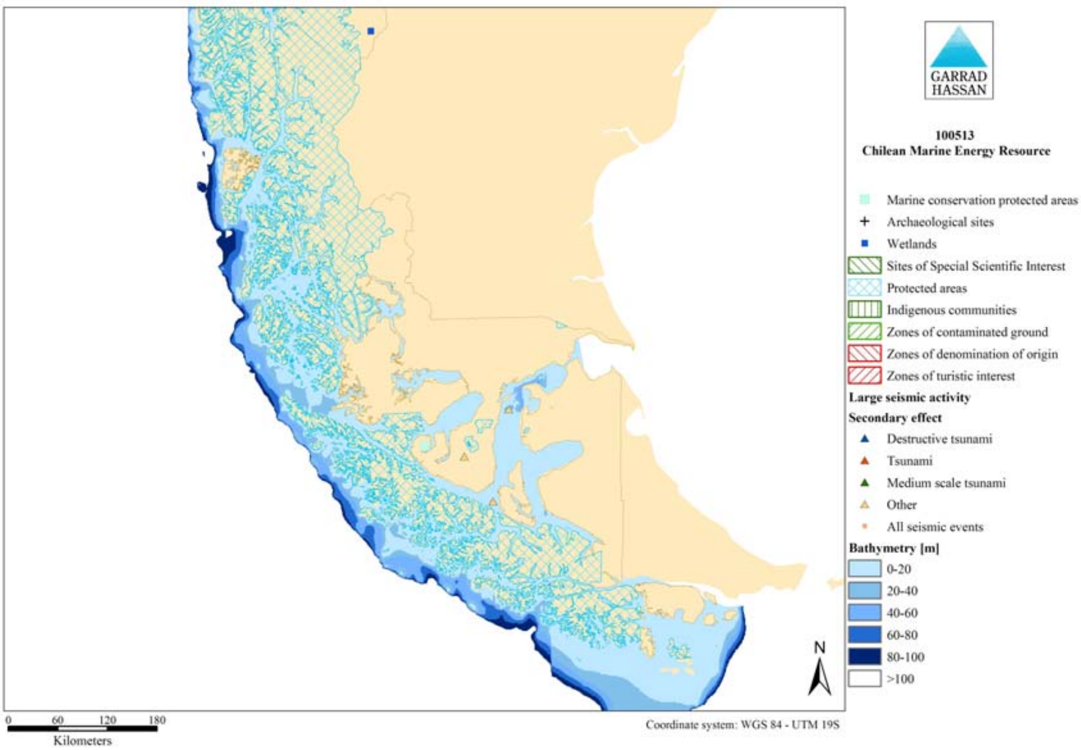

Figure 3-14 Environmental issues in Region XII

Table 3-7 Ecological issues near or at the identified areas

Zone	In/Close to protected area
Chacao channel	No
Apaio channel	No
Corcovado Gulf	No
Gusto mouth Chiloe SE pinnacle	No
Darwin channel	Yes
Angostura Inglesa	Yes
Gabriel channel	Yes
Primera Angostura (Straits of Magallanes)	No

There is a proposed AMCP area for a 1000km of coastline along the Gulf of Corcovado (42.403 S 73.091W). This may affect both the Apaio channel and Corcovado Gulf zones, but until approved, the impact is not considered in this study.

3.3.3 Identification of the three most promising areas for tidal stream project developments

The selection process to evaluate suitable zones for tidal stream energy projects is reliant on good tidal resource information. In this study the resource data has originated from a variety of limited sources and as a result, much of the underpinning analysis to characterise the resource could be subject to improvements if and when site data were to become available. The individual assessment of attributes is combined and scored in the table below:

Table 3-8 Location Typical depths at the identified areas

Zone					Conflicts		
	Resource	Depth	Grid connection	Dist to port	Fishing	Navigation	Environment
Weighting	35%	10%	20%	20%	5%	5%	5%
Chacao channel	3	1	1.5	3	0	0	1
Apaio channel	1	0	1	1	1	0	1
Corcovado Gulf	2	1	1	0	1	1	1
Gusto mouth Chiloe SE pinnacle	1	1	0.5	0	1	1	1
Darwin channel	2	0	0	0	1	1	0
Angostura Inglesa	1	0	0	2.5	1	1	0
Gabriel channel	2	0	0	1	1	1	0
Primera Angostura (Straits of Magallanes)	3	1	0	0	1	0	1

Incorporating the specific weighting the areas are ranked against each other as follows:

Table 3-9 Result of zone ranking

Zone	Score (0-10)
Chacao channel	9.0
Corcovado Gulf	5.7
Primera Angostura (Straits of Magallanes)	5.5
Gusto mouth Chiloe SE pinnacle	4.3
Apaio channel	4.2
Gabriel channel	4.0
Angostura Inglesa	3.8
Darwin channel	3.3

The scoring assessment shows that the Chacao channel offers the most promising area for the development of a potential test site/commercial project development. The Chacao channel scores highly in the top weighted attributes (i.e. resource, grid and distance to port). The depth at the narrowest part of the channel are beyond present technical capabilities, however, there are other areas both east and west which could offer depths that are more suitable to a demonstration site (i.e. ~40-50m). The areas south of Chacao and parallel to the island of Chiloe also show promise, but it is critical to get further details of the resource and depths at these areas. The proposed AMCP area along the Corcovado Gulf coast line could increase the difficulties of grid connection and hence reduce the attractiveness of this site. A preliminary energy yield assessment has been conducted for the Corcovado Gulf and this is reported below. Interesting the Primera Angostura channel in the Straits of Magallanes scores highly despite the lack of grid, ports and possible navigation conflict, this result reflects the weighting associated with the resource.

The table below presents the results of the resource assessment for the top three zones. The assumptions from which values are derived are contained within Appendix B.

The local flux at the Corocovado Gulf location is deemed insufficient for a commercially economic site. This is due to the lower flow conditions (i.e. Vmsp < 2.5m/s). In contrast the energy estimate at Chacao and Magallanes are very good given the flow speed. These estimates are based on crude assumptions regarding the sizing of the devices, and with proper design these values could be improved. The resulting capacity factors are very good because the ratio of mean to max flow is high. The potential for energy extraction is significant and estimated based on analysis of measured data and cross-sectional area of the channel, suggest that between 100 -500MW annual mean power could be extracted[22]. Subsequent to the initial analysis, additional information regarding the flows through the Chacao channel enabled a more detailed analysis (see Appendix B&D). The raw energy estimate is found to be between 600 and 800MW, although the technically extractable resource will be a function of the spatial variation of the flow, the bathymetry, and navigation requirements and is likely to be 20-60% of the raw power. However, further site specific studies/analysis would be required to evaluate the technically extractable resource.

