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**Ocean Wave Energy Resource Assessment-  
hotspots, exceedance-persistence, and predictability**

**A thesis presented in partial fulfilment of the  
requirements for the degree of**

**Master of Applied Science**

**in**

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**at Centre for Energy Research,**

**Massey University, Palmerston North,  
New Zealand.**

**James Edward Frazerhurst**

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# Ocean Wave Energy Resource Assessment- hotspots, exceedance-persistence, and predictability



Figure A. (Title page). A breaking wave from the perspective of a surfer travelling inside (source: [www.surfermag.com](http://www.surfermag.com)).

## **Abstract**

Ocean wave energy conversion is evolving towards commercial viability. Succinct resource assessment is essential to the conversion of wave energy for grid supply electrical generation. The ability to differentiate potential wave energy locations by means of comprehensible evaluations is particularly useful to the commercial developers of wave energy power plants.

This report establishes an assessment of wave energy that provides an understanding of the resource in both spatial and temporal resolution. Three aspects of the wave resource are established; mapping of wave energy **hotspots** due to wave focusing, visualisation of the probability of wave energy **exceedance** and **persistence**, and calculation of the **predictability** of wave energy for a particular aspect of coast. These three assessments are explained with a review of the science surrounding the phenomena of wave creation and propagation, the development of wave energy converter devices, as well as visualisation and manipulation of wave resource assessments. The outputs of these assessment methodologies are comparable, uncomplicated, graphic representations of the resource.

Case studies for seven locations encircling New Zealand were investigated, in order to demonstrate the practicalities of the wave energy resource assessment methodology developed by this project.

This study modelled the transformation of several hundred combinations of wave height, period and direction from deep-water to shore. The different conditions were ranked in terms of probability of occurrence. Recombination of these iterations created hotspot maps. The locations examined in this study were then compared to other infrastructure for wave energy utilisation.

Historical wave data was processed to establish the probability of levels of wave energy being exceeded and persisting. This information establishes how often a potential wave energy plant might provide significant output and for how long this output might persist.

Collection of wave prediction data for aspects of New Zealand allowed the comparison of up to seven day forecasts with a “now forecast”. Assessment was then

made of the predictability of the climatic conditions creating waves for a location. The ability to be able to provide accurate forecasts of potential wave energy plants is of significant interest to generation companies in New Zealand in order to manage a diverse generation portfolio.

Key finding of this investigation:

- Waves and wave energy have significant variation of spatial, and temporal scales.
- Waves can be predicted for an aspect of coastline dependant upon the predictability of the climatic conditions of the wave generation location.
- Wave energy resource assessment is often presented as a single figure of averaged kilowatts per meter wave front that fails to adequately incorporate the temporal, spatial, and predictive aspects of the resource.
- A methodology was compiled to create “hotspot” (areas of intensified wave energy) mapping of a location utilising a wave transformation model. These maps can then be used to access spatial relationships to other digital information (electricity grid nodal locations, marine protected areas, navigation requirements, etc).
- Processing of wave climate data utilising Matlab© script developed by ASR Ltd identified the probability of wave energy being exceeded and persisting for a given location.
- Forecasts of wave characteristics are published on the Internet. Calculation of error between a “now forecast” and the previous day’s forecast for today (up to six days out), can give an assessment of the predictability of an aspect of a location provided the wave forecast model utilises significant climatic variables.
- Case studies of wave energy resource assessment (using the developed hotspot, exceedance persistence, and predictability methods) for seven locations encircling New Zealand, identified three classes of wave resource; exceptional (Southland), good (Otago, Taranaki, Auckland, Hokianga), and poor (Canterbury, Wellington).

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## **Table of contents**

<b>ABSTRACT .....</b>	<b>- 3 -</b>
<b>ACKNOWLEDGEMENTS .....</b>	<b>- 5 -</b>
<b>TABLE OF CONTENTS .....</b>	<b>- 6 -</b>
<b>TABLE OF FIGURES .....</b>	<b>- 10 -</b>
<b>TABLE OF TABLES .....</b>	<b>- 14 -</b>
<b>1 INTRODUCTION .....</b>	<b>- 15 -</b>
<b>1.1 PROBLEM IDENTIFICATION .....</b>	<b>- 16 -</b>
<b>1.2 RESEARCH AIM .....</b>	<b>- 16 -</b>
<b>1.3 OBJECTIVES .....</b>	<b>- 16 -</b>
<b>2 IDENTIFICATION OF PARAMETERS AND PRINCIPALS .....</b>	<b>- 18 -</b>
<b>2.1 WAVES.....</b>	<b>- 18 -</b>
2.1.1 WAVE CREATION AND DEEP WATER PROPAGATION .....	- 18 -
2.1.1.1 SUMMARY OF WAVE CREATION AND DEEP WATER PROPAGATION .....	- 27 -
2.1.2 WAVE TRANSFORMATION .....	- 28 -
2.1.2.1 SHOALING, REFRACTION AND DIFFRACTION .....	- 28 -
2.1.2.2 DISSIPATION DUE TO FRICTION AND PERCOLATION .....	- 31 -
2.1.2.3 BREAKING .....	- 33 -
2.1.2.4 GROWTH DUE TO THE WIND AND WAVE-WAVE INTERACTIONS.....	- 34 -
2.1.2.5 WAVE-CURRENT INTERACTION.....	- 34 -
2.1.2.6 SUMMARY OF WAVE TRANSFORMATION .....	- 35 -
2.1.3 OBSERVATION AND PREDICTION .....	- 35 -
2.1.3.1 MEASUREMENT.....	- 36 -
2.1.3.2 FIRST AND SECOND GENERATION WAVE PREDICTION MODELS.....	- 38 -
2.1.3.3 THIRD GENERATION WAVE PREDICTION MODELS.....	- 39 -
2.1.3.4 TRANSFORMATION MODELS .....	- 39 -
2.1.3.5 SUMMARY OF OBSERVATION AND PREDICTION.....	- 41 -
<b>2.2 WAVE ENERGY RESOURCE ASSESSMENT METHODOLOGIES .....</b>	<b>- 41 -</b>
2.2.1 TIME-AVERAGE WAVE ENERGY EVALUATION.....	- 42 -
2.2.1.1 SUMMARY OF TIME-AVERAGE WAVE ENERGY EVALUATION. ....	- 44 -
2.2.2 JOINT PROBABILITY TABLES .....	- 44 -
2.2.2.1 SUMMARY OF JOINT PROBABILITY TABLES .....	- 45 -
2.2.3 SPATIAL WAVE EVALUATION .....	- 45 -
	- 6 -

2.2.4	TEMPORAL WAVE EVALUATION .....	- 46 -
2.2.5	WAVE FORECASTING .....	- 48 -
2.2.6	SUMMARY OF SPATIAL, TEMPORAL WAVE EVALUATION AND WAVE FORECASTING.....	- 49 -
2.2.7	GEOGRAPHIC INFORMATION SYSTEMS (GIS).....	- 49 -
2.2.7.1	GIS ARCHITECTURE.....	- 51 -
2.2.7.2	GIS AND WAVE ENERGY ASSESSMENT.....	- 51 -
2.2.7.3	SUMMARY OF GIS.....	- 51 -
<b>2.3</b>	<b>RENEWABLE ENERGY SYSTEMS .....</b>	<b>- 52 -</b>
2.3.1	COMMON BENEFITS.....	- 52 -
2.3.1.1	SUSTAINABLE DEVELOPMENT, SUSTAINABLE ENERGY.....	- 52 -
2.3.1.2	AVOIDING CO <sub>2</sub> EMISSIONS .....	- 54 -
2.3.1.3	DISTRIBUTED GENERATION.....	- 55 -
2.3.1.4	COST EFFECTIVENESS.....	- 55 -
2.3.2	COMMON BARRIERS.....	- 56 -
2.3.2.1	“NOT IN MY BACK YARD” (NIMBYISM).....	- 57 -
2.3.2.2	RESOURCE CONSENT IN NEW ZEALAND .....	- 57 -
2.3.2.3	GOVERNANCE.....	- 58 -
2.3.2.4	ECONOMIC RISK.....	- 58 -
<b>3</b>	<b>WAVE ENERGY CONVERTER DEVICES .....</b>	<b>- 60 -</b>
3.1.1	EXTREME WAVES AND SURVIVABILITY .....	- 61 -
3.1.2	A PLETHORA OF DEVICES .....	- 62 -
3.1.3	DEVICE DEVELOPMENT.....	- 64 -
3.1.4	THE CAPTURE WIDTH RATIO (CWR).....	- 66 -
3.1.5	DEVICES COMPARED FOR IMPLEMENTATION OF PILOT AND A COMMERCIAL WAVE POWER PLANT. ....	- 66 -
3.1.6	ENVIRONMENTAL IMPACTS.....	- 67 -
3.1.7	GRID CONNECTION .....	- 70 -
3.1.8	DEPLOYMENT.....	- 71 -
3.1.9	FUTURE DEVELOPMENTS.....	- 72 -
3.1.10	WAVE ENERGY CONVERTER DEVICES.....	- 72 -
3.1.11	SUMMARY OF WAVE ENERGY CONVERTER DEVICES .....	- 73 -
<b>4</b>	<b>WAVE ENERGY ASSESSMENT OF NEW ZEALAND.....</b>	<b>- 75 -</b>
<b>4.1</b>	<b>WAVE CLIMATE –WAM TWENTY-YEAR HINDCAST MODEL.....</b>	<b>- 75 -</b>
4.1.1	VALIDATION.....	- 75 -
4.1.2	WAVE PARAMETERS FROM THE SPECTRA OF A 3G WAM MODEL.....	- 77 -
4.1.3	SUMMARY OF WAVE CLIMATE .....	- 80 -

<b>4.2</b>	<b>BATHYMETRIC DATA.....</b>	<b>- 80 -</b>
4.2.1	DATA ACQUISITION METHOD.....	- 81 -
4.2.2	SUMMARY OF BATHYMETRY .....	- 85 -
<b>4.3</b>	<b>WAVE FORECASTS .....</b>	<b>- 86 -</b>
4.3.1	EXAMPLE DATA COLLECTION.....	- 89 -
4.3.2	WAVE CHARACTERISTICS DURING PERIOD OF STUDY. ....	- 93 -
4.3.3	SUMMARY OF WAVE FORECASTS.....	- 95 -
<b>4.4</b>	<b>INFRASTRUCTURE .....</b>	<b>- 95 -</b>
4.4.1	ENERGY DEMAND.....	- 95 -
4.4.2	TRANSMISSION .....	- 96 -
4.4.3	PORTS .....	- 101 -
4.4.4	SUMMARY OF INFRASTRUCTURE DATA.....	- 102 -
<b>5</b>	<b>DATA ASSESSMENT .....</b>	<b>- 103 -</b>
<b>5.1</b>	<b>IDENTIFYING HOTSPOTS.....</b>	<b>- 103 -</b>
5.1.1	WAVE TRANSFORMATION MODELLING .....	- 103 -
5.1.2	RECALCULATION OF ITERATIONS AND GEO-REGISTRATION...-	104 -
5.1.3	HOTSPOT INTERPRETATION.....	- 104 -
5.1.4	SUMMARY OF HOTSPOT IDENTIFICATION METHODOLOGY .....	- 105 -
<b>5.2</b>	<b>EXCEEDANCE-PERSISTENCE.....</b>	<b>- 105 -</b>
5.2.1	SUMMARY OF EXCEEDANCE-PERSISTENCE METHODOLOGY ..-	108 -
<b>5.3</b>	<b>PREDICTABILITY .....</b>	<b>- 108 -</b>
5.3.1	PREDICTABILITY CALCULATION.....	- 109 -
5.3.2	PREDICTABILITY INTERPRETATION .....	- 112 -
5.3.3	SUMMARY OF PREDICTIVE METHODOLOGY .....	- 114 -
<b>6</b>	<b>NEW ZEALAND CASE STUDIES .....</b>	<b>- 115 -</b>
<b>6.1</b>	<b>HOTSPOTS .....</b>	<b>- 116 -</b>
6.1.1	HOTSPOT MAPS.....	- 119 -
<b>6.2</b>	<b>EXCEEDANCE-PERSISTENCE.....</b>	<b>- 128 -</b>
<b>6.3</b>	<b>PREDICTABILITY .....</b>	<b>- 137 -</b>
<b>6.4</b>	<b>WAVE ENERGY POSSIBILITIES .....</b>	<b>- 138 -</b>
<b>7</b>	<b>FUTURE DEVELOPMENTS .....</b>	<b>- 142 -</b>
<b>7.1</b>	<b>HOTSPOTS .....</b>	<b>- 142 -</b>
7.1.1	BATHYMETRIC DATA.....	- 143 -
7.1.2	WAVE GENERATION AND PROPAGATION MODELLING.....	- 143 -
<b>7.2</b>	<b>EXCEEDANCE-PERSISTENCE.....</b>	<b>- 144 -</b>

7.3	PREDICTABILITY .....	- 145 -
8	SUMMARY AND CONCLUSIONS.....	- 146 -
8.1	KEY FINDINGS OF THIS INVESTIGATION:.....	- 146 -
9	REFERENCES .....	- 149 -
10	APPENDIX A, SEASONAL EXCEEDANCE-PERSISTENCE .....	- 154 -
10.1	HOKIANGA.....	- 154 -
10.2	AUCKLAND .....	- 156 -
10.3	TARANAKI .....	- 158 -
10.4	WELLINGTON .....	- 160 -
10.5	CANTERBURY .....	- 162 -
10.6	OTAGO.....	- 164 -
10.7	SOUTHLAND.....	- 166 -

## Table of figures

Figure A. (Title page). A breaking wave from the perspective of a surfer travelling inside (source: www.surfermag.com).....	3 -
Figure 2.1. Waves grow in height first at a linear rate (a straight line), then exponentially (a rising curve), and finally reach saturation when growth is limited (a horizontal line) (Source: Butt and Russell, 2002).....	19 -
Figure 2.2. Exponential wave growth. Turbulent eddies, (shown as clockwise rotating red “squiggles”) increase in size at the same time as wave height. The eddies and waves are inextricably linked creating a positive feed back loop of both wave height and eddy size (Source: Butt and Russell, 2002)..	20 -
Figure 2.3. Generation of irregular waves (a sea) by a storm (wind to ocean energy transfer), the propagation of regular swell waves across the ocean (energy-transfer agent), and shoaling and final breaking of wave on the shore (energy dissipation as heat, sound and kinetic sediment transportation) (Source: Komar 1998).....	21 -
Figure 2.4. Energy density of waves and the period ( $T$ ) of the waves is a common method of describing the wave spectrum. During the processes of wave generation (a sea), propagation (as swell), and shallow water seabed interaction (surf) (Source: Komar 1998).....	22 -
Figure 2.5. Individual waves in a wave group travel at twice the velocity of the group and move through from the front to the back (demonstrated by the red wave), and appear to an observer to be “born” at the back and “die” at the front. (Source: Butt and Russell, 2002).....	24 -
Figure 2.6. Wave half life (time required for wave height to decrease by one half) according to decay in wave height ( $H$ ) and internal friction (Source: Keulegan 1950 in Komar, 1998).....	26 -
Figure 2.7. Wave refraction and an aerial photograph of the refraction process. $C_{\infty}$ and $C$ are the offshore and shoreward phase velocities. $\alpha_{\infty}$ is the offshore angle of approach, $\alpha$ the shoreward angle of approach $S_{\infty}$ and $S$ are the spacing of wave orthogonals offshore and shoreward respectively. The increase in length from $S_{\infty}$ to $S$ shows a divergence of energy per metre of wave front. (Source: Frazerhurst and Mead 2003, Komar, 1998).....	30 -
Figure 2.8. Wave transformation across bathymetric features. Left hand side shows a canyon with subsequent diverging wave orthogonals. Right hand side shows ridge (or shoal) with subsequent concentration (or focus) of wave orthogonals (Source: United States Army Corps of Engineers, 2002).....	30 -
Figure 2.9. Water particle displacements from mean position for shallow-water, and deepwater. (Source: United States Army Corps of Engineers, 2002).....	32 -
Figure 2.10. Local fluid velocities and accelerations during wave propagation (Source: United States Army Corps of Engineers, 2002).....	32 -
Figure 2.11. Simple classification of breaker types, and right hand side with wave rider’s perspective with vortex length ( $l$ ), width ( $w$ ) and angle ( $\theta$ ). $H$ is the estimated wave height. (Source: Mead, 2003)...	34 -
Figure 2.12. Schematic diagram of several types of wave measurement systems (Source: Brooks, 2004).....	37 -
Figure 2.13. Approximate global wave distribution of time-average wave power in kW/m. (Source: Brooks, 2003).....	42 -
Figure 2.14. Idealised wave heights for North and East aspect coastlines of Oahu Hawaii , USA. Average wave height is less for the North Shore than adjacent East Side notwithstanding large seasonal swells. (Idealised example from James Frazerhurst’s personal observation).....	47 -
Figure 2.15. Contour map and perspective visualisation output of GIS Wind Farmer (Source: Garrad Hassan, 2005).....	50 -

Figure 2.16. Cost (\$/kW) of renewable energy technology with cumulative production capacity (MW) and the involvement of government funding to realise commercial equality. (Source: Electric Power Research Institute, 2004b).....- 59 -

Figure 3.1. Classification of ocean wave energy conversion processes based on mode of energy absorption (pitch, heave, surge or combined modes), type of absorber (A), and type of reaction point (B). (Source: Hagerman 1995 in Brooke 2003) .....- 64 -

Figure 4.1. Position of wave buoys (+) used for comparison with the Hindcast model. Shaded squares indicate dry cells in the 1.125°x 1.125° New Zealand regional grid, while grid cells from which hindcast output spectra were interpolated are marked (\*). (Source: Gorman *et al*, 2003b) .....- 76 -

Figure 4.2. Significant wave height (Hs) at a wave buoy site near Foveaux Strait (Fig. 4.1) show as time series data simulated by the wave model and as measured by the buoy. (Source: Gorman *et al*, 2003b) .....- 76 -

Figure 4.3. Significant wave height (Hs) at a wave buoy site near Foveaux Strait (Fig. 4.1) as simulated by the wave model and as measured by the buoy, show as regression, with the line of best fit and equivalence lines shown by solid and dashed lines respectively. (Gorman *et al*, 2003b).....- 77 -

Figure 4.4. The components of spectral density  $F(f, \Theta)$  at the prediction point P, for propagation direction  $\Theta_1$ . As an example this uses an up fetch spectrum at E, interpolated from hindcast spectra at cells A and C. For propagation direction  $\Theta_2$ , the fetch to the coast (PG) was used to compute a fetched-limited spectral density (Gorman *et al*, 2003b). .....- 79 -

Figure 4.5. The use of multibeam survey to determine the bathymetry of a site. Swathes are made across the ocean floor as the vessel makes passes (black lines). Location of vessel is kept in check with real time kinetic global positioning systems (RTK-GPS)(Source [www.niwa.cri.nz](http://www.niwa.cri.nz)). .....- 81 -

Figure 4.6. Screen capture of the geo-processing of navigation chart NZ42 Sample shows Northland Peninsular, North Island. ....- 82 -

Figure 4.7. Screen capture of the digitising of geo-registered navigation charts using MapInfo Professional GIS. X, Y, Z data was collected with X, Y being NZMG northing and easting, and Z being the ocean depths. Sample shows Hokianga Harbour and adjacent coastline.....- 83 -

Figure 4.8. Screen capture of Surfer© (Golden software 1996). X, Y, Z data (in red) converted into a grid using Surfer grid creation capabilities. Data was rotated according to convention of wave transformation model. The land has been blanked. The grid will now be trimmed of locations lacking in X, Y, Z data. Sample shows Hokianga Harbour and adjacent coastline. ....- 84 -

Figure 4.9. Screen capture of the plotting of the modified bathymetry data for the wave transformation model in the 3DD suite of hydrodynamic models. Sample shows Hokianga Harbour and adjacent coastline extending to the continental shelf (>200m depth).....- 85 -

Figure 4.10. Screen capture of buoyweather.com site. Wave characteristics are viewed across the middle of this web page by way of a bar graph in crimson for a particular location at a particular date, in this case 37° S 173.75° E on 4/21/04 .As this is a United States of America based site the dates are shown as MM/DD/YY and wave heights are in feet. Peak wave heights, significant wave heights, average period, and direction are provided at six hourly intervals. (Source: [www.buoyweather.com](http://www.buoyweather.com))....- 87 -

Figure 4.11. Excel spreadsheet for organizing e-mailed data for a single location. Significant wave heights (Hs) and wave periods (T) are shown but direction (Dir) was also collated. The yellow cells represent the first day of records, the blue the second day. This staggering of each 24 hour predictions allowed comparison for the same day on the same line. Hence line 28-31 shows the first full six days prediction and the “now forecast”.....- 89 -

Figure 4.12. Locations of the virtual buoy sites for this investigation represented in yellow (Source: [www.buoyweather.com](http://www.buoyweather.com)).....- 91 -

Figure 4.13a. The national electricity grid for New Zealand including the varying sizes of transmission lines, grid nodes, power stations, and sub stations (source: Transpower, 2005) .....- 97 -

Figure 4.13b. The national electricity grid for New Zealand including the varying sizes of transmission lines, grid nodes, power stations, and sub stations (source: Transpower, 2005) .....- 99 -

Figure 4.14. Locations of where new generation might more easily be connected to existing grid nodal points. ....- 100 -

Figure 5.1 . Front-end window of the ASR Ltd Exceedance-Persistence Matlab script. ....- 106 -

Figure 5.2. Screen capture of a portion of the Excel file for the probability output table of the ASR Matlab script. The increasing numbers on the left hand side represent kW/m of energy. These extend down to less than or equal to 100 kW/m. The numbers across the top of the table represent hours. These extend out to 240 hours. The three hour intervals correspond to the temporal resolution of the hindcast data. This figure only shows the corner of the full table as the full table is too large to be able to show details. ....- 107 -

Figure 5.3a. Exceedance-persistence example showing 100 different data lines for 0 to 100 kW/m energy calculations for a Hokianga location during winter (legend can be found at figure 5.10). The 0 kW/m line and 100 kW/m are indicated by the red text and arrows. ....- 108 -

Figure 5.3a. Legend for the exceedance-persistence charts. The values are for the wave energy calculated from the wave spectrum generated from the WAM hindcast and represent the exceedance of energy (hence  $\geq$ ). ....- 108 -

Figure 5.4. Calculation of RNMSE, highlighted in yellow for the 1 to 6 day forecasts for a particular location. ....- 110 -

Figure 5.5. Comparison of the RNMSE as percentage for the significant wave height ( $H_s$ ) for six locations around New Zealand. ....- 111 -

Figure 5.6. Comparison of the RNMSE as a percentage of the wave periods (T) for six locations around New Zealand. ....- 111 -

Figure 5.7. Comparison of the RNMSE as a percentage of the swell direction for six locations around New Zealand .....- 112 -

Figure 5.8. Swell heights from buoyweather.com predictions for SS NZ.....- 113 -

Figure 5.9. Swell heights from buoyweather.com predictions for NNE NZ .....- 114 -

Figure 6.1. Locations based on WAM hindcast data show the average wave energy (calculated from the spectral modelling).....- 116 -

Figure 6.2. A combination of all hotspot modelling on a continuous scale of wave heights from 0 kW/m (blue) to a maximum of 55kW/m (red). Hotspot modelling has used the general method of energy calculation (equation 2.6) and weighted average combining iterations of wave model WBEND.....- 118 -

Figure 6.3. Weighted average wave energy for coastline adjacent to Hokianga harbour derived from WAM 20 year wave hindcast and digitised bathymetry 200m x 200m cells. Note that the nearest grid node (Kaikohe) is not visible at this scale. ....- 120 -

Figure 6.4. Weighted average wave energy for coastline adjacent to Waitemata harbour derived from WAM 20 year wave hindcast and digitised bathymetry 300m x 300m cells. ....- 121 -

Figure 6.5. Weighted average wave energy for Taranaki coastline derived from WAM 20-year wave hindcast and digitised bathymetry 2000m x 2000m cells.....- 122 -

Figure 6.6. Weighted average wave energy for coastline adjacent to Wellington region from WAM 20 year wave hindcast and digitised bathymetry 500m x 500m cells. ....- 123 -

Figure 6.7. Weighted average wave energy for Canterbury coastline derived from WAM 20year wave hindcast and digitised bathymetry 2500m x 2500m cells.....- 124 -

Figure 6.8. Weighted average wave energy for coastline adjacent to Otago harbour derived from WAM 20 year wave hindcast and digitised bathymetry 200m x 200m cells. ....- 125 -

Figure 6.9. Weighted average wave energy for coastline adjacent to Southland harbour derived from WAM 20 year wave hindcast and digitised bathymetry 3000m x 3000m cells. ....- 126 -

Figure 6.10. Legend for the exceedance-persistence charts. The values are for the wave energy calculated from the wave spectrum generated from the WAM hindcast and represent the exceedance of energy (hence  $\geq$ ). .....- 128 -

(a) Great Barrier Island .....- 129 -

(b) Mahia.....- 129 -

(c) Wellington .....- 130 -

(d) Hokianga.....- 130 -

(e) Auckland.....- 131 -

(f) Cape Egmount.....- 131 -

(g) Greymouth.....- 132 -

(h) Banks Peninsular .....- 132 -

(i) Otago Peninsular .....- 133 -

(j) South West Cape .....- 133 -

Figure 6.11 (a-j). Comparison of ten day, annual, wave energy, exceedance-persistence charts for Great Barrier Island (a), Mahia (b), Wellington (c) Hokianga (d), Auckland’s West Coast (e), Cape Egmount (f), Greymouth (g), Banks Peninsular (h), Otago Peninsular (i) and South West Cape (j).....- 133 -

Figure 6.12. New Zealand coastline and exceedance-persistence diagrams representative of major coastline aspects.....- 135 -

Figure 6.13. Comparison of the probability of wave exceedance for a persistence of 3 hours. ....- 136 -

Figure 6.14. Comparison of the probability of wave exceedance for a persistence of 48 hours. ....- 136 -

Figure 6.15. Comparison of the probability of wave exceedance for a persistence of 96 hours. ....- 137 -

Figure 6.16. Wave height (metres), period (seconds) and direction (degrees) percentage root normalized mean square errors for 6 locations around New Zealand. ....- 138 -

Figure 7.1. The Distributed Integrated Ocean Prediction System (DIOPS). Interaction of several wave models (described here by domain objects) is a pattern that the mapping of hotspots should attempt to emulate beyond the “offshore” and “nearshore” models (WAM, and WBEND respectively) of the case studies.....- 144 -

## **Table of tables**

Table 2.1. Joint probability table of significant wave height (Hs) and peak period (Tp) for Muriwai. Twenty-year hindcast providing the data. Probabilities are expressed as percentages with totals of each height bin and period bin on the bottom row and far right column respectively. This table represent 90.45 % of the total yearly wave conditions. ....	44 -
Table 2.2. Wave energy calculated from wave height and period from Table 2.1 above to show the kilowatt-hours per metre wave front, in each combination of wave height and period.....	45 -
Table 2.3. Comparison of wind energy turbines and relative (Sims, 2004) .....	56 -
Table 3.1. Environmental effects of wave energy converters (Source: Thorpe, 1992). ....	68 -
Table 3.2. Issues and impacts of offshore wave energy converters upon the environment (Source: Electric Power Research Institute 2004c).....	70 -
Table 4.1. buoyweather.com e-mail example of a seven day forecast. The swell (ft), period (sec), and surf direction (deg) columns are collated. From this table 7/28 6am, 12pm, 6pm and 7/29 12 am were deemed the now forecast. ....	88 -
Table 4.2. The resulting now forecast and six days of predictions for the significant height of a single location, after the accumulation of seven day’s data.....	90 -
Table 4.3. Average wave significant height (Hs), period (T) and direction (Dir) for now forecast sites and corresponding twenty-year hindcast locations. Data from buoyweather.com was converted from feet into metres for comparison. Great Barrier Island has been abbreviated to GBI.....	93 -
Table 4.4. Regional estimates of New Zealand’s national annual electricity energy usage. Estimates are based upon information collected for year up to end of March 2002. (Energy Efficiency Conservation Authority, 2005).....	96 -
Table 6.1. Hotspot map interpretations. ....	127 -
Table 6.2. Case study assessment summaries .....	139 -
Table 6.3. Summary of case study wave energy possibilities including preliminary anthropocentric considerations.....	139 -

# **1 Introduction**

Significant advancements are being made in the field of ocean wave energy conversion. After a period of inactivity in the 1980s and early 1990's, developmental inertia is resulting in devices being developed to full-scale prototype level, and global R&D funding from several sources is becoming available (Electric Power Research Institute, 2005). The industry is evolving towards commercial viability.

Assessment of wave energy resources has been hinted at during several stages of this development (Pontes *et al*, 2003). Descriptions of the required elements of assessment have been made, but a methodology of assessment has not been consolidated that provides an understanding of the resource in both spatial and temporal resolution. This type of understanding is particularly pertinent to the conversion of wave energy for grid supply electrical generation.

This report provides such an assessment through:

- mapping of wave energy **hotspots**,
- visualisation of wave energy **exceedance** and **persistence**, and
- calculation of the **predictability** of wave energy.

These three assessments are explained with a review of the science surrounding the phenomena of wave creation and propagation, the development of wave energy converter devices, as well as visualisation and manipulation of wave resource assessments. These assessments are the result of channelling the skills and resources (in the form of the 3DD suite of hydrodynamic models, section 2.1.3.4.) made available by ASR Ltd, a marine and freshwater consultancy specialising in numerical modelling of ocean and coastal dynamics. The outputs of the three assessment methodologies are comparable, uncomplicated, graphic representations of the wave resource.

A perspective is maintained to provide an assessment service for electricity generating companies (locally represented by such companies as Might River Power and Meridian Energy). It is expected that these organisations could become future commercial developers of wave energy power plants in New Zealand.

Case studies for seven locations around New Zealand are presented in order to demonstrate the practicalities of the wave energy resource assessment methodology developed by the studies described in this thesis.

## 1.1 Problem identification

Currently wave energy resource assessment is often expressed as a single calculation of wave energy per metre wave front (kW/m). This measure simplifies the temporal and spatial variation of wave energy. In reality wave energy can vary greatly along a relatively short distance of coastline due to interactions between waves and the seabed. Mapping of the spatial variation of wave energy (hotspots) and visualisation of the probability of wave energy exceedance and persistence overcomes these deficiencies.

Wave predictability is a possible advantageous characteristic of wave energy conversion to electricity. Calculating the error of wave forecasts identifies the predictability of the climatic conditions that generate waves.

Hotspot mapping, wave energy exceedance-persistence analysis, and identification of the predictability of waves for an aspect of coast, provides an assessment that allows the electricity generation stakeholders to properly evaluate wave energy potential for a given location.

## 1.2 Research Aim

To produce a methodology of wave energy resource assessment incorporating the spatial, temporal, and predictive variables of the resource, relevant to project developers.

## 1.3 Objectives

- Objective One

*To identify available current knowledge on wave energy resource assessment techniques and wave energy conversion.*

- Objective Two

*To develop a method for analyzing wave resource data to identify the optimum locations for installing wave energy conversion devices around the coast of New Zealand.*

- Objective Three

*To use this methodology for evaluating the wave energy potential on a regional basis around the New Zealand coastline including proximity to load and grid connection points.*

## **2 Identification of Parameters and Principals**

### **2.1 Waves**

Energy is transferred from the sun which in part creates climatic conditions in the atmosphere with concentrated areas of high winds (storms). When above the ocean these storm systems interact with the ocean surface and produce concentrated energy transfer agents, waves. Waves then propagate across the ocean away from the areas of generation with little loss of energy in deep waters. A small amount of wave energy is expelled through several processes in deep water and then in shallow water through frictional contact with the seabed. Any remaining energy is finally exchanged through the act of waves breaking in the nearshore.

A general description of the above process follows with emphasis upon factors relevant to the development of a spatial wave energy resource assessment.

Several fundamental terms are used in describing waves.

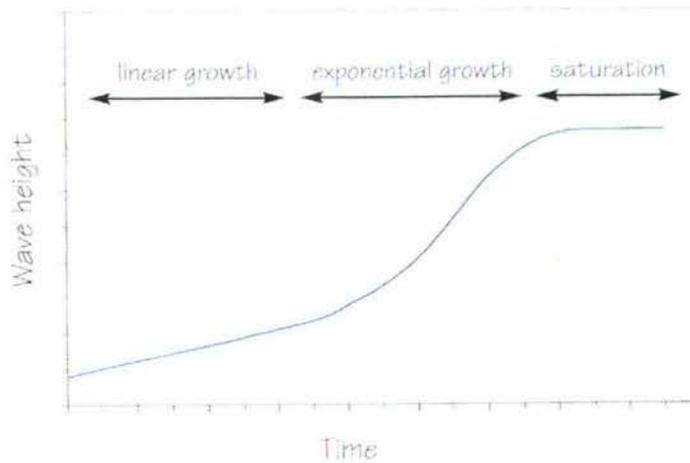
- Wave height ( $H$ ) or amplitude, the distance from the lowest point (trough) to the highest point of a wave.
- The wavelength ( $L$  or  $\lambda$ ) is the horizontal distance from a nominal point to the same point of the next wave, often crest to crest.
- Wave period ( $T$ ) is the time for a single wave to pass from a nominal point to the same point of the next wave, often crest to crest.
- Wave frequency ( $f$ ) =  $1/T$ .
- Velocity of wave propagation ( $C$ ).
- Group velocity of waves ( $C_g$ ).

(Komar, 1998)

#### **2.1.1 Wave creation and deep water propagation**

The processes that create waves require an understanding for wave resource evaluation. The factors that come together to produce waves useful for energy conversion are the fundamental methodology.

Waves are created through the interaction of the atmosphere and the surface of water. Wind moving across a smooth sea surface will produce ripples; a persistent wind will produce waves (Komar, 1998). The wind strength, duration that it blows at a particular strength and the distance that the wind blows over in a linear direction (fetch), all influence the waves produced. Over a particular length of fetch, the longer and harder the wind blows, the greater the height of the waves, until a dynamic equilibrium of height is met. This growth has three stages (Fig. 2.1), linear growth exponential growth and a saturation level (Butt and Russell, 2002).



**Figure 2.1.** Waves grow in height first at a linear rate (a straight line), then exponentially (a rising curve), and finally reach saturation when growth is limited (a horizontal line) (Source: Butt and Russell, 2002).

Linear growth takes place from smooth flat sea, where wave height is zero. As wind begins passing over the water there are forces acting downward upon the surface. This downward force comes from the vertical components of disturbances (vortices) that are a naturally occurring turbulence, spinning (in part) about a horizontal axis. These random disturbances force air down, indenting the surface of the water. Surface tension “springs” the water level up and a ripple propagates away (Butt and Russell, 2002).

The vortices will be travelling also with the greater wind flow, and may follow the ripple continually adding energy in a linear manner. This process will provide a “roughness” to the water surface allowing the following mechanism to greatly increase wave height.

The second mechanism of wave growth is self-perpetuating and results in exponential growth. The creation of ripples on the surface upsets the flow of wind over the surface of the water leading to the creation of turbulent eddies. Eddies, unlike the vortices involved in the linear growth of ripples, are not random and are inextricably linked to wave motion (Fig. 2.2). An increase in surface roughness increases the turbulence, which further increases the roughness resulting in greater turbulence, etc. Hence a positive feedback loop is created with an exponential growth of “roughness” that is now becoming discernible as wave height (Fig. 2.2).

This exponential growth of wave height is limited by several factors that are explored when wave propagation is described below. These limiting factors create a dynamic equilibrium shown in Fig. 2.1 as the saturation level (Komar, 1998; Young, 1999; Butt and Russell, 2002; United States Army Corps of Engineers, 2002).

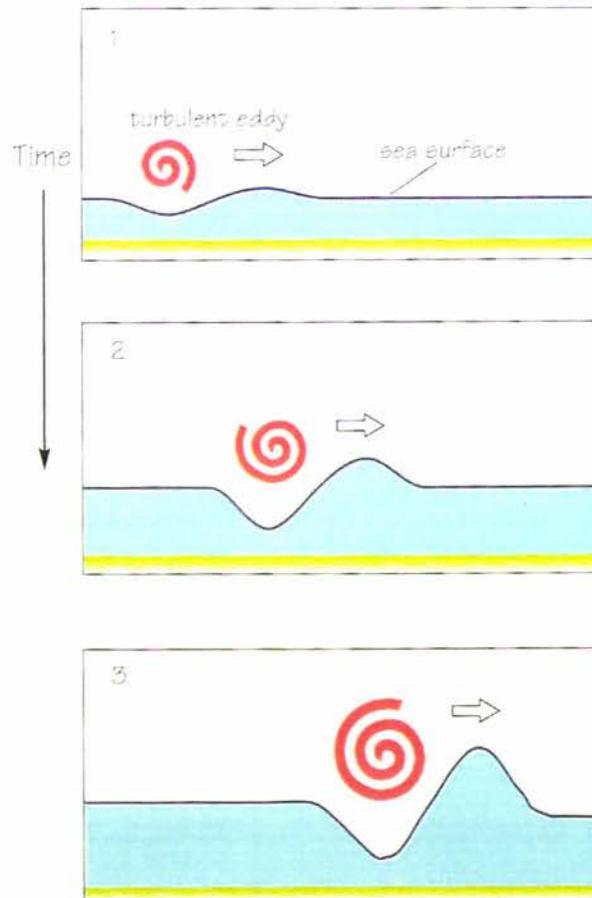


Figure 2.2. Exponential wave growth. Turbulent eddies, (shown as clockwise rotating red “squiggles”) increase in size at the same time as wave height. The eddies and waves are inextricably linked creating a positive feed back loop of both wave height and eddy size (Source: Butt and Russell, 2002).

The length of the distance where there is interaction of wind and sea is called the fetch ( $F$ , Fig. 2.3). Within a fetch waves are present which have been created when wind first interacted with the ocean surface (for time  $D$  of storm duration, Fig. 2.3) as well as ripples created only seconds ago. This variation of wave heights can be considered within a simplified storm, where wind is stable in velocity, and direction. Even with this simplified arrangement of wind and ocean surface, a complex arrangement of waves and ripples will result (Komar, 1998; United States Army Corps of Engineers, 2002).

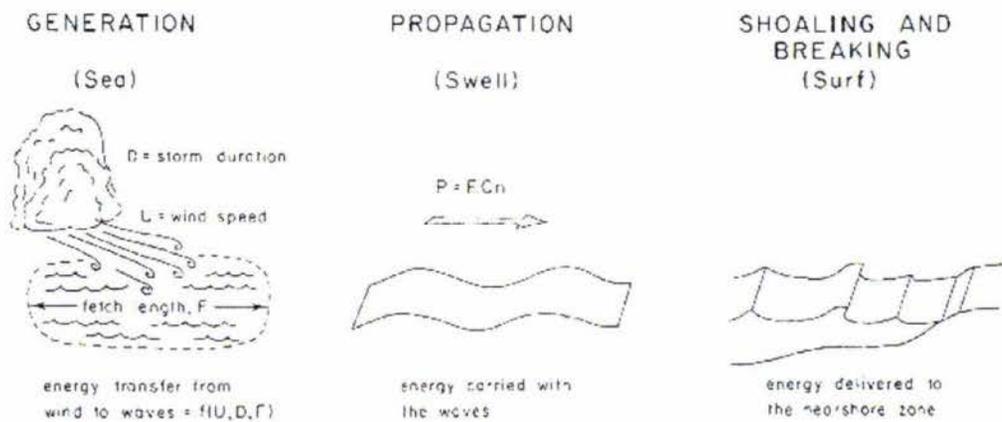


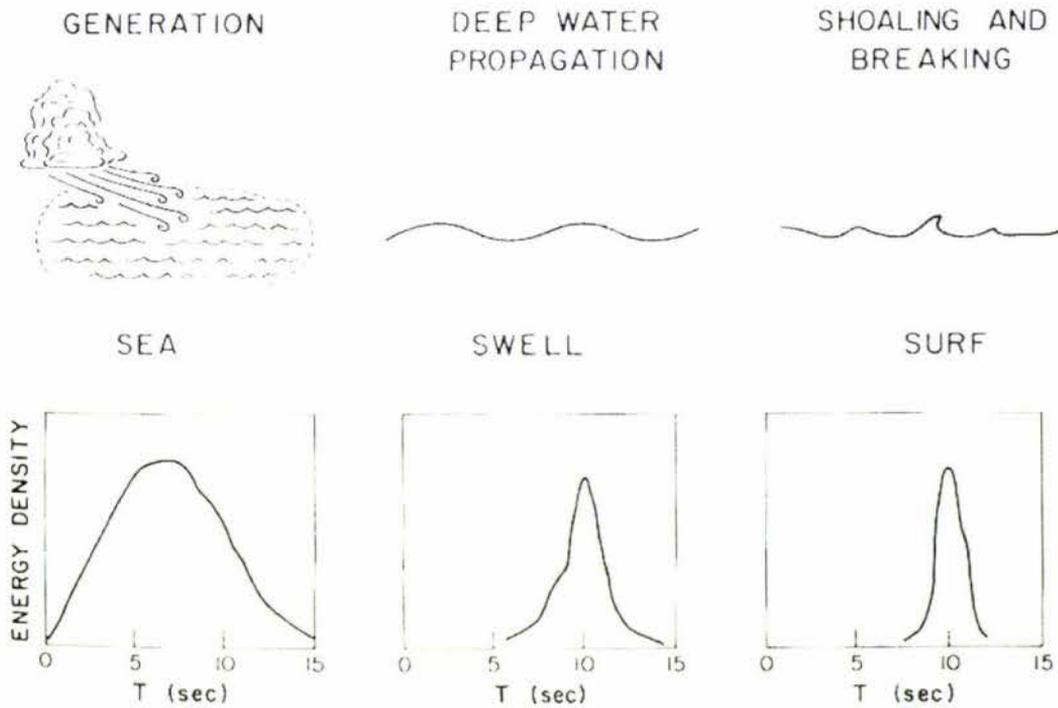
Figure 2.3. Generation of irregular waves (a sea) by a storm (wind to ocean energy transfer), the propagation of regular swell waves across the ocean (energy-transfer agent), and shoaling and final breaking of wave on the shore (energy dissipation as heat, sound and kinetic sediment transportation) (Source: Komar 1998).

Waves within an actual storm are highly complex and are referred to as “sea”. Observation of a sea appears as a combination of multiple waves in apparent random configuration. Winds of an actual storm vary in direction creating waves moving in differing directions. As waves pass through one another, heights are combined, opposed and negated, adding to the complexity. Winds at surface level vary in velocity, as cresting and spilling over waves (white capping), can both shelter and exacerbate wind velocities and pressures.

A storm of any type will have a variety of wave heights and periods. The various heights and periods of waves created by a storm are, collectively, termed a wave spectrum. The wave spectrum in a developing sea can be thought of as in two

portions, an equilibrium range of higher frequency roughness (ripples or chop, where the energy content is at a maximum and cresting and “white capping” are present), and a growth range of lower frequencies where energy is being added to grow more regular swells (Butt and Russell, 2002; Komar 1998).

The wave spectrum produced by a storm changes as waves propagate away from the area of generation (Fig. 2.4). The wave spectrum is a representation of the wave energy at each period or frequency. Wave energy is the total of kinetic energy and potential energy. The kinetic energy is attributed to water particle’s motion (velocities) associated with wave motion. Potential energy results from part of the fluid mass (the crest) being raised above the trough (United States Army Corps of Engineers, 2002). Wave energy conversion devices transform either or both of these forms of energy to electrical energy.



**Figure 2.4.** Energy density of waves and the period ( $T$ ) of the waves is a common method of describing the wave spectrum. During the processes of wave generation (a sea), propagation (as swell), and shallow water seabed interaction (surf) (Source: Komar 1998).

As waves propagate away from the area of generation, and are no longer influenced by the winds of the generating storm, they begin to disperse according to their periods. The velocity that waves traverse the ocean is related to the period ( $T$ ) of

the waves. The longer the period the faster the wave will travel. Propagation takes place in groupings of waves with equal wavelengths (and hence periods).

The velocity of groups of waves ( $C_g$ ) can be calculated as:

$$C_g = \frac{1}{2} (g T / 2\pi) \quad \text{Equation 2.1}$$

where  $g$  is the acceleration due to gravity.

Wave groups of differing periods will propagate at differing velocities, with longer period wave groups moving more quickly than wave groups of shorter periods. Hence a process of dispersal will occur, and waves will appear more regular and homogeneous in period (and wavelength) the further from the generation location. Hence the closer to the area of generation the more confused the ocean will appear.

The group velocity of the waves ( $C_g$ ) is only half the velocity of individual waves ( $C$ ). This means that as a group of waves propagates, waves will appear to move through the group, disappearing as they reach the front of the grouping (Fig. 2.5). This process will continue until the waves enter shallow water (section 2.1.2.2). Upon reaching a certain shallower water depth individual waves will reduce velocity, wave height will increase, but the period will remain constant. The individual wave velocity ( $C$ ) will eventually match the group velocity ( $C_g$ ). Therefore in shallow water the apparent movement through the wave group by individual waves, will cease (Komar, 1998; Young, 1999; Butt and Russell, 2002; United States Army Corps of Engineers, 2002).

The changes that happen to waves as they propagate away from the generation area are important for the fact that the spectral density (the width of the wave spectra) of swells from a particular storm will vary according to the distance from that storm (Fig. 2.5). A local storm and its subsequent apparent swells will have shorter period waves (for example 4-8 seconds) as any longer period wave will not have had time to “speed away” from waves of a shorter period and will be part of the same sea state. A generating storm a greater distance from an observation point will first be observed by wave groupings of the longest period. The further the distance from the generating storm a location is the longer the period of the observed waves.

Wave spectra and the division of energy within the spectra is of importance to wave energy conversion due to the abilities of devices to extract energy from particular periods (section 3.1.4). The interaction of wind and sea surface to produce particular spectra is the basis for modern wave modelling (section 2.1.3).

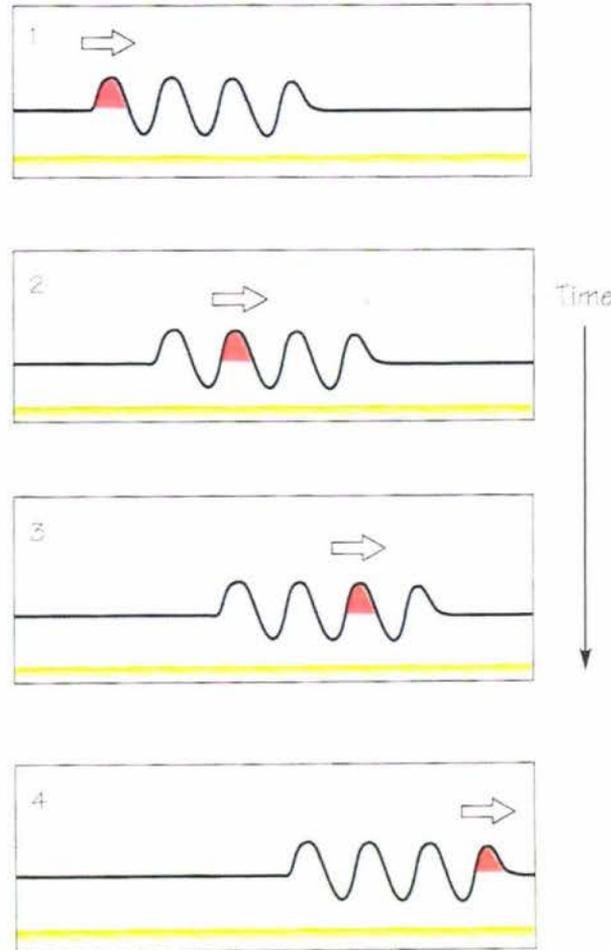


Figure 2.5. Individual waves in a wave group travel at twice the velocity of the group and move through from the front to the back (demonstrated by the red wave), and appear to an observer to be “born” at the back and “die” at the front. (Source: Butt and Russell, 2002).

An example of these propagation phenomena can be made from a generating storm centred in the Southern Ocean between Australia and New Zealand. The winds of a storm such as this will be predominantly from the southwesterly direction. Swells from this storm may reach the western coast of New Zealand with a period of 6-12 seconds, depending upon how close the generating storm is to the coast. A study of a globe will show that a Great Circle route across the Pacific can, and does, reach the North American West Coast. Swells travelling this route have a period of 12-20

seconds upon intersecting the locations upon this Great Circle. Shorter period waves do not travel as far because of the process of internal viscous damping decay where reduction of wave height directly related to the period of the waves.

Swells of periods greater than 20s have also been recorded at North and Central American coasts from storms generating from the southern Indian Ocean. These swells have followed the Great Circle between Antarctica and Australia, entered the Pacific and travelled more than 15,000 km. (Komar, 1998)

Several limiting factors will result in losses of energy immediately beyond the area of generation these include:

- internal viscous damping;
- angular spreading of waves as they travel away from generating storms;
- winds opposing the orthogonal wave direction; and
- wave-to-wave interactions.

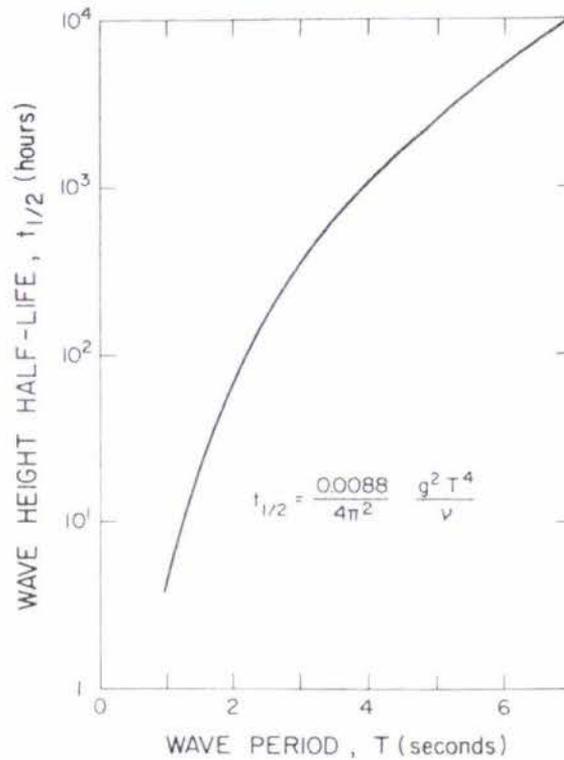
(United States Army Corps of Engineers, 2002)

These saturation factors will limit the height that waves will reach (height and energy being proportional). This results in a natural maximum height created by the generating conditions (Fig. 2.1).

Internal viscous damping leads to decay of wave height exponentially with time. This decay is strongly related to the period of a swell which has a fourth power exponent (Fig. 2.6). The result of this damping reduces the height (and hence energy) of shorter period swells and is of little consequence to the heights of longer period swells. Thus typically due to the velocity of ocean waves the majority of the energy lost by the total spectrum from a generating area happens within the first 1,000 km in the mean direction of the generating fetch. This is calculated (Fig 2.6) from the equation:

$$H=H_i \exp (-32\pi^4 \nu t / g^2 T^4) \quad \text{Equation 2.2}$$

where  $H_i$  is the initial wave height at  $t=0$ ,  $\nu$  is the kinematic viscosity of water and  $T$  is wave period (Komar, 1998).



**Figure 2.6.** Wave half life (time required for wave height to decrease by one half) according to decay in wave height ( $H$ ) and internal friction (Source: Keulegan 1950 in Komar, 1998).

Angular dispersal of waves from the area of generation relates to the variation in direction of generating winds. A very small variation of only a few degrees will develop into a vast difference in destination across 1,000 kilometres of ocean. A large amount of variation of a storm's winds (which is typical in all storms close to the water's surface), and the storm's path, will greatly increase the amount of radial energy dispersed. A storm unswerving in intensity and direction will have less energy dispersed from angular dispersal. As waves propagate away from the generating location there will be a concentric expansion of the swell and a diminishing of energy per metre of wavelength with distance from the area of generation (Komar, 1998; Butt and Russell, 2002).

Winds opposing the direction the wave crests are travelling (orthogonal direction) will create drag, thus reducing the swell energy. This, however, is minimal as the profile of long period waves on deep water is low, and offers little drag (Komar 1998; United States Army Corps of Engineers, 2002). Conversely the effect of a wind against swell shall be more significant upon swells increasing in amplitude due to the effects of shallow water or wave-to-wave interaction.

Wave-to-wave interaction is particularly relevant close (less than 1,000 km) to the area of generation as a method of energy attenuation. Wave breaking (white capping) and directional scattering occur from these wave-to-wave interactions, predominantly when waves are of similar periods (Komar, 1998).

Another type of wave is known as infra-gravity waves. These are longer than the wind induced gravity waves and have, typically, periods of more than 50 seconds. These waves, whilst not useful for energy conversion, are important to the practicality of wave energy conversion. Infra-gravity waves are related to the characteristics of wave-trains (in deep water) and “surf beat” in shallow water.

These long period, infra-gravity waves, and associated groups of waves, are referred to (by waveriders) as sets of waves (Butt and Russell, 2002). Sets may arrive in a constant barrage of relatively similar height waves and be almost undetectable to the casual observer, or be the most striking feature of the surf zone, with a number of considerable waves arriving periodically out of an apparently flat ocean. The latter is most common when the dominated swells are longer period gravity waves, created by more distant storms. This variation in wave heights may have the effect of requiring differing smoothing techniques when extracting energy from locations with variation in “surf beat”.

Whilst prediction of the long period waves is possible (e.g. Nakamura, 1996) an understanding is required of the specific requirements of an energy converter device in order to assess the applicability of a device for a location. The variation in surf beat and its characteristics beyond the breaking zone are not well studied. These phenomena have, however, been extensively researched regarding effects and the consequences of infra-gravity waves entering embayments and harbours (McComb and Goring, 2004). All wave energy conversion technology will require greater knowledge of these long period waves ( and their subsequent pulses of gravity waves) to reduce short term (30 second to 5 minute) intermittence of electricity supply.

#### **2.1.1.1 Summary of wave creation and deep water propagation**

*Wind energy interacts with the ocean to create waves. This interaction creates a variety of wave types distinguished by their height, period, and direction that are collectively termed a wave spectrum. In deep water waves lose little of the*

*energy transferred from the generating wind. Over long distances from their source they become sorted into efficient longer period waves.*

*Wave energy conversion devices are able to transform concentrated energy from distant storms. Resource evaluation requires an account of the creation of waves over half the circumference of the earth away.*

## **2.1.2 Wave transformation**

Wave transformation from deep to shallow water is important to wave conversion as the location of devices will most likely be within shallow water (in order to economically connect to electricity grids). An understanding of the transformations that can both accentuate and negate energy is essential to evaluate potential wave energy conversion locations.

Processes that can affect a wave as it propagates from deep into shallow water include:

- shoaling, refraction, and diffraction;
- dissipation due to friction and percolation;
- breaking;
- additional growth due to the wind;
- wave-current interaction; and
- wave-wave interactions.

(United States Army Corps of Engineers, 2002)

Determination of the depth at which the transfer from deep to shallow water takes place is determined by the wavelength of a wave. Since the wavelength of deep-water waves is proportional to the period, this transition (deep to shallow) will differ for waves within a spectrum.

### **2.1.2.1 Shoaling, refraction and diffraction**

At a basic level Snell's law governs refraction:

$$\sin \alpha = (C / C_{\infty}) \sin \alpha_{\infty} \quad \text{Equation 2.3}$$

where  $C_\infty$  is the offshore wave phase velocity,  $\alpha_\infty$  is angle of approach, and  $C$  and  $\alpha$  are the inshore equivalents (e.g. Komar, 1998).

The angle of approach is in relation to the bathymetry contours, with  $0^\circ$  relating to wave orthogonals perpendicular to the bathymetry contours (i.e. wave crests parallel to depth contours) and  $90^\circ$  relating wave orthogonals parallel to bathymetry contours (i.e. wave crests perpendicular to depth contours)

Since phase velocity ( $C$ ) is related to water depth ( $h$ ):

$$C = \sqrt{gh} \quad \text{Equation 2.4}$$

where  $g$  is the acceleration due to gravity.

Thus since phase velocity decreases with decreasing water depth, the ratio of  $C/C_\infty$  also decreases, which results in a smaller inshore angle of approach. This change in the direction of wave propagation causes wave crests to align more parallel with the seabed contours, (Fig. 2.8). On simple planar bathymetry, the main effect of refraction is the re-alignment of the wave crest to a more parallel orientation to the shoreline.

Snell's law also determines the transformation of wave crests propagating over irregular bathymetry and can be applied to depth variation across an irregular bathymetry resulting in the transformations of wave orthogonals. The movement of wave energy through this process will create areas of convergence and divergence (Fig. 2.9) (Frazerhurst and Mead, 2003; United States Army Corps of Engineers, 2002; Brooks, 2004).

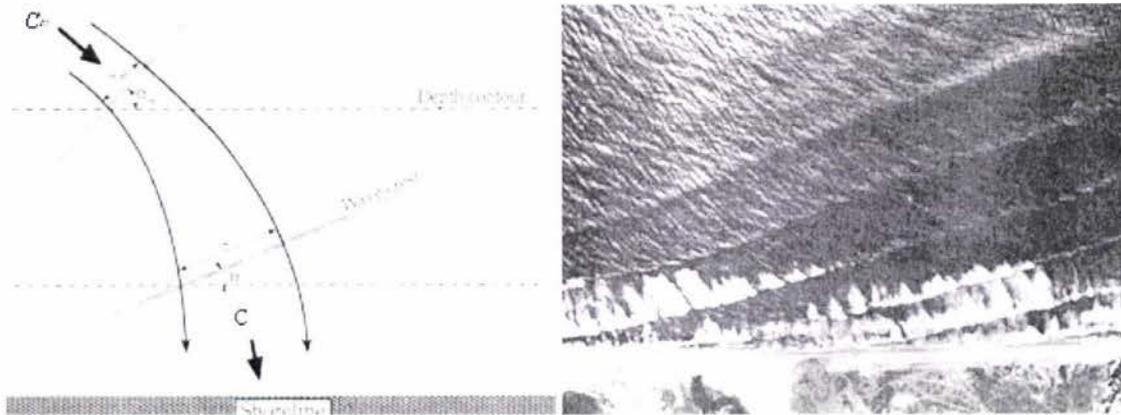


Figure 2.7. Wave refraction and an aerial photograph of the refraction process.  $C_\infty$  and  $C$  are the offshore and shoreward phase velocities.  $\alpha_\infty$  is the offshore angle of approach,  $\alpha$  the shoreward angle of approach  $S_\infty$  and  $S$  are the spacing of wave orthogonals offshore and shoreward respectively. The increase in length from  $S_\infty$  to  $S$  shows a divergence of energy per metre of wave front. (Source: Frazerhurst and Mead 2003, Komar, 1998)

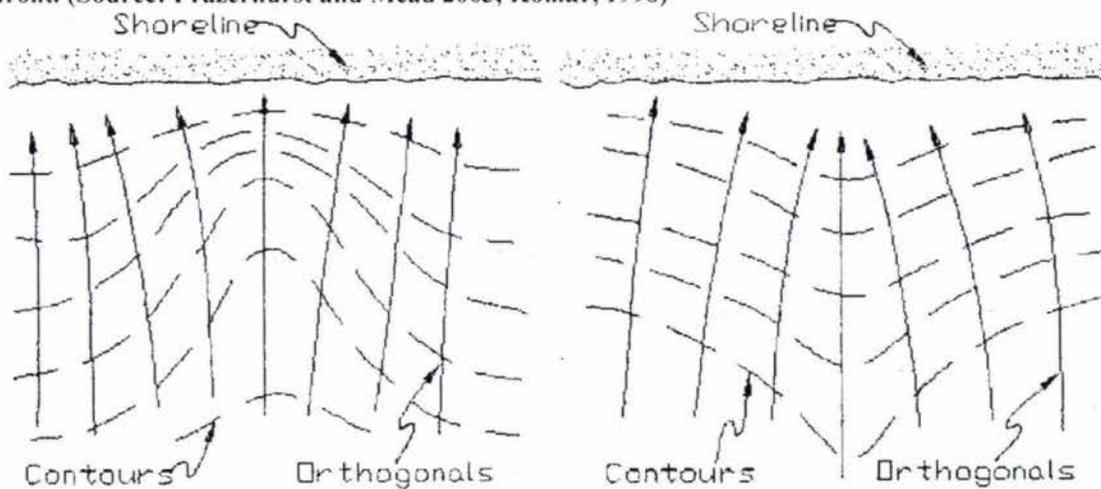


Figure 2.8. Wave transformation across bathymetric features. Left hand side shows a canyon with subsequent diverging wave orthogonals. Right hand side shows ridge (or shoal) with subsequent concentration (or focus) of wave orthogonals (Source: United States Army Corps of Engineers, 2002).

Areas of convergence are termed a focus or shoal. These areas of concentrated wave energy have been termed by the wave energy transformation industry as “hotspots” (Pontes *et al*, 2003; Electric Power Research Institute, 2003; Brooks 2003).

Diffraction can be defined as an energy transfer laterally along wave crests from sections of higher wave heights to lower sections. This process is most noticeable when energy has been lost due to interaction with barriers such as structures (breakwalls), or significant nature sink features (islands, pinnacles), creating “wave shadow” areas. Wave energy will traverse into these areas with diffraction becoming the major influence on geomorphology in sheltered embayments

and cause undesirable effects in harbours (United States Army Corps of Engineers, 2002).

Convergence and divergence of wave energies through the process of refraction across irregular bathymetry may also result in a large variation of wave heights (Frazerhurst and Mead, 2003). Practically, if strong wave convergence occurs, breaking either due to depth constraints or steepness constraints naturally limits the wave height. However, situations which generate strong gradients or discontinuities in wave height along a wave crest give rise to diffraction effects, which can reduce the wave height and keep it below the breaking value (Komar, 1998, United States Army Corps of Engineers, 2002).

### 2.1.2.2 Dissipation due to friction and percolation

Water particles in deep water waves (Fig. 2.9) move in an orbital motion. These orbital velocities reduce exponentially with distance from the surface. The distance which wave energy will penetrate (the kinetic energy component from the orbital velocities of water particles Fig. 2.10) depends upon the diameter of the surface orbit. This orbit is determined by the wavelength (and hence period and frequency) of the wave. The longer the wavelength, the greater the distance the wave energy descends.

The vertical distance down of wave energy dimensions and its relationship to wave period provides a preliminary understanding of why changes to wave characteristics happen as waves propagate into shallower water. The orbital (now elliptical) direction of water particles at the ocean floor (at depth  $d$  Fig. 2.10) is now within the vertical distance downward dimension of the wave. This transformation has the effect upon the deepest orbital velocity of having no vertical ( $w$ ) component (Figs 2.10 and 2.11) only horizontal velocity  $u$ . This interaction of horizontal movement of water particles and the sea floor includes friction and a subsequent loss of the wave kinetic energy.

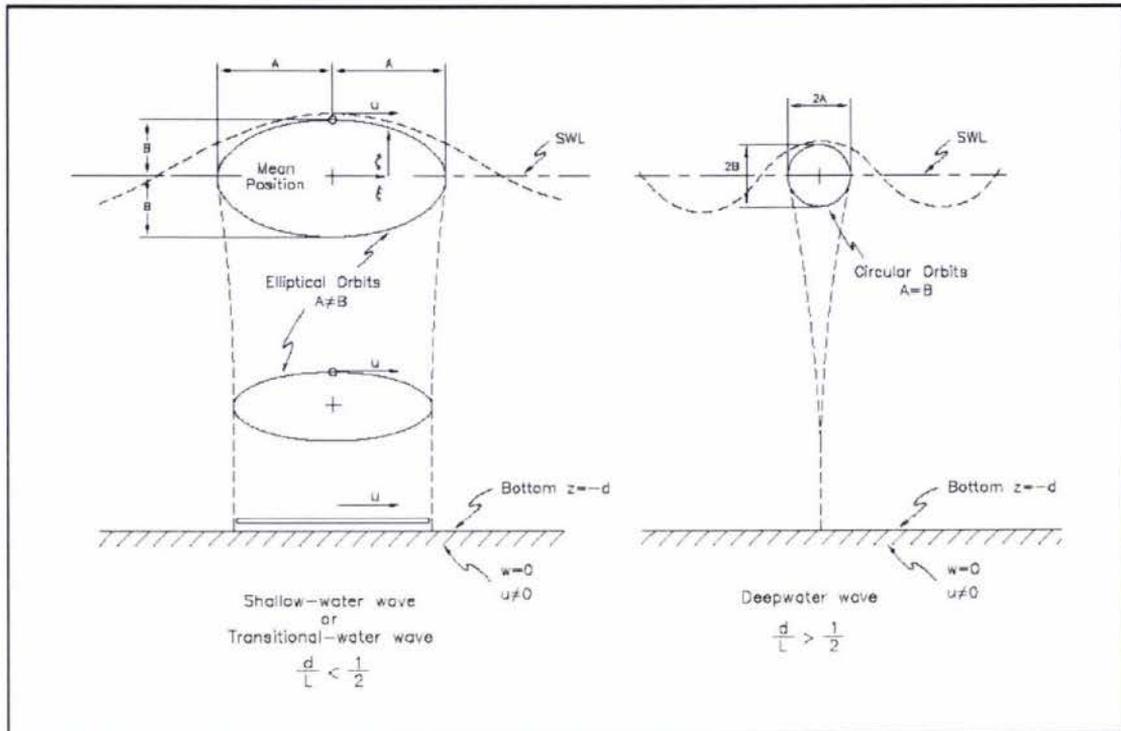


Figure 2.9. Water particle displacements from mean position for shallow-water, and deepwater. (Source: United States Army Corps of Engineers, 2002)

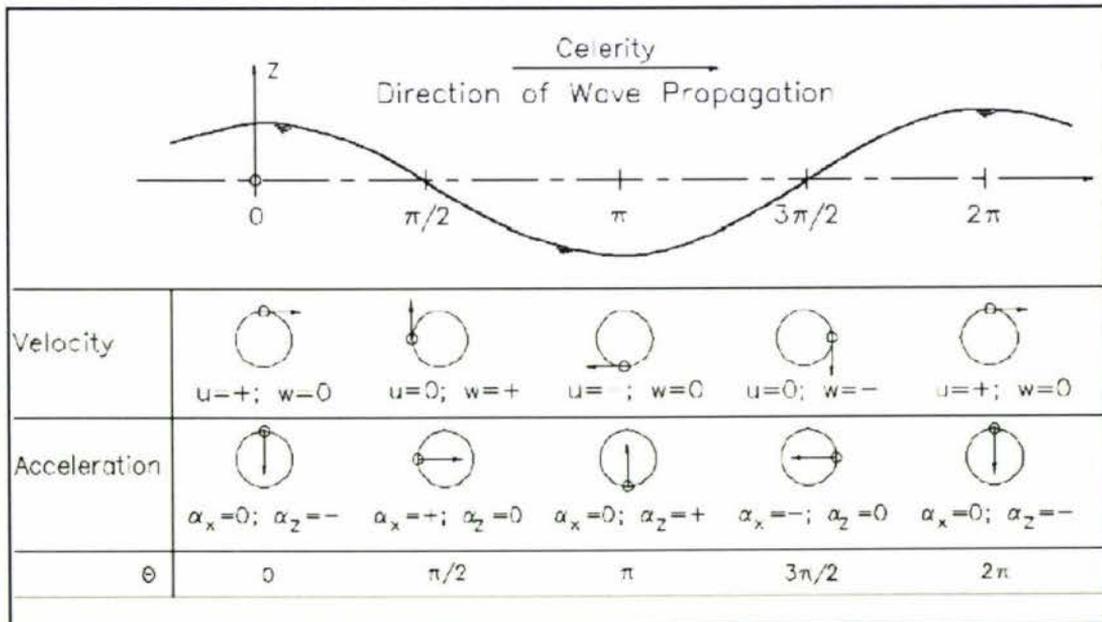


Figure 2.10. Local fluid velocities and accelerations during wave propagation (Source: United States Army Corps of Engineers, 2002)

Orbital velocities are greatest closest to the surface. A shallower depth, results in greater energy interaction with the seabed. The type of sediments (size, shape, density, and matrix), bedrock (roughness, geology), and biomass (algae, corals) that

waves interact with on the sea floor influence the energy lost by either friction or percolation through the interaction of the horizontal water particles (United States Army Corps of Engineers, 2002).

### 2.1.2.3 Breaking

Unlike the commonly held notion, waves do not break due to the drag with the bottom, causing waves to topple forward. It has been established that the “over steepness” resulting from the shortening wavelength as waves interact with the bottom causes the velocity water particles at the wave crest to exceed the velocity of the wave form, surging the crest ahead (Komar, 1998).

The breaking of waves is a process that transfers a large amount of a swell’s energy to other forms in a short time period. Energy is transferred into sound, heat, and the kinetic energy of entrapped sediments (sand and rocks). Simple classification of breaking waves (spilling, plunging, collapsing and surging (Fig. 2.12)) is made by the combination of height, wavelength, and depth from the mean water level (MWL) (Komar 1998).

Greater detailed and intricate descriptions of the shape and metamorphosis of breaking waves have been described (Walker, 1974). Subsequently identification of the waves breaking characteristics have been made from the perspective of wave riders (Moffat and Nichol, 1989; Mead and Black, 1999). These identifications have detailed the importance of the bathymetry matrix, where depth, aspect, slope, and juxtaposition to other bathymetric features will influence swells breaking characteristics and location.

The location of a wave’s breaking point is determined by the depth limitation,

$$H > \delta h \quad \text{Equation 2.5}$$

where the height of the wave ( $H$ ) is greater than the depth ( $h$ ) at MWL, and  $\delta$  is 0.6-0.8 (Black, 2002).

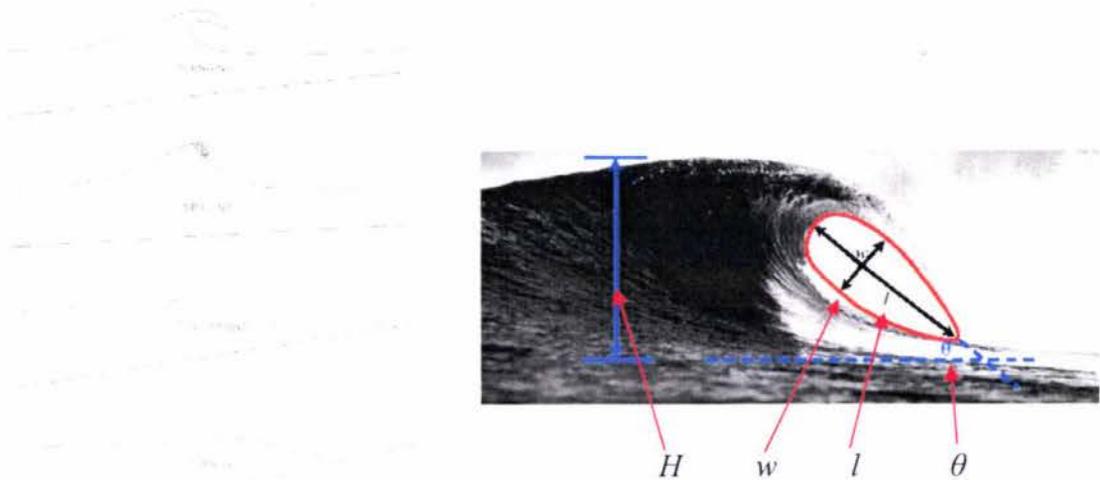


Figure 2.11. Simple classification of breaker types, and right hand side with wave rider's perspective with vortex length ( $l$ ), width ( $w$ ) and angle ( $\theta$ ).  $H$  is the estimated wave height. (Source: Mead, 2003)

The increased wave height from shoaling will effect the break point depth limitation, along a wave crest (section 2.1.2.1).

#### 2.1.2.4 Growth due to the wind and wave-wave interactions

Wind adds energy to swells often in the form of short period waves (created by winds across the ocean surface) interacting with the longer period swells. The direction of these waves will be important as the closer the orthogonal directions of both sets of waves, the greater the addition of energy from the short to long period waves. Wind may also induce over-steepness and energy loss due to instability and subsequent white capping

Waves crossing with skewed orthogonal directions can cause loss of energy. This is most pronounced when wave interactions cause the steepness of swells to become such that instability results in white capping and loss of energy (United States Army Corps of Engineers, 2002).

#### 2.1.2.5 Wave-current interaction

Current fields may interact with swells. Depending on the scale of the currents, wave current interactions may result in changes to wave appearance very similar to interactions with irregular bathymetry. Shoaling, refraction, and diffraction

may all occur when a current's flow is counter the direction of the swell. There is loss of energy because of waves breaking, as well as through the direct countenance of water particle velocities (United States Army Corps of Engineers, 2002).

#### **2.1.2.6 Summary of wave transformation**

*From deep water to the shoreline waves lose nearly all of their energy (a small amount is reflected back out to sea). A number of identifiable factors determine the make up of this loss of energy. Waves are transformed at differing, depths and locations dependant on their height, period and direction. Complex bathymetry complicates these transformations and may result in wave energy reinforcement at some location. Locations of intensified wave energy are referred to as "hotspots", and are useful for the optimal locating of wave energy converter devices.*

#### **2.1.3 Observation and prediction**

The vast distances and geophysical processes that are involved in the creation and propagation of useful waves (for energy conversion), mean that the evolution of the ocean science required for effective resource evaluation has mirrored the development of mankind's observation of the physical world.

The understanding of the various characteristics of ocean waves began with simple viewing from beaches, shorelines, and ship's decks. Waves appear as a component of a rather unique vista, and the dynamic equilibrium of gravity and infra-gravity waves, tides, and the ebb and flow of the sediment budget. Those whom have for centuries relied upon perceptive observations of the sea for survival have often quantified their observations.

It is only in the last thirty years that instrumentation has introduced widespread scientific methods to observation of the sea, observations predating this era have an influence upon present measured characteristics. An excellent example of this influence is the measure of significant wave height ( $H_s$ ), defined as the average of the highest one third of the waves measured over a stated period (usually 17 or 20 minutes). The significant wave height closely corresponds to the wave height determined by casual observation a majority of people would estimate, which is why it is the most commonly used wave height statistic (Komar, 1998).

An understanding of the wave climate of a location requires long-term wave data. This requires uninterrupted observation for a lengthy period, usually incorporating several years. Pickrill and Mitchell (1979) compared various wave records to produce an insight into the wave climate of New Zealand. Data was derived from *in situ* recorders upon hydrocarbon drilling rigs as well as records from the observations of mariners and lighthouse keepers.

The coast surrounding New Zealand and the majority of the rest of the Southern hemisphere is under-instrumented compared to the Northern hemisphere. This has led to greater reliance upon wave prediction models. Gorman *et al* (2003a) updated Pickrill and Mitchell's (1979) work utilising wave prediction models and was validated (Gorman *et al* 2003b) from *in situ* data and remote sensed satellite records, largely superseding observation records.

#### **2.1.3.1 Measurement**

There are a number of differing methods of measuring waves (Fig. 2.13) divided into *in situ*, and remote sensing. *In situ* devices can be further divided into surface piercing, pressure sensing, and surface following (Komar, 1998). Remote sensing measurement is by active methods with laser or radar mounted aboard satellite or aircraft, and passive methods using videogrammetry.