[22] These numbers are based on a Vrms of 2.46 m/s, a cross-sectional area of $0.1km^2$ and a significant impact factor of between 10% and 60%.

Table 3-10 Energy estimate for the three top zones

Zone	Water depth [m]	O&M base	Average distance to nearest substation - cable routing [km]	Closest Electrical Grid (SIC)	Local Tidal Resource[23] [kW/m^2]	Estimate of the energy yield for a 30 MW tidal farm [GWh/annum]
Chacao	30-100	Cabo Froward or Puerto Montt	0-10 ~60	110kV 220kV	3.8 - 5.2	101-152
Corcovado Gulf	20-100	Cabo Froward or Puerto Montt	~30 ~95	66kV 110kV	0.72	19
Straits of Magallanes (Primera Angostura)	50 -70	Austral	none		3.6	99-126

The flow data used to evaluate the local tidal resource at the Chacao channel comes from site data collected as part of a bridge engineering feasibility study [3.20], which collected several months of ADCP bottom mounted data, as well as some transect data. The Corcovado Gulf flow distribution was evaluated by scaling the measured distribution at the mouth of the Chacao channel [3.12] to numerical model results [3.19]. A flow distribution for the Straits of Magallanes was constructed using the SHOA tide table data. Spring and Neap values where used to construct a harmonic model, yield a flow distribution. Further detailed are found in Appendix B.

Some further information about Chacao channel is included here:

As previously discussed the Chacao channel connects the Pacific Ocean and the Chilean Inland Sea, as shown in Figures 3.14 to 3.17 below. The channel is approximately 40 km long with an average width of 4 km and exhibits tidal currents of 3 to 4.5 m/s and tidal ranges of 5.5 to 6.0 m [3.14]. There are some significant issues that are associated with installing tidal stream technology within Chacao Channel, these include: Very short slack water periods ~ <15 min, variable bathymetry and possible high levels of turbulence generated from features such as Romolinos Rocks (see Figures 3.18 & 3.19).

[23] This is the depth averaged kinetic energy flux using a 1/7th power law.

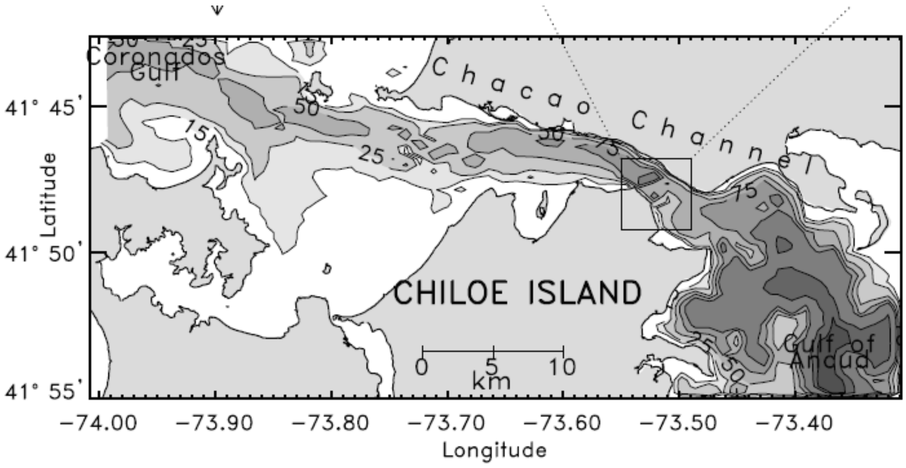

Figure 3-15 Map of the Chacao channel, source [3.11]

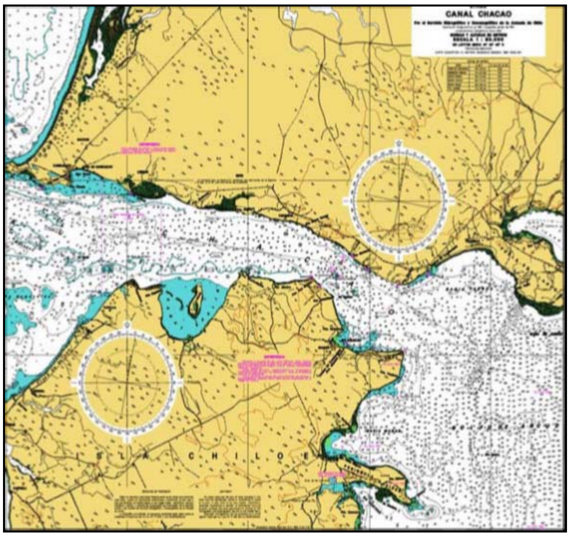

Figure 3-16 SHOA chart of the Chacao channel, source [3.12]

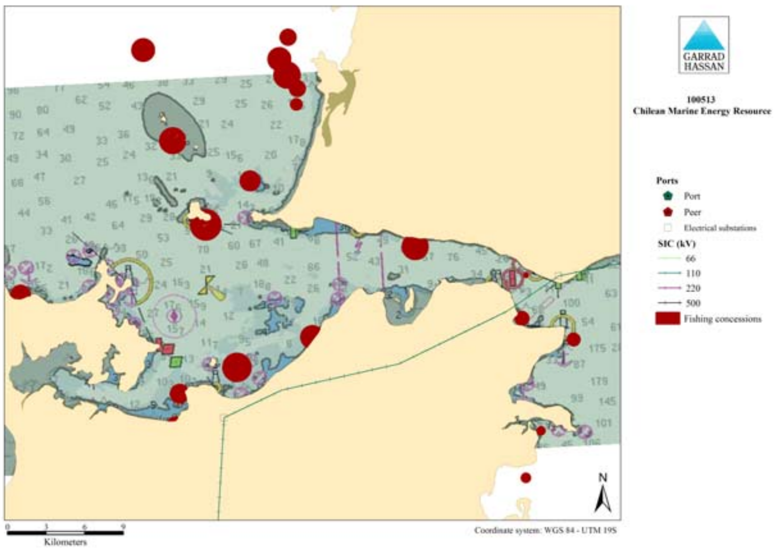

Figure 3-17 SHOA web chart of the Chacao channel source [3.5] including GIS database of Grid, ports and fishing concessions