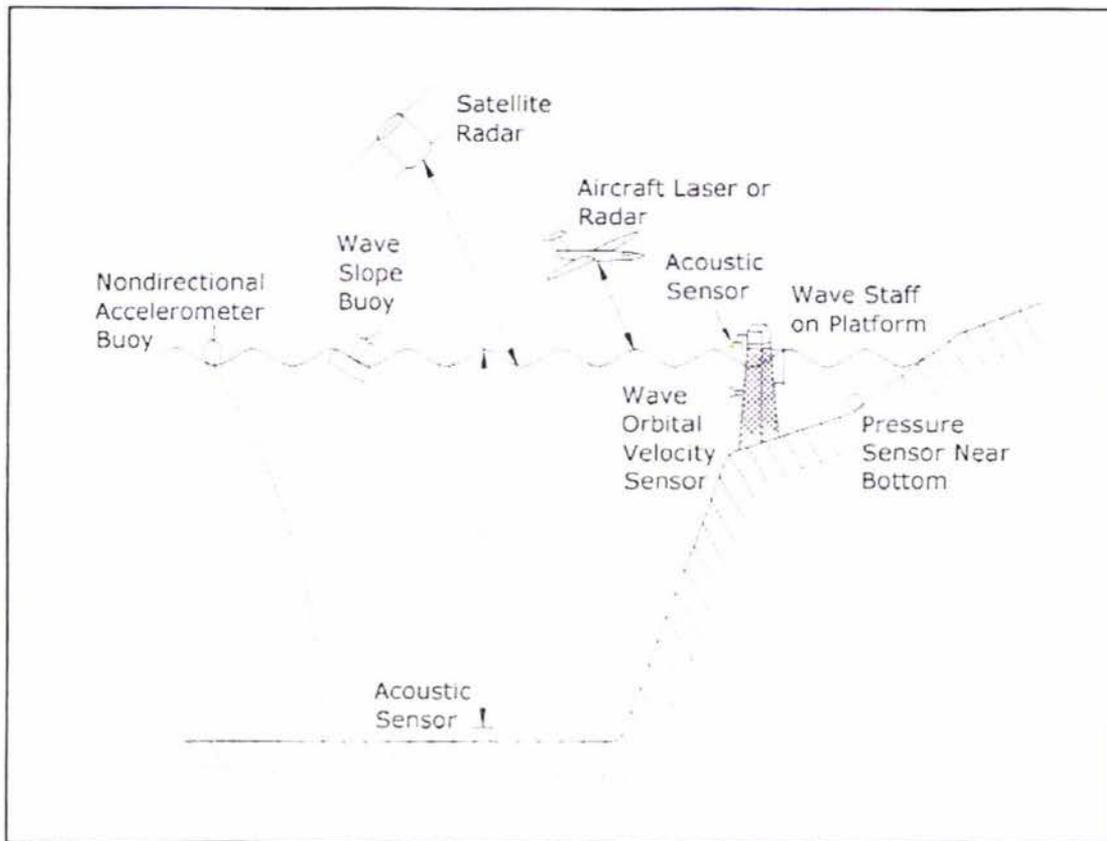


Figure 2.12. Schematic diagram of several types of wave measurement systems (Source: Brooks, 2004)

The cost of data collection is often the determining factor in the length of time a monitoring system is maintained. *In situ* deployment is the most detailed method of collecting wave characteristics; however it is the most expensive. Satellite records are obtained in conjunction with other oceanographic and environmental data collection. The initial cost of collected data from satellites and aircraft is high. However when the vast scope of coverage, and various avenues of investigation (environmental, military, commercial) are considered the costs become manageable. Passive remote sensing can provide localised long term records of wave characteristics for relatively low cost, and can be accurate for a number of applications when calibrated with *in situ* gathered data.

Capturing empirical data has in recent times become only part of the understanding of the ocean dynamics of a location. The data regardless of the method of capture, but with the associated errors and statistical assembly taken account of, can be utilised in order to validate wave creation, and transformation models. This

modelling can then provide information for a greater area, and longer time frame than *in situ* instrumentation. A fisherman with decades of time on the sea “knowing from experience”, could translate to the statement “validation of models from empirical data”. The fisherman’s knowledge and the validation of models have a commonality of a long period of time observing the ocean. What has changed is that “knowledge” has become mathematically expressible, and “experience” equates to systematic long-term measurement.

### **2.1.3.2 First and second generation wave prediction models**

Quantified understanding of how waves are generated has a long history beginning with the classic work of Kelvin (1887) and Helmholtz (1888). Many scientists, engineers, and mathematicians have since addressed various forms of water wave motions and interactions with the wind. It was not however until World War II that an organized effort was made to collect observational data (notably for the use and understanding of shoreline conditions for beach front invasion forces). This became the basis for empirical wave prediction formulae (United States Army Corps of Engineers, 2002).

The work produced by Munk and colleagues during the 1940s provided an empirical model that considered linear wave growth, wind strength, fetch and duration (Butt and Russell, 2002).

The Miles-Philips mechanism developed in 1957 is essentially the two-stage development of linear and exponential wave growth (section 2.1.1.) (United States Army Corps of Engineers, 2002). The action-balanced equation (also referred to as the radiative transfer equation) calculated wave heights from the two-stage development, the limit of height from overstep breaking (white capping), and friction. Equations using these functions are termed first generation (1G) wave models.

The phenomenon of energy transfer from wave-to-waves (rather than transfer of energy from wind to wave) was largely ignored in the 1G models, and was discovered in 1963 by Klaus Hasselmann. In 1973 Hasselmann and colleagues from the Planck Institute of Meteorology in Germany performed a large experiment called the Joint North Sea Wave Experiment (JONSWAP) showing the shape of the wave spectrum was similar in any growing sea (United States Army Corps of Engineers, 2002). This discovery enabled the compensation of the “ignored” phenomena of the

1G models with the addition of a process termed parameterisation. This second-generation wave model (2G) can be described as wave models utilising predetermined spectral “shape” (Komar, 1998; Young, 1999; Butt and Russell, 2002).

### **2.1.3.3 Third generation wave prediction models**

As increasingly more sophisticated 1G and 2G models emerged, Hasselmann invited researchers to Hamburg to investigate the possibility of a joint wave modelling group (WAM) to develop a third generation model. This was realised in the WAM Model in the mid 1980’s (Young, 1999).

One of the notable differences of 3G models is that there are no prior assumptions made as to the “shape” of the energy density spectrum. This allows a more realistic mimicking of the interactions of the atmosphere (in the form of winds and pressures) as well as the transformations described in sections 2.1.2.1 - 2.1.2.5. This is achieved by utilising the atmospheric conditions (either predicted or actual) of an area in the form of a grid as inputs to the models, (rather than a simple generating location with wave radiation outwards as in 1G and 2G models) to produce a wave spectrum.

With the rapid development of computing power from the early 1970’s to mid 1980’s, the WAM group was able to expand calculations and elaborate assumptions made in earlier of wave models. On going research is constantly refining the 3G models (WAM, WAVEWATCH, SWAN) often coinciding with the growth of computing memory and processing speeds (Butt and Russell, 2002; Young, 1999). The intricacies of the evolution of wave models and the development of the entities and assumptions within the model will not be covered further here.

Validation of the WAM model on a global scale has been the most extensive of any previous wave model and resulted in the deep-water wave climate data.

### **2.1.3.4 Transformation models**

The wave data calculated by third generation models (WAM) provides the basis for the second stage of identification of the wave energy resource. The spatial variation of wave energy as it transforms from deep to shallow water is required to identify the spatial dimension of wave energy. This calculated geographic information

provides valuable information as to the optimum locations for wave energy converter devices.

Transformation of waves to shore (section 2.1.2.1) is dependant upon the depth of the water. Simple planar bathymetry results in a simple refraction of waves (Fig. 2.13). Complex bathymetry is made up of ridges, canyons, and an undulating sea floor, and results in complex refraction, diffraction, and shoaling wave transformations. Modelling of these transformations, for any complexity of bathymetry, requires a matrix of interacting calculations including:

- shoaling, refraction, and diffraction;
- dissipation due to friction and percolation; and
- breaking.

For this study the wave model utilised was WBEND, being part of the 3DD suite of hydrodynamic dynamic models from ASR Ltd. The following is ASR Ltd's description of the 3DD suite from the model manual (Black, 2002).

*"WBEND is a 2-dimensional refraction/diffraction and longshore sediment transport model for monochromatic or spectral inputs over variable topography. The model applies an iterative, finite-difference solution to the wave action equations to rapidly solve for wave height and angle. Longshore sediment transport fluxes, bottom orbital currents, near-bed reference concentrations of suspended sediments, breakpoint location and breaker heights and angles are determined by the model.*

*The three dimensional hydrodynamic model 3DD has been used successfully in numerous studies around the world and in New Zealand. The model is a primary component of the 3DD Computational Marine and Freshwater Laboratory (©Dr. K. Black, 2000), which provides accurate and comprehensive simulations of a complete range of processes, over time scales of seconds to weeks. Based around highly accurate mixed Eulerian/Lagrangian mathematical techniques, the model 3DD provides state-of-the-art hydrodynamic and dispersal simulations. Developed and sustained by comprehensive field measurements and supplementary modelling packages, the 3DD suite has been validated to achieve an unprecedented level of numerical refinement.*

- *3DD is essentially five different models coupled into one fully-linked computer code dealing with:*

- *Side-view, 2-dimensional, 3-dimensional homogeneous and 3-dimensional stratified hydrodynamics*
- *Lagrangian and Eulerian dispersal models, including buoyant plumes*
- *Ocean/Atmosphere heat transfers*
- *"Boussinesq" short waves*
- *Radiation-stress wave-driven circulation*

*3DD is fully coupled with dispersal, sediment transport, oil spill and wave refraction and wave generation models so that model-generated information can be transferred within the suite to enable the world's most complex environments to be accurately simulated" (Black 2002).*

### **2.1.3.5 Summary of observation and prediction**

*Methods for the measurement of characteristics of waves have evolved with the technology to observe and predict the ocean's behaviour. Measurements are recorded for periods of time and statistically refined to produce uniform measures (i.e. peak period, significant wave height). Many techniques have been developed for this purpose often with the goal of providing accurate long-term information for as little cost as possible.*

*Wave modelling utilises the combined knowledge of wave generation from wind dynamics and wave propagation transformations, in both deep, and shallow water to predict wave characteristics for a particular area. These models require validation from in situ or remote sensed measurements.*

*Wave creation and transformation numerical modelling allows identification of the spatial variation of useful wave energy. Predictive models allow the identification of future (for up to days ahead) wave energy converter device outputs to be incorporated into the generation matrix.*

## **2.2 Wave energy resource assessment methodologies**

There are several methods for assessing the resource potential of locations for wave energy conversion, which vary from a simplistic general method using time-averages (a single value), to direct assessment of empirical real time captured records (possibly millions of values) obtained from an array of *in situ* and/or remote sensing

devices. The difference in these methodologies is the resolution variation in the spatial and/or temporal dimension.

The practicalities of energy conversion for a location require an inclusion of anthropocentric considerations. These include infrastructure for construction and maintenance, as well as connection to energy distribution networks.

Electrical energy demand is also a variable that changes in the temporal dimension (with peaks in the mornings and evenings, and changes with seasonal demand). A complete assessment will identify the wave energy of location occurring during these times of increased demand and be able to predict useful wave energy events, days into the future.

### 2.2.1 Time-average wave energy evaluation

The time-average method of wave energy evaluation (to be called in this report the General Method) is an often-expressed evaluation of wave energy. The global map in Fig. 2.14 is an often-reproduced example.

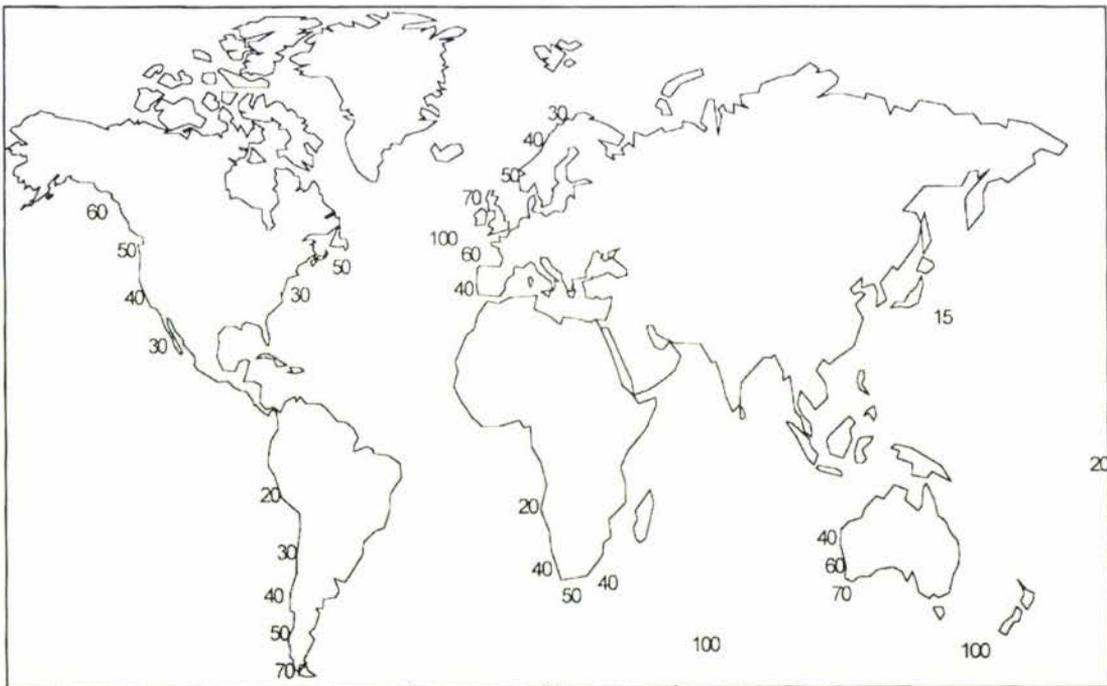


Figure 2.13. Approximate global wave distribution of time-average wave power in kW/m. (Source: Brooks, 2003)

The General Method utilizes three factors to determine wave power (P) (expressed in units of kilowatts per metre width of wave crest) (Özger *et al* , 2004)

$$P = 0.42 H_s^2 T_p \quad \text{Equation 2.6}$$

where  $H_s$  is the significant wave height (described in section 2.1.3.);  $T_p$  is the peak wave period for a measured sea state record and 0.42 is a non-dimensional wave spectrum coefficient representing the relative components of energy for the various frequencies of waves which may range between values of 0.3 and 0.5. The value 0.42 has been used here as it is the value expressed in an evaluation study produced by the Electric Power Research Institute (2003).

A more accurate evaluation of the energy that is also expressed as a single value is the energy flux derived from the wave spectrum section. Gorman *et al* (2003a) explains of this calculation as follows:

*“The wave energy flux is a vector, whose components are defined as:*

$$[P_x, P_y] = \rho g \int_0^{\infty} df \int_0^{2\pi} d\theta S(f, \theta) C_g(f) [\cos\theta, \sin\theta]$$

*where  $\rho$  is the density of water;  $g$  is gravitational acceleration, and  $C_g(f)$  is the wave group velocity. The energy flux is often referred to as the wave power. Both the vector energy flux and its magnitude  $P = \sqrt{P_x^2 + P_y^2}$  are computed, as well as onshore and longshore components.”*

The energy flux from each modelled or recorded spectra is then averaged to result in a similar wave energy resource assessment as can be calculated from the General Method.

This General Method, with a single value of kilowatts per metre of wave front for a location, has limited usefulness. Single values fail to appreciate daily, monthly, seasonal and climatic variations of wave energy. This method also fails to provide understanding of localised transformation of deep-water wave energy (hotspot identification), the likelihood and duration of a swell event (exceedance-persistence), as well as the predictability of swell generating climatic conditions (low pressure systems, storms) .

**2.2.1.1 Summary of time-average wave energy evaluation.**

*The Time-average wave energy evaluation (the General Method) provides a simple way of describing the energy of a location from averaged values of height, period, and a wave spectrum coefficient. This simple value has often been used to determine casual possibilities for wave energy utilisation but provides no concept of spatial wave energy intensification “hotspots”, or the temporal nature of wave energy.*

**2.2.2 Joint probability tables**

Joint probability tables provide a method of identifying the probability of two concurring variables, in this case wave height and wave period. This presentation of data is achieved through the analysis of time-coded populations of these two variables. The variables are classified into bins, usually of 0.5 – 1 seconds period and 0.25 – 1.0 metres height. These characteristics of height and period can be calculated in a number of ways (zero up or down crossing period, peak period, average wave height, significant wave height, etc) so correct identification of the characteristics is required. Table 2.1 shows an example of a joint probability table

**Table 2.1. Joint probability table of significant wave height (Hs) and peak period (Tp) for Muriwai. Twenty-year hindcast providing the data. Probabilities are expressed as percentages with totals of each height bin and period bin on the bottom row and far right column respectively. This table represent 90.45 % of the total yearly wave conditions.**

Hs (m)	Tp (sec)											Totals	
	6	7	8	9	10	11	12	13	14	15	17		
5.5	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0
4.5	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0
3.5	0	0	0.04	0.02	0.06	0.06	0.14	0	0.02	0.04	0	0.38	
3	0	0	0.28	0.56	0.46	0.34	0.44	0	0.18	0.24	0	2.5	
2.5	0	0.02	0.66	1.02	1.17	0.9	1.11	0	0.93	0.48	0	6.49	
2	0.18	0.72	1.72	1.15	1.92	3.25	2.3	0	2.58	1.07	0	14.89	
1.5	1.26	1.39	3.13	2.22	3.55	7.01	6.33	0	3.33	0.95	0	29.17	
1	2.46	0.97	3.24	3.67	9.48	9.39	5.58	0	1.69	0.54	0	37.02	
Totals	3.9	3.1	9.27	8.64	16.64	20.95	15.9	0	8.73	3.32	0	90.45	

This method of expressing the wave climate of a location provides for a greater indication of the nature of the wave resource. Using equation 2.6, the energy of each cell of Table 2.1 can be obtained. This energy value can then be multiplied by the percentage probability of these two characteristics, and the number of hours per year (8766 hours) to create a “kilowatt hours per metre wave front table” (Table 2.2).

Outputs can be produced for monthly, seasonal, or annual probabilities through temporal division of input wave height and period data.

**Table 2.2. Wave energy calculated from wave height and period from Table 2.1 above to show the kilowatt-hours per metre wave front, in each combination of wave height and period.**

kWh/m-year											
Hs (m)	Tp (sec)										
	6	7	8	9	10	11	12	13	14	15	17
5.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3.5	0.0	0.0	144.2	81.1	270.4	297.5	757.2	0.0	126.2	270.4	0.0
3	0.0	0.0	741.7	1668.9	1523.2	1238.4	1748.4	0.0	834.4	1192.1	0.0
2.5	0.0	32.2	1582.1	2110.9	2690.4	2276.5	3062.9	0.0	2993.9	1655.6	0.0
2	158.9	741.7	2025.0	1523.2	2825.6	5261.3	4061.8	0.0	5315.7	2362.0	0.0
1.5	625.8	805.5	2072.9	1654.0	2938.8	6383.3	6288.1	0.0	3859.3	1179.6	0.0
1	543.0	249.8	953.6	1215.2	3487.9	3800.2	2463.6	0.0	870.5	298.0	0.0

This use of kWh can then be used in conjunction with a Capture Width Ratio (CWR) matrix for particular wave energy conversion devices to determine an estimation of possible electrical energy outputs for a location. Wave energy converter devices have different CWR for each combination of wave height and period (section 3.1.4).

### 2.2.2.1 Summary of joint probability tables

*Joint probability tables provide a method to identify the probability of two concurring variables occurring, in this case wave height and wave period in a scatter diagram. These tables require a population of wave data collected over a long period of time (years). The energy per metre wave front for each of combination of height and period can be calculated and used to estimate wave energy utilisation. Wave energy converter devices have different efficiencies for each combination of wave height and period.*

### 2.2.3 Spatial wave evaluation

Ocean waves transform as they travel over the seabed towards shore. Wave transformation models simulate the variation in wave characteristics by applying interactive formulae to the wave heights across a specified area of the coast (from the continental shelf to shore). These models provide an output of grid (raster) coverage for these locations of wave height and direction (period remains constant as waves transform) and can therefore be used to calculate wave energy (using the general

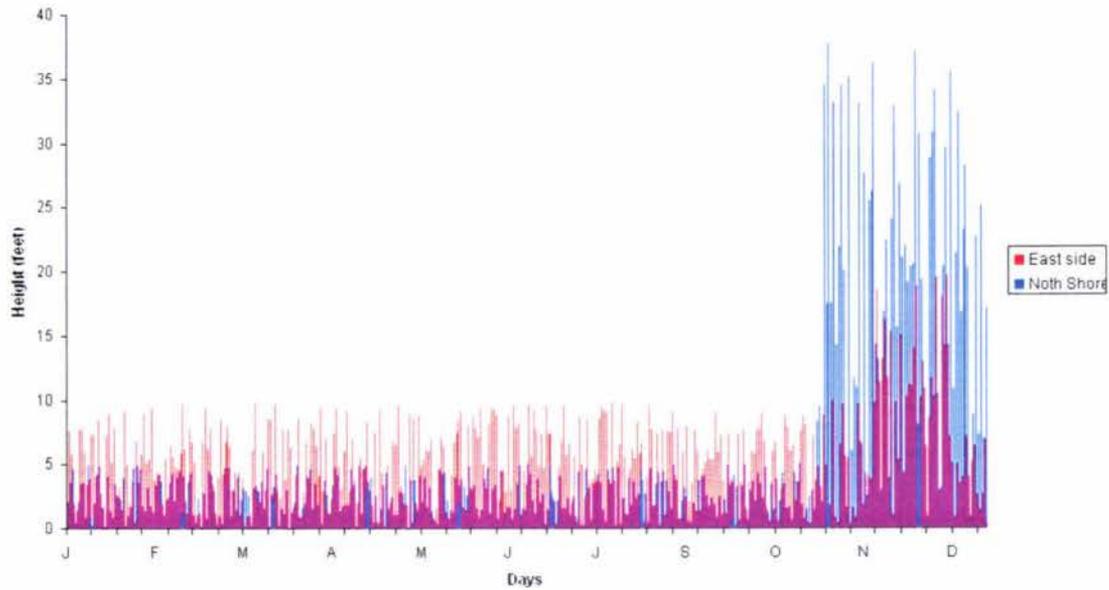
method calculation, equation 2.6). The output of these models requires geo-registration in order for the areas of wave energy to be related to other anthropocentric entities (the national electricity grid, maintenance location, shipping channels, ports etc). Validation of a model output is highly recommended through the comparison of *in situ* wave measuring instruments. For this study, due to financial limitations, *in situ* validations were not performed.

General wave energy evaluation methods assume that the wave energy in shallow water is less than the offshore climate. This generalisation ignores the process of refraction and specifically the phenomena of wave focusing where energy can be increased significantly. These locations are referred to as “hotspots” (Pontes *et al*, 2003; Electric Power Research Institute, 2003a and 2003b; Brooks, 2003). Combination of various transformation model iterations referenced to the temporal characteristics of wave energy events of a wave climate hindcast (percentage probability of occurrence); will assist in the locating of hotspots. Matrices showing the location of weighted average wave energy of a section of ocean adjacent to a coastline can then be used for further wave energy resource assessment and anthropocentric considerations. A more detail description of the process of creating hotspot maps is provided in section 5.1

#### **2.2.4 Temporal wave evaluation**

The temporal nature of wave energy (seconds, hours, days, seasons, and multi year climatic events such as *El Niño*) means that the general resource assessment of wave energy using averaged values of a deep-water environment is not acceptable when creating a realistic evaluation of how wave energy might contribute to the energy requirement of a location. Butt and Russell (2002) provided an example when discussing the average wave climate of the North Shore of Oahu, Hawaii. This location is described as having wave heights of no more than 0.6 m for the majority of the year, but in excess of 6.0 m for a few weeks of the year, during the Northern hemisphere winter. This would of course result in an average of 1.5-2, which provides little information for the determination of suitable wave energy conversion locations (or places to travel to surf waves, the context of Butt and Russell’s (2003) discussion).

The difficulty in representing the temporal dimension of wave energy is what has motivated the use of averages. The General Method of wave energy resource analysis is often produced from the average of significant wave heights which can be exceedingly misrepresentative (Fig. 2.15).



**Figure 2.14. Idealised wave heights for Noth and East aspect coastlines of Oahu Hawaii , USA. Average wave height is less for the North Shore than adjacent East Side notwithstanding large seasonal swells. (Idealised example from James Frazerhurst's personal observation)**

By identifying times within wave climate data when there is an exceedance of wave energy, and identifying the persistence of wave energy, an attempt can be made to address the temporal nature of wave energy. The reason for the identification of exceedance and persistence is due to the ability of conversion devices to provide full capacity of output when higher energy events are in effect (Brooke, 2003). The ability to assess the potential temporal outputs of a wave energy conversion plant allows for a determination of the likelihood that energy output from an installed device will match daily demand fluctuations (i.e. if a wave energy device will output at full capacity for 50 hours it is likely those fifty hours will correspond to two peak evening electricity demand periods). The detail available will be limited to the temporal resolution of the wave climate data (i.e. three hour intervals).

### 2.2.5 Wave forecasting

A disadvantage of some renewable energy sources is the intermittent fluctuations in the primary “fuel” supply. This leads to an uncertainty of the capacity and availability of these generation methods compared to biomass or non-renewable energy sources such as the combustion of fossil fuels. Waves have a greater predictability than other renewable energy sources, particularly wind and solar energy (Twidell and Weir, 2000). Forewarning of wave energy events to a location of conversion devices will mean that several advantageous processes may be possible. These include;

- assessment of the following day(s) wave energy generating capacity, and the contribution possible to a grid;
- pre-tuning of conversion converter devices; and
- scheduling of maintenance of devices.

The electricity market place in New Zealand has the ability to sell energy with up to two hours notice. It is conceivable that a combination of a predictable wave power plant, a hydropower station, and /or thermal plant may be beneficial to maximise not only the power from the renewable marine source for financial gain, but also the opportunity cost of preserving the hydro lake levels or fossil fuel stocks. “Mighty River Power Ltd” identified a prediction time frame of two days certainty as most advantageous for a mix into a wholesale supply market (Jewel, 2004).

Wave energy events can be predicted using wave-forecasting models whose effectiveness is dependant on the stability of the pattern of atmospheric conditions where the waves are generated (Komar, 1998; Gorman *et al*, 2003a and 2003b). This predictability can be evaluated by comparison of daily predictions with a present or “now” forecast. This comparison (provided that the model has an established validation history) means that rather than an evaluation the model’s ability to predict wave characteristics, the predictability of an aspect of coastline, and its associated low-pressure systems, is assessed. This is an important point as the waves generated represent an “echo” of the activity in a section of the ocean. The ability to predict the waves from a location represent the predictability of the climatic conditions of that particular section the ocean and hence the ability to predict output of a wave energy converter plant.

### 2.2.6 Summary of spatial, temporal wave evaluation and wave forecasting.

*Wave energy is not evenly distributed especially in shallow water where processes of diffraction; refraction and focusing can create “hotspots” of intensified wave energy. Hotspots can be identified using wave transformation modelling. The outputs of these models can then be manipulated to provide the location and intensity of hotspots relative to other factors both natural (bathymetry, sea bed geometry, whale migration routes, etc), and infrastructure (ports, shipping lanes, marine protected areas, electrical grid nodal points. etc).*

*Average wave characteristics provide misleading evaluation of the potential energy output from energy converter devices. Identification of the probability of exceedance and persistence can provide a greater evaluation of convertible energy potential. The temporal evaluation of wave energy is limited to the resolution of a wave hindcast.*

*Average wave characteristics provide misleading evaluation of the potential energy output from energy converter devices. Identification of the probability of forecasting wave energy supply to an electricity grid can provide a greater evaluation of convertible energy potential. The predictability of wave events for a location can be evaluated through comparisons of predicted and present wave characteristics.*

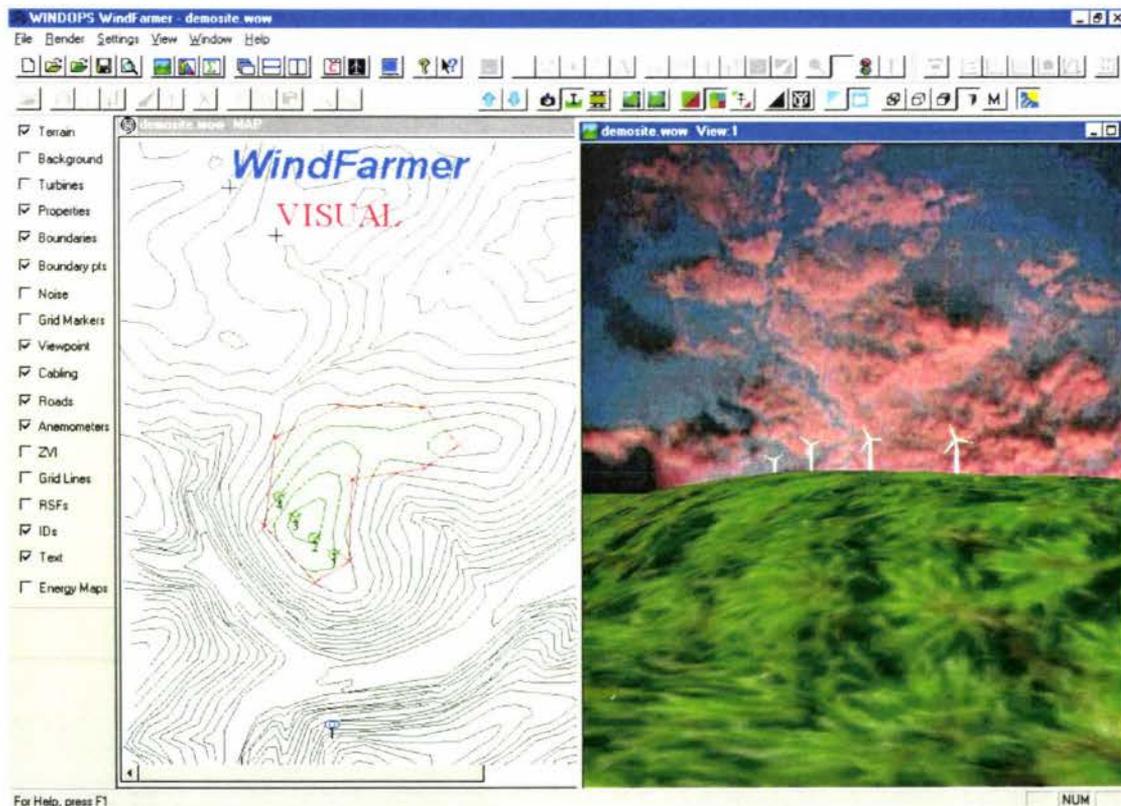
### 2.2.7 Geographic Information Systems (GIS)

“What is GIS? An organized collection of computer hardware, software, geographic data, and personnel designed to efficiently capture, store, update, manipulate, analyse, and display all forms of geographically referenced information.” (ESRI, 2005)

GIS is far more than computerised cartography it can be thought of as the high-tech equivalent of a map. It is the storage of data in an easily accessible digital format enabling complex analysis and modelling. (DeMers, 2000; Longley *et al*, 2001). GIS has the ability to overlay map objects with digital information and combine these data in a multitude of ways to answer various questions.

Natural energy flows are associated with geographic information. Rivers, areas of intensified wind flow, solar variations of aspect and atmospheric clarity, geothermal fields, coastal tidal movements, and ocean waves all have geographic peculiarities and characteristics. Development of electricity generation plant that utilises these decentralised energy resources must analyse the resources spatial characteristics for optimal energy extraction. Planning must also analyse other broader spatial information of the physical and human environment.

An example of this analysis and planning is the siting a wind farm project. Spatial locations of high wind speeds can be modelled and identified providing hectares of potential sites. These potential sites are reduced by such factors as the practicalities of transmission lines, and the recommended distances between turbines. The geographical spatial characteristics such as visual concerns, noise, land use, radio interference, potential for bird strike, will all further reduce the potential turbine sites. Garrad Hassan (2005) has combined these spatial elements into commercial software GIS package called “Wind Farmer” (Fig 2.16) that is able to integrate many and varied spatial features associated with wind farm developments.



**Figure 2.15.** Contour map and perspective visualisation output of GIS Wind Farmer (Source: Garrad Hassan, 2005)

The identification of optimal ocean wave energy hotspots (section 2.1.2.1.) as spatial data will allow for the potential to combine other spatial features for analysis in a GIS. This analysis will determine the usefulness of the wave resource to electricity generators.

#### **2.2.7.1 GIS architecture.**

The decision as to which GIS software should be utilised for each stage of the wave energy resource assessment will largely be a component of the practicalities of the user / software interface. Although it may be possible to use a single GIS architecture to create the total resource assessment, access to GIS components, file formats for models, simplicity of repetitive tasks, and accesses to tutors or tutorials have meant a number of GIS tools are used. The reasons for each tool used will be explained in the relevant data assessment (section 5).

#### **2.2.7.2 GIS and wave energy assessment.**

The modelling of wave energy by 3G-wave models (WAM, SWAN, 3DD) can be carried out using bathymetric matrices and various spatial information. These matrix manipulations are conducted upon architecture devised for matrix manipulation (Matlab). Output from these wave models is then required to be geo-registered (the process of adjusting one image to the geographic location of a “known good” reference image, surface or map) in order to be compared with other spatial information. Whilst it may be possible to combine these operations using a GIS, at present, the speed and simplicity of separating specialist operations requires the use of several software architectures.

In literature the spatial variability of wave energy and assessment of intensified location hotspots has received no more than acknowledgment that the use of wave transformation models would be useful. Combination of model output upon GIS has obvious advantages compared to other digital spatial input, most notable the ability to analyse the hotspot locations with infrastructural considerations.

#### **2.2.7.3 Summary of GIS.**

*GIS has the ability to combine digital data for analysis. The spatial nature of renewable energy resources means that GIS able to effectively assess the potential*

*and practicalities of resource utilisation. Digitised resource information is then able to be evaluated in the context of other anthropocentric requirements. Wave energy has a spatial variation where areas of intensification (hotspots) require locating and evaluating. This spatial element of wave energy resource assessment can then be combined with other natural and anthropocentric geographic features to help make decisions about utilisation of the resource.*

## **2.3 Renewable energy systems**

Wave energy has a number of commonalities with some other renewable energy sources both in terms of benefits and barriers to utilisation. There also a number of factors, which distinguish wave energy from other renewable energy sources. This section will briefly cover some of the benefits and barriers of generic renewable energy technology and utilisation.

### **2.3.1 Common benefits**

Benefits from the use of renewable sources of energy to displace non-renewables (hydrocarbon fuels), can include:

- a sustainable energy future;
- less environmental impacts (particularly reduced CO<sub>2</sub> emissions);
- distributed generation of energy and security of supply; and
- cost effective energy supply.

The subject of “beneficial reasons for the adoption of renewable energy sources” penetrates into almost every facet of modern society.

#### **2.3.1.1 Sustainable development, Sustainable energy**

The principles of sustainable development require an understanding of the interrelated actions and reactions of all activities, both in spatial and temporal extents. They can be explained by:

- inter-generational equity;
- intra-generation equity; and
- trans frontier responsibility (Selman, 1996; World Commission on Environment and Development, 1987)

Inter-generational equity means that following generations should inherit the Earth with a value equal to that which the present generation inherited (World Commission on Environment and Development 1987; Selman, 1996). Disregard for this principle can be found in the human induced extinction of species such as the Tasmanian tiger, dodo, moa, etc

Intra-generational equity can be thought of as a social justice requiring development to consider basic human needs of clean water, nutritious food, and shelter. Other expectations and rights are often included which relate to an expected quality of life (WCED, 1987; Selman, 1996). Disregard for this principle can be found in the numerous health problems in the developed world due to excessive food intake, and the chronic malnutrition in many areas of the developing world.

Trans frontier responsibility acknowledges simply that the advantage to a spatial location should not be at the expense of another location. Division of locations of development upon the Earth's surface is often expressed in terms of political boundaries relating to regulatory authorities. This principle expresses the understanding that ecological, biological, and geographic phenomena are oblivious to these human induced distinctions (Selman, 1996). Astronauts gazing over this blue world quickly identified human induced damage that crossed invisible political borders (Kelly, 1988). An example of neglecting the principal of trans frontier responsibility is the neo-liberal practice of creating a market for pollutants (Clapp, 1994). This inevitably leads to a concentration of solid, gaseous, and liquid waste in areas (neighbourhoods, provinces, states, continents) of lower socio-economic value. This movement of waste and the subsequent spatial concentrations has been dubbed "environmental injustice" or, due to the exciting racial divisions between the areas of waste movement, "environmental racism" (Pulido 2000).

These principles, when analysed, can be connected to matter and energy laws fundamental to the activities of everything in the universe and hence known as natural laws (Common, 1995). The essence of the first energy law states output cannot exceed input (you can't get something for nothing). The second law reasons that any energy transfer will always encounter losses. Therefore the theoretical "breakeven" (same output as input) that the first law implies, is not possible. The law of conservation of matter tells us that that matter is never created nor destroyed only

transformed. Hence it is impossible to dispose of matter, and every thing must go somewhere. (Tyler-Miller, 1980)

The utilisations of renewable energy systems that divert natural energy cycles in a manner that has minimal impact are, by definition of the above laws and principles, sustainable. This is not to negate the cause and effect scenario of these laws and it must always be appreciated that damming rivers, and construction of large wind turbines or wave energy converters will also have negative impacts somewhere. However making these impacts a single “one off” pressure, rather than an ongoing negation of the environment (mineral store, atmosphere), and maximising the efficiency of these energy diverting mechanisms, makes renewable energy close to sustainable energy. A rational disconnected view of the civilization’s energy requirements at all scales (local to global) would place high priority on the development and implementation of sustainable energy.

### **2.3.1.2 Avoiding CO<sub>2</sub> emissions**

The release of carbon to the atmosphere in the form of carbon dioxide from the combustion of fossil fuels (petroleum, coal) exacerbates a process called the “greenhouse effect”. This effect is connected to major environmental changes collectively referred to as (human induced) climate change. Climate change has been discovered to be a constant process across all of geologic history resulting either in a heating or cooling the atmosphere. The concern with present increases in temperatures is the rate at which that change is taking place.

The removal of hydrocarbon’s from the Earth, combusting them, and releasing carbon to the atmosphere has taken place over a far shorter time frame than would have occurred naturally. The carbon extraction / emission are due to the use of hydrocarbons for energy. This is why climate change is referred to as a human induced environmental effect. The removal of hydrocarbons from the Earth for combustion is a one way, unsustainable activity. The build up of atmospheric carbon concentration is one result of this unsustainable activity

The use of sustainable energy that has no greenhouse gas emissions is therefore a logical answer to the problem of climate change. Implementation of policy to encourage renewable energy, however, is significantly more complex.

One of the major advantages of hydrocarbon's as an energy fuel is the high density of stored energy. This has resulted in the economic, social, and physical infrastructure of these fuels becoming entrenched in the growth and accelerated development of the last one hundred and fifty years. The introduction (and sometimes reintroduction) of less dense, variable, zero greenhouse gas emitting, sustainable energy sources is therefore not a simple exercise.

### **2.3.1.3 Distributed generation**

The term "distributed generation" (DG) refers to a system where the generation of electricity (typically small scale) takes place at a number of decentralised locations either islanded, standalone or within an electricity grid. DG is typically now referred to in terms of small niche generation systems located close to demand (Centre for Advanced Engineering, 2003). DG has been highlighted recently in New Zealand due to the possibilities of localised generation in remote locations faced with uncertainty of grid supply following a change in the financial and legislative environment due on 1 April 2013 (Jayamaha, 2003). After this date line companies will be no longer obligated to continue to supply and service uneconomic electricity lines.

The possible energy contribution that will be demonstrated by this study is similar in nature to that which is presently (and increasingly) made by wind farms (wind turbine arrays) and /or community based generation facilities. DG has the capacity to provide several advantages including security of supply through diversity of generation fuels, increased value of transmissions lines to areas of low demand, additional capacity of network for peak loading (Jayamaha, 2003).

### **2.3.1.4 Cost effectiveness.**

It is an irony that for an energy source whose fuels are effectively free and often ownerless, the costs of generation and distribution of renewable energies are presently far greater than traditional energy systems such as oil.

Gains in efficiency and reduced cost of plant are expected to increase the effectiveness of renewable energies. This has already been realised in part, by the mature renewable technologies of hydro, wind, geothermal and biomass.

The development of, so called, traditional non-renewable fuel sources (hydrocarbons) has been the product of over one hundred and fifty years of developments, as well as continued subsidisation and financial bolstering. The comparatively low levels of effort that have been devoted to renewables to date have however procured devices and systems that do compete. The advancement of wind energy for example has resulted in large turbine capacity and lower costs of outputted electricity (table 2.3).

**Table 2.3. Comparison of wind energy turbines and relative (Sims, 2004)**

Year	Capacity	Price NZ\$ /kW
1988	55 kW	\$2600
1992	225 kW	\$2100
1997	660 kW	\$1700
2004	5000 kW	\$1500

As renewable energy technologies reduce in cost, and improve in reliability and efficiency, the true cost of unsustainable energy is becoming apparent and factored into use. This is accomplished through either “carrot” or “stick” measures including taxation of pollution, factoring of mitigating into development, and the use of carbon credit markets. These initiatives are levelling the energy generation economic playing field, a process that is realizing the competitive advantage of sustainable renewable energy supply.

### **2.3.2 Common barriers**

A lack of understanding of renewable energy and the multitude of disciplines involved can often be sited as one of the greatest barriers to the development of renewable energy sources (Twidell and Weir, 2000). This multi disciplined requirement means that any of the “parts” that are required for development (public policy, physical geography, geophysics, statistical analysis, project management, etc) may produce a weak link if not approached in the correct manner. Several of these “parts” are currently at substandard levels and are considered barriers to the uptake of

renewable energy, in comparison to non-renewable energy sources. These barriers include:

- NIMBYism;
- lack of political far-sightedness; and
- greater economic risk (at present).

### **2.3.2.1 “Not in my back yard” (NIMBYism)**

The siting of infrastructure, change of use of adjacent lands, or the construction of industrial plant have all become prey to the phenomenon known as NIMBYism. This phenomenon refers to the objection of nearby land occupiers at the proposal of one of the aforementioned activities. The quantifier “I realise this is important for the country/community /economy/ but just not in my back yard.” is often referred to.

This is a difficult barrier to renewable energy development. Opposition to proposals can become very prominent in a short space of time. Misinformation and accent upon the negative are common denominators. The news media appear to thrive on conflict and may deliver a disproportionate amount of attention to what might ultimately be a small minority who may actually have no basis for complaint due to no direct effect upon them as a concerned party. The feeling of grievance is maybe the only uniting factor for a NIMBY group, therefore resolution of grievance is an impossibility as this would remove identity.

### **2.3.2.2 Resource consent in New Zealand**

The New Zealand Coastal Policy Statement (1994), Treaty of Waitangi (1840) claims to the Waitangi-Tribunal, combined with highly contentious Foreshore and Seabed Act (2004) mean the process of gaining consent for development in the marine environment requires significant planning and development in its own right.

The planning structure in New Zealand and the Resource Management Act (RMA, 1991) can result in many and varied machinations of the relationship between developers and stakeholders. Development in New Zealand’s coastal and ocean environment has become significantly politicised and emotional over the past decade. These various interactions will not be expressed further in this report. However it is noted that resources must be allocated at the beginning of a project’s instigation in

order to inform, be accessible, and foster goodwill. A real and true effort must be made to “*avoid, remedy, or mitigate*” (RMA 1991) any adverse effects, and be prepared to accept the stakeholder’s interpretation of what are the effects.

### **2.3.2.3 Governance**

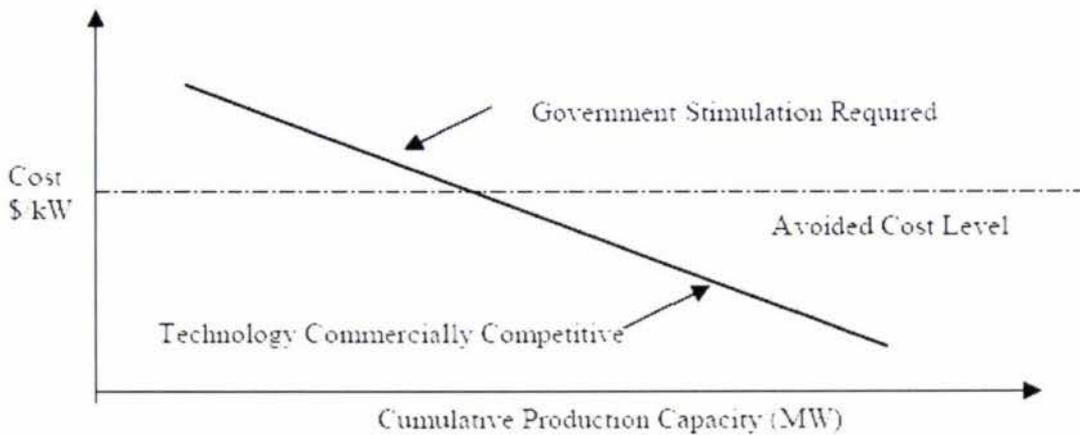
*“Policy Statements could be required to give Regional Councils a new framework for decisions. Developers observe that it is far easier to obtain resource consents (and there is less public opposition) for combined cycle gas turbine plants than for hydro or geothermal developments.”* (East Harbour Management Services Ltd, 2002). This statement is a demonstration of the current state of governance for renewable energy development as well as the public position outlined in section 2.3.2.1. Policy statements are a mechanism to direct Regional Government in matters that have national significance. This lack of a direction in dealing with the development of sustainable renewable energy has resulted in the barriers being greater than for unsustainable energy developments. Cohesive, far sighted, investigation of the barriers regarding sustainable energy, and the opportunities for governance to help overcome these barriers would provide for and address this imbalance.

### **2.3.2.4 Economic risk**

Development requires capital from investment. Investment requires a return which competes with other investment opportunities. There are risks involved with all investment and it is expected that for higher risk investments the returns will be greater. Capital also requires a degree of foresight not necessarily related to the risks involved with an investment, but with the present and future values of capital. It is the combination of all of these factors which provides the basis for any investment of capital.

Investment in renewable energy technology is considered a greater risk than some other investment opportunities due to the short length of time most renewable energy technologies have been in existence, low historic returns on investment and relatively high capital investment. In addition several renewable energy options that looked promising for commercial development, have since become unsuccessful (hot dry rock geothermal energy and solar thermal engines). Several renewable technologies that are considered to have made significant progress to

commercialisation have only recently become attractive to investors. This comes at a stage of technology development when the capital (relative to the initial development) is low. It is for this reason that investment by government is sought early in the development (Fig. 2.17).



**Figure 2.16. Cost (\$/kW) of renewable energy technology with cumulative production capacity (MW) and the involvement of government funding to realise commercial equality. (Source: Electric Power Research Institute, 2004b)**

Government's investment in this type of venture also requires a return but it is far less tangible than pure economics (although financial benefits are often calculated in secondary effects). This also means that funding at the project level can become highly politicised.

Perceived risk is also heightened when a project suffers catastrophic failure. This failure often intensifies pressure on projects that, although technically different are considered to be related through similar resource utilisation or location, i.e. wave energy failures impacting upon tidal currents projects. This is found in the East Harbour Management Services' report (2002) where wave and tidal options were omitted because "wave power developments in other countries have met with notable failures in recent years" it was however recognised that "some uptake may occur in future but will have to await renewed investor confidence on the international scene."

### **3 Wave energy converter devices**

The variation in present converter devices designs can be attributed to several factors, none greater than the peculiarities of the wave energy resource itself. Ocean waves are complex energy mediums with variations in all three dimensions as well as at several magnitudes of time (seconds, hours, and seasons). Ocean waves also experience variation due to interaction with the ocean floor, interaction with ocean currents, and the characteristics of low pressure systems and storms (section 2.1.1.). An understanding of ocean waves in both the temporal and spatial scale is required to assess the scope and applicability of this energy source.

Wave energy converter devices have a colourful and long history of invention (Ross 1995). Commercialisation (the taking of an invention from concept to mature product or service) has not taken place to date. Methods of conversion are many and varied with over 1500 patents existing for such purposes (Sanders *et al*, 2004). No devices, at this time, convert energy at what is considered a commercial level by the energy industry. Review of many of the inventions shows a lack of understanding of the wave resource and the characteristics of high-energy ocean environments.

This lack of understanding has been most dramatically demonstrated in the destruction of two full-scale prototype devices (the Kvaerner Oscillating Water Column (OWC) and OSPREY OWC (Ross, 1995)), and under performance of other devices (LIMPET OWC) (Whittaker *et al*, 2003).

The Kvaerner OWC was a Norwegian device that consisted of a steel tube bolted to a cliff and a “bi-directional airflow” turbine. The device was damaged in a storm shortly before Christmas 1988. No effort was able to be made in addressing the damage of the storm due to the holiday season. A second storm (few days later) completely destroyed the device.

The OSPREY OWC was a large steel structure constructed by Wavegen of Scotland. Towed to its intended location, partially submerged during inclement weather and subsequently damaged. During an attempt to tow the device back to shore it was destroyed (Ross 1995).

Wavegen also constructed the LIMPET OWC on the Scottish island of Islay in 2000. Although it continues to produce electricity to this day is being down rated from a capacity of 500 kW to 250kW. This is due to a section of reef eighty metres seaward of the device that causes the waves to break. This dissipation of wave energy does not allow the full force of the wave climate to interact with the device. A simple observation of the waves or a depth survey of the seabed in front of the device prior to installation would have highlighted this obvious folly.

Experience gained from these prototype devices provide ruthless lessons in the standards demanded of an environment circumvented, or avoided by engineering endeavours throughout human history (United States Army Corps of Engineers, 2002). A greater respect of high-energy ocean environments is demonstrated in the vigorous and systematic processes applied to current development, particularly the Pelamis program from Ocean Power Delivery Ltd (Yemm *et al*, 2004) that was described by Rob Rainey of structural and mooring independent verification engineers WS Atkins' at the Fifth European Wave Energy Conference (Rainey and Yemm, 2003) as being "more intense than development of commercial aircraft" (a service WS Atkins also performs).

### **3.1.1 Extreme waves and survivability**

Significant wave height (section 2.1.3) provides a method of classifying waves useful for the calculation of wave climate. The possible energy that might actually be encountered in the real ocean by a device is magnitudes larger than the averages calculated by the significant wave height (Komar 1998). The design of devices requires a balance of being "visible" to low wave energy to maximise the energy available for transformation and curtailing the abundance of energy from very large waves. Pelamis utilises a complex process termed "hydrostatic clipping" that can simply be described as "ducking" through swells using the orbital motion to negate much of the excess energy. This process is not dissimilar to how paddling surfers are able to pass through large waves without being thrown shoreward.

There are methods that can be used to identify the return period of extreme wave events. These however are used to identify extreme wave events based on the wave climate and do not pertain to individual single waves. Single waves several

times larger than the preceding and following waves have been recorded may times but are completely unpredictable (Komar 1998). Survivability and the ability to manage extreme single waves must be a primary design objective, no matter where the device is expected to be deployed.

### **3.1.2 A plethora of devices**

There are a number of proven methods of power generation from wave energy all very different in their fundamental methodology. Devices differ in their method of reference (self referencing, to the seabed, or to the shoreline), as well as the motion (heave, pitch, and surge), which drives power take-off (Hagerman, 1995; Thorpe, 2000; Brooke, 2003). Each type of wave power generation design can be multiplied by the motions (or combined motions) of the waves themselves leading to a very large number of potential designs

A comparison to the wind energy industry shows that there was a similar multitude of conversion devices proposed in the early 1970's when the industry was in its infancy (the darrieus rotor, screened paddle wheel, cupped vertical, counter-rotating bladed, single bladed, double bladed, three bladed, etc). The commercially successful design of a single tower, three bladed, horizontal axis, direct drive, turbine is now accepted. For wave energy one design may ultimately provide the efficiency, durability and cost effectiveness required of a commercial system for electricity generation (Brooke, 2003). Deciding which design will become the successful device for this purpose is very difficult (or impossible), at the present stage of development. Several designs are awaiting technology breakthroughs in similar or conjoined fields (linear generators, kinetic control systems, distributed generation, and the hydrogen revolution) (Thorpe, 2000).

Evaluation of different devices is becoming standardised with the release in 2005 of a standard by the European Marine Energy Centre, a product of their Orkney test site. The purpose of this standard is to provide a uniform methodology that will ensure consistency and accuracy in the measurement and analysis of power performance of ocean wave conversion devices. This is a first step on the road to enabling the comparison of vastly differing designs by stakeholders (European Marine Energy Centre, 2004).

Many designers of energy conversion devices contemplated a design in the context of an overly simplistic sea state. This approach has resulted in numerous devices which are ludicrously inadequate to meet the complexities and volatility of the ocean and her many moods. The lack of formal criteria of completed devices and a deficit of ocean awareness, as well a desire for speedy results and pressures of funding agencies, has resulted in what are evolutionary dead ends. Many of these devices have not progressed past drawing or scale model stage and of those that have progressed further (notably OWC) and have had spectacular failures with complete disaster and destruction, or significant underperformance (Ross, 1995; Thorpe, 1999; Cle'ment *et al*, 2002; Brooke, 2003; Whittaker *et al*, 2003). These under achievements have provided useful lessons for most every aspect of the wave energy industry (funding, development, deployment, marketing etc), even if the lesson is simply "what not to do".

The maturity of the wave energy industry can be expressed as pre-commercial or prototype level. Brooke (2003) used the analogy of the development of new energy production methods as that of personal development, with wave energy in its infancy, wind energy as a teenager, and conventional energy as an adult (Brooke, 2003).

Hagerman (1995) identified twelve distinct process variations, (Fig. 3.1). The main features that distinguish one process from another are mode of oscillatory motion for energy absorption, type of absorber, and type of reaction point. Energy can be absorbed from heave (vertical motion), surge (horizontal motion in the direction of wave travel), pitch (angular motion about an axis parallel to the wave crests), yaw (angular motion about a vertical axis) or some combination of these motions. Absorbers can be fabricated from rigid or flexible material, or can be the free surface of the water itself. Reaction points can be inertial masses (suspended plates, buoyant spines, or other absorbers), sea-floor anchors (deadweight or pile), or fixed, surface-piercing masses (concrete or land). Brooke (2003) introduced two additional types; a "Floating articulated cylinder with mutual force reaction", and "Submerged pulsating -volume body with sea floor reaction point". The "Pelamis" and the "Archimedes Wave Swing (AWS)" (AWS BV, 2005) represent these two types.

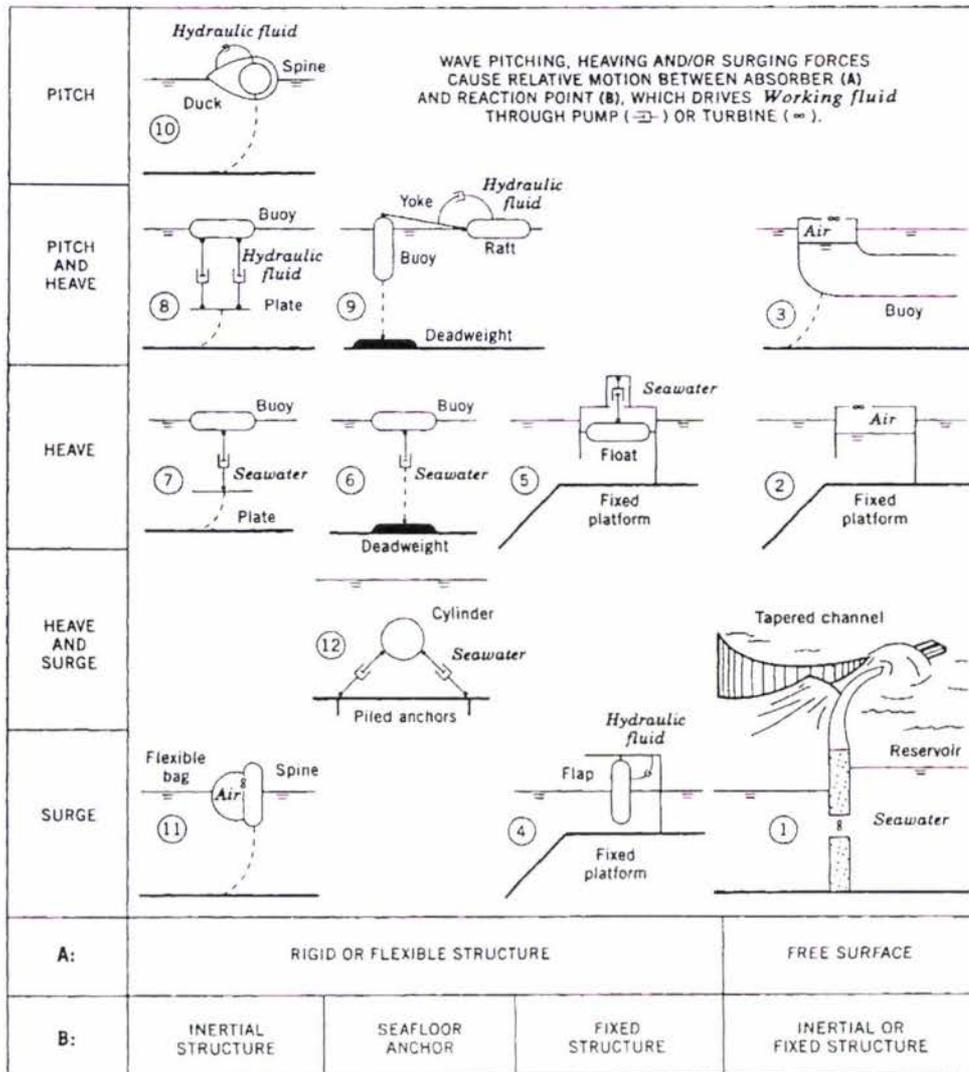


Figure 3.1. Classification of ocean wave energy conversion processes based on mode of energy absorption (pitch, heave, surge or combined modes), type of absorber (A), and type of reaction point (B). (Source: Hagerman 1995 in Brooke 2003)

### 3.1.3 Device development

Several organizations plan or have constructed scale model and full size devices. These each attempt to convert energy through utilization of different power take off mechanisms each attributed to differing aspects of wave characteristics (i.e. surge, heave, pressure etc). For all devices the efficiency of energy capture will vary with regard to the resonance of the device agreeing with the period of the ocean waves. These result in the relative efficiency of energy capture per metre of wavelength varying with the period of the waves input thus creating a “capture efficiency curve” for each device. The capture efficiency curve can be varied for most devices to best match the sea conditions encountered either through the physical

dimensions of the device during initial design (thus constructing a device for a specific ocean environment), or a flexible variation which may be altered to match maximum capture efficiency at a temporal scale of up to seconds before waves are encountered (hence a kinetic, real-time, informed, control system) (Falnes, 2003). Other devices interpret the sea conditions from swells that have recently been encountered and adjust accordingly (Brooke 2003).

The ocean wave energy converter industry has, to date, found it somewhat difficult to:

- ascertain the time required until unassisted commercial development;
- realistically identify costs involved; and
- identify developmental leaders.

These difficulties may be due to a number of factors including:

- regional bias of review organisations (a European tertiary educational institutional design and funding ethos (Pontes *et al*, 2003), a market led incubus in the Americas, Asian countries lack of international collaboration);
- commercial sensitivity reducing information sharing; and
- a lack of standardisation of performance factors of devices.

To date several device development programmes claim to be significantly advanced towards the commercial stage of development. There is a tendency to fail to identify the “down side” of an emerging technology (Sanders *et al*, 1998) which may account for the misidentification of leading devices in previous financially based evaluations of wave energy. Systematic vetting of conversion devices with an expert knowledge applied to all expected areas of wave energy integration (marine structure requirements, seabed cable practicalities, the electricity market, distributed generation practicalities, marine environmental impacts, risk assessment, human resource requirements, health and safety, etc) will provide a rational identification of devices that could make a future contribution to energy supply.

### 3.1.4 The Capture Width Ratio (CWR)

Attempts are presently in place to explain and standardise the “efficiency” of devices using capture width ratio (CWR), a dimensionless ratio that can be calculated by

$$\text{CWR} = P_{\text{abs}} / (J \times D_y) \quad \text{Equation 3.1}$$

Where  $P_{\text{abs}}$  = power absorbed by the device (kW)

$J$  = incident power of the sea state (modelled or actual) (kW/m)

$D_y$  = the cross-wave dimension of the device (m)

This is a useful measure to compare devices of various sizes in terms of physicality and energy conversion and comes about due to a lack of published and standardised details of power production for devices. The use of CWR for definitive sea states makes possible comparisons of devices for specific sites (and hence wave climates), and when discernible, comparisons of cost of similar devices in terms of power production (Electric Power Research Institute, 2003).

### 3.1.5 Devices compared for implementation of pilot and a commercial wave power plant.

The Electric Power Research Institute (EPRI), has made an evaluation of the present state of the wave energy industry with a directive to provide a practical framework for both a 1,500 MWh per annum pilot plant and a 300,000 MWh per annum commercial plant to be implemented in a number of US coastal States by 2005 (Electric Power Research Institute, 2004a). These studies provide a practical consideration of the requirements of generic infrastructure, as well as a comprehensive and methodical comparison of device development. This standardisation of location analysis, as well as evaluation of design, manufacture, and innovator readiness to meet defined near-future goals, means the Electric Power Research Institute 2004 study supersedes all wave industry overviews to date.

The comparison of devices included a systematic comparison of all levels of design as well as an evaluation of manufacturing companies' abilities to provide

sustained support to a project. Ocean Power Delivery's Pelamis device was deemed the only device to meet all criteria for the terms of reference, although it was noted that several other devices are approaching a similar level of development. (Electric Power Research Institute, 2004a).

Electric Power Research Institute completed preliminary studies for the Pelamis device for San Francisco California, and Cape Cod Massachusetts in late 2004. These provided detailed information about instigation of both a pilot (1,500 MWh per annum) and full commercial (300,000 MWh per annum) plants as well as detailed environmental issues report. The studies are the most detailed, comprehensive proposals for full-scale commercial utilisation of wave energy to date.

### **3.1.6 Environmental Impacts**

A number of concerns have been raised about the environmental impacts of wave devices. While providing a clean, reliable source of energy, the installation of any artificial device into the environment will affect in some way the:

- marine life;
- sea and seabed;
- local landscape; and
- fishing and shipping activities.

(Select Committee on Science and Technology (UK); 2001. Electric Power Research Institute, 2004c)

Concerns have been raised about the danger from wave devices to marine animals, such as seals and fish. However there is no evidence that this is a significant problem. Such devices may actually benefit the local fauna by creating non-fishing "havens" and structures such as anchoring devices may create new reefs for sea life to colonization.

By altering wave patterns and tidal streams, devices will undoubtedly have an effect upon the deposition of sediment. Research carried out to date would seem to indicate that the effects would not be significant (Black, 2007). However any wave shadow or wave rotation effect may alter the sediment supply and in turn cause a change in accretion or erosion. Detailed numerical modelling prior to deployment of devices and monitoring of shorelines post deployment is recommended (Black, 2007).

Offshore wave devices would almost certainly require areas to be closed to fishing and shipping activities. The locating of such devices would have to be negotiated, therefore, with relevant local groups (for example, fishermen, local iwi), as well as with national and international bodies.

Wave energy is generally considered to provide a clean source of renewable energy, with limited negative environmental impacts. In particular, wave power is seen as a large source of energy not involving large CO<sub>2</sub> emissions. The limited experience with wave power schemes makes it possible to form only an incomplete picture of possible environmental effects. In 1992 Thorpe summarized the environmental impacts of wave energy conversion technologies (Table 3.1).

**Table 3.1. Environmental effects of wave energy converters (Source: Thorpe, 1992).**

Environmental Effects	Shoreline	Nearshore	Offshore
Land use/sterilization	W		
Construction/maintenance sites	W		
Recreation	W	W	
Coastal erosion	W	W M	W M
Sedimentary flow patterns		W	W
Navigation hazard		W	W
Fish & marine biota	W	W	W
Acoustic noise	W		
Working fluid losses		W	W
Endangered species	W	W	
Device/mooring damage		W M	W M

W: Weak effect; M: Medium effect

Thirteen years after Thorpe's table and half a world away, New Zealand's response to commercial energy developments is under more scrutiny than ever. The shoreline and nearshore devices of the Thorpe report (1992) are extremely unlikely to be developed, due to the affinity and value New Zealanders place upon the coast. As with the American experience of extrapolating expected environmental concerns, offshore generation arrays operating at approximately 50 metres water depth, appear to be the only practical approach (Electric Power Research Institute, 2005). This makes sense for both generation (more energy offshore) and environmental reasons.

Generation of electricity by offshore arrays takes place "beyond the horizon" and has very little environmental effects. Electricity then "appears as if by magic" from a cable landward of the coast. The likelihood of offshore development in New Zealand would undoubtedly mirror the Electric Power Research Institute (2005) when

listing the potential of offshore wave energy conversion“...*First with proper siting, converting ocean energy to electricity is believed to be one of the most environmentally benign ways to generate electricity. Second, offshore wave energy offers a way to minimise the “Not In My Back Yard “(NIMBY) issues that plague many energy infrastructure projects, from nuclear to coal and to wind generation. Because these devices have a very low profile and are located at a distance from shore, they are generally not visible.”*

Tables 3.1 and 3.2 compare the changes in environmental concerns as well as the more thorough assessments available from more detailed plant designs. Assessment, monitoring and understanding of impacts will be required to evolve and adapt as the technology develops and the need for sustainable energy supply is realised by a greater proportion of the population.

**Table 3.2. Issues and impacts of offshore wave energy converters upon the environment (Source: Electric Power Research Institute 2004c)**

ISSUE/	IMPACT(S)
Withdrawal of wave energy	Wave height reduction on the order of 10-15% immediately behind plant, with diffraction substantially re-establishing longshore uniformity of wave height within 3-4 km behind plant.
Interactions with marine life, seabirds and benthic ecosystems	Wave power plants may provide artificial hauling-out space for seals and sea lions or nesting space for seabirds, enabling larger populations to exist than otherwise might exist under natural conditions. Likewise, submerged surfaces of wave energy devices and associated seafloor structures such as anchors and power cables will provide substrates for colonization by algae and invertebrates, creating "artificial reefs," which may be a beneficial impact.  Reduction in wave energy levels shoreward of a wave power plant may alter the community structure of algae communities in the nearshore and intertidal zones, favoring certain species over others, but consequential effects on fish and invertebrates are expected to be negligible.
Atmospheric and oceanic emissions	Expected to be of concern only for devices with closed-circuit hydraulic systems, where working fluid may leak or be spilled during transfers.
Interaction with coastal sedimentary processes	Lowering of wave energy levels reaching the coast may reduce longshore sediment transport, possibly reducing erosion in the vicinity of the plant while increasing erosion "downcoast." This impact is likely to be significant only for devices located within 1 or 2 km of the shoreline.
Visual appearance and noise	Visual appearance and noise emissions are device-specific. Submerged devices and slack-moored floating devices with low freeboard will not be visible from shore or visible only in exceptionally calm and clear weather. Taut-moored or fixed devices with high freeboard will be visible more often. Airborne noise is likely to be a concern only with oscillating-water-column devices having pneumatic turbines. Underwater noise may have adverse impacts on marine mammals.
Conflicts with other uses of sea space	Potential conflicts with recreational use (particularly surfing), commercial shipping, commercial fishing, dredge-spoil disposal, and other activities may be avoided with early dialogue during the wave power plant site selection process.
Installation and decommissioning	The main installation impacts will be associated with the laying of submarine power cables and associated shore-crossing; other impacts can be avoided by careful planning. Decommissioning concerns include shock to pinniped or seabird populations that rely on devices for hauling out or nesting and disposition of fixed and floating structures. These likewise can be avoided by careful planning.

### 3.1.7 Grid connection

Grid connection in New Zealand has become a complicated issue in recent years. The privatisation of lines companies and obligations to supply electricity make the future of new power stations of any type uncertain. What is more certain are that smaller scale, close to destination, energy suppliers will become more important and sought after (see section 2.3.1.3). New Zealand may well benefit from localised wave energy plant (of various magnitudes of capacity) close to her mostly coastal populations to aid and bolster grid supply.

The geographical makeup of New Zealand and the proximity of much of the population to high wave energy coastal areas may mean that the dilemma of grid connection and extensive new grid infrastructure faced by European countries is less of an issue. The sites of hydro energy stations in New Zealand and their long distances from population centres may also mean that grid connections are seen as less of a barrier.

### **3.1.8 Deployment**

The successful deployment of any wave energy device represents a major engineering challenge. Not only must it effectively convert the kinetic and potential energy of the waves into electricity, but also it must survive the extremely challenging environment of the ocean. It must overcome such factors as:

- saltwater corrosion;
- marine fouling (barnacles, seaweed, etc.);
- access difficulties; and
- storm damage.

Rough weather, in particular, has often been thought to rule out wave and tidal energy, especially for offshore devices. Most of the problems of working in sea conditions have already been conquered by the offshore oil and gas industries, which have operated effectively in some of the world's worst sea conditions for the past 40 years or more. They have maintained extensive structures many miles from the shore, laid vast lengths of submarine pipelines and cables and developed such methods as cathode protection to prevent corrosion. Ship builders have also had to conquer many similar problems for large moving metal objects (Select Committee on Science and Technology (UK), 2001).

In many respects there are actually fewer technical obstacles for energy devices in the sea than for land. For example the damage caused to wind turbines in urban areas from sulphur dioxide pollution in the air was far greater than anything that would be experienced underwater (Select Committee on Science and Technology (UK), 2001).

Devices that have been designed to survive, with extensive maintenance and deployment systems are desirable (Electric Power Research Institute, 2004a). In this

regard the Pelamis device was deemed to be ahead of its competitors, perhaps due to survivability being its prime directive from the initial conception of its method of power takeoff (Yemm *et al*, 2003).

### **3.1.9 Future developments**

The main wave energy barriers result from the energy carrier itself, the sea. As stated previously, the peak-to-average load ratio in the sea is very high and is difficult to predict. For example, it is difficult to define accurately the 50-year return period wave for a particular site, when the systematic, *in situ* recording of wave properties started just a few years ago. The result is either under or over-estimation of the design maximum load for a device. If under-estimated the total or partial destruction of the facility is to be expected. In the latter case, the high construction costs induce high power generation costs, thus making the technology uncompetitive. These constraints, together with misinformation and lack of understanding of wave technology by the industry, government and public, have often slowed down wave energy development (Cle'ment *et al*, 2002).

Factors such as increasing costs of traditional energy sources, direct funding through renewable incentives, pollution markets, and guaranteed energy purchase agreements make future innovation in this field increasingly likely (Twidell and Weir, 2000; Thorpe, 2000; Brooke 2003). These factors are the result of governments seeking a sustainable energy future. Optimism for development is due to the centres of wave energy device design being in countries that have expressed a desire for greater contributions from renewable sources to their energy supplies. These countries have to date contributed, and have signalled future effort, to this goal (Brooke 2003; Electric Power Research Institute, 2003).

### **3.1.10 Wave energy converter devices.**

With the combination of uncertainties regarding financial and developmental situation for conversion devices, several assumptions were made for this study.

- Devices will require connection to the national electricity grid.

- Location of optimal wave energy will need to be within an acceptable distance from infrastructure such as ports and settlements, or locations where these may be developed.
- Areas of intensified wave energy are optimal.
- Arrays of devices will be used to supply energy.
- Arrays will be situated “offshore” (section 3.1.5)
- Devices will need to be “tuned” to the broad wave characteristics of a location.
- The financial considerations (which are subject to variation from technological development and relative energy costing) are secondary to the actual physical restrictions of the resource for this report.

These assumptions were used when deciding upon the direction of wave energy resource assessment, and the case studies for New Zealand presented in section 6. No device is picked as the potential “winner” of the current developmental race.

### **3.1.11 Summary of wave energy converter devices**

*There are a multitude of ideas for the transformation of wave energy. Several of these ideas have resulted in large-scale prototypes being constructed, and one or two appear to be on the brink of taking wave energy conversion to commercial generation.*

*Many of the designers appear to be singularly concentrating upon maximum efficiency of energy conversion with other factors such as siting of devices, maintenance practicalities, and survivability being of secondary concern. This approach can have disappointing consequences on the road to commercialisation.*

*As more complete devices are tested, projected electricity energy outputs from various sea states can be calculated with greater confidence than from original modelled capture ratios to add to the confidence of investors and developers. Assumptions of environmental effects, as well as the practicalities of*

*grid connection and ocean deployment, are also able to be determined with greater certainty.*

*Methods of comparing very different “styles” of devices have been developed and in recent times a “wave device race” appears to be developing. It is expected that for electricity generation a single style of device may win out, similar to how the horizontal axis, direct drive, and three bladed wind turbine, is now the industry standard for wind energy.*

## **4 Wave energy assessment of New Zealand**

### **4.1 Wave climate –WAM twenty-year hindcast model**

The wave climate data is required for:

- combination with bathymetry in wave transformation modelling to determine hotspots and
- analysis of time coding to provide probability of wave energy exceedance and persistence.

A twenty-year wave hindcast was carried out by the National Institute of Atmospheric Research (NIWA) supported by the contract C01X0115 of the Foundation for Research, Science and Technology. A WAM wave generation model was implemented over a domain covering the Southwest Pacific and Southern oceans. The model hindcast the generation and propagation of deep water waves incident on the New Zealand coast (Fig. 4.1) using wind data from the U.K based European Centre for Medium Range Weather Forecasting . The temporal resolution was at three hourly intervals for twenty years (58440 records) (Gorman *et al*, 2003a).

Thirty-five sites around New Zealand coastline had a wave spectrum generated using the WAM numerical wave propagation model, which accommodates the processes of wind generation, white capping and bottom friction, and includes a direct estimate of non-linear energy transfer through four-wave interactions.

#### **4.1.1 Validation**

The twenty-year hindcast was validated by Gorman *et al* (2003b) using actual data from a variety of sources (Fig. 4.1). This was compared with hindcasted data (Figs 4.2 and 4.3).