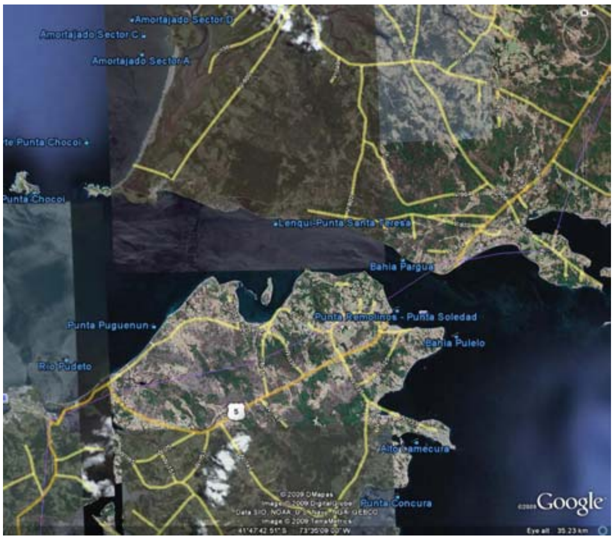

Figure 3-18 Google earth image of the Chacao channel

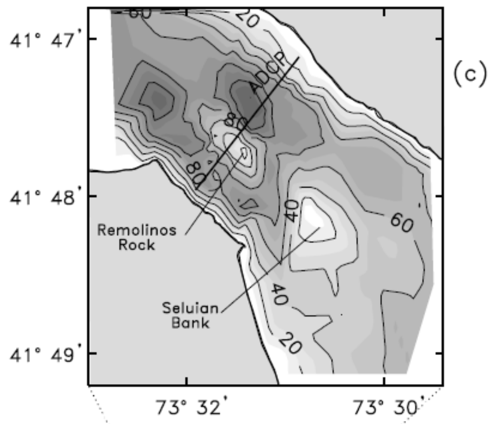

Figure 3-19 Narrowest section in the Chacao channel, source [3.11]

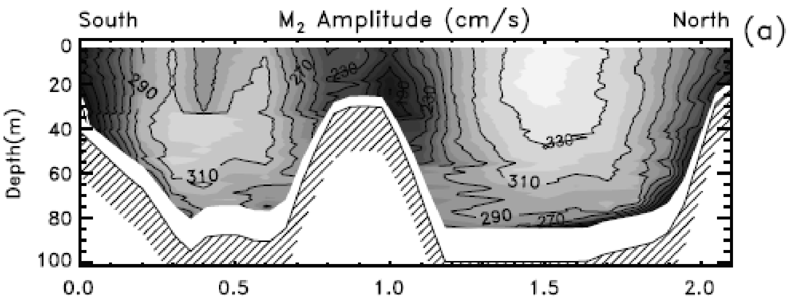

Figure 3-20 ADCP transect results of M2 constituent at the narrowest section in the Chacao channel, source [3.11]

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APPENDIX A WAVE

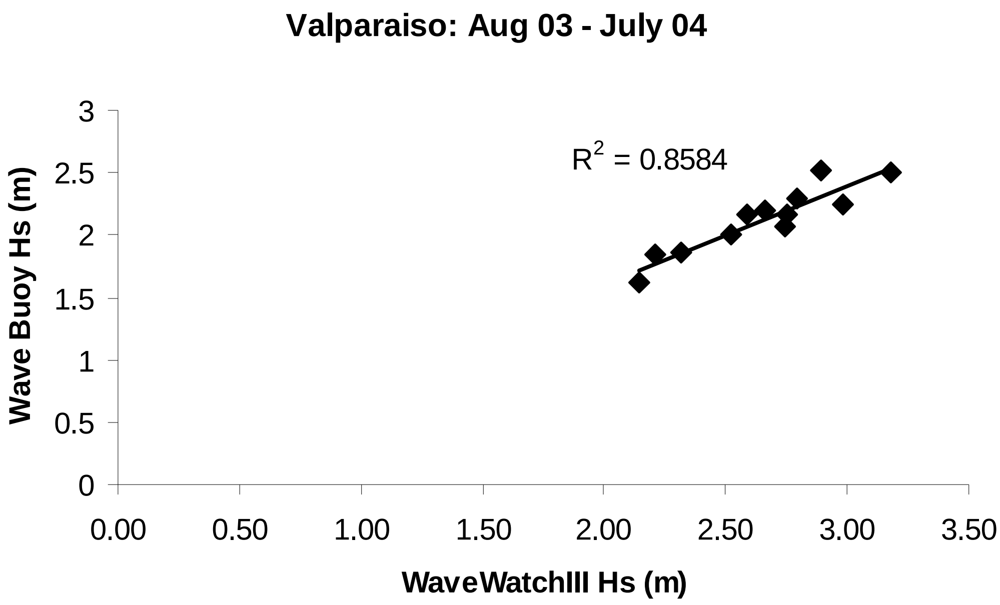
The long-term reference wave data used in this study (see Section 2.2) was extracted from the NOAA website (ftp://polar.ncep.noaa.gov/pub/history/waves) and uses the WaveWatchIII model. In summary, WaveWatchIII is a third generation spectral wave model which solves the energy balance equation outside the surf zone (offshore wave climate). The post-processing methodology applied in GH Waves allows the extrapolation of SHOA's measured wave data, although this is limited due the absence of comparable recoding periods in some buoy locations. Where possible (Valparaíso) a correlation between long-term reference (WaveWatchIII) and local measured short-term data (SHOA) was derived, and the numerical model updated to derive long-term estimates. This methodology is described in detail in [3.6]. A site specific exercise would follow a similar approach, yet it would use local wave data (short-term) from the desired locations, thus the need to conduct short-term site specific measurement campaigns in the priority areas when planning a Chilean Marine Energy Test Centre.

The tables below specify the sources of data used. The average distance between the nearest WaveWatchIII data point and the SHOA wave buoy locations is 44.66km, which prompts the need to derive a correlation between the long-term estimates (WaveWatchIII) and the measured wave buoy data (short-term). This was derived for case 7 - Valparaiso (the figure in the following page illustrates the comparisons and the correlation coefficient associated with the significant wave height, Hs). Similar comparisons were made for the peak period, Tp.