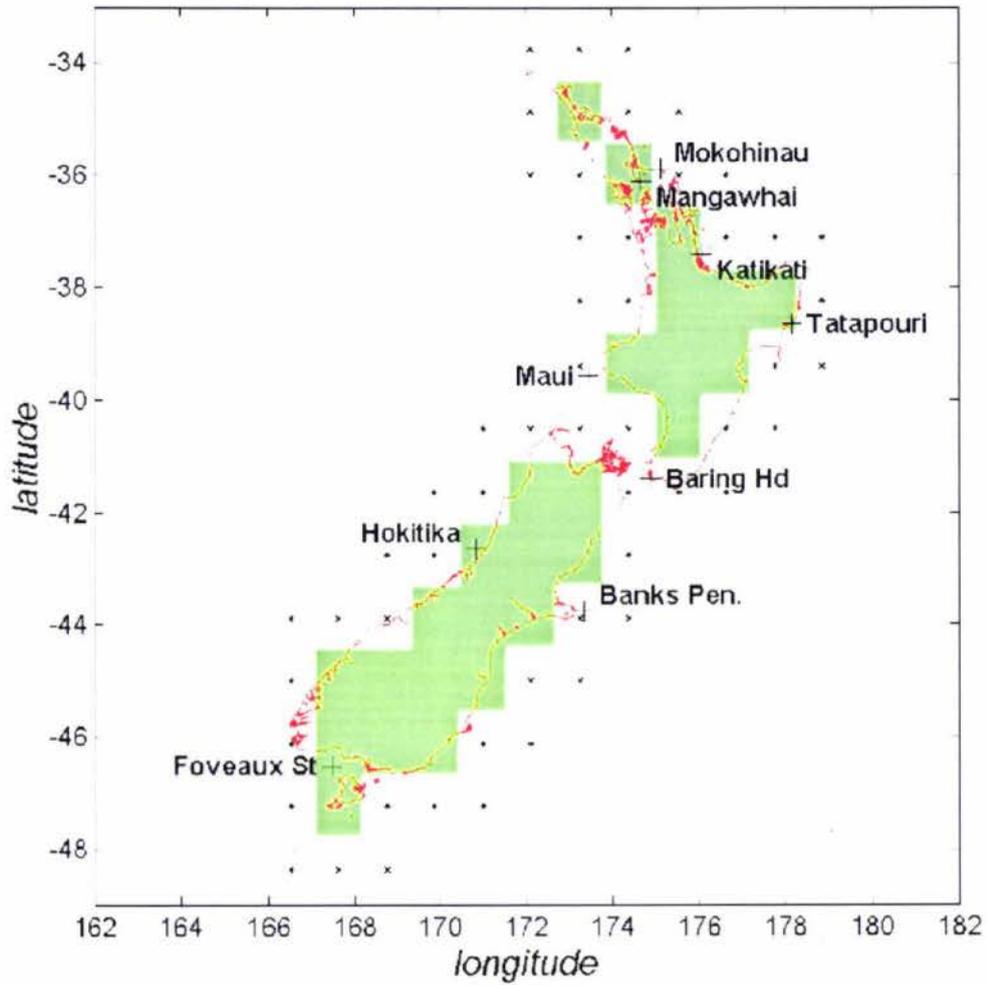


Figure 4.1. Position of wave buoys (+) used for comparison with the Hindcast model. Shaded squares indicate dry cells in the  $1.125^\circ \times 1.125^\circ$  New Zealand regional grid, while grid cells from which hindcast output spectra were interpolated are marked (\*). (Source: Gorman *et al*, 2003b)

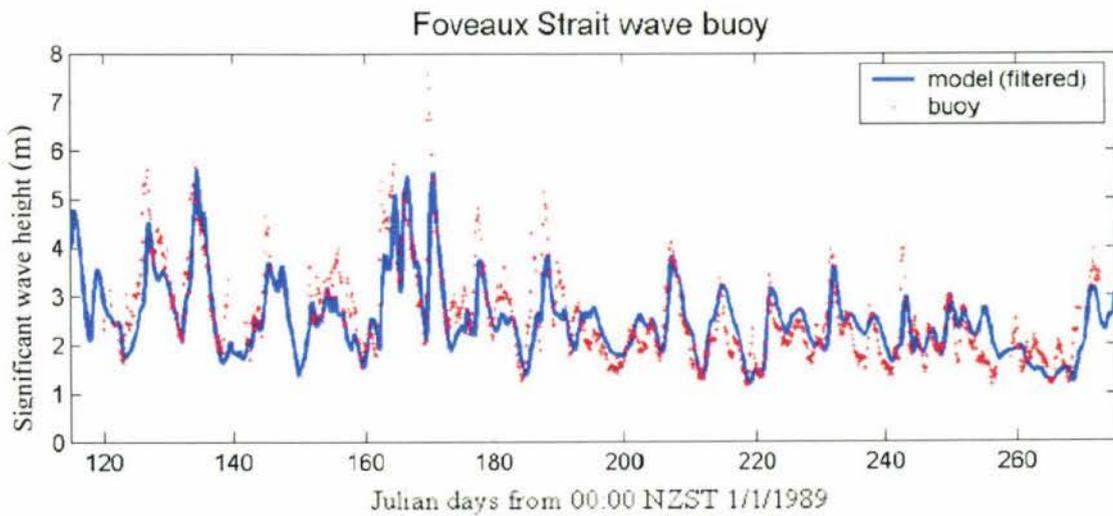


Figure 4.2. Significant wave height ( $H_s$ ) at a wave buoy site near Foveaux Strait (Fig. 4.1) show as time series data simulated by the wave model and as measured by the buoy. (Source: Gorman *et al*, 2003b)

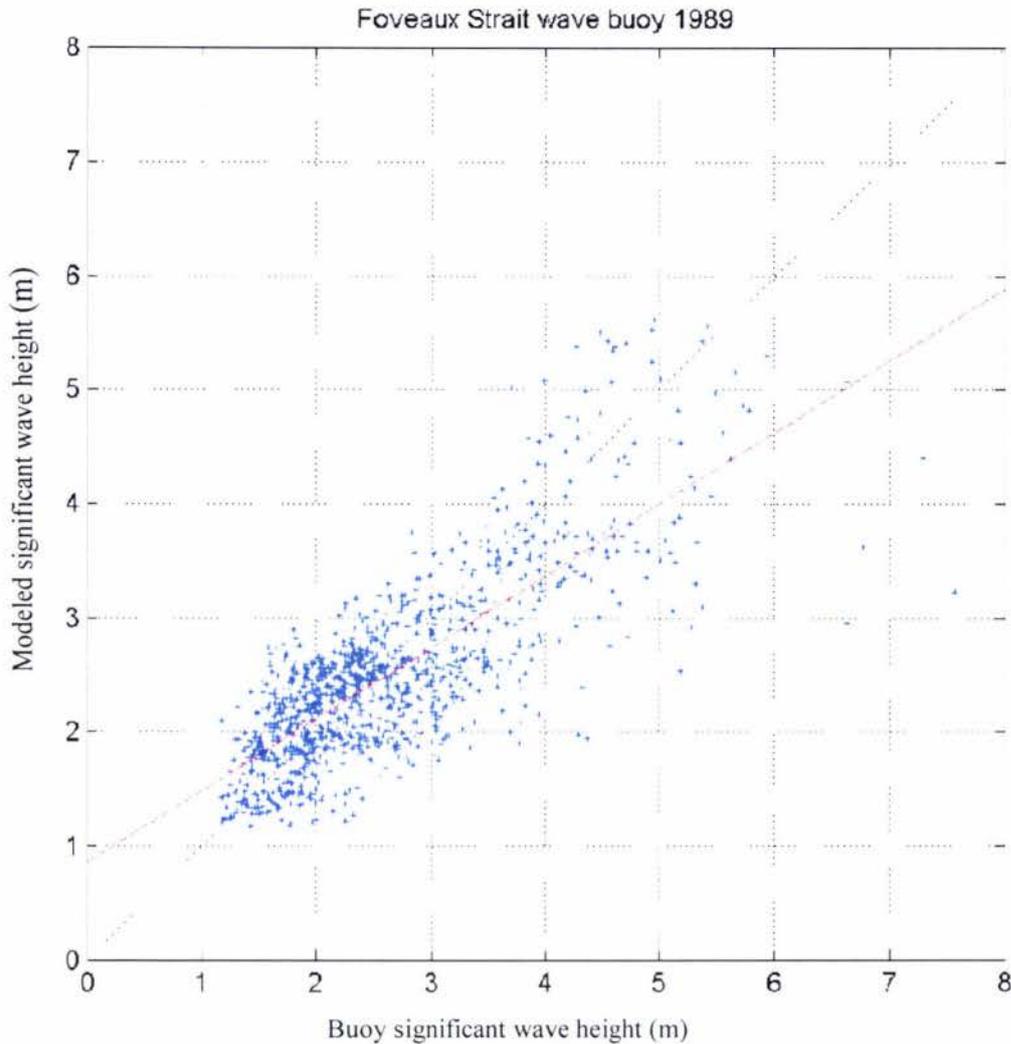


Figure 4.3. Significant wave height ( $H_s$ ) at a wave buoy site near Foveaux Strait (Fig. 4.1) as simulated by the wave model and as measured by the buoy, show as regression, with the line of best fit and equivalence lines shown by solid and dashed lines respectively. (Gorman *et al*, 2003b)

The only noticeable variation from this comparison was that the hindcast tended to undervalue extreme wave events with calculation of wave heights being approximately 30% under valued. As height is, generally, squared in energy calculations potential wave energy generation calculations from these data can be considered conservative.

#### 4.1.2 Wave parameters from the spectra of a 3G WAM model

The twenty-year hindcast dataset was created for use in evaluating energy distribution relating to sediment transportation and coastal process (Gorman 2002). Several variables are of use to evaluated wave energy converter case study sites later in this report (section 6). The following in *italics* is presented in Gorman et al (2003a

and 2003b). These calculations describe the ocean characteristics, several of which have been used in this study.

“Given a directional wave spectrum  $S(f, \theta)$ , the 1-dimensional spectrum is obtained by integrating over directions:

$$S(f) = \int_0^{2\pi} S(f, \theta) d\theta \quad (1)$$

From the computed spectral energy density  $S(f)$ , the peak frequency  $f_p$  and peak energy  $S_p = S(f_p)$  of the spectrum are located. Spectral moments

$$M_j = \int_0^{\infty} f^j S(f) df \quad (2)$$

are computed, allowing further statistics to be defined:

$$\text{significant height} \quad H_s = 4\sqrt{M_0} \quad (3)$$

$$\text{mean apparent period} \quad T_{mean} = \sqrt{M_0 / M_2} \quad (4)$$

$$\text{mean frequency} \quad f_{mean} = M_1 / M_0 \quad (5)$$

$$\text{mean crest period} \quad T_{cr} = \sqrt{M_2 / M_4} \quad (6)$$

$$\text{spectral width} \quad SW = 1 - \frac{M_2^2}{M_0 M_4} \quad (7)$$

Two directional moments are also computed:

$$M_c = \int_0^{\infty} \int_0^{2\pi} S(f, \theta) \cos \theta d\theta df \quad (8)$$

$$M_s = \int_0^{\infty} \int_0^{2\pi} S(f, \theta) \sin \theta d\theta df \quad (9)$$

The mean direction

$$\theta_0 = \arctan\left(\frac{M_s}{M_c}\right) \quad (10)$$

and directional spread

$$\Delta = \sqrt{2 - \frac{2\sqrt{M_c^2 + M_s^2}}{M_0}} \quad (11)$$

may also be computed.

The wave energy flux is a vector, whose components are defined as:

$$[P_x, P_y] = \rho g \int_0^{\infty} df \int_0^{2\pi} d\theta S(f, \theta) C_g(f) [\cos \theta, \sin \theta] \quad (12)$$

where  $\rho$  is the density of water,  $g$  is gravitational acceleration, and  $C_g(f)$  is the wave group velocity. The energy flux is often referred to as the wave power. Both the vector energy flux and its magnitude  $P = \sqrt{P_x^2 + P_y^2}$  are computed, as well as onshore and longshore components."

These data were calculated for three hourly intervals. The significant wave height ( $H_s$ ) (section 2.1.3), peak period ( $T_p$ ) (the period of the largest energy density "spike" of a wave spectra), the peak wave direction (the direction the swell of the largest energy density "spike" of a wave spectra is moving towards), and the energy flux magnitude, are the variables that are used as inputs for the modelling of wave energy hotspots. The time series energy flux magnitudes are used to determine the exceedance-persistence of wave energy for a location.

Fig. 4.1 shows the grid resolution and the shape of New Zealand as determined by the WAM model (Gorman et al, 2003b). Fig. 4.4 shows how deep-water wave information was determined for specific sites from this grid. Interpolation uses the direction of propagation ( $\Theta_1$ ) and the characteristics of the distance to shore (local fetch).

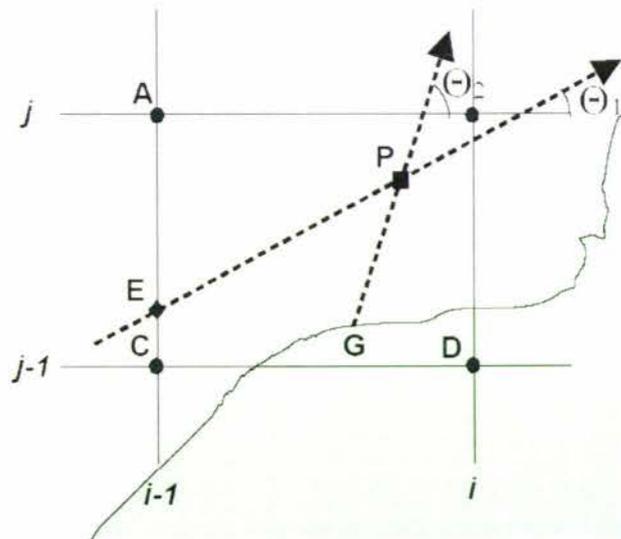


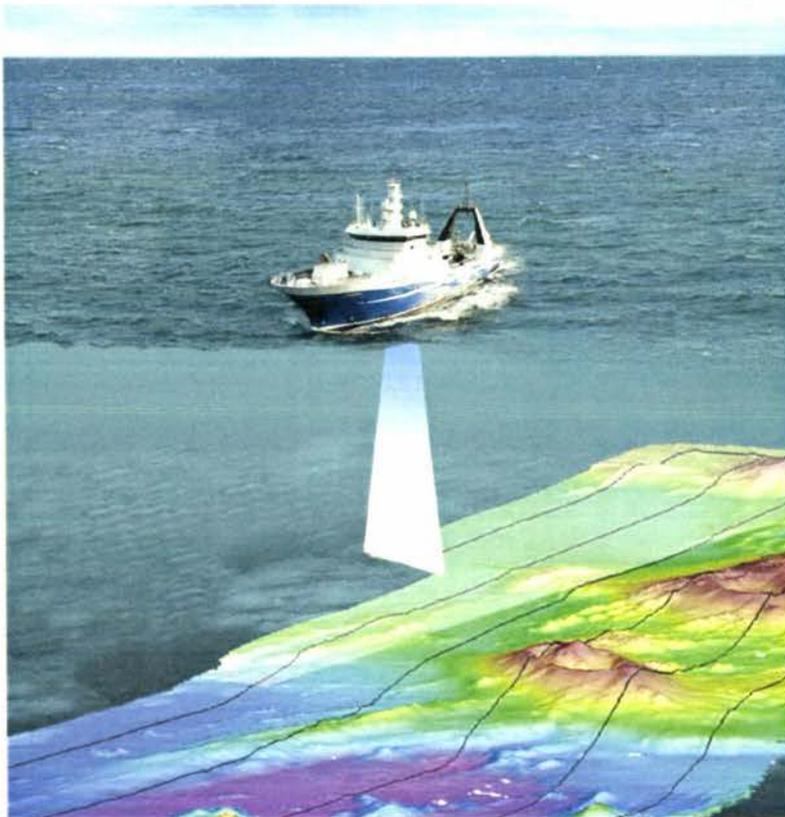
Figure 4.4. The components of spectral density  $F(f, \Theta)$  at the prediction point P, for propagation direction  $\Theta_1$ . As an example this uses an up fetch spectrum at E, interpolated from hindcast spectra at cells A and C. For propagation direction  $\Theta_2$ , the fetch to the coast (PG) was used to compute a fetched-limited spectral density (Gorman et al, 2003b).

### 4.1.3 Summary of wave climate

*Wave climate data was described from a third generation spectral wave model (WAM) using twenty years of wind data. The spatial grid of the wave model used cells  $1.125^\circ$  in size. The output of this grid was interpolated for any particular location, and wave characteristics were equated from the hindcast spectra. The wave characteristics were validated by the hindcasters through comparison with empirical data.*

## 4.2 Bathymetric data

Bathymetric data are the X, Y, and Z co-ordinates (latitude, longitude, and depth) of the topology of the ocean floor. This data could have come from a variety of sources (commercial ASCII files of navigational charts, empirical survey data, multibeam survey (Fig. 4.5)). Bathymetric data for wave modelling is generally required to be in a raster grid format. A raster grid is a data file or structure representing a generally rectangular grid matrix with values assigned to each cell (i.e. depth). As with any data it is important to match the resolution of end output with the complexity of the input.



**Figure 4.5.** The use of multibeam survey to determine the bathymetry of a site. Swathes are made across the ocean floor as the vessel makes passes (black lines). Location of vessel is kept in check with real time kinetic global positioning systems (RTK-GPS)(Source [www.niwa.cri.nz](http://www.niwa.cri.nz)).

#### 4.2.1 Data acquisition method

The size of the raster grid cells that would be the output of bathymetric data (and the input for the wave transformation modelling in this study) for the case studies in this report had the smallest cell size of 200 m by 200 m (4 ha), and largest of 3,000 m by 3,000 m (900 ha). Grids of these sizes were used to in accordance with direction from ASR Ltd, developers of the 3DD modelling suite (Mead, 2004). Cost of analysis was also a consideration. It was therefore decided that the digitising of navigation charts would provide an accuracy and acceptable resolution for the case studies.

The first stage of this process required an acquisition of the appropriate charts available from Land Information New Zealand (LINZ) in the TIF (Tagged Image File) digital image format on the web site ([www.linz.govt.nz](http://www.linz.govt.nz)). The charts had to be chosen to cover an area from the shoreline adjacent to the relative location (i.e. the Hokianga harbour and enough coastline to encompass possible electrical transmission) to beyond the continental shelf where seabed depths were beyond the interaction of waves and the ocean floor, i.e. over 200 m deep for a wave of approximately 14 seconds period (section 2.1.2.1). To cover the location under investigation this sometimes required a combination of charts (Fig. 4.6).

These charts then had to be geo-registered requiring the “pinning” of known co-ordinates from the chart to the relative digital co-ordinates using Blue Marble Geographics- Geographic Transformer© (Fig. 4.7). This process could have been done with a number of other GIS programmes (ArcMap, MapInfo, Idrisi Kilimanjaro). Because Geographic Transformer© allowed a simple "image-to-world" relationship between image and map co-ordinates and projected the chart into a geo-referenced image map it was chosen for this task. The co-ordinate system used was the New Zealand Map Grid (NZMG) geodetic datum 1949 (Molodensky method).

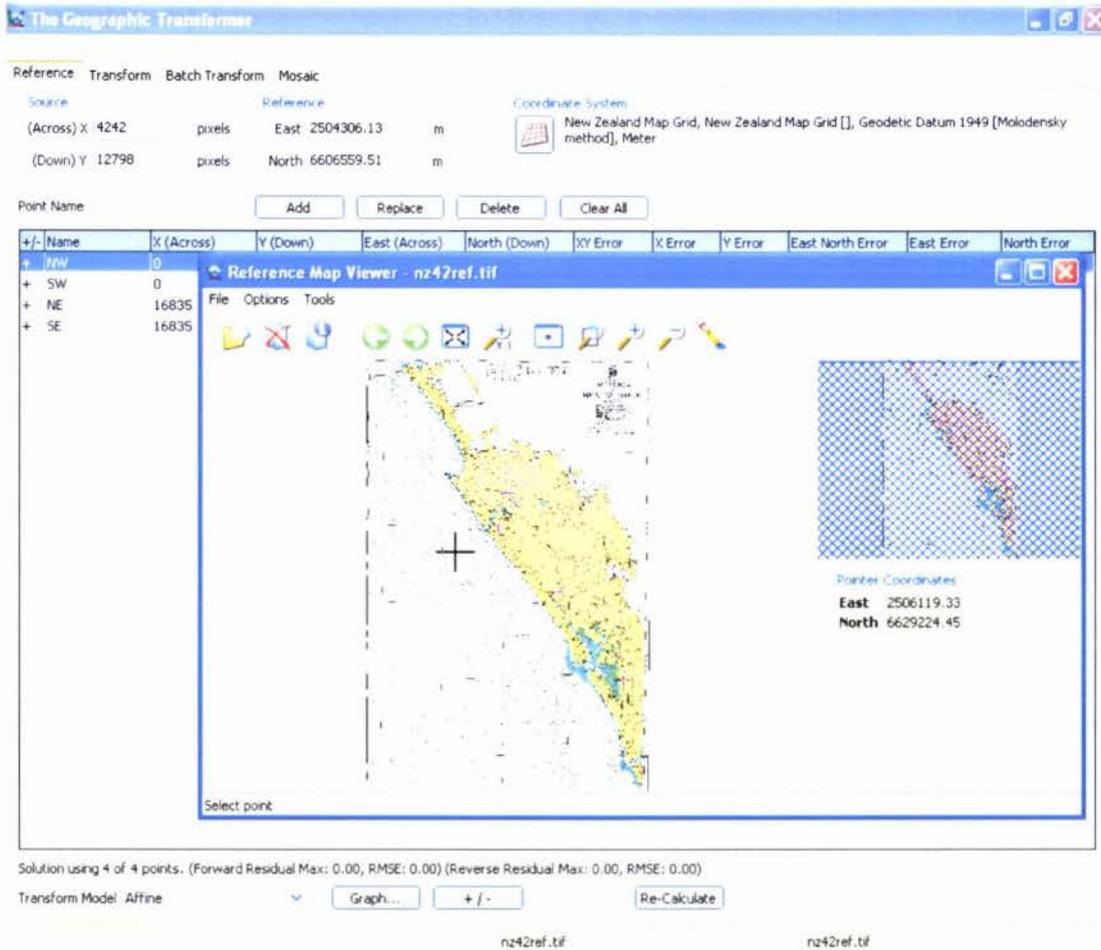


Figure 4.6. Screen capture of the geo-processing of navigation chart NZ42 Sample shows Northland Peninsular, North Island.

These geo-registered charts were then digitised to locate the X, Y Z data using MapInfo Professional GIS (Fig. 4.7). Digitising consisted of locating depth contour lines and spot depths with the cursor. These were then inputted (“clicked”), and the depth value added to the northing/easting (NZMG metric latitude and longitude) coordinates. A zero depth line (the shoreline) was made, as was a nominal shoreward contour with a Z value of -10 as required by the wave transformation model. Data for a “Surfer software-blanking blanking file” was also made with a continuous circling perimeter landward of all other digitised points so that the land became “no data” values. This blanking is required so that during the process of contour grid creation from the discrete digitised X Y Z data, bathymetry contours are not created for the land.

These data were then projected back onto the digitising screen to make sure there was a full coverage of the data (Fig. 4.7). All of the X, Y, and Z data now are collated together.

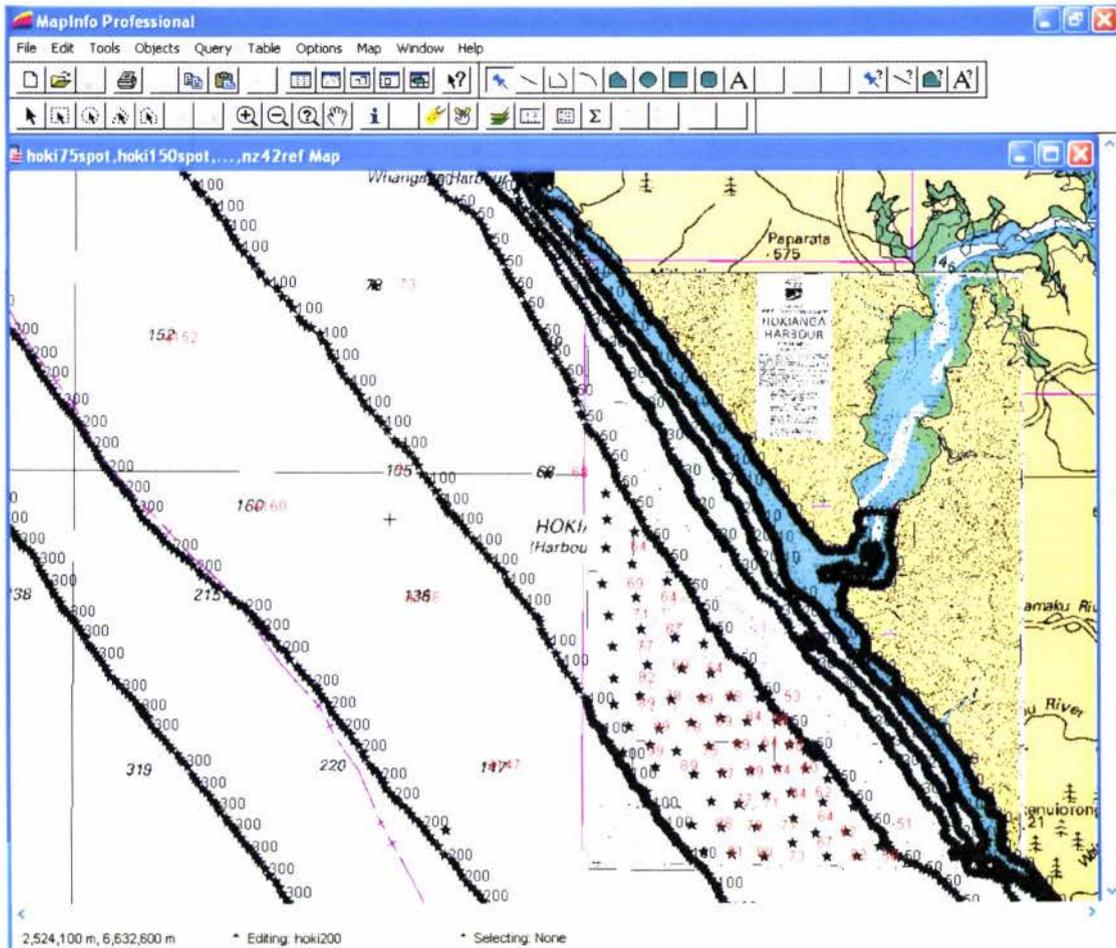


Figure 4.7. Screen capture of the digitising of geo-registered navigation charts using MapInfo Professional GIS. X, Y, Z data was collected with X, Y being NZMG northing and easting, and Z being the ocean depths. Sample shows Hokianga Harbour and adjacent coastline.

The X, Y, Z data was saved as an ASCII file and posted to Surfer© (Golden software 1996) GIS. The data was checked so that the rotation was correct for the wave transformation model and the input directions of the wave climate. The data was rotated if to meet the model's requirements (swells approaching from the left side of the grid). The Surfer software converted the point data (vector format) into a grid (raster format) (Fig. 4.8). The blanking file created in the previous step was then used to remove the land component of the grid which was trimmed to expunge rotated parts that were lacking in X, Y, Z data. The grid size was such that the numbers of cells were acceptable to the wave transformation model.

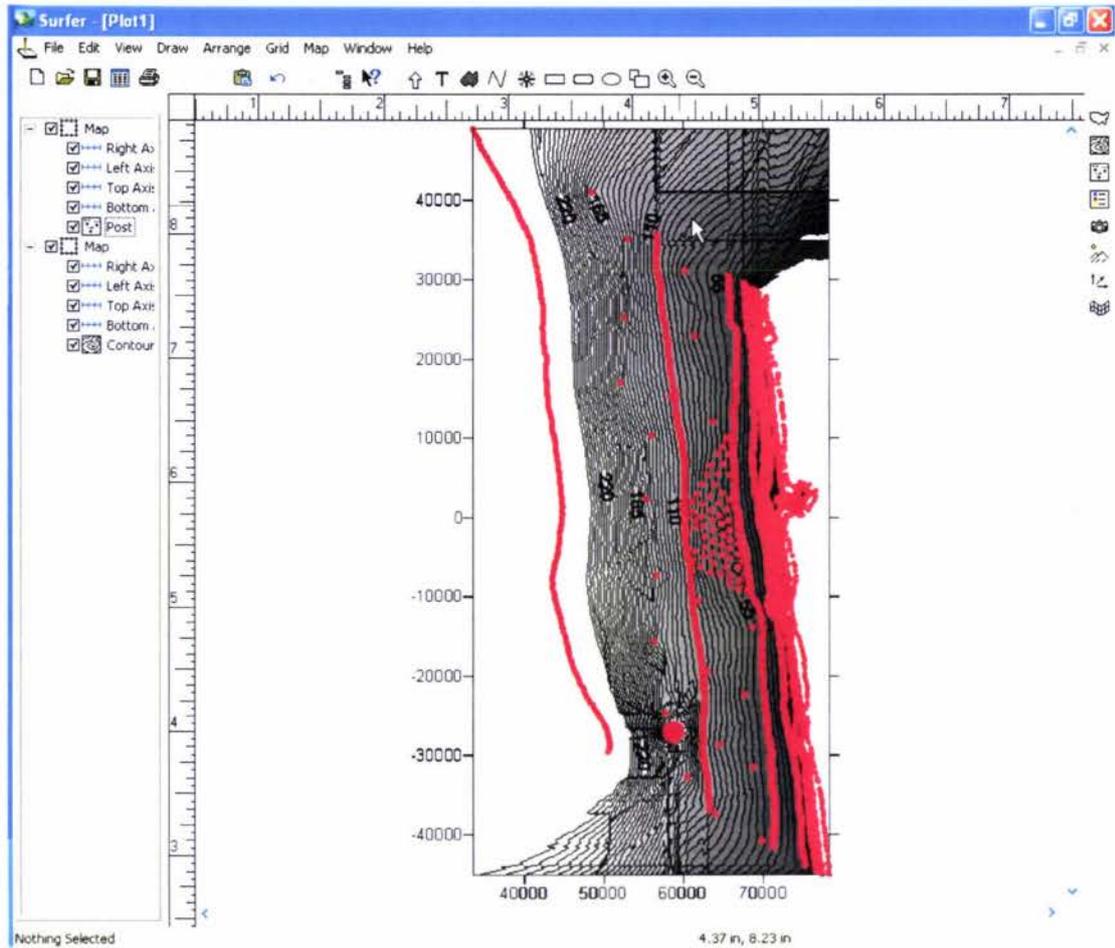


Figure 4.8. Screen capture of Surfer© (Golden software 1996). X, Y, Z data (in red) converted into a grid using Surfer grid creation capabilities. Data was rotated according to convention of wave transformation model. The land has been blanked. The grid will now be trimmed of locations lacking in X, Y, Z data. Sample shows Hokianga Harbour and adjacent coastline.

The surfer grid was converted to a MD file format (a mid point value of the cells, file, so therefore another vector file) using the 3DD wave transformation software resources (Black, 2002). This was then checked using the plotting screen of the 3DD software (Fig. 4.9).

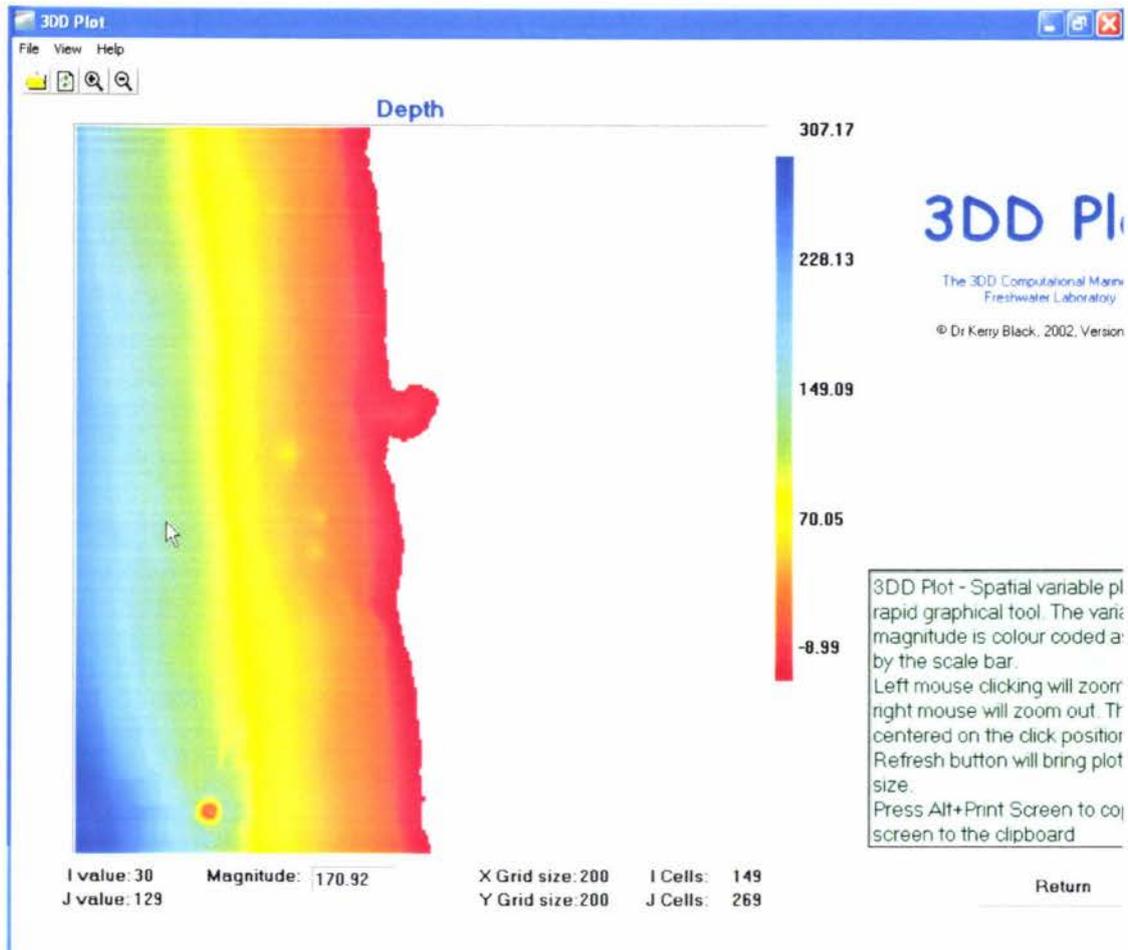


Figure 4.9. Screen capture of the plotting of the modified bathymetry data for the wave transformation model in the 3DD suite of hydrodynamic models. Sample shows Hokianga Harbour and adjacent coastline extending to the continental shelf (>200m depth).

The bathymetry data was now in format acceptable for the wave transformation model WBEND.

#### 4.2.2 Summary of Bathymetry

*Navigation charts were chosen to show coastline adjacent to possible wave energy conversion locations and the bathymetry offshore extending to the continental shelf. Bathymetry data was transferred from navigation charts to XYZ ASCII files. These data transformed from XYZ points into a raster grid and rotated if necessary. The land component of the grid was blanked out and the grid trimmed. The grid was then converted to a mid-point file for the wave transformation model WBEND.*

### 4.3 Wave Forecasts

The “Predictability” of a potential wave energy location is a test of the climate that produces the waves, rather than of the usefulness of wave forecasting tools.

Ocean wave characteristics for a particular location are published at various sites on the Internet. Buoyweather.com was employed for this study (Fig. 4.10). These websites use the ocean wave predictions of the National Oceanic and Atmospheric Administration/ National Weather Service/ National Centres for Environmental Prediction (NOAA / NWS / NCEP), that are produced using the wave model WAVEWATCH III (a third generation WAM, described in section 2.1.3.3. utilizing the operational products of NCEP as input. This combination of inputs and wave model is called NOAA WAVEWATCH III. This forecast used a global grid of 1.25° (longitude) by 1.25° (latitude) referred to as the “global NWW3” an acronym from NOAA WAVEWATCH III).

The buoyweather.com site provides a seven-day predictive wave data for a location. A subscription to this site allows requests to be made for seven-day forecasts for a particular location to be sent by e-mail (Table 4.1) .The data is provided at a predetermined time and is a tabulated version of what is available from the web pages (Fig. 4.10).

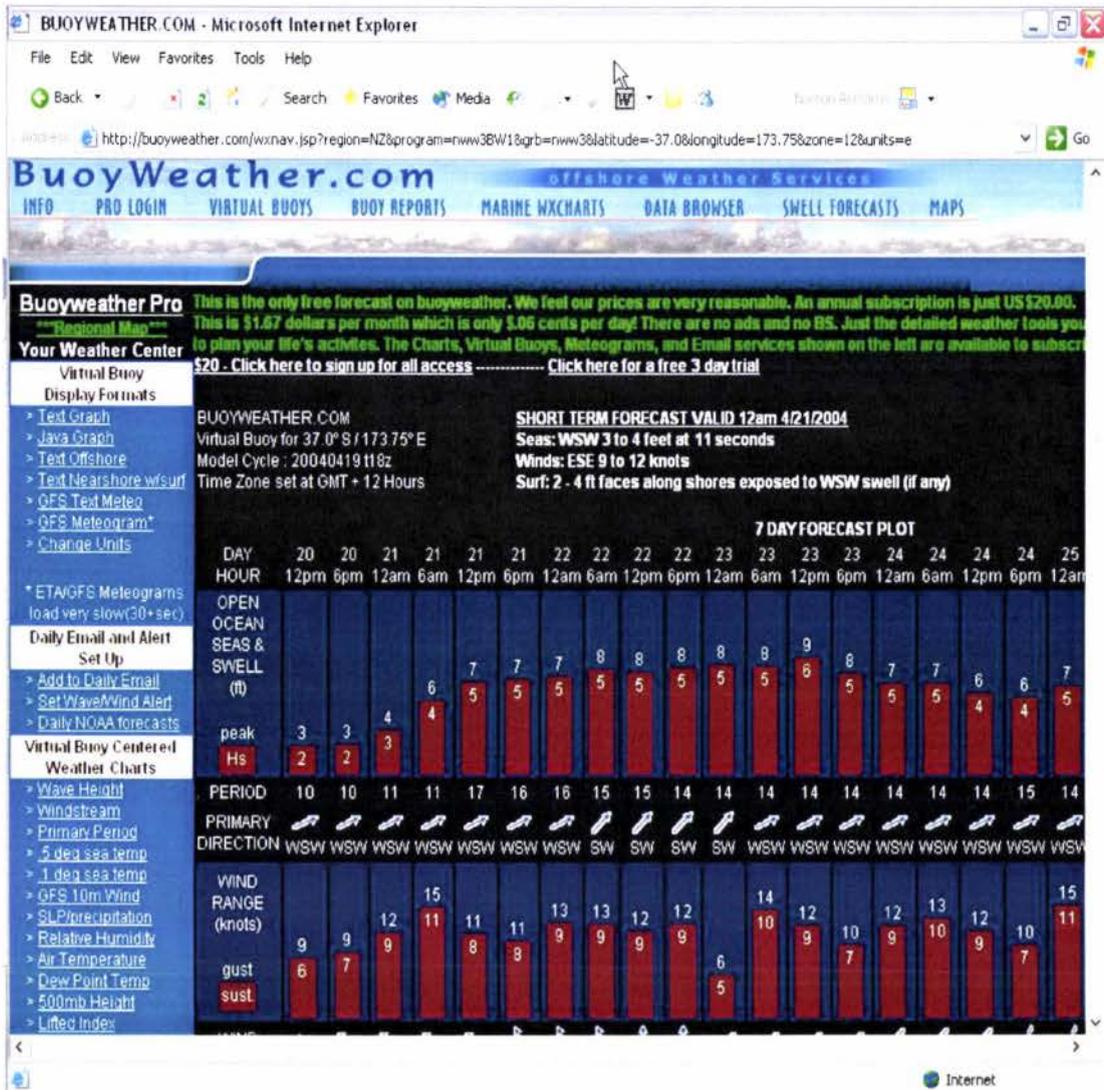


Figure 4.10. Screen capture of buoyweather.com site. Wave characteristics are viewed across the middle of this web page by way of a bar graph in crimson for a particular location at a particular date, in this case 37° S 173.75° E on 4/21/04. As this is a United States of America based site the dates are shown as MM/DD/YY and wave heights are in feet. Peak wave heights, significant wave heights, average period, and direction are provided at six hourly intervals. (Source: [www.buoyweather.com](http://www.buoyweather.com) )

**Table 4.1. buoyweather.com e-mail example of a seven day forecast. The swell (ft), period (sec), and surf direction (deg) columns are collated. From this table 7/28 6am, 12pm, 6pm and 7/29 12 am were deemed the now forecast.**

<i>BUOYWEATHER.COM Virtual Buoy Forecast</i>							
<i>Location : 47.0S 166.25E</i>							
<i>Cycle : 20040727 t18z</i>							
<i>Time Zone: GMT + 12 hours</i>							
-----							
	<i>SURF</i>	<i>SURF DIR</i>	<i>SWELL</i>	<i>PERIOD</i>	<i>WIND</i>	<i>WND/DIR</i>	
	<i>(ft)</i>	<i>(deg)</i>	<i>(ft)</i>	<i>(sec)</i>	<i>(kts)</i>	<i>(deg)</i>	
-----							
7/28	6am	10 - 20	WSW 247	14.9	11.3	22 - 30	NNW 332
7/28	12pm	10 - 21	WSW 247	15.3	11.6	23 - 31	NNW 331
7/28	6pm	11 - 22	WSW 241	16.0	12.0	24 - 32	NW 326
7/29	12am	12 - 24	WSW 240	16.2	12.6	13 - 18	WSW 235
7/29	6am	11 - 22	WSW 235	14.7	13.0	17 - 23	SSW 195
7/29	12pm	10 - 21	WSW 234	13.6	13.0	11 - 15	SSW 191
7/29	6pm	9 - 19	WSW 234	12.6	12.7	9 - 13	SSW 203
7/30	12am	9 - 18	WSW 232	12.2	12.3	8 - 11	SW 218
7/30	6am	8 - 17	WSW 232	11.7	12.1	10 - 13	W 267
7/30	12pm	7 - 15	WSW 233	11.1	11.9	14 - 18	W 272
7/30	6pm	7 - 15	WSW 233	10.7	11.8	16 - 21	W 271
7/31	12am	7 - 14	WSW 237	10.6	11.7	19 - 25	WNW 282
7/31	6am	7 - 14	WSW 237	10.6	11.3	16 - 22	WNW 296
7/31	12pm	7 - 14	WSW 236	10.7	11.6	12 - 16	W 278
7/31	6pm	6 - 13	WSW 233	9.6	11.8	20 - 27	ESE 128
8/1	12am	7 - 14	WSW 236	10.5	11.4	24 - 32	ESE 114
8/1	6am	6 - 13	WSW 235	10.1	11.2	24 - 32	ESE 100
8/1	12pm	6 - 12	WSW 234	9.1	11.0	21 - 29	E 87
8/1	6pm	2 - 5	ESE 100	8.1	5.7	19 - 26	ENE 78
8/2	12am	2 - 4	E 93	7.0	5.5	16 - 21	ENE 61
8/2	6am	1 - 3	ENE 61	6.3	5.0	16 - 21	NE 37
8/2	12pm	2 - 4	N 4	6.4	6.4	14 - 19	NNE 18
8/2	6pm	2 - 5	N 355	7.0	6.8	17 - 24	N 3
8/3	12am	4 - 8	N 355	9.8	7.0	22 - 30	NNW 348
8/3	6am	5 - 10	N 352	11.1	7.5	20 - 27	NNW 343
8/3	12pm	5 - 11	N 350	12.1	7.7	19 - 27	N 3
8/3	6pm	6 - 13	NNW 349	12.8	8.6	17 - 23	NNE 20
8/4	12am	8 - 17	NNW 346	14.0	10.2	20 - 28	NNE 24
8/4	6am	10 - 21	NNW 347	15.9	11.4	21 - 29	NNE 26

The predictability of wave characteristics for particular locations will utilise this internet / e-mail provided data in two ways:

- in part due to the lack of real time wave measurement devices in the waters being investigated, the first four predictions of the bouyweather.com forecast, (covering the immediate twenty four hours when the forecast was received) shall be deemed to be a “now forecast” and represent what would otherwise be the actual conditions of the site;
- the previous predictions were used to identify the predictability of the generating systems for an aspect of the coastline.