		SHOA Wave Buoy Location			Nearest WaveWatchIII point		
No.	Location	Latitude	Longitude (W)	Longitude (E)	Latitude	Longitude (W)	Longitude (E)
1	Arica	-18.45	70.37	289.63	-18.00	71.25	288.75
2	Iquique	-20.17	70.02	289.98	-20.00	70.00	290.00
3	Antofagasta	-23.63	70.42	289.58	-24.00	70.00	290.00
4	Caldera	-27.05	70.87	289.13	-27.00	71.25	288.75
5	Isla de Pascua	-27.15	109.45	250.55	-27.00	110.00	250.00
6	Coquimbo	-29.92	71.37	288.63	-30.00	71.25	288.75
7	Valparaíso	-32.98	71.62	288.38	-33.00	71.25	288.75
8	Constitucion	-35.28	72.52	287.48	-35.00	72.50	287.5
9	San Vicente	-36.72	73.15	286.85	-37.00	73.75	286.25
10	Golfo Coronados	-41.67	73.93	286.07	-42.00	73.75	286.25
11	Faro Félix	-52.96	74.07	285.93	-53.00	73.75	286.25
12	Diego Ramirez	-56.53	68.63	291.37	-57.00	68.75	291.25

No.	Location	Distance between (km)
1	Arica	105.67
2	Iquique	19.04
3	Antofagasta	59.38
4	Caldera	38.09
5	Isla de Pascua	57.01
6	Coquimbo	14.60
7	Valparaíso	34.62
8	Constitucion	31.22
9	San Vicente	61.86
10	Golfo Coronados	39.65
11	Faro Félix	21.90

12	Diego Ramirez	52.83
	Average Distance (km)	44.66



With the relationship between the two data sets defined, long-term estimates for the 12 locations were derived. Due to the lack of comparable measurements periods for the other locations, the Valparaíso correlation (i.e. the update to the numerical model weights) was used, although ideally the above described procedure would be repeated for each location. Nevertheless SHOA's data (12 monthly averages per location) are still useful to assess annual variability. The final annual and monthly breakdown used in this study is listed in the tables below. Note that Hs is the significant wave height and Tp the peak period.

	Mean Hs (m) - Monthly											
No.	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	1.59	1.58	1.81	1.99	2.04	2.25	2.13	2.18	2.14	2.07	1.82	1.62
2	1.74	1.73	1.95	2.13	2.18	2.39	2.29	2.35	2.32	2.25	1.98	1.78
3	1.98	1.94	2.15	2.26	2.27	2.52	2.43	2.49	2.49	2.45	2.19	2.02
4	2.29	2.19	2.46	2.58	2.54	2.82	2.76	2.80	2.80	2.81	2.56	2.36
5	2.16	2.26	2.50	2.71	3.03	2.99	3.01	2.98	2.86	2.66	2.32	2.15
6	2.55	2.39	2.64	2.69	2.60	2.87	2.80	2.83	2.84	2.93	2.75	2.61
7	2.48	2.33	2.50	2.53	2.50	2.78	2.64	2.65	2.60	2.70	2.52	2.48
8	2.71	2.59	2.73	2.80	2.81	3.10	2.93	2.95	2.83	2.89	2.69	2.67
9	2.74	2.72	2.83	2.97	3.04	3.36	3.17	3.18	2.99	3.01	2.75	2.69
10	2.81	2.76	3.00	3.26	3.27	3.69	3.55	3.55	3.17	3.27	2.93	2.84
11	3.60	3.51	3.63	3.97	3.51	3.49	3.81	3.98	3.62	4.03	3.68	3.59
12	3.59	3.68	3.74	4.10	3.65	3.47	4.02	4.31	3.88	4.20	3.72	3.57

Mean Hs (m) - Yearly

No.	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
1	1.82	2.01	2.01	1.87	1.99	1.87	2.00	1.93	1.84	1.96	1.99	1.99
2	1.91	2.15	2.11	1.99	2.10	2.01	2.13	2.11	2.06	2.17	2.22	2.20
3	2.08	2.34	2.31	2.10	2.19	2.11	2.26	2.25	2.28	2.41	2.49	2.45
4	2.45	2.67	2.70	2.46	2.57	2.47	2.57	2.56	2.51	2.68	2.72	2.67
5	2.63	2.71	2.66	2.44	2.51	2.44	2.70	2.63	2.65	2.77	2.72	2.88
6	2.38	2.71	2.63	2.55	2.65	2.58	2.80	2.74	2.72	2.93	2.96	2.90
7	2.35	2.63	2.57	2.42	2.55	2.48	2.66	2.55	2.50	2.69	2.65	2.68
8	2.67	2.90	2.88	2.64	2.81	2.69	2.84	2.77	2.76	2.92	2.90	2.96
9	2.82	3.01	3.02	2.74	2.93	2.80	2.92	2.89	2.96	3.14	3.10	3.21
10	3.07	3.23	3.21	2.96	3.10	3.02	3.19	3.10	3.18	3.43	3.29	3.41
11	3.40	3.96	3.88	3.38	3.83	3.21	3.74	3.61	3.49	3.81	4.06	4.09
12	3.46	4.08	4.15	3.46	4.05	3.37	3.81	3.73	3.54	3.84	4.22	4.28

	Mean Tp (s) - Monthly											
No.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	11.43	11.87	12.35	12.75	12.96	12.90	12.35	12.68	12.70	12.66	11.92	11.48
2	11.69	12.03	12.36	12.59	12.81	12.76	12.25	12.53	12.41	12.48	11.78	11.43
3	11.89	12.15	12.38	12.38	12.63	12.60	12.01	12.22	11.99	12.16	11.54	11.45
4	11.43	11.86	11.98	12.05	12.36	12.35	11.52	11.82	11.67	11.62	10.90	10.86
5	12.27	12.31	12.25	12.12	12.16	12.11	11.70	11.46	11.97	12.00	11.51	12.23
6	10.65	11.31	11.57	11.96	12.24	12.25	11.52	11.82	11.46	11.35	10.46	10.21
7	10.96	11.44	11.95	12.15	12.30	12.20	11.85	11.99	11.93	12.00	10.92	10.51
8	10.73	11.28	11.86	12.10	12.20	12.09	11.76	11.98	11.95	12.04	11.02	10.45
9	10.98	11.13	11.74	12.09	11.97	11.90	11.68	11.90	11.91	12.07	11.19	10.60
10	11.33	11.52	11.70	11.90	11.72	11.42	11.40	11.53	11.64	11.91	11.19	10.92
11	10.23	10.46	10.59	10.99	11.08	10.84	10.99	11.14	11.09	11.13	10.37	10.14
12	10.21	10.35	10.43	10.90	10.94	10.67	10.91	10.96	11.03	11.07	10.39	10.13

	Mean Tp (s) - Yearly											
No.	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
1	12.14	12.64	12.53	11.95	12.23	11.58	12.50	12.31	12.28	12.65	12.59	12.84

2	12.011	12.65	12.41	11.82	12.17	11.52	12.45	12.25	12.13	12.70	12.43	12.76
3	11.824	12.69	12.23	11.73	12.07	11.46	12.30	12.12	12.00	12.51	12.04	12.52
4	11.075	12.25	11.57	11.18	11.51	10.99	11.74	11.63	11.76	12.33	11.94	12.52
5	11.659	12.57	12.29	12.02	11.63	11.89	12.19	11.81	11.95	12.17	11.53	12.32
6	11.519	12.26	11.96	10.90	11.40	10.80	11.23	11.11	11.03	11.61	11.23	11.95
7	11.59	12.31	12.08	11.19	11.64	11.10	11.46	11.51	11.51	12.00	11.73	12.29
8	11.253	12.09	11.80	11.12	11.54	11.07	11.56	11.57	11.58	12.03	11.87	12.17
9	11.143	12.05	11.70	11.19	11.49	10.98	11.69	11.63	11.48	11.96	11.92	12.06
10	10.973	11.96	11.71	11.13	11.52	10.85	11.54	11.63	11.31	11.72	11.93	11.97
11	10.305	11.01	10.84	10.29	10.69	10.24	10.75	10.81	10.67	11.09	11.16	11.28
12	10.219	10.93	10.78	10.23	10.63	10.08	10.62	10.69	10.57	11.00	11.18	11.15

Assuming that Tp and Te (energy period) are related by the constant defined by the Pierson-Moskowitz approximation for fully develop seas (Tp=Te/0.859; see e.g. [3.7]), the long-term offshore wave climate at each buoy location can be estimated (see table below). Some key statistics can be derived (including annual energy yeld, assuming a fixed capacity factor). The raw offshore wave resource is therefore estimated at 164.9GW.

No.	Location	Hs (m)	Te (s)	P (kW/m)
1	Arica	1.94	10.61	19.57
2	Iquique	2.10	10.54	22.72
3	Antofagasta	2.27	10.41	26.33
4	Caldera	2.59	10.06	32.98
5	Isla de Pascua	2.65	10.31	35.38
6	Coquimbo	2.71	9.81	35.32
7	Valparaíso	2.56	10.05	32.30
8	Constitucion	2.81	10.00	38.74
9	San Vicente	2.96	9.97	42.83
10	Golfo Coronados	3.18	9.90	49.08
11	Faro Félix	3.71	9.25	62.21
12	Diego Ramirez	3.83	9.17	66.00

Average Chilean Coastline	**38.62kW/m**
Length (North to South)	4270km
Offshore Wave Powe (Raw Potential)	**164.91GW**
Energy yield (CF 30%)	433.38TWh/y

APPENDIX B TIDAL

SCORING KEY

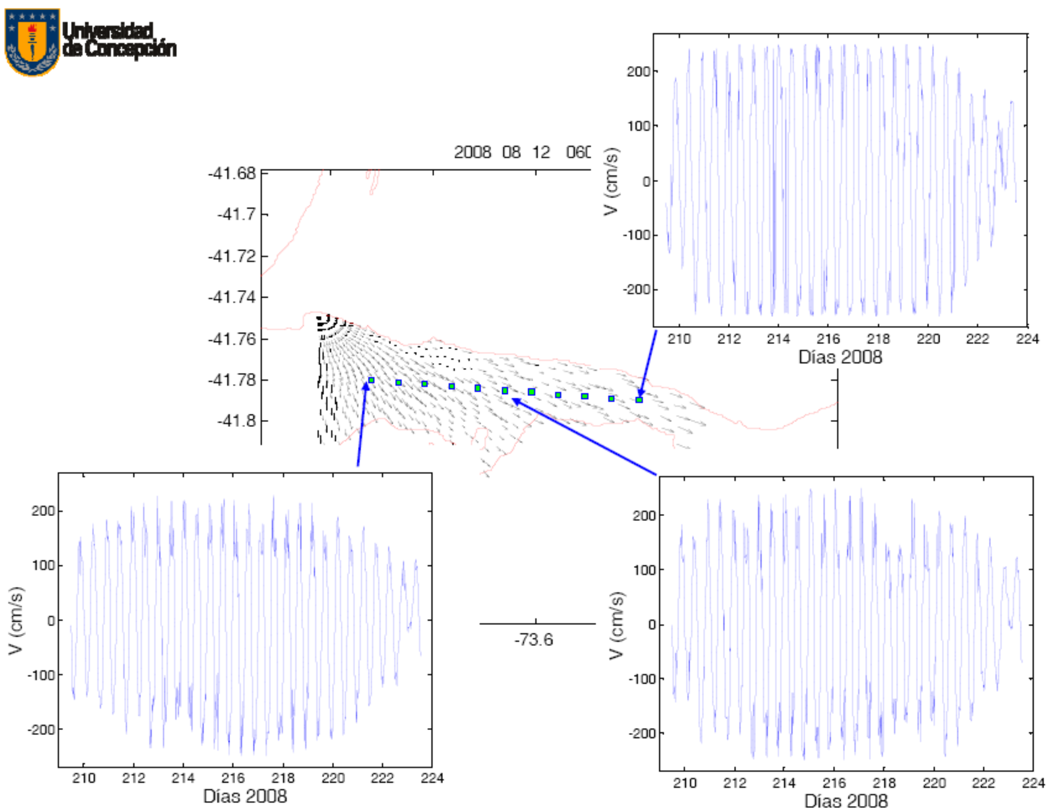
ATTRIBUTE	RANGE/VALUE	SCORE			Comment
Mean spring peak (m/s)	2.7+	3			Target resource for a commercial site
	2-2.7	2			Good resource Target resource for a commercial site
	1.5 - 1.9	1			Low energy site: situated to either a test centre or a site with very good grid connection (hence reducing significantly reducing capex)
Depth range (m)	<100	1			At present no tidal stream technology device developers are investigating operating in depths beyond 100m (there are some researchers in the US developing deep water concepts to tap into the Gulf stream) and there preference is for depths of between 30 – 80 m. However due to the limited resolution of the depth data assessment scoring is based on the weather the majority of the site has a depth greater or less than 100m.
	100+	0			
GRID		220kV	110kV	66kV	The larger the project size the greater the grid capacity requirement and thus the requirement for a test centre are much reduce compared to a commercial project (e.g. the EMEC test centre has five 11kV cables connected to a onshore 11kV substation). As the premise of this site selection study is to incorporate the potential for development into a commercial scale site the matrix of scores reflects the two key attributes of system capacity (kV) and proximity to grid. The two bands of distance are based on a review of the grid system. To maintain a constant infrastructure cost per device, project sizes have to be increased as the distance from the grid increases.
	<140km	1.0	0.5	0.3	
	<70km	1.5	1.0	0.5	
Distance from port	0-25	3			Distance to the nearest port is a critical cost driver for installation as well as O&M. Installation and O&M strategies vary between technology developers, but in all cases costs are reduced significantly with distance. The non-linear scoring aims to represent the step changes in cost with vessel size (larger vessels are required for longer trips).
	25-50	2.5			
	50-75	2			
	75-100	1			
	100+	0			
Fishing concessions	None	1			The scoring reflects the added advantage of few or none fishing concessions. The greater the number the lower the scoring.
	<2	0.5			
	3+	0			
Navigation issues	0	1			The scoring reflects the added advantage of no identified navigation conflicts.
	Possibility of conflict	0			
Environmental issues	In/close to AMCP	1			The scoring reflects the added advantage of not being close or in a designated AMCP
	None	0			