### 4.3.1 Example Data Collection

The data for this study was received, via e-mail, each day from buoyweather.com for a number of locations relating to an aspect of a coastline. The data set for each location required sorting into a suitable format for analysis using Excel spreadsheets, organising the data such that the prediction for each day was compiled on the same line (Fig. 4.11).

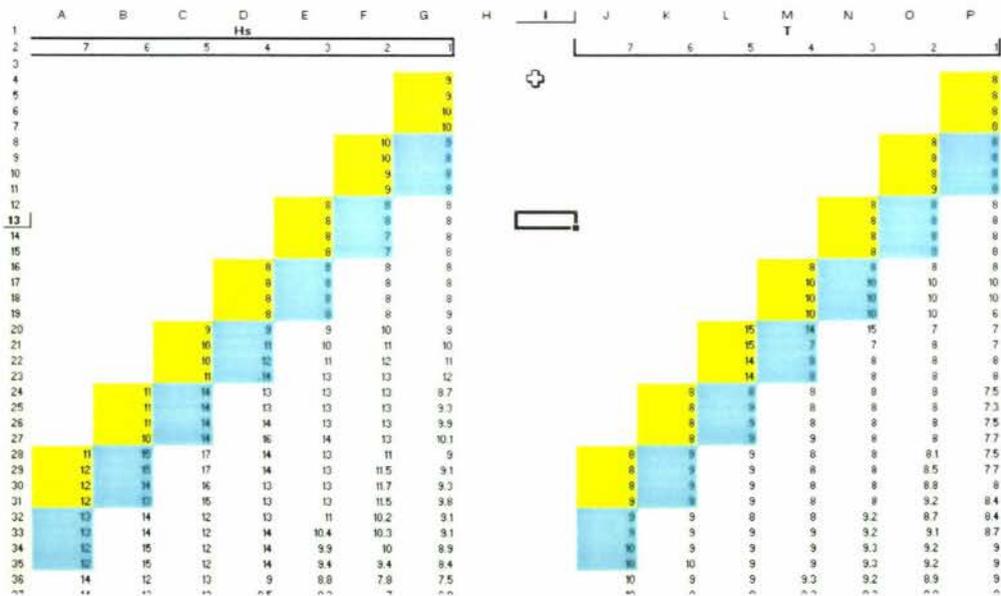


Figure 4.11. Excel spreadsheet for organizing e-mailed data for a single location. Significant wave heights (Hs) and wave periods (T) are shown but direction (Dir) was also collated. The yellow cells represent the first day of records, the blue the second day. This staggering of each 24 hour predictions allowed comparison for the same day on the same line. Hence line 28-31 shows the first full six days prediction and the “now forecast”.

Reorganisation of the data to show a resulting “now forecast” and six days of predictions (Table 4.2) provided the format required for the assessment of the predictability of wave characteristics for a given location. Comparison of the now forecast and the previous day’s prediction for the date of the “now forecast” is described in section 5.3.

**Table 4.2. The resulting now forecast and six days of predictions for the significant height of a single location, after the accumulation of seven day’s data.**

	6 day	5 day	4 day	3 day	2 day	1 day	Now Forecast
Fraction of day	Hs (feet)						
0.25	7	8	7	6	5.6	4.9	5
0.5	8	7	6	5.7	5.2	4.9	5.5
0.75	8	8	8	6.2	5.9	5.4	5.9
1	9	9	10	6.9	6.3	6	6.2

The direction of swells is included in this investigation of predictability. However it must be remembered that the cardinal rose has only three hundred and sixty degrees (before returning to zero) and the difference between 350° and 5° degrees is 15° rather than 345°. Using a spreadsheet, it was possible to identify the differences in the actual (now forecast) and predicted directions that are greater than 180 degrees, and remedy this occurrence correcting the difference between now and prediction to the results that are less than 180°, hence identifying the real difference in direction of wave measured in degrees.

The predictability study began June 21<sup>st</sup> 2004 and ran until 10th August 2004. A complete six-day forecast and a now forecast are not available until one week has passed. Hence the study period actually began on June 27<sup>th</sup>

For this investigation six sites were selected (Fig. 4.12) and represent aspects of the New Zealand coast. The sites are described by their latitude and longitude and are labelled with regard to their relative position (i.e. NNE NZ representing the north north east, SE NZ the south east).

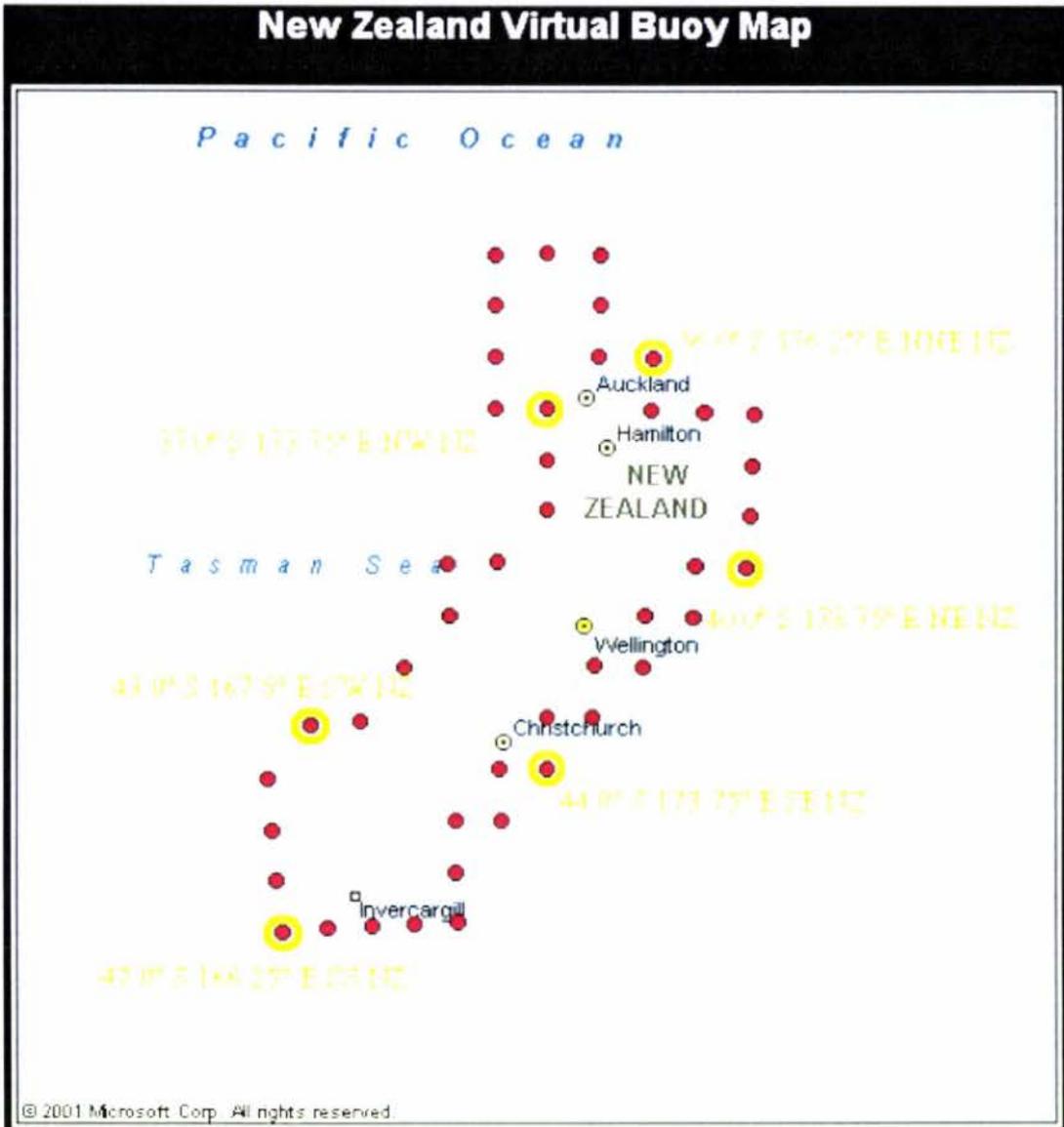


Figure 4.12. Locations of the virtual buoy sites for this investigation represented in yellow (Source: buoyweather.com)

Differing aspects represent locations that receive swell from various wave generating storm locations, as well as the differing shadowing effects from New Zealand's land masses (Frazerhurst and Mead, 2003).

The use of global third generation wave prediction models has been discussed for use in wave energy resource assessment and found to be advantageous in both prediction and hindcasting (Pontes *et al*, 1996), both functions have been utilised in this study. Gorman *et al* (2003a and 2003b) also promote the use of third generation wind-wave models, especially for use in under-instrumented locations, particularly the Southern Hemisphere and oceans surrounding New Zealand.

The WAVEWATCH III model may have systematic errors and inaccuracies which mariners and especially interested coastal parties utilise (due to the changes in swell behaviour as bathymetry shallows) when interpreting swell height and direction charts. Understanding the variation in predictions and reality is most prevalent amongst persons observing the changes in the ocean environment on a regular and systematic manner, and who have a stake in the predictions. Hence the marketing and language of the Internet sites is tuned to those putting to sea (fishers, mariners), and coastal users (surfers). These groups will undoubtedly incorporate a holistic observation of predicted characteristics and other intuitive indicators of wave climate.

For this study variation and changeability due to localised characteristics were avoided. Localised characteristics include; the effects of regional bathymetry, currents and tidal flows as well as topographical varied winds and thermally induced sea/land breezes. It is for this reason that sites (be expressed in latitude and longitude for buoyweather.com) were required which are considered beyond (offshore) the influence of said localised factors. However it is also desirable for the sites to have a geographic connection to the coastal aspect that is being assessed.

The use of a “now forecast” in this study has come about due to the lack of instrumentation, and data recording in New Zealand’s surrounding oceans. Whilst this can be seen as a disadvantage when comparing the predicted wave characteristics of a wave model and actual ocean conditions, this method actually allows for the assessment of the characteristics of the generating climatic systems rather than the WAVEWATCH III model. This subtle, but important, difference is reliant on the model being sufficiently accurate and dependable in its outputs. This validation has been made and is ongoing with studies by NOAA and other independent commercial users (NOAA, 2004) and for the purposes of this report can be assumed to be as accurate. Validation of the model means that when errors are found for a location it is a reflection of the climatic conditions of that location rather than the model itself. Hence a larger error will result from a location that has wave generating conditions that are variable in their movements, intensities and durations, than a location that has systematic, continuous, and usual dynamics.

### 4.3.2 Wave characteristics during period of study.

The average wave height, period, and direction for each site are show in Table 4.3 which also shows the average height period and direction of waves from the twenty-year hindcast for locations nearest to the sites used in this study.

**Table 4.3. Average wave significant height (Hs), period (T) and direction (Dir) for now forecast sites and corresponding twenty-year hindcast locations. Data from buoyweather.com was converted from feet into metres for comparison. Great Barrier Island has been abbreviated to GBI.**

Location	Paramete	Now Forecast	20 Year Hindcast	Location
NNE NZ	Hs (m)	2.30	1.08	GBI
	T (s)	6.74	8.45	
	Dir (deg)	10.72	69.86	
NW NZ	Hs (m)	2.87	1.77	Muriwai
	T (s)	10.68	11.49	
	Dir (deg)	261.66	241.54	
NE NZ	Hs (m)	2.99	1.76	Mahia
	T (s)	8.65	10.34	
	Dir (deg)	261.66	309.13	
SW NZ	Hs (m)	3.74	1.98	Westcoast
	T (s)	11.57	11.17	
	Dir (deg)	260.82	256.04	
SE NZ	Hs (m)	2.38	1.97	Otago
	T (s)	9.13	11.35	
	Dir (deg)	160.39	262.71	
SS NZ	Hs (m)	4.38	3.01	Stewart Is
	T (s)	11.58	11.56	
	Dir (deg)	265.93	268.82	

There is significant variation in comparison of forecast and WAM twenty year hindcast data, a reason being the extremely large difference in populations of the two data. The WAM hindcast is populated from twenty years, multiplied by three hundred sixty five days, plus five leap days, (29<sup>th</sup> February), with eight records for each day, totalling 58440 records. This population is considered of sufficient size to act as a mean (Gorman *et al*, 2003a and 2003b). The buoyweather.com data was collected from the 21<sup>st</sup> June to the 10<sup>th</sup> August, adding up to fifty-one days with four records per day, totalling 204 records. The smaller population of the now forecast allows for single weather events or seasonally bias events to dominate the population. It is expected with a far longer period of collection spanning an even number of seasons the now forecast averages would approach the values derived for the hindcast.

An evaluation of the locations (and the variations) when described as a single event show the variation may be due to the brevity of the now forecast collection time. The NNE and Great Barrier Island (GBI) location shows a more northerly swell direction ( $10.72^\circ$ ), shorter period (6.74 seconds), and larger significant height (2.3 metres) for the now forecast than for the WAM hindcast ( $69.86^\circ$ , 8.45 seconds, and 1.08 metres). This translates (when describing the average wave characteristics as a single event) as a depression of greater intensity, closer to the coastline, in a more northerly location during the time of the study than the averages of the hindcast.

This general description also can be applied to the adjacent coastline and the NW NZ and Muriwai sites, although not with the same degree of variation. This would be accountable due to the same type of weather pattern that influenced the NNE site during the study (strong northerly winds, from a northern depression) also affecting the northwest coast. The lessening of this effect compared to the NNE results can be explained by the combination of the northern weather system and wave characteristics from the Southern Ocean systems

The influence of the northern weather system can also be seen in the NE NZ and Mahia results. A northerning of swell direction, shortening of period and increase in wave heights was observed. As with the NNW / Muriwai situation the addition of southern generated waves lessens the impact from the northern storms.

The remainder of the locations have similar correlations of all characteristics with the exception of increased wave heights of approximately one metre, and the slightly lessened wave period for the SW NZ / Otago location. Increased wave height can be accounted for by intense depressions in the Southern Ocean generating waves of greater height. The lack of variation of the period and direction places these lows in a similar position to what is expected from the WAM hindcast. The lesser period for SW NZ may also be due to the influence of the northern systems described above.

The method in this assessment can be considered relatively basic and more sophisticated measures and assessments would be required as the next stage of evaluation of predictability methods. Comparison of the low cost simple methodology used in this report, with a location specific, spectral data forecasting research project carried out for the Westgate port of Taranaki by ASR Ltd showed good correlation of results. (This comparison is unable to be published due to commercial sensitivity)

### 4.3.3 Summary of wave forecasts

*Internet based wave forecasts provide the output of third generation global wave models calculated from global wind forecasts. This link to wind forecast means the prediction of waves echoes the predictability of atmospheric conditions. The predictability of atmospheric conditions varies on a global scale. By identifying the error of forecasts, an assessment of the predictability of an aspect of coastlines (open to swells from particular regions) can be made.*

*Swell forecasts must be linked to atmospheric conditions as closely as possible in order for the assessment to be of the wave generating atmospheric situations rather than the worth of the models. Bouyweather.com provides a forecasting service that was utilised. Comparisons of data collected with the averages from the WAM hindcast allowed for identification and description of events during the study period.*

## 4.4 Infrastructure

Although the focus of the resource assessment for this study is the physical locality and temporal characteristics of wave energy, identification of anthropocentric considerations will be made. The infrastructure of the possible locations includes such things as:

- the demand for energy by the population adjacent to the location;
- the location of electricity grid nodal points for connection;
- naturally occurring harbours; and
- present and possible development for the construction and maintenance of wave conversion devices.

### 4.4.1 Energy demand

The Energy Efficiency and Conservation Authority (EECA) have published a breakdown of New Zealand's energy usage derived from delivered electrical energy of each area of the country (Table 4.4).

**Table 4.4. Regional estimates of New Zealand's national annual electricity energy usage. Estimates are based upon information collected for year up to end of March 2002. (Energy Efficiency Conservation Authority, 2005)**

<i>Auckland:</i>	<i>8,171 GWh</i>
<i>Bay of Plenty:</i>	<i>1,667 GWh</i>
<i>Canterbury :</i>	<i>4,048 GWh</i>
<i>Gisborne:</i>	<i>261 GWh</i>
<i>Hawke's Bay:</i>	<i>953 GWh</i>
<i>Manawatu-Wanganui:</i>	<i>1,805 GWh</i>
<i>Marlborough :</i>	<i>346 GWh</i>
<i>Nelson:</i>	<i>369 GWh</i>
<i>Northland :</i>	<i>959 GWh</i>
<i>Otago :</i>	<i>1,566 GWh</i>
<i>Southland :</i>	<i>5,371 GWh</i>
<i>Taranaki :</i>	<i>949 GWh</i>
<i>Tasman :</i>	<i>313 GWh</i>
<i>Waikato :</i>	<i>2,963 GWh</i>
<i>Wellington :</i>	<i>3,002 GWh</i>
<i>West Coast :</i>	<i>309 GWh</i>
<i>Total</i>	<i>33,051 GWh</i>

This information is a broad picture of the present energy requirements of each area providing a start point to predict future generation capacity requirements. Determining the future electricity demand from these present demands requires information about future economic growth and development predictions often expressed as a percentage growth. Application of these percentage growth figures is a method employed to access the generation required into the future.

#### **4.4.2 Transmission**

Transpower New Zealand Ltd is a state-owned enterprise is owner and system operator of New Zealand's high-voltage electricity transmission grid, linking generators to distribution companies and major industrial users (Figs.4.13a and 4.13b).

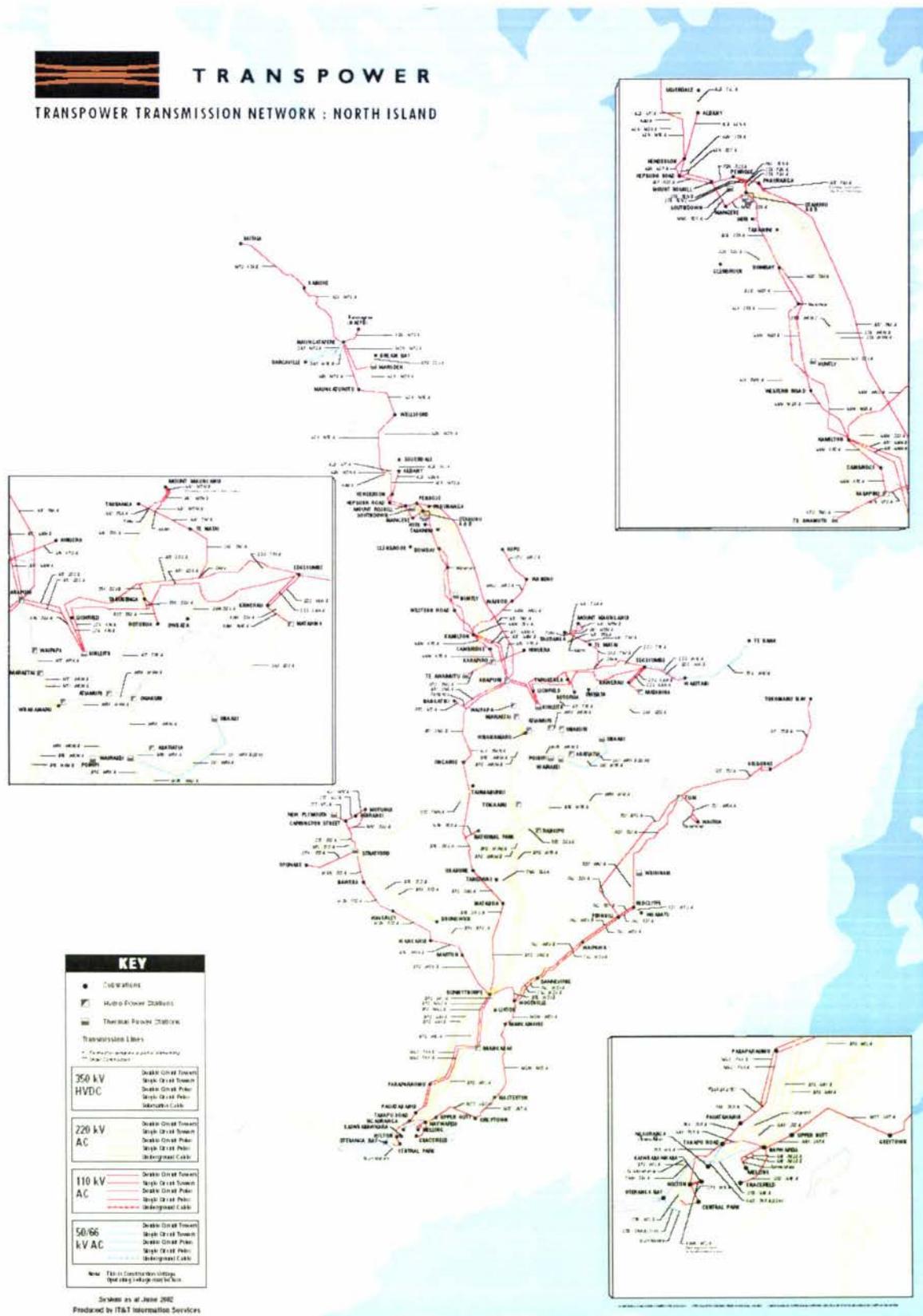
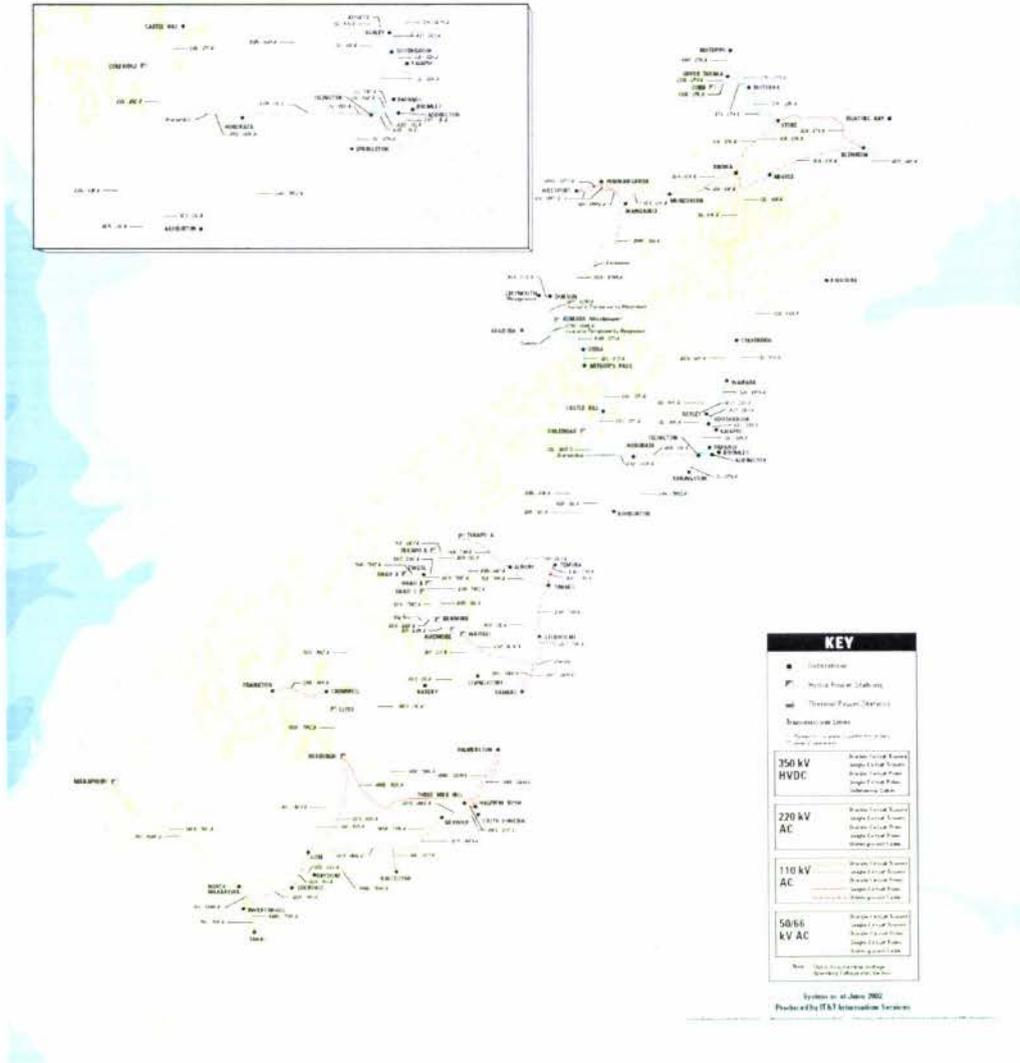


Figure 4.13a. The national electricity grid for New Zealand including the varying sizes of transmission lines, grid nodes, power stations, and sub stations (source: Transpower, 2005)



**TRANSPOWER**

TRANSPOWER TRANSMISSION NETWORK : SOUTH ISLAND



**Figure 4.13b. The national electricity grid for New Zealand including the varying sizes of transmission lines, grid nodes, power stations, and sub stations (source: Transpower, 2005)<sup>1</sup>**

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<sup>1</sup> These diagrams were in pdf (portable document file) format. Captures were made and geo-registered to the NZMG co-ordinate system. The nodal points were digitised as well as substations and power generation locations (Fig.4.14).



These digitised locations represent places where connections could be made to the grid (Fig 4.14). This is a basic assumption but provides an indication of the distances that may be involved in transfer of energy from locations of intensive wave energy, to the grid. Connection to local smaller networks may also be possible but dependant upon capacity and the networks ability to integrate generation. Present studies (Electric Power Research Institute, 2005) make the assumption that wave power plant will be of a size (150-100MW) to require connection to high voltage power lines.

The use of nodal points in this study makes the assumption that the network has the ability to incorporate further generation capacity. It is acknowledged that this assumption is not correct for a large part of the national grid. However the digitising of nodal points provides an excellent example of the spatial integration of infrastructure and wave energy hotspots.

#### **4.4.3 Ports**

It is envisioned that the resource assessments explored by this report (hotspots, exceedance-persistence, predictability) might eventually become part of a “Systems Level Design” such as that completed for San Francisco (Electric Power Research Institute, 2004b). This type of investigation of site-specific wave energy requires identification of locations for construction and maintenance of wave energy converter devices. It is for these reasons that all of the locations investigated by this report are all near to a port or harbour.

The natural protection offered by these locations, or artificial protection that has been developed, is such that infrastructure could be fairly easily developed for wave energy device construction and maintenance. Understanding the many varied, multidisciplined, investigations would be required for such an undertaking by the wave energy device manufacturer and project developer but is not part of this study. It was introduced to extrapolate the usefulness of the three assessments this report promotes. The ultimate decision as to where and to what degree development of infrastructure might be located (complete construction, modular fabrication, or basic maintenance) would be subject to greater planning procedures than the actual wave array and cabling. This complexity of location infrastructure is the reason that a basic

identification of suitable natural and developed harbours is all that is provided in this report.

#### **4.4.4 Summary of infrastructure data**

*Infrastructural requirements demonstrate the possible integration of the temporal and spatial resource assessment with other factors (though they are not discussed further in this report). The resolution of the data of the electricity grid nodes, possible construction locations, and the electricity demand in the region is coarser than the physical resource assessment, and only used for an example of as to how a wave energy power plant might be assembled*

## **5 Data Assessment**

### **5.1 Identifying hotspots**

#### **5.1.1 Wave transformation modelling**

The spatial variation of wave energy is due to the various factors described in section 2.1.2. and also due to shadowing by landmasses. Deep-water wave data can be modelled across bathymetry as described in section 2.1.3.4. The deep-water data must be chosen to provide relevant data for an aspect of the coastline to avoid obvious shadowing. For this investigation the wave data comes from the twenty-year hindcast (section 4.1.).

The data from the twenty-year hindcast was collated into a format for the support of the 3DD suite of models (Black, 2002), and specifically the model WBEND (section 2.1.3.4.). The joint probabilities of wave height, period, and direction were binned to create a boundary file for the wave transformation model WBEND. Directional data required adjustment for WBEND and makes an arc of  $-70^\circ$  to  $+70^\circ$  entering from the left hand side of the model. This manipulation was coordinated with the bathymetry data rotation (section 4.2.1).

Conditions of height, period and direction were each treated individually as a monochromatic wave, transforming the height and direction of the input wave as they mathematically propagate over a matrix comprised of the depths of ocean floor from the deep water to shore. The matrix of depths is comprised of bathymetry data from digitised navigation charts (Figs 4.6, 4.7, 4.8 and 4.9). The period of the monochromatic waves will remain unchanged, only the height and direction will vary.

Monochromatic wave transformation modelling rather than spectral transformation modelling is used so that a larger number of sites can be assessed. This is because the computing time and effort required is significantly longer for spectral modelling. The monochromatic modelling presented in the case studies for this report each required many hundreds of iterations. These iterations all require further processing, consuming further time and efforts.

### 5.1.2 Recalculation of iterations and geo-registration

The output of the wave transformation model WBEND is a matrix of wave heights and directions for each of the bin probabilities. A matrix of wave energy was created (Equation 2.6) using the non-dimensional wave spectrum coefficient 0.42. This factor will vary as the wave spectrum changes in shape in shallower water (Fig. 2.4). (However this change will be ignored in this analysis. A more refined spatial resource assessment would use an actual wave spectrum that can then be modelled in place of the monochromatic waves described here). The matrices of wave energy were then weighted by the probability of occurrence. Adding the matrices together provided a weighted average wave energy (kW/m) matrix. This matrix was transformed into a raster grid, and then geo-registered using cell size, co-ordinate system, and ground control reference points associated with the bathymetric input data of the model within a geographic information system.

### 5.1.3 Hotspot interpretation

Locations of intensified wave energy can now be readily identified, including locations where, due to focusing, wave energy is greater than the offshore (deep water) wave climate. The size of the location can also be compared to the possible area, arrays of devices would require.

This raster is now a map object and can be analysed using other spatial information such as:

- water depth – important for differing converter device mooring systems;
- marine currents- many wave energy converter devices and their mooring systems are dependent on maximum currents;
- navigation routes- although unlikely as heavy wave energy is usually avoided by shipping, any possible disruption to coastal shipping must be investigated;
- marine protected areas;
- designated easements-these areas could be utilised as often permits have been issued for restricting common access. This is expected to be

a simpler process than removal of areas from common access and is explored in Electricity Innovation Institute, 2004b;

- geological surveys- to optimise cable laying routes, and mooring systems; and
- prevention of possible NIMBY situations.

#### 5.1.4 Summary of hotspot identification methodology

*Wave climate and bathymetry were combined in wave transformation models. Model output was a matrix of wave heights for each joint probability iteration of period, height, and direction inputs to the model. An energy matrix was calculated for each iteration and multiplied by the percentage of probability, creating a weighted energy matrix. Combining these data provided a weighted average of the spatial area. This matrix was geo-referenced into a GIS for comparison of intensified areas of wave energy called hotspots.*

## 5.2 Exceedance-Persistence

This assessment provides a method to identify the temporal dimension of wave energy. The energy flux (calculated from the wave spectrum as described in the *transposed* calculations of section 4.1.2) for a location is expressed as 3 hourly time series in the 20 year hindcast. Analysis of this time series identified the percentage probability of energy levels being greater than set values (exceedance), in this study these set increments were 1 kW/m from 0 to 100 kW/m. Analysis also identified the probability that the these energy levels would continue over time (persistence), in this study these time increments were set at the 3 hourly temporal resolution of the hindcast and probability calculated out to 10 days (240 hours) persistence.

These calculations were performed upon the Matlab© architecture using script designed by ASR Ltd with commercial value so not included here in detail. Each location's energy time series data was prepared for the ASR script and saved as a non delimited text file then loaded by the front end window shown in Fig. 5.1.

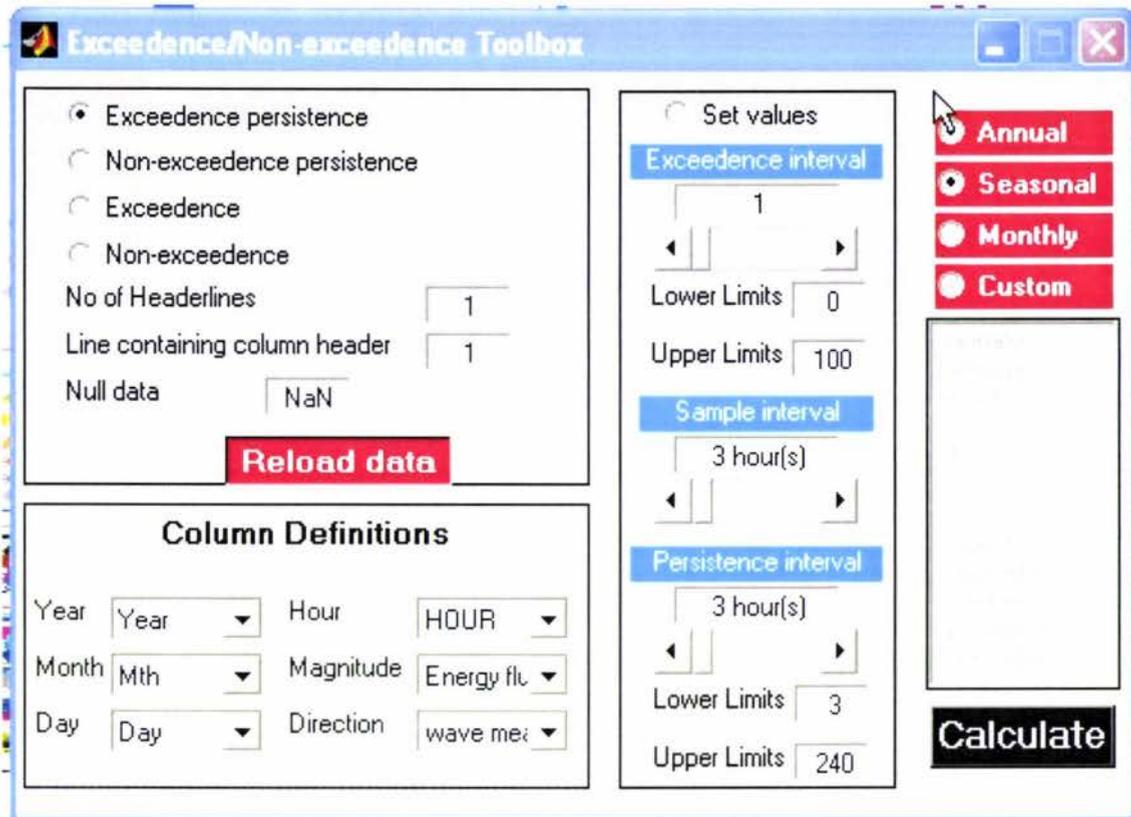


Figure 5.1 . Front-end window of the ASR Ltd Exceedance-Persistence Matlab script.

The front end window asks for several values:

- the exceedance interval (set here as 1 kW/m);
- the limits of the exceedance interval (set here as 0-100kW/m);
- the persistence interval (set here to be the same as the sample interval, 3 hours);
- the limits of the persistence interval (set here as 3 hours to 240 hours , being 10 days); and
- The dateline which is to be calculated (set here as Seasonal).

The Excel file output shows kW/m on the left hand side of the table and hours across the top. The values are a percentage of the time each condition is met (for example 99.35 % wave energy is greater than 2 kW/m lasting more than 3 hours).

	A	B	C	D
1		3	6	
2	>= 0	100	100	100
3	>= 1	99.29	99.29	99.29
4	>= 2	96.35	96.34	96.34
5	>= 3	91.89	91.89	91.89
6	>= 4	86.57	86.55	86.55
7	>= 5	80.81	80.79	80.79
8	>= 6	75.91	75.87	75.87
9	>= 7	71.19	71.18	71.18
10	>= 8	66.43	66.38	66.38

Figure 5.2. Screen capture of a portion of the Excel file for the probability output table of the ASR Matlab script. The increasing numbers on the left hand side represent kW/m of energy. These extend down to less than or equal to 100 kW/m. The numbers across the top of the table represent hours. These extend out to 240 hours. The three hour intervals correspond to the temporal resolution of the hindcast data. This figure only shows the corner of the full table as the full table is too large to be able to show details.

Output data is graphed to show the pattern of exceedance-persistence for a given location (Fig. 5.3a). To be able to compare locations the entire table from 0-100 kW/m is shown. Showing less than the full data led to problems distinguishing between locations of poor and good temporal wave resource. Congestion of information is particularly prominent at the higher energy levels which are itself an indicator of the assessment. Case studies (section 6.2) were used to analyse variations in the output of exceedance-persistence of wave energy for contrasting locations.

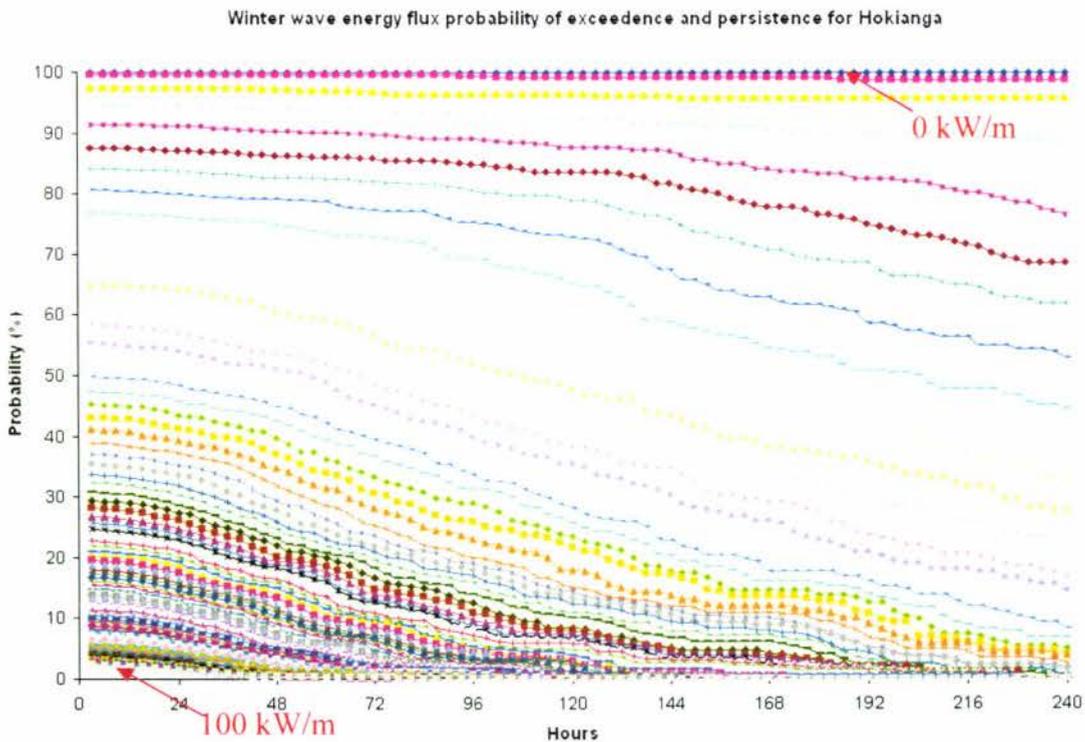


Figure 5.3a. Exceedance-persistence example showing 100 different data lines for 0 to 100 kW/m energy calculations for a Hokianga location during winter (legend can be found at figure 5.10). The 0 kW/m line and 100 kW/m are indicated by the red text and arrows.

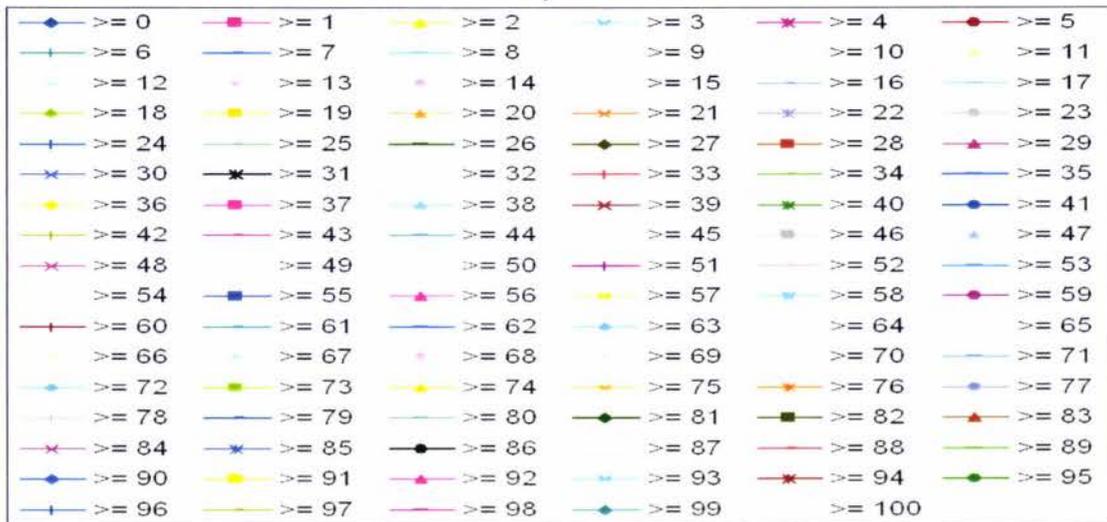


Figure 5.3a. Legend for the exceedance-persistence charts. The values are for the wave energy calculated from the wave spectrum generated from the WAM hindcast and represent the exceedance of energy (hence >=).

### 5.2.1 Summary of Exceedance-Persistence methodology

*Exceedance–persistence used the Matlab script developed by ASR Ltd to filter wave climate data and identify probability that wave energy is greater than a particular value (exceedance), and the length of time that value is greater (persistence).*

## 5.3 Predictability

This process provided an assessment of the predictability of waves for a specific stretch of coastline. Data from web based wave prediction source, buoyweather.com was utilised for this procedure.

Comparisons of the “now forecast”, over a twenty-four hour period, were made with the prediction of the wave height, period and direction, for the six, five, four, three, two and one previous days.

### 5.3.1 Predictability calculation

Once the data (section 4.3) was arranged and compiled for a set time, comparisons of the “now forecast” for actual heights and periods were made with the previous 24 hours predictions. This gave a measure of error for each day.

Average heights, periods and directions of the now forecast were compared with the twenty-year hindcast averages and evaluated for the differences in location, the period of assessment of the now forecast (as opposed to the complete full year, hindcast), and variations in seasonal/climatic conditions for each data set assessed.

The measure of the predictability of a location was made using the “root normalised mean square error” (RNMSE) (equation 5.1) calculated within a spreadsheet (Fig. 5.4).

$$RNMSE = \sqrt{\frac{(P_i - O_i)^2}{P_i \cdot O_i}}$$

Equation 5.1

where  $P_i$  is the predicted wave information;

$O_i$  is the observed, in this case the now forecast; and

“ $\bar{\quad}$ ” represents the mean of the values shown underneath.

The RNMSE provided a measure of accuracy of the model’s prediction. The lower the value the more predictable the location. A result of zero would be perfectly predictable.

Once the RNMSE has been calculated this error can be observed and compared to that for each of the other days. Plotting these results and comparing to other locations gave an estimate of the predictability of differing aspects of a coastline.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1		Hs								6 day	5 day	4 day	3 day	2 day	1 day	
2			7	6	5	4	3	2	1	25.23636	25.16736	23.77065	17.32841	12.06529	8.270708	
3	0															
4	0.25															9
5	0.5															9
6	0.75															10
7	1															10
8	1.25							10								9
9	1.5							10								8
10	1.75							9								8
11	2							9								8
12	2.25						8	8								8
13	2.5						8	8								8
14	2.75						8	7								8
15	3						8	7								8
16	3.25				8		8	8								8
17	3.5				8		8	8								8
18	3.75				8		8	8								8
19	4				8		8	8		6 day	5 day	4 day	3 day	2 day	1 day	
20	4.25			9	9	9	10	9		6pd Mean	5pd Mean	4pd Mean	3pd Mean	2pd Mean	1pd Mean	Mean ob
21	4.5			10	11	10	11	10		7.805	7.906111	7.796667	7.497222	7.391667	7.308333	7.286667
22	4.75			10	12	11	12	11								
23	5			11	14	13	13	12		RNMSE	RNMSE	RNMSE	RNMSE	RNMSE	RNMSE	
24	5.25		11	14	13	13	13	8.7		0.252364	0.251674	0.237707	0.173284	0.120653	0.082707	
25	5.5		11	14	13	13	13	9.3		FB	FB	FB	FB	FB	FB	
26	5.75		11	14	14	13	13	9.9		-0.068691	-0.081545	-0.067624	-0.028484	-0.014307	-0.002969	
27	6		10	14	16	14	13	10.1		6 day forec	5 day forec	4 day forec	3 day forec	2 day forec	1 day forecast	
28	6.25	11	15	17	14	13	11	9		Mean((ob-	Mean((ob-	Mean((ob-	Mean((ob-	Mean((ob-	Mean((ob-	Mean((ob-
29	6.5	12	15	17	14	13	11.5	9.1		4	36	64	25	16	4	
30	6.75	12	14	16	13	13	11.7	9.3		8.41	34.81	62.41	24.01	15.21	5.76	
31	7	12	13	15	13	13	11.5	9.8		7.23	22.09	44.89	13.63	13.63	5.76	
32	7.25	13	14	12	13	11	10.2	9.1		4.84	10.24	27.04	10.24	10.24	2.89	
33	7.5	13	14	12	14	10.4	10.3	9.1		15.21	24.01	8.41	15.21	3.61	1.21	
34	7.75	12	15	12	14	9.9	10	8.9		15.21	24.01	8.41	24.01	1.69	1.44	
35	8	12	15	12	14	9.4	9.4	8.4		3.61	37.21	3.61	26.01	1	1.21	
36	8.25	14	12	13	9	8.8	7.8	7.5		12.96	43.56	12.96	31.36	1	1	
37	8.5	14	12	13	8.5	8.2	7	6.8		42.25	20.25	30.25	2.25	1.69	0.09	
38	8.75	13	12	13	8	7.7	6.7	6.5		51.84	27.04	38.44	2.89	1.96	0.04	
39										42.25	30.25	42.25	2.25	1.44	0.04	

Figure 5.4. Calculation of RNMSE, highlighted in yellow for the 1 to 6 day forecasts for a particular location.

The RNMSE is shown graphically as a percentage error (Figs 5.5, 5.6, and 5.7) for each of the days leading to the now forecast. Hence day six is the seven-day forecast from Table 4.1, and day one is the two-day forecast. The one-day forecast was then reclassified as the now forecast

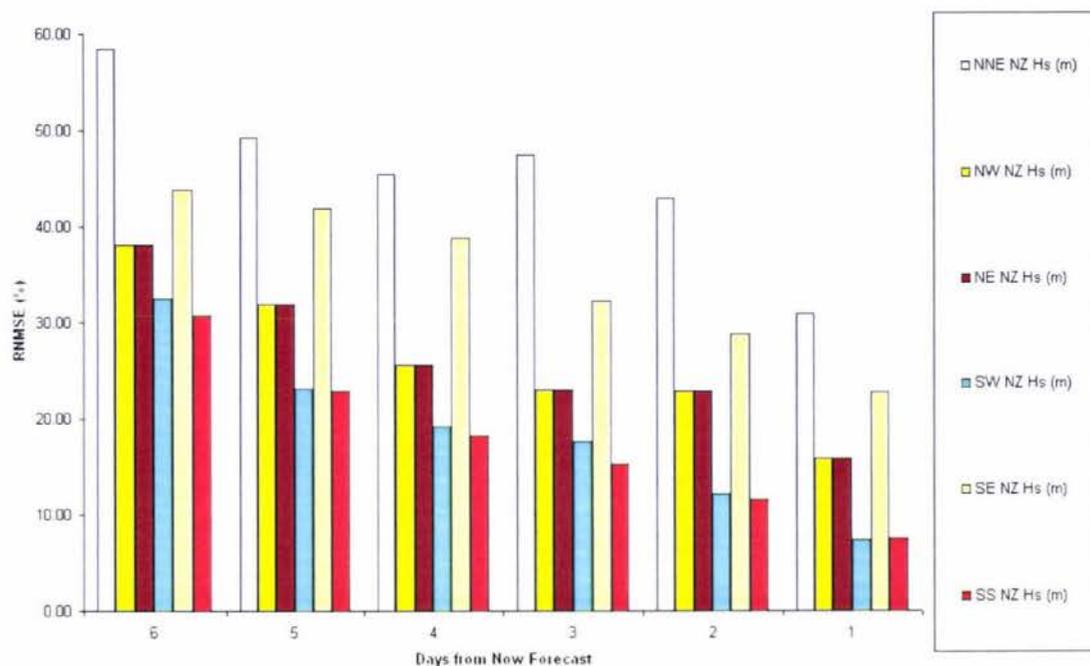


Figure 5.5. Comparison of the RNMSE as percentage for the significant wave height ( $H_s$ ) for six locations around New Zealand.

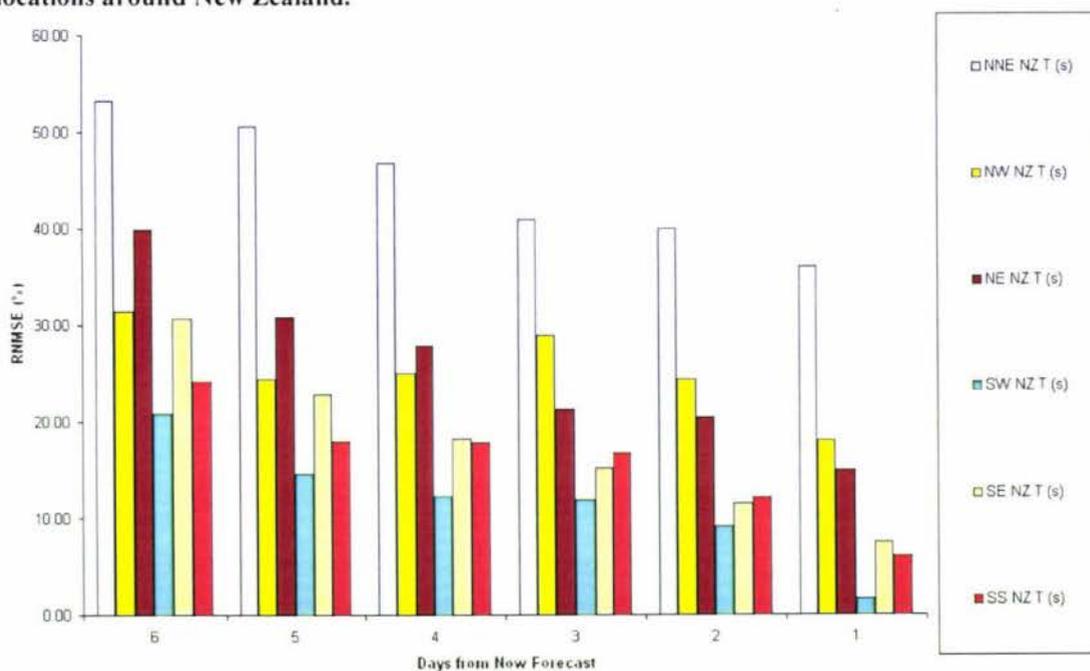


Figure 5.6. Comparison of the RNMSE as a percentage of the wave periods ( $T$ ) for six locations around New Zealand.

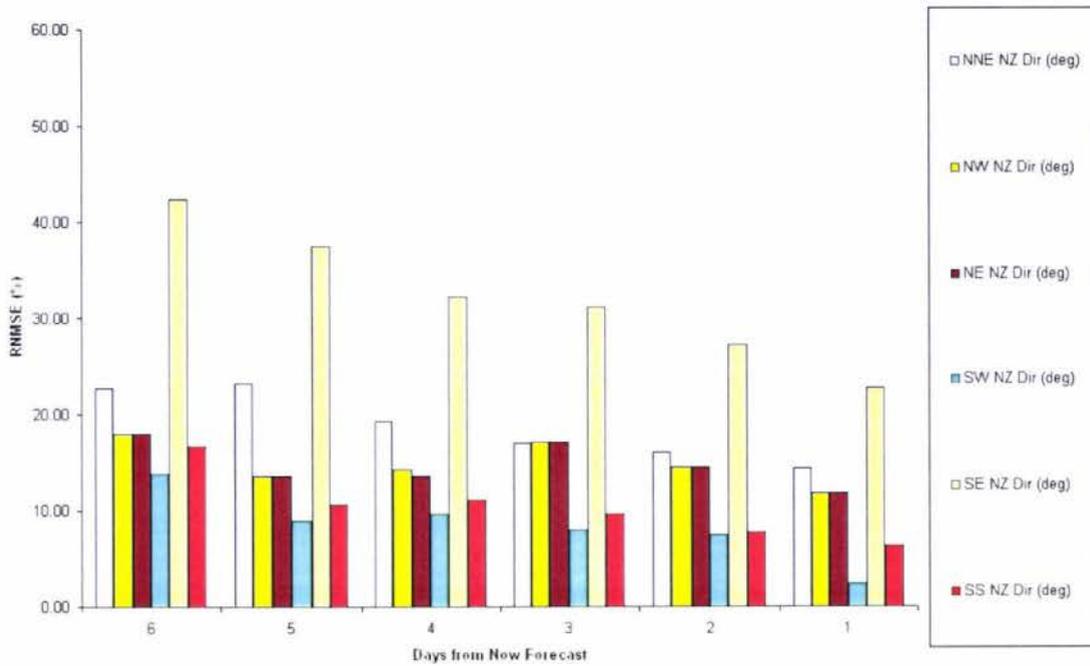


Figure 5.7. Comparison of the RNMSE as a percentage of the swell direction for six locations around New Zealand

### 5.3.2 Predictability interpretation

The RNMSE is a useful method for comparing actual and predicted results that may be under or over predicted and can be compared to modelling of a separate set of inputs (i.e. for several locations). It is for these reasons that this method of error identification was utilised in this study.

The RNMSE, (Figs. 5.5, 5.6, and 5.7), was expressed as a percentage to simplify explanations. For example the predictability of significant wave height for the following day at the southern most location (SS NZ, Fig 5.5) has a 7.5 % error, or in other words can be forecast with 92.5% certainty.

Figs. 5.5, 5.6, and 5.7 show that there is a significant reduction in error from north to south, east to west consistent with the conclusions expressed by Gorman *et al* (2003). The constant procession of low pressure systems traversing the Southern Ocean south of Australia and New Zealand, as well as the lower portions of both the Tasman Sea to the west, and the south western Pacific to the east, have a great influence as generating systems of swell upon New Zealand’s coast (Pickrill and Mitchell, 1979; Gorman *et al*, 2003b). A majority of coastline, from North Cape circling the country anti-clockwise to East Cape has aspect to these generating

systems. The majority of coastal aspect was found to be the most predictable. The greater the exposure of an aspect to the south and west, the greater the confidence in the prediction. A second factor was lack of exposure to possible ocean climatic conditions from the north, and to a lesser extent from the east, resulting in greater error at aspects having this characteristic. Hence the location SS NZ had the least error, NNE NZ the greatest.

The generating climatic conditions for North Cape to East Cape of the North Island was less predictable and had greater variability in intensity, direction, and frequency than the generating systems of the south and west. These observations are consistent with the findings of Gorman *et al* (2003a and 2003b), where the variability of the northern and eastern systems resulted in greater variability in the swell characteristics. This variability is compared in Fig. 5.8 and 5.9, where wave heights predicted for both SS NZ and NNE, represented the largest (NNE NZ) and smallest errors (SS NZ). The “spikiness” of the NNE graph demonstrates this variability with wave heights varying from zero to approximately twenty feet in very small periods of time. These wave events were created by fast moving intense generating storms that are inherently difficult to model and hence predict.

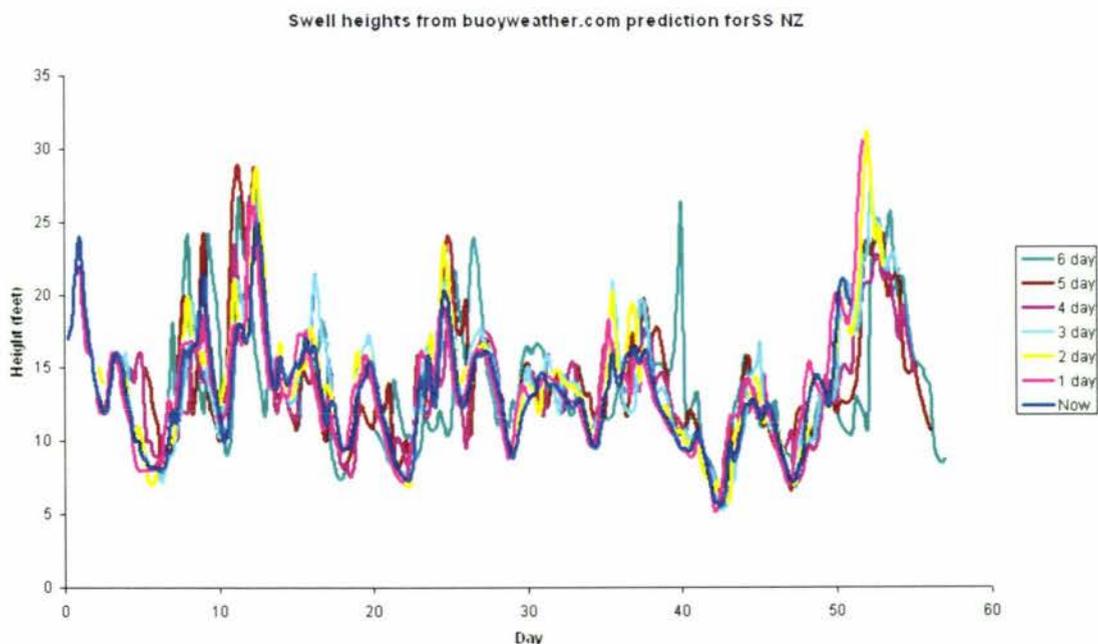


Figure 5.8. Swell heights from buoyweather.com predictions for SS NZ

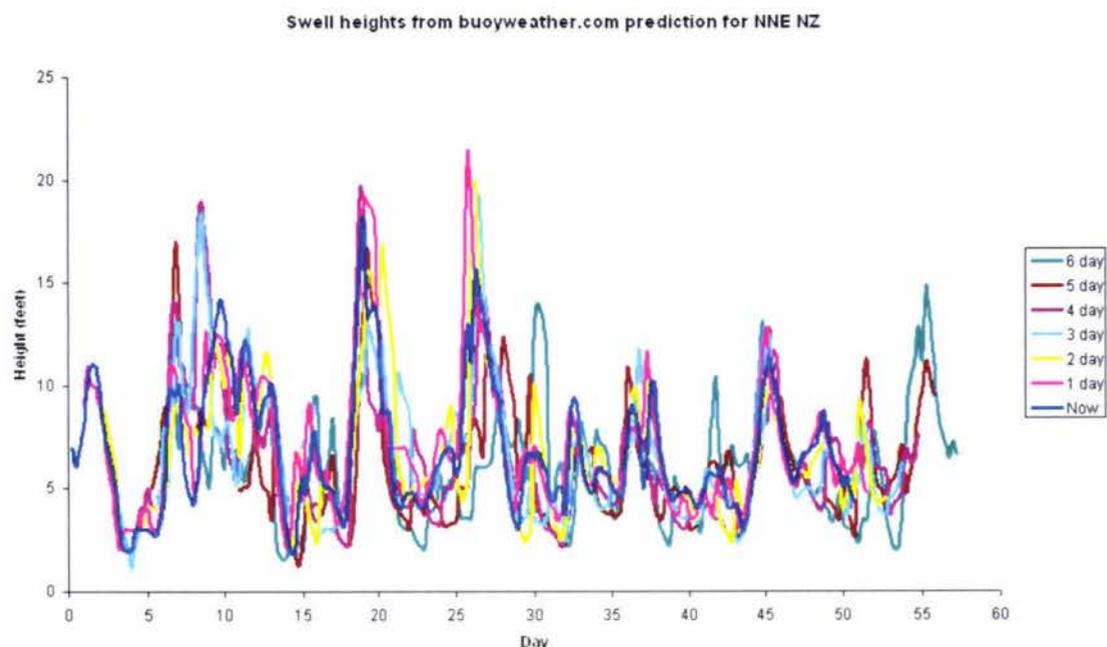


Figure 5.9. Swell heights from buoyweather.com predictions for NNE NZ

### 5.3.3 Summary of Predictive methodology

*The use of validated third generation wave models for prediction analysis allows for an understanding of the variability of swell generating storms that correspond to aspects of a coastline.*

*The differences calculated between observed and predicted wave characteristics quantify the dynamic stability of the swell generating storms impaction upon a location. Different locations can then be compared and the predictability of the wave climate accessed.*

*Greater predictability is especially useful for identifying, with confidence, outputs from wave energy plant. Confidence of future outputs allows for planning and adjustment of grid inputs.*

## 6 New Zealand Case Studies

Case studies for a variety of locations around New Zealand were chosen using criteria of:

- a nearby port capable of being developed to construct and maintain wave converter devices;
- the possibility of grid connection (being close to nodal points of the national grid); and
- close to a nearby population of substantial size (to support the infrastructure required for maintenance and operations).

This investigation evaluated the wave energy environment of locations adjacent to the coastline, with anthropocentric influences of local infrastructure (grid, ports, and energy demand) presently developed or open to development. Present developments of specific devices were negated by generic design assumptions made regarding the use of “wave power plants” (arrays), the adaptation of conversion devices to local conditions, and the working depths of various energy extraction techniques.

The studies had a coarse resolution in temporal, spatial, and anthropocentric dimensions and demonstrate the process output and interpretation of wave energy evaluation by use of hotspot identification and the influence of exceedance-persistence, and predictability.

The wave climate data from the WAM hindcast (section 4.1.) provided values of wave energy flux calculated from the modelled wave spectrum. The energy flux was averaged for each location of the hindcast (Fig. 6.1). These averaged values provide an assessment of wave energy similar to the general method described in section 2.2.1 and assisted the selection of locations studied that met the assumptions for an offshore wave energy plant made for this report.

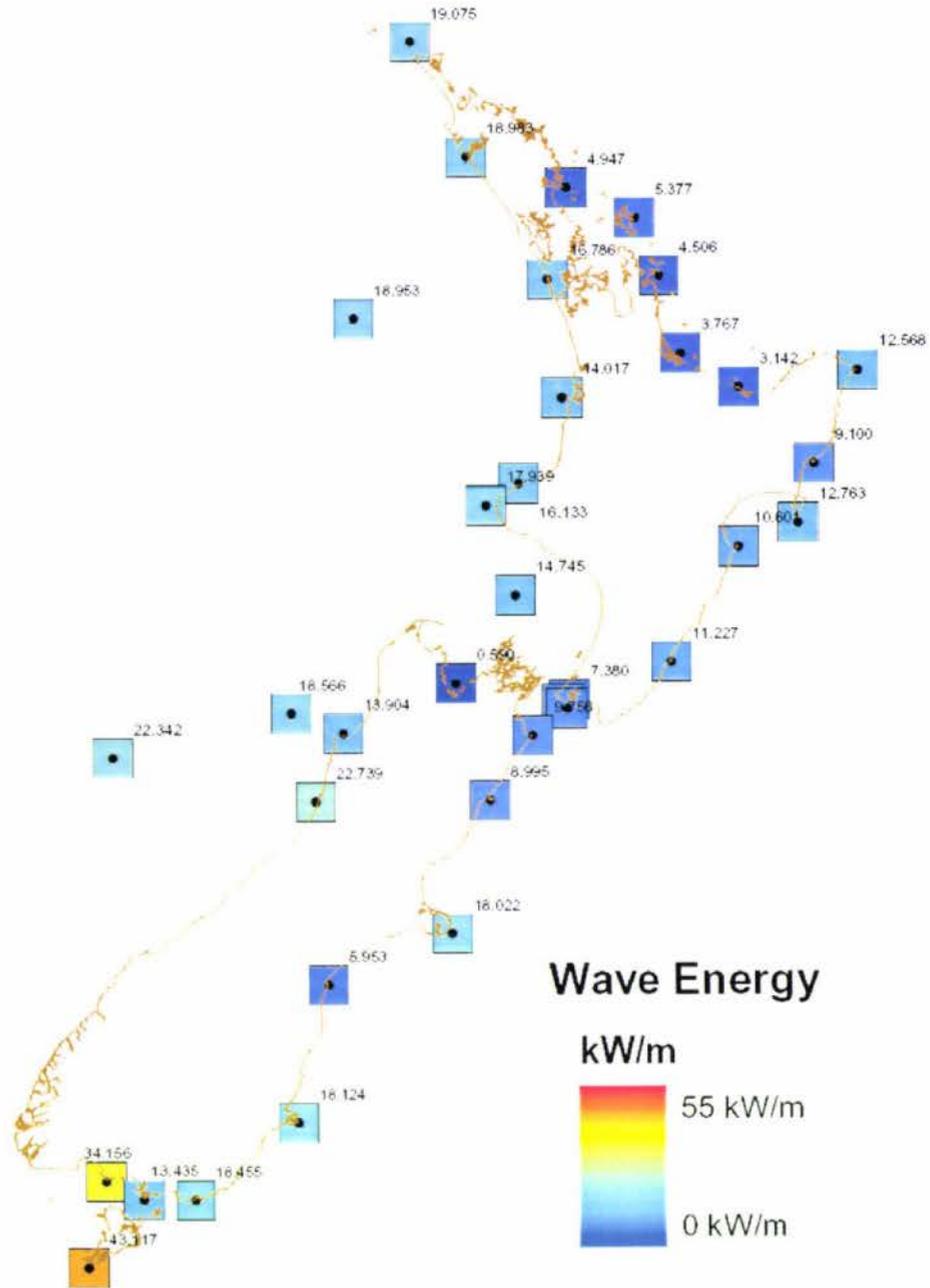


Figure 6.1. Locations based on WAM hindcast data show the average wave energy (calculated from the spectral modelling)

### 6.1 Hotspots

The modelled output of hotspots for all case study locations (Fig. 6.2) represent a variety of resolutions of cell size and coverage. The use of a graduated colour representing wave energy rather than the binned classifications shown in each of the preceding hotspot maps, smooth these variations in grid cell size. The

influence of greater wave energy exposure to Southern Ocean is immediately apparent.

At this scale (national) the variability due to variation in bathymetry and possible hotspots are not immediately apparent and require closer inspection. However the deepwater coastline of Fiordland, parts of the Otago Peninsular, and the Hokianga coast, appear to have higher levels of wave energy, than what might have been expected (due to shadowing from the landmass and the frictional losses close to shore). These locations may also have bathymetric features (at this scale) that promote higher wave energies close to shore.

Representation of wave energy at this national scale also demonstrates the locations that may be lacking in sufficient wave energy for utilisation. In this regard Fig. 6.2 is similar to the time-average wave energy of Fig. 6.1. However the differences between these two variations of wave energy assessment, the single location, and the spatial variation, demonstrate the advantages of hotspot mapping has over a single location energy values, especially when providing high energy possibilities closed to shore. The map objects created with the spatial variation modelling become most advantageous when combined with other data to answer pertinent questions. These may include:

- How far will sub-seas cabling need to be to reach sufficient resource?
- How deep is the location of high energy?
- How fast do currents move in the location?

And a question answerable with the inclusion of national grid nodal points, in the case studies:

- How far from the hotspots to possible grid connection?

### 6.1.1 Hotspot Maps

Hotspot maps for the coastlines adjacent to case study locations (Fig. 6.3 to 6.9) are derived from WAM twenty-year wave hindcast and digitised bathymetry. Cell sizes varying from 200m x 200m to 3000m x 3000m were used with the input wave climate data cell located at a depths over 300 m. Modelling using WBEND requires rotation of the digitised bathymetry. The modelling required the creation of up to two modelling runs with differing grids, when the input wave directions exceeded 140° (the extent of directional wave information for WBEND). Modelled iterations were combined and geo-register in the GIS.

Grid nodes digitised from Transpower diagrams of National Grid are visible in most maps. These are intended to provide an indication of where a major wave energy array might be connected to the national grid.

The maps are not validated as no empirical data was collected. An array of *in situ* devices, as well as remote sensing systems would be required to provide calibrated validated hotspot maps. This map is only intended as an example of the method of hotspot modelling, and to provide an indication of wave energy potential.

The creation of each of these maps required significant effort (section 5.1). It is estimated that the process used over fifty hours per map. Many hundreds of monochromatic wave transformation iterations (representing fractions of a percent of probability) were created often to be disregarded. The management of many large files (often of several gigabytes) required forward planning as the following stages of the process described in section 5.1 often had software limitations and required “work around” or recalculations to reduce file sizes. These compromises are represented in the many cell sizes utilised at each location (Figs 6.3-6.9).

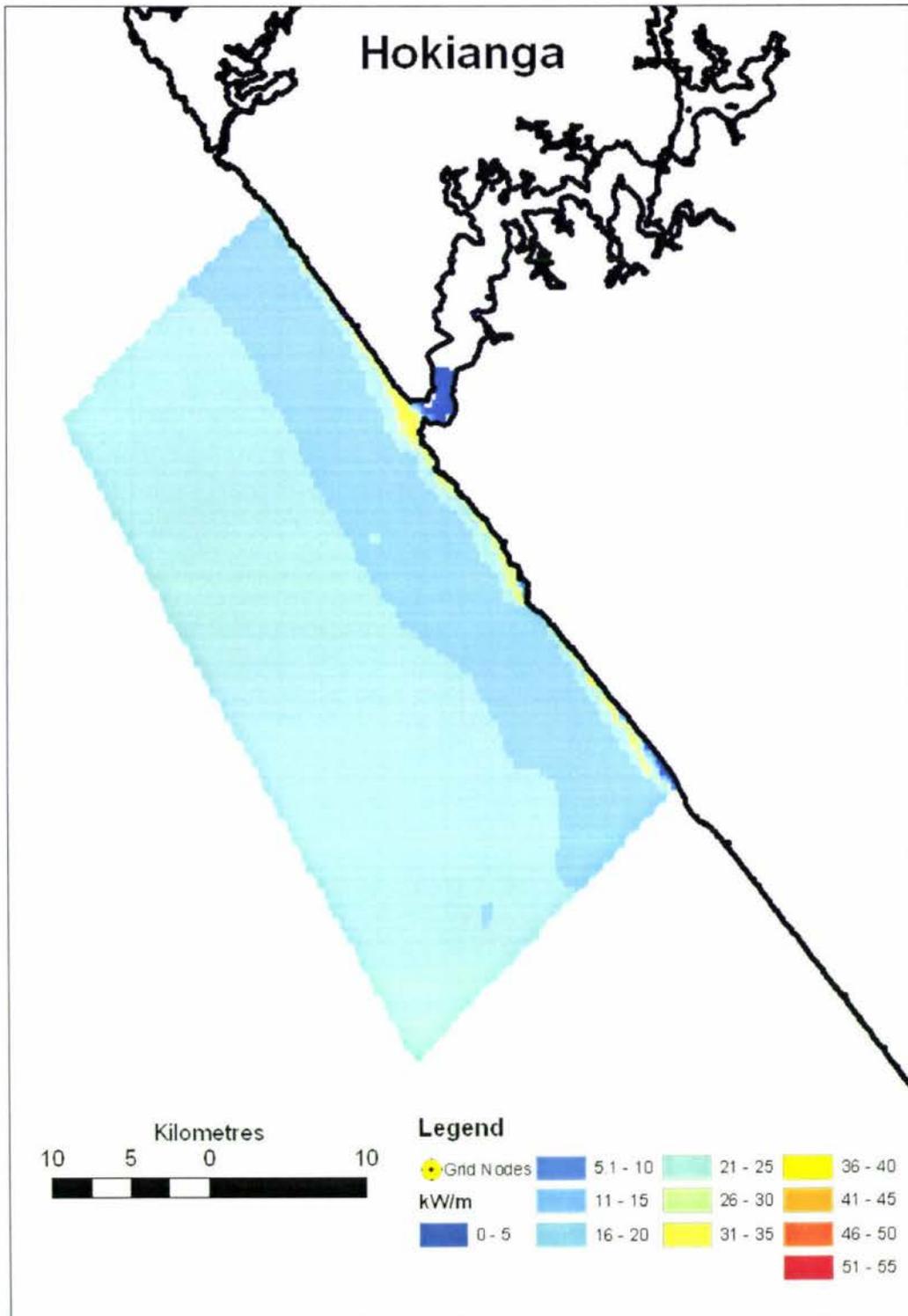


Figure 6.3. Weighted average wave energy for coastline adjacent to Hokianga harbour derived from WAM 20 year wave hindcast and digitised bathymetry 200m x 200m cells. Note that there nearest grid node (Kaikohe) is not visible at this scale.