SCORING ASSESSMENT

List potential sites:	Coordinates	Site size		Mean spring peak		Depth range		GRID		Distance from port		Fishing concessions		Naviagtion issues		Environmental issues	
		Width	Len gth														
		km	km	m/s	Score	m	Score		Score	km	Score		Score		Score	In/close to protected areas	Score
Chacao channel	41 45.5S 73 60.5W	2 - 5	10	3.5 - 4	3	31-100	1	0-10km to 110kV ~ 60km to 220kV	1. 5	0-25	3	3 in location area	0	Chacao ferry crossing, fishing vessels	0	No	1
Apaio channel	42 40S 73 08.2W	2	2	~1.8	1	100	0	~60 to 110kV	1	75-100	1	None	1	Possible shipping conflict	0	No	1
Corcovado Gulf	43 00S 73 17.04W	4	10	~2	2	20-100	1	~30km to 66 kV ~65km to 110kV	1	100+	0	None	1		1	No	1
Gusto mouth Chiloe SE pinnacle	43 23S 73 36W	5	25	~1.8	1	20-100	1	~35km to 66 kV ~130km to 110kV	0. 5	100+	0	None	1		1	No	1
Darwin channel	45 24S 74 17W	~0.5	~2	2	2	100	0	na	0	100+	0	None	1		1	Yes	0
Angostura Inglesa	48 57.8S 74 25.5W	<1	1-2	1.9	1		0	na	0	25-50	2. 5	None	1		1	Yes	0
Gabriel channel	54 07S 70 55W	0.5-1.5	25	2.1	2	100+	0	na	0	75-100	1	None	1		1	Yes	0
Primera Angostura (Straits of Magallanes)	52 34S 69 40W	3	14	2.75	3	50 -70	1	na	0	100+	0	None	1	Significant shipping route	0	No	1

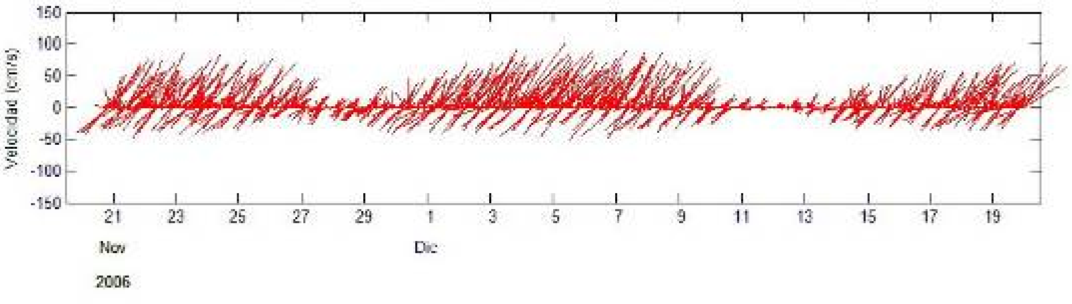
Information and flow analysis at Chacao

Some radar measurements have been made at the Chacao channel and are presented by Dante Figeroa (source [3.13])



The method is needs further validation in tidal races areas, due to the unsteady wave current interaction, and deep water dispersion relationship assumption. Also the supplied magnitude is the speed travelling away from the radar location and thus no always the dominate flow direction. The wind effect is also another factor.

The fact that the measurements were taken during a spring cycle [3.18] and that the did not exhibit a typical sinusoidal spring peak (as compare to the measurements in the figure below



They also don't correlate well with side scan ADCP data.

A probability distribution for the Chacao channel (source [3.12]). The distribution was scaled to yield a Vrmc value for the Corcovado Gulf

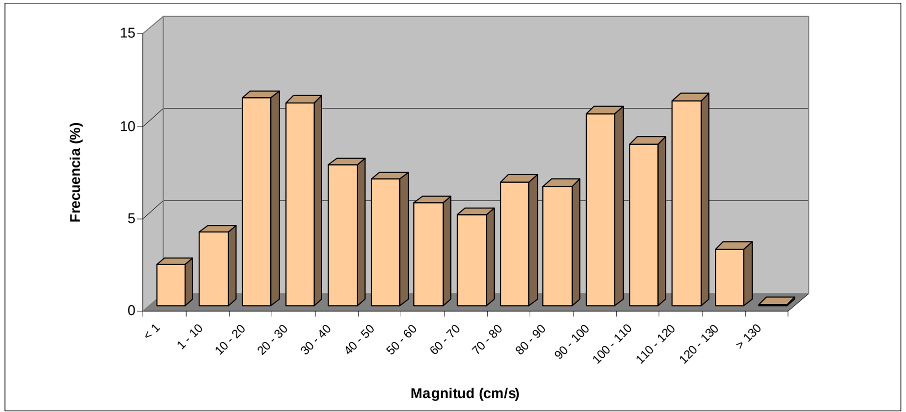
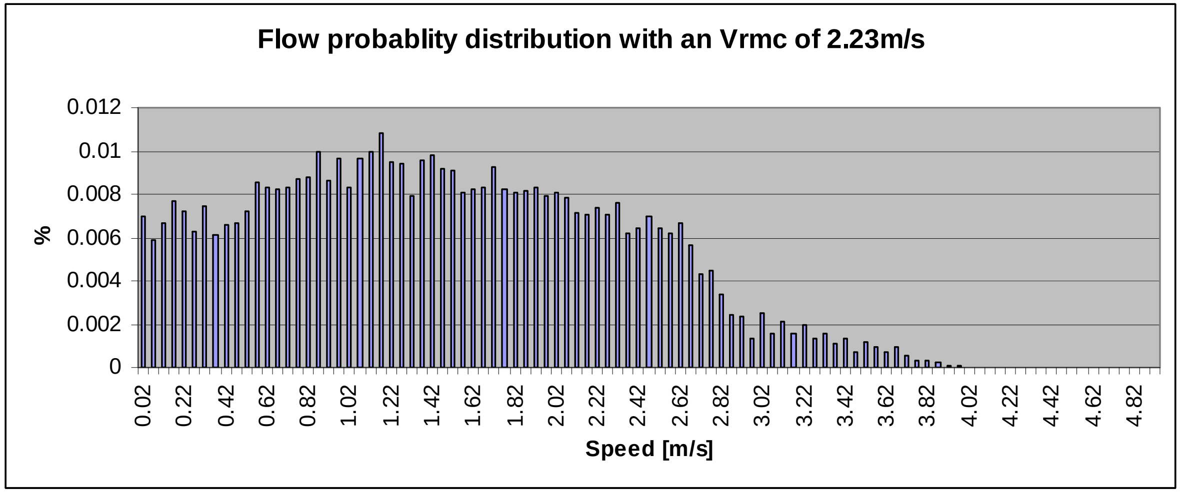


Figura 1: Distribución porcentual de intensidad de corrientes registradas **en Punta Coronel**. Noviembre-diciembre del 2006.

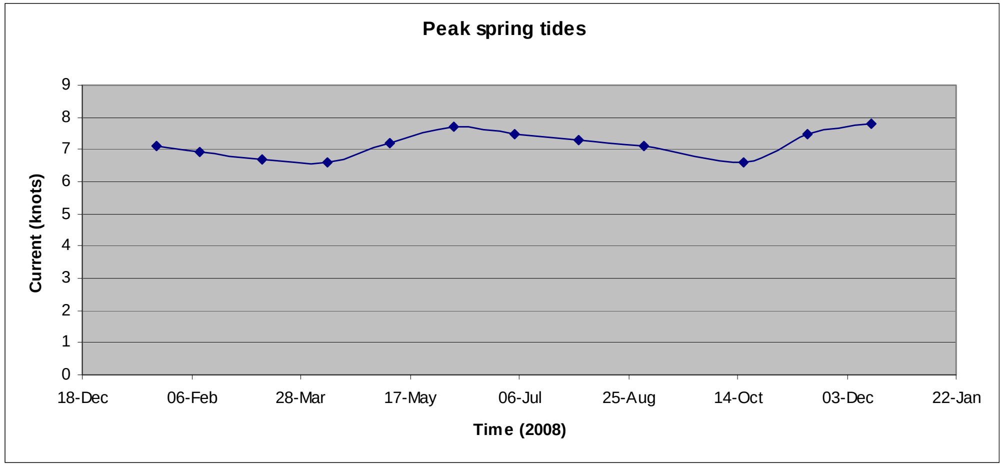
Additional data regarding the Chacao channel (source [3.20]) was used to find the harmonic constituents for the Chacao channel. Difference spatial assumptions were then applied to yield varying flow probability distributions. An example flow probability distribution is given below:



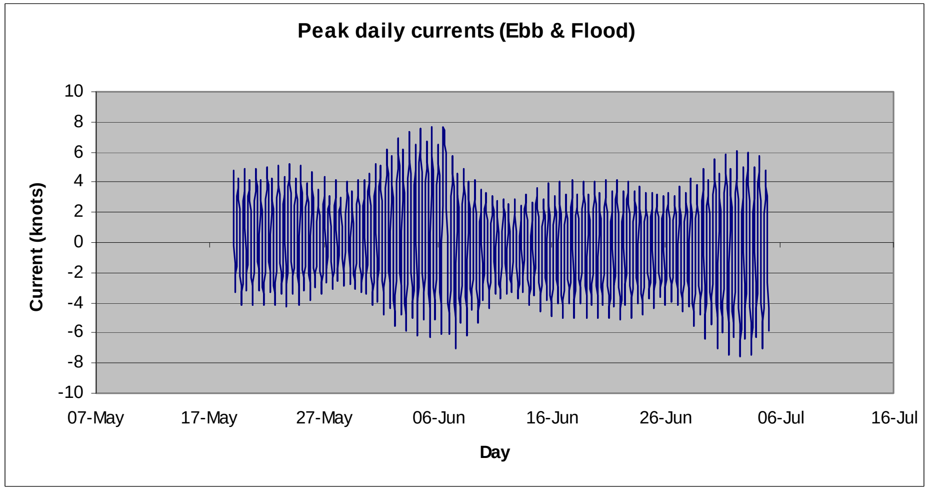
Also from which the varying estimates of the total raw kinetic energy are calculated:

Site Name	Grid ref.	Surface Area of Site(km²)	Estimated effective channel width(m)	Estimated effective channel depth(m)	Vmsp(m/s) (estimate)	Vpeak m/s)	Vpeak/Vmsp		Cub.Root of mean Cubed Velocities Vrmc (m/s)	Ratio mean to peak	Mean Annualised Power Flux (kW/m2)	Total Mean Annualised Power (MW)
Chacao channel (long term)		1.372	1290	80	3.50	5.00	1.43	0.45	2.23	0.45	5.66	584
Chacao channel (spatial correction, flood only)		1.372	1290	80	3.50	5.00	1.43	0.49	2.47	0.49	7.69	793
Chacao channel (spatial correction, flood & ebb)		1.372	1290	80	3.50	5.00	1.43	0.47	2.34	0.47	6.53	674

The two figures below use SHOA tide time information to construct a flow probability distribution at the Straits of Magallenes.



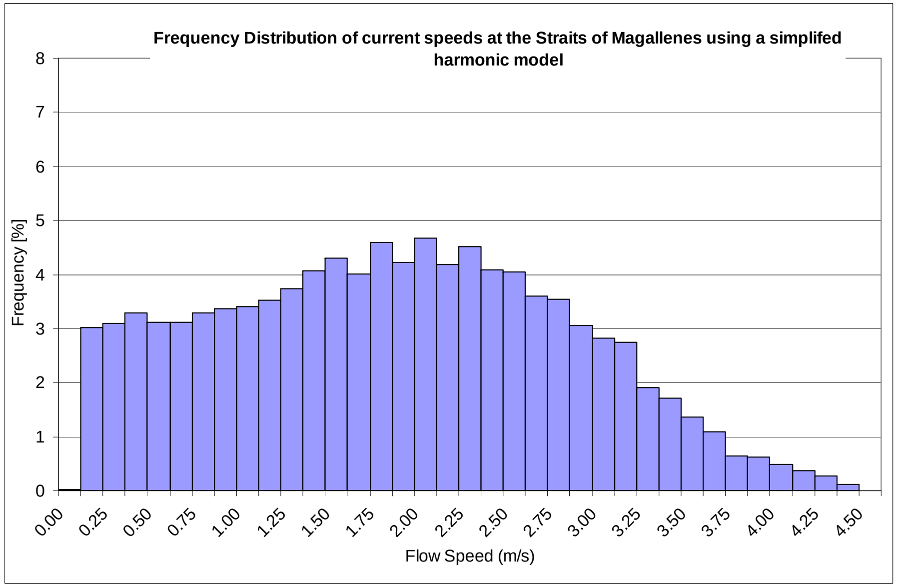
Flow spring peaks at the Straits of Magallenes, allowing a mean spring peak current of 7.2 knots (3.69m/s) to be evaluated.



The daily variation over two spring neap variations to allow a spring/neap and an average ebb and flood ratio to be evaluated.

Constructed probability distribution of the flow at Magallenes using the following input data and a simplified harmonic model

Variable	Symbol	Value	Unit
Site Characteristics			
Site		Estrecho de Magallanes	
Mean spring peak velocity	Vmsp	3.69	m/s
Mean neap peak velocity	Vmnp	2.39	m/s
Estimated max peak velocity	V peak	4.34	m/s
Mean peak velocity	V mp	3.04	m/s
Spring Ebb/flood ratio		0.81	
Neap Ebb/flood ratio		0.81	
Boundary layer profile (power law)		1 1/7	
Depth LAT	D	70.00	m



The table below shows the 30MW farm analysis for the three top sites:

	length [km]	width [m]	Surface area [km^2]	depth [m]	Vrms - surface [m/s]	Vpeak [m/s]	Vmsp [m/s]	hub height (hh) [m]	Vmsp hh [m/s]	Vrms - hh [m/s]	Depth average (1/7th power law) Vrms [m/s]	rms power flux [kW/m^2]	Vrated factor	efficiency at Vrated	gearbox efficiency	generator efficiency	total machine efficiency	Vrated [m/s]	Rated electrical power [MW]	rotor diameter [m]	mean efficiency	Grid efficiency	Farm Availablity	total efficiency	mean power to grid [MW]	No of device in farm	GWh/yr
Chacao lower estimate (set rating)	10	1290	12.9	80	2.23	4.5	3.96	40	3.59	2.02	1.95	3.79	71.0	45	95	95	40.6	2.55	1	19.30	35	95	94	31.3	0.38	30	101
Chacao mid estimate (set rating)	10	1290	12.9	80	2.34	4.7	4.16	40	3.76	2.12	2.05	4.38	71.0	45	95	95	40.6	2.67	1	17.95	35	95	94	31.3	0.38	30	101
Chacao upper estimate (set rating)	10	1290	12.9	80	2.47	5.0	4.39	40	3.97	2.24	2.16	5.15	71.0	45	95	95	40.6	2.82	1	16.55	35	95	94	31.3	0.38	30	101
Chacao lower estimate (set dia)	10	1290	12.9	80	2.23	4.5	3.96	40	3.59	2.02	1.95	3.79	70.5	45	95	95	40.6	2.53	1	19.50	35	95	94	31.3	0.39	30	103
Chacao mid estimate (set dia)	10	1290	12.9	80	2.34	4.7	4.16	40	3.76	2.12	2.05	4.38	67.2	45	95	95	40.6	2.53	1	19.50	35	95	94	31.3	0.45	30	119
Chacao upper estimate (set dia)	10	1290	12.9	80	2.47	5.0	4.39	40	3.97	2.24	2.16	5.15	63.7	45	95	95	40.6	2.53	1	19.50	35	95	94	31.3	0.53	30	140
Chacao mid estimate (large dia)	10	1290	12.9	80	2.34	4.7	4.16	40	3.76	2.12	2.05	4.38	62.0	45	95	95	40.6	2.33	1	22.00	35	95	94	31.3	0.58	30	152
Corcovado Gulf (set dia)	10	4000	40	60	1.28	2.0	1.75	30	1.59	1.16	1.12	0.72	159.1	45	95	95	40.6	2.53	1	19.50	35	95	94	31.3	0.07	30	19
Estrecho de Magallenes (set rating)	14	3000	42	70	2.20	4.3	3.81	35	3.45	1.99	1.93	3.64	71.0	45	95	95	40.6	2.45	1	20.47	35	95	94	31.3	0.41	30	109
Estrecho de Magallenes (set dia)	14	3000	42	70	2.20	4.3	3.81	35	3.45	1.99	1.93	3.64	73.3	45	95	95	40.6	2.53	1	19.50	35	95	94	31.3	0.38	30	99
Estrecho de Magallenes (large dia)	14	3000	42	70	2.20	4.3	3.81	35	3.45	1.99	1.93	3.64	67.7	45	95	95	40.6	2.33	1	22.00	35	95	94	31.3	0.48	30	126

Highlights input value
Highlights calculation