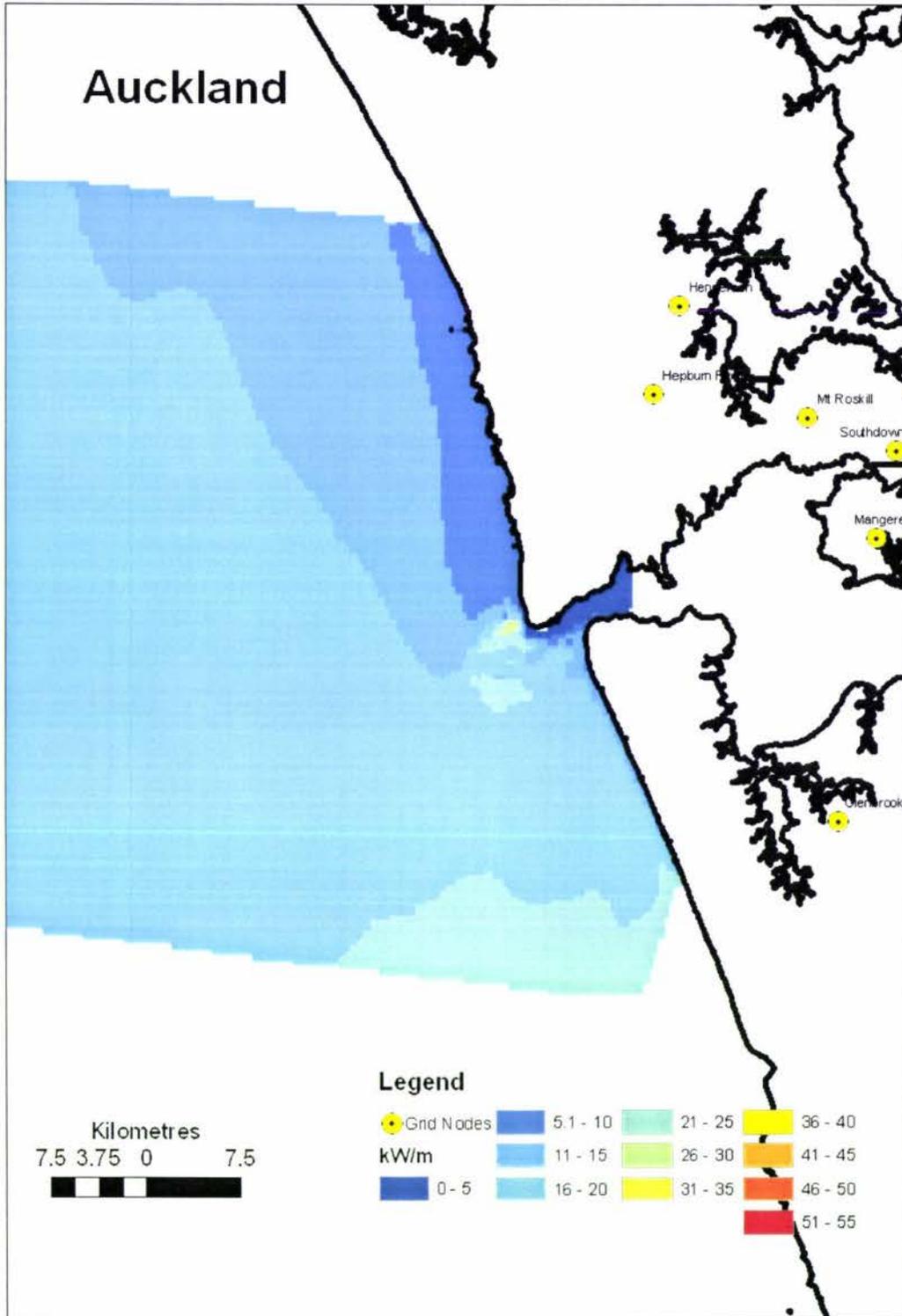


Figure 6.4. Weighted average wave energy for coastline adjacent to Waitemata harbour derived from WAM 20 year wave hindcast and digitised bathymetry 300m x 300m cells.



Figure 6.5. Weighted average wave energy for Taranaki coastline derived from WAM 20-year wave hindcast and digitised bathymetry 2000m x 2000m cells.

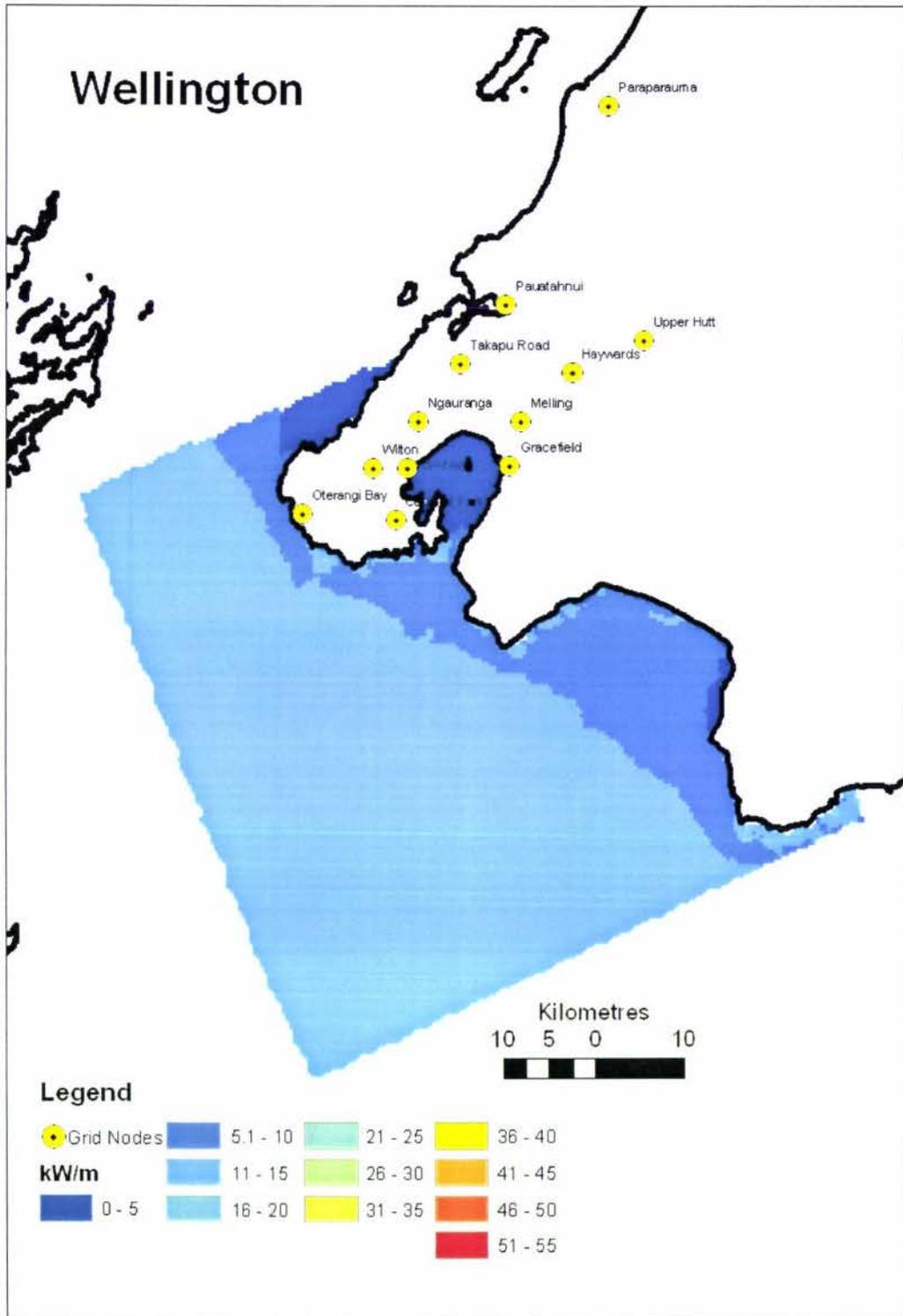


Figure 6.6. Weighted average wave energy for coastline adjacent to Wellington region from WAM 20 year wave hindcast and digitised bathymetry 500m x 500m cells.

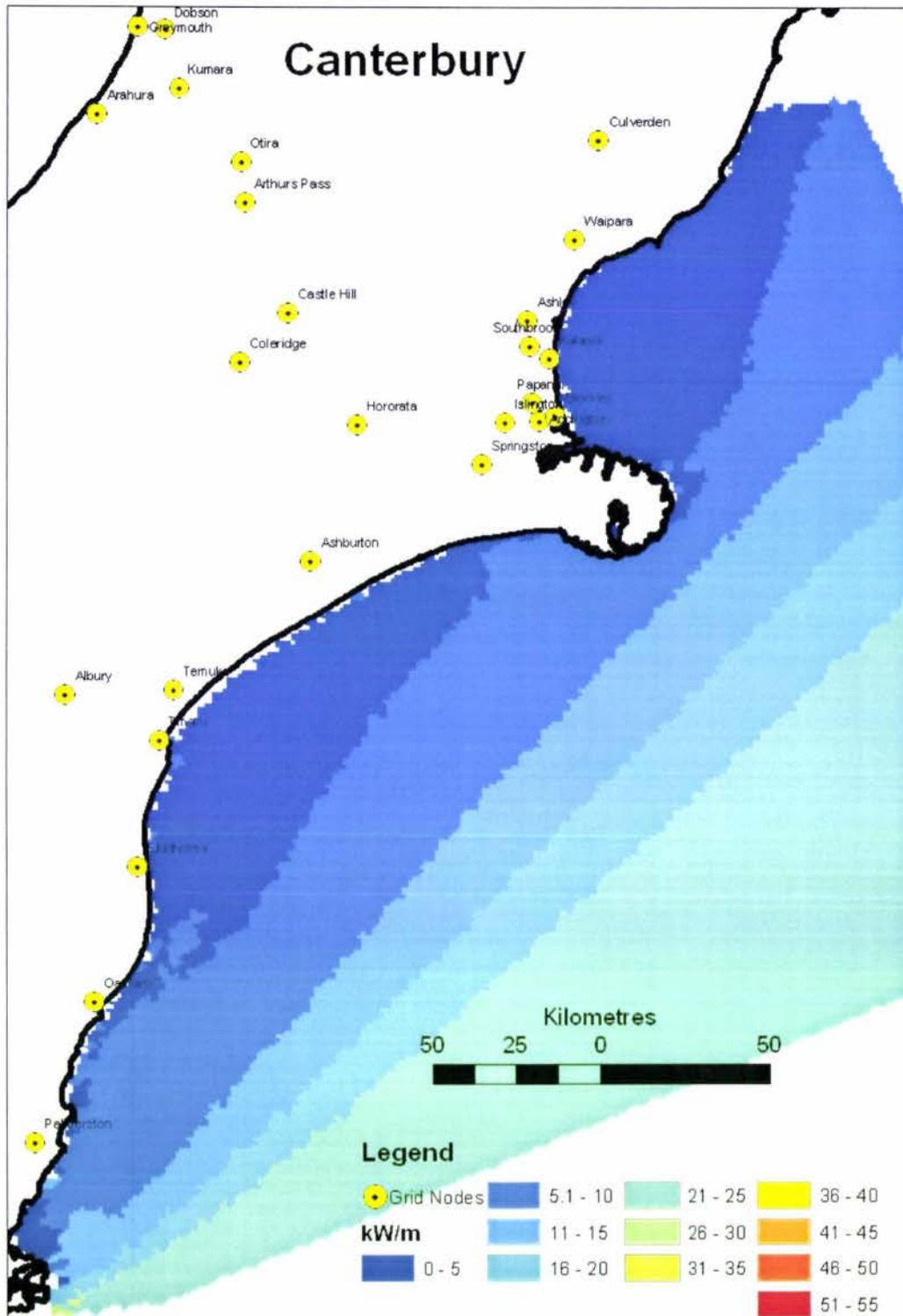


Figure 6.7. Weighted average wave energy for Canterbury coastline derived from WAM 20year wave hindcast and digitised bathymetry 2500m x 2500m cells.

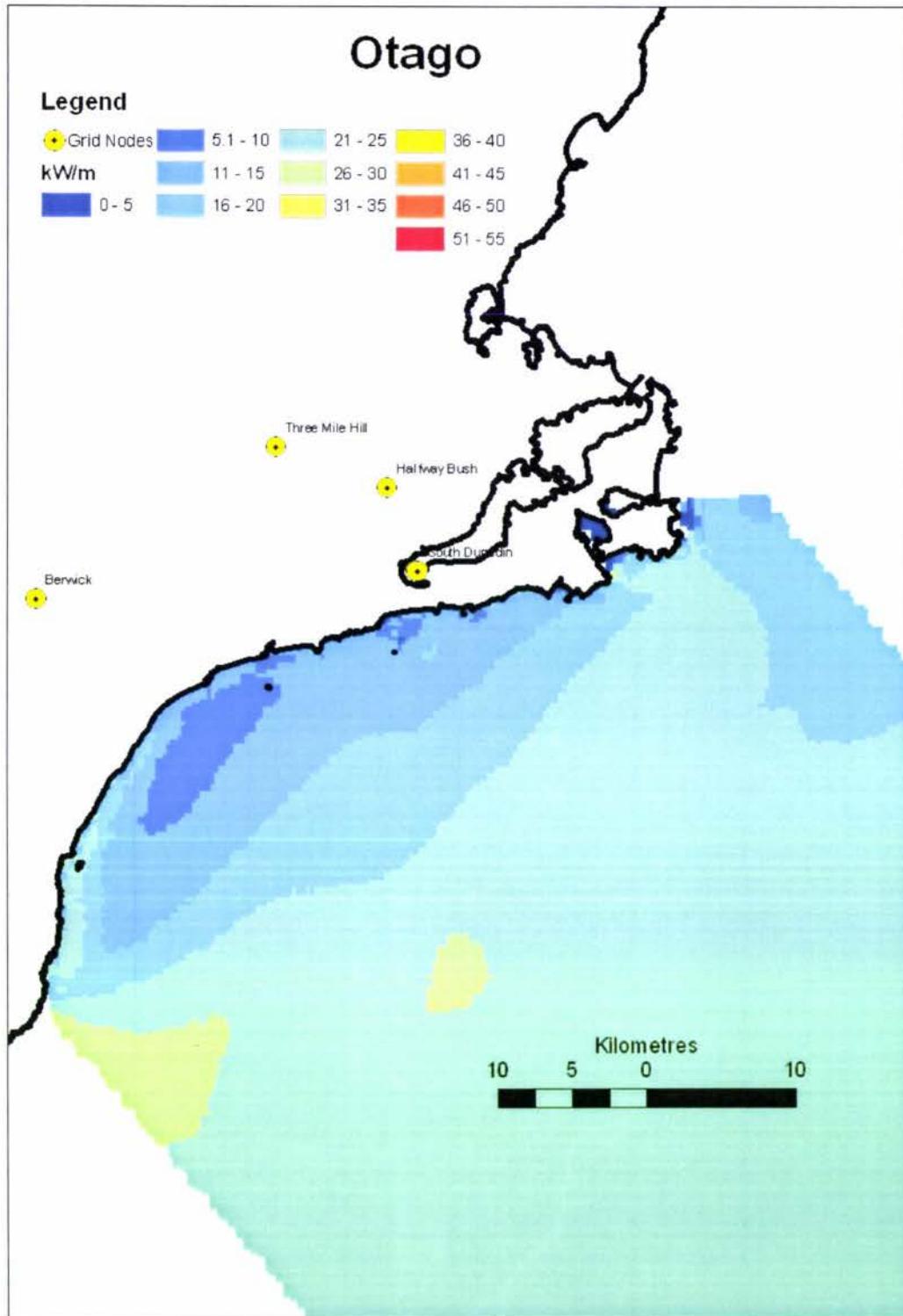


Figure 6.8. Weighted average wave energy for coastline adjacent to Otago harbour derived from WAM 20 year wave hindcast and digitised bathymetry 200m x 200m cells.

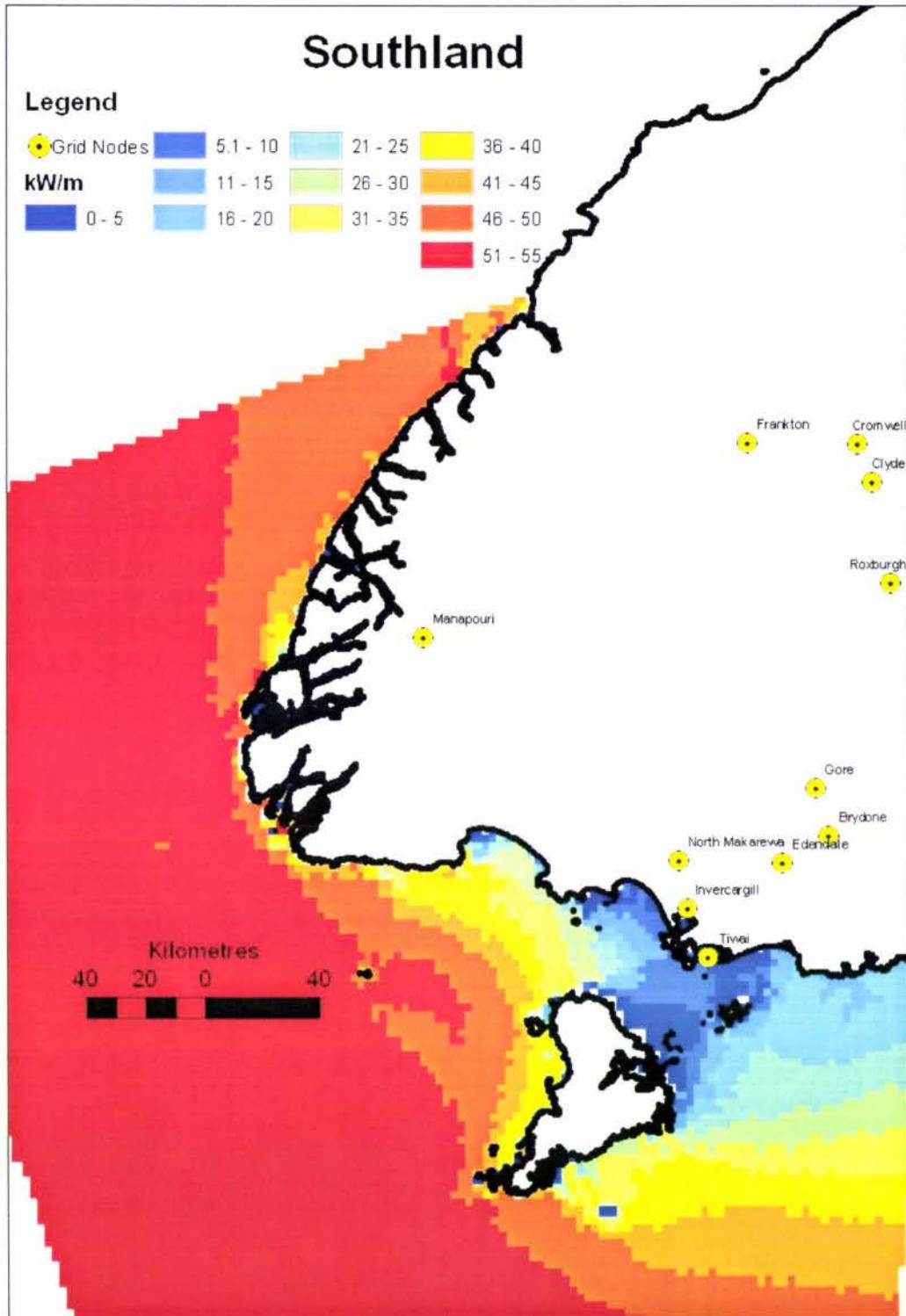


Figure 6.9. Weighted average wave energy for coastline adjacent to Southland harbour derived from WAM 20 year wave hindcast and digitised bathymetry 3000m x 3000m cells.

Interpretations of hotspot maps (Table 6.1) identify the location wave energy intensification and distances to shore. This is simple use of the geo-registered maps. More complex utilisation of the maps would incorporate and analyse wave energy with other spatial information (section 2.2.7).

**Table 6.1. Hotspot map interpretations.**

Hokianga (Fig 6.1)	Intensified areas of wave energy appear around the entrance to the harbour (31-35 kW/m) very close to the twin towns of Opononi and Omapere. It is expected that harbour mouth would be subject to tidal currents as well as sediment transportation.
Auckland (Fig 6.2)	Intensified areas of wave energy appear around the entrance to the harbour (26-30 kW/m). It is expected that these areas would be subject to extreme tidal currents as well as sediment transportation. Intensified areas also appear to the south of the harbour bar. If these areas are verified by empirical data, this may represent as significant length of coastline with higher wave energy and lacking the navigational and sediment difficulties of the harbour entrance.  Grid nodes are visible in this map. The Manukau node is less than 10 linear kilometres from the harbour entrance. Significant grid infrastructure exists overmuch of the region, and may be adaptable to create new nodes.
Taranaki (Fig 6.3)	Intensified areas of wave energy extend off the coastline in concentric bands of energy. An area of focus appears to the west of New Plymouth. Regions of reduced wave energy to the south dominate the map. The grid resolution of 2000m x 2000m is not expected to show significant locations of wave focusing; these are however expected to exist as the volcanic history of the region has resulted in variable bathymetry, visible at a much smaller resolution.  Grid nodes visible in this map. Nodes in New Plymouth as well as the Opunaki node may be useful. Significant grid infrastructure exists overmuch of the region, and may be adaptable to create new nodes.
Wellington (Fig 6.4)	Wave energy is significantly reduced close to the shoreline however several foci are present including south of the grid node where the Cook Strait cable lands (Oterangi). This location shows higher wave energy than the offshore resource with 21-25 kW/m.
Canterbury (Fig 6.5)	Wave energy is very low for a large part of this coastline (0-5 kW/m) and slightly better within distance of Bank Peninsular (11-15 kW/m). Grid nodes are visible in this map. The large cell size would not be expected to demonstrate localised focusing, however the bathymetry of this area (planar) is such that significant hotspots are not expected.
Otago (Fig 6.6)	A significant hotspot is visible close to shore in the northern section of the Otago Peninsular (26-30 kW/m) and the southern section of this map (31-35 kW/m). Grid nodes visible in this map. The variable bathymetry has resulted in areas of divergence and convergence.
Southland (Fig .6.7)	The variable bathymetry has resulted in areas of divergence and convergence. The wave energy for this location is significantly higher than all the other locations from around the country. The size of the cells makes identification of localised hotspots impossible, but does provide identification of wave shadowing, particularly by Stewart Island. Wave energy appears to be diminished close to nodal points in the immediate Invercargill (although this may be reinvigorated, could be identified with nested modelling using finer cell resolution). The most significant resource in the country (41-45 kW/m), that is within reasonable distance of a nodal point (Manipuri) is visible adjacent to the Fiordland coast.

## 6.2 Exceedance-Persistence

The annual exceedance-persistence charts for case study locations, as well as Great Barrier Island, Mahia, and Greymouth are shown (Figures 6.11 (a-j)) with the legend for these charts in Fig 6.10. Each chart has identical colours and symbols to represent the probability of wave energy exceedance from 0-100 kW/m in 1kW/m increments and the persistence of wave energy from 3 to 240 hours.

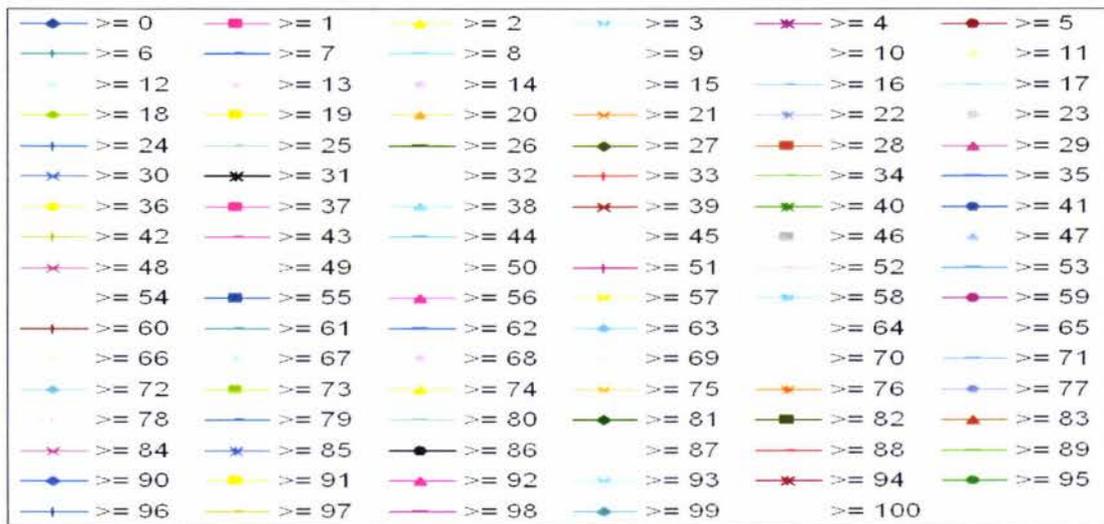
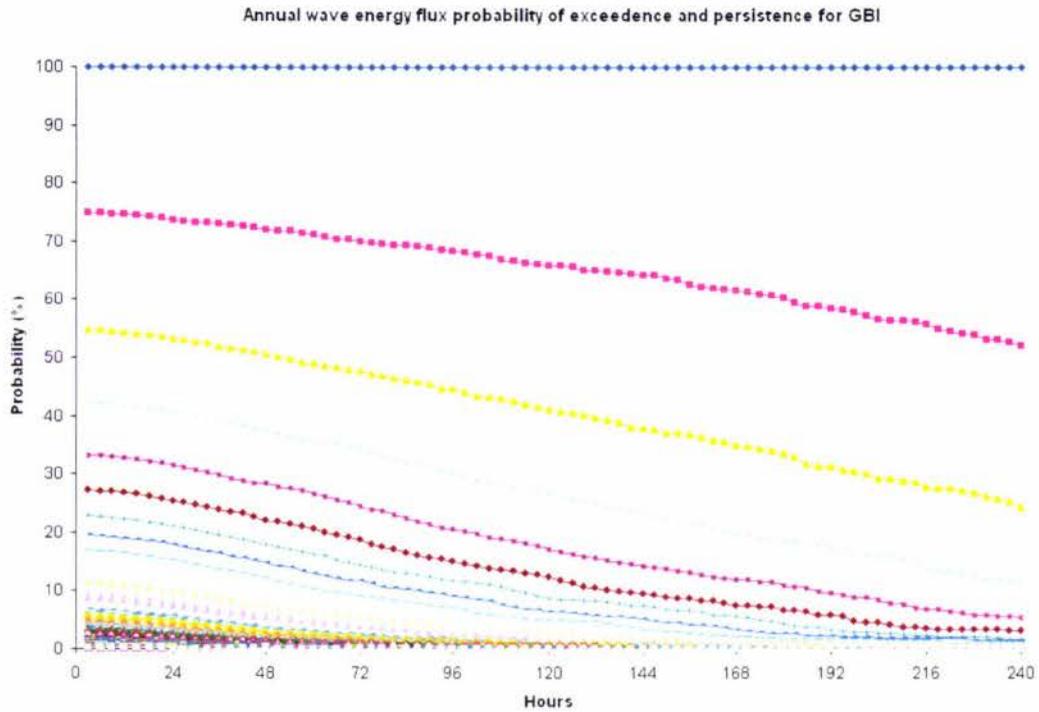
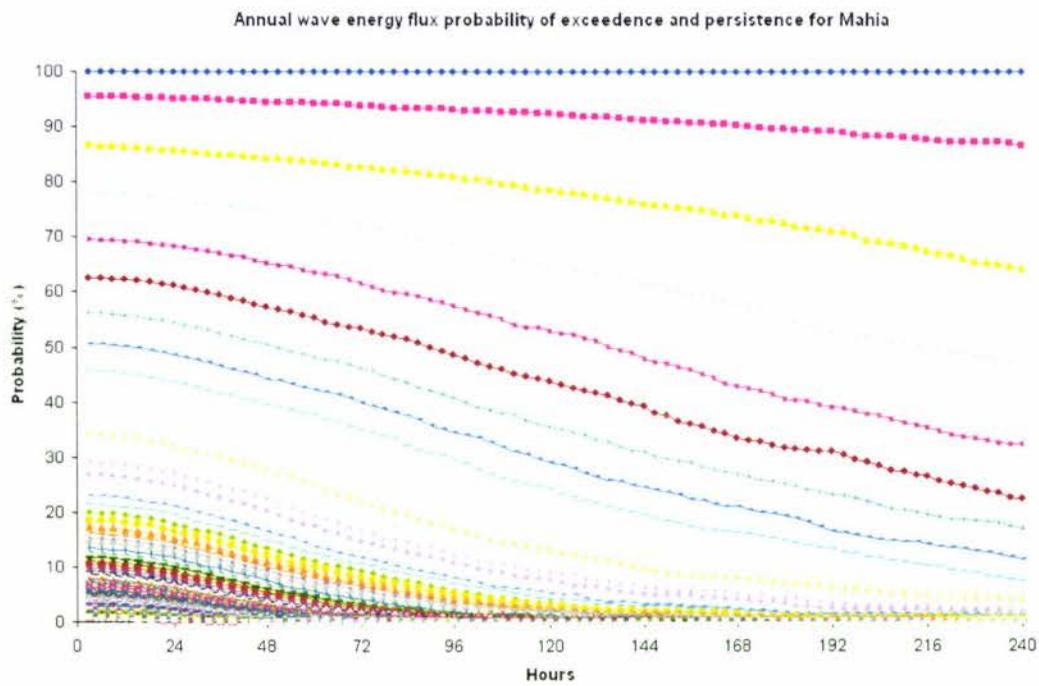


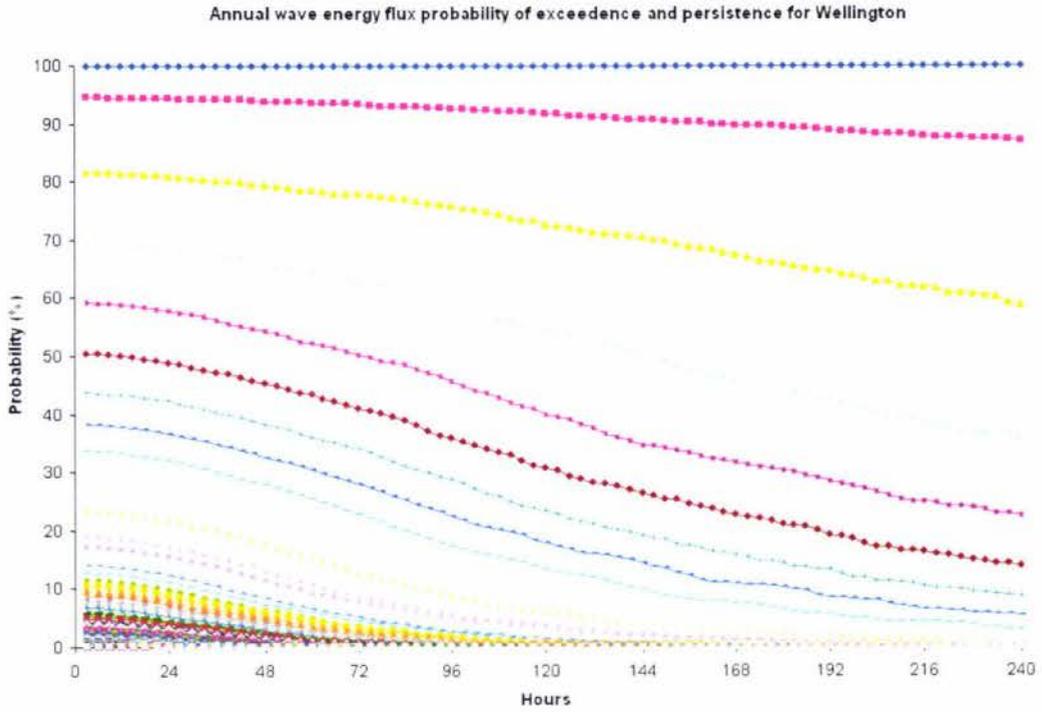
Figure 6.10. Legend for the exceedance-persistence charts. The values are for the wave energy calculated from the wave spectrum generated from the WAM hindcast and represent the exceedance of energy (hence  $\geq$ ).



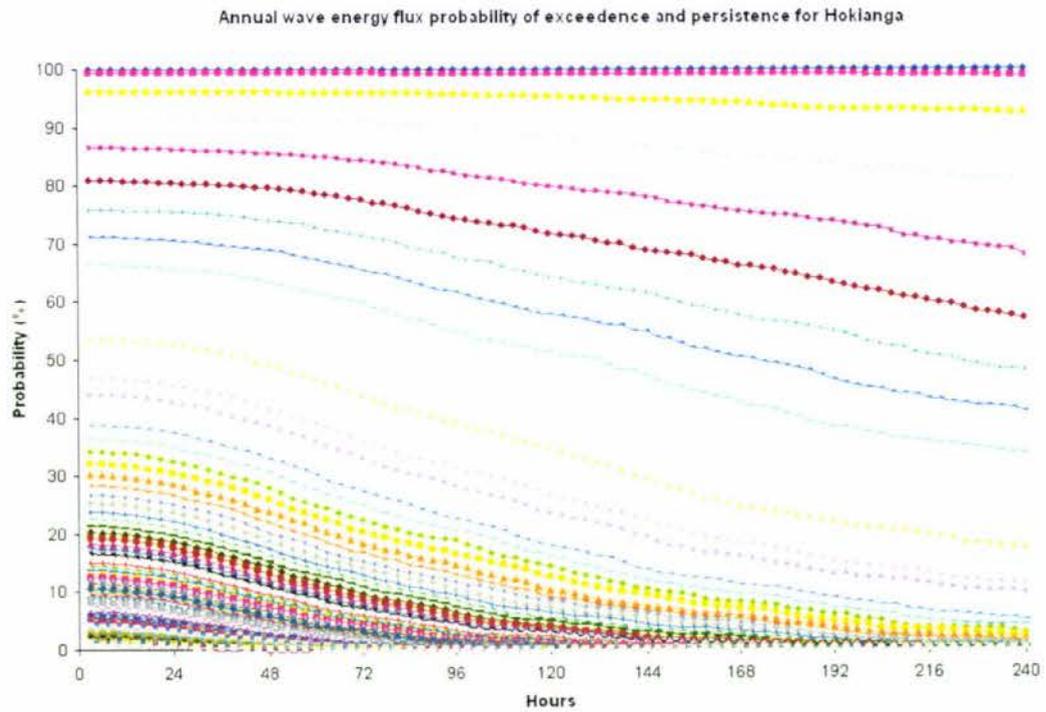
(a) Great Barrier Island



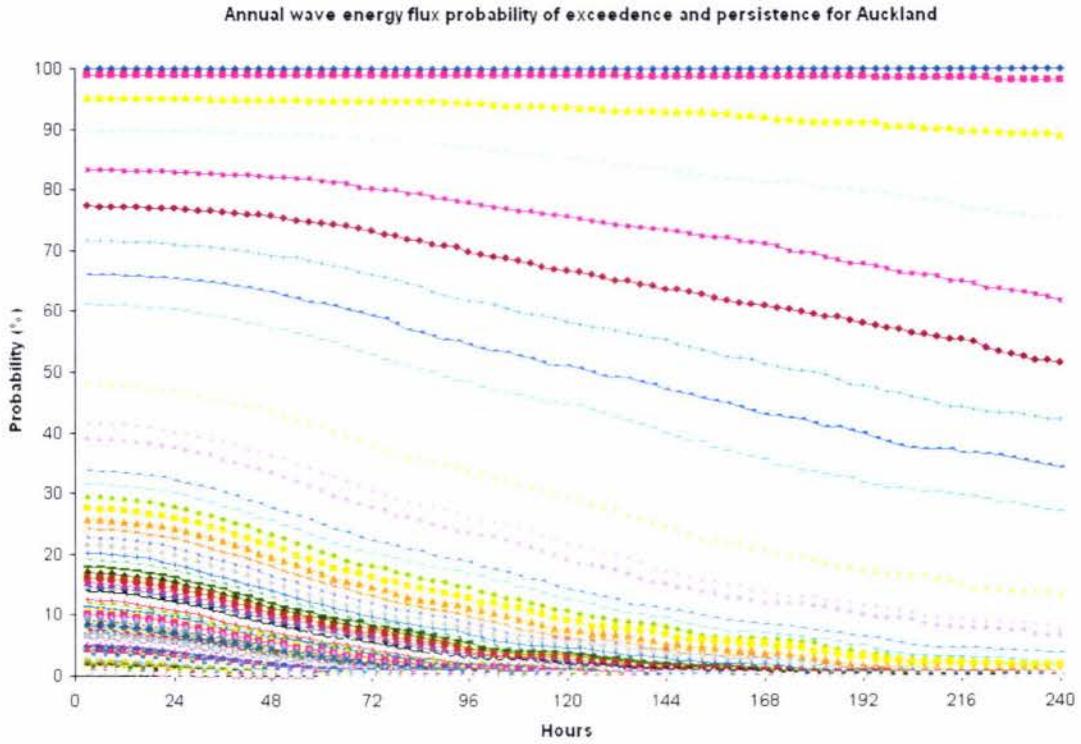
(b) Mahia



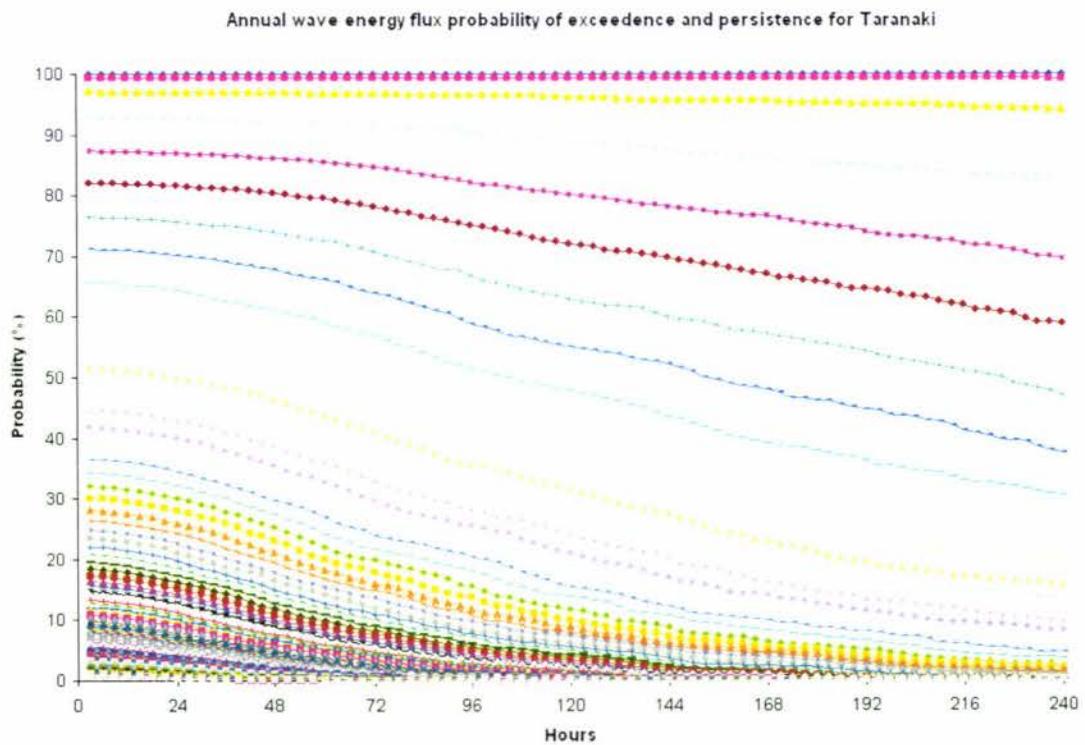
(c) Wellington



(d) Hokianga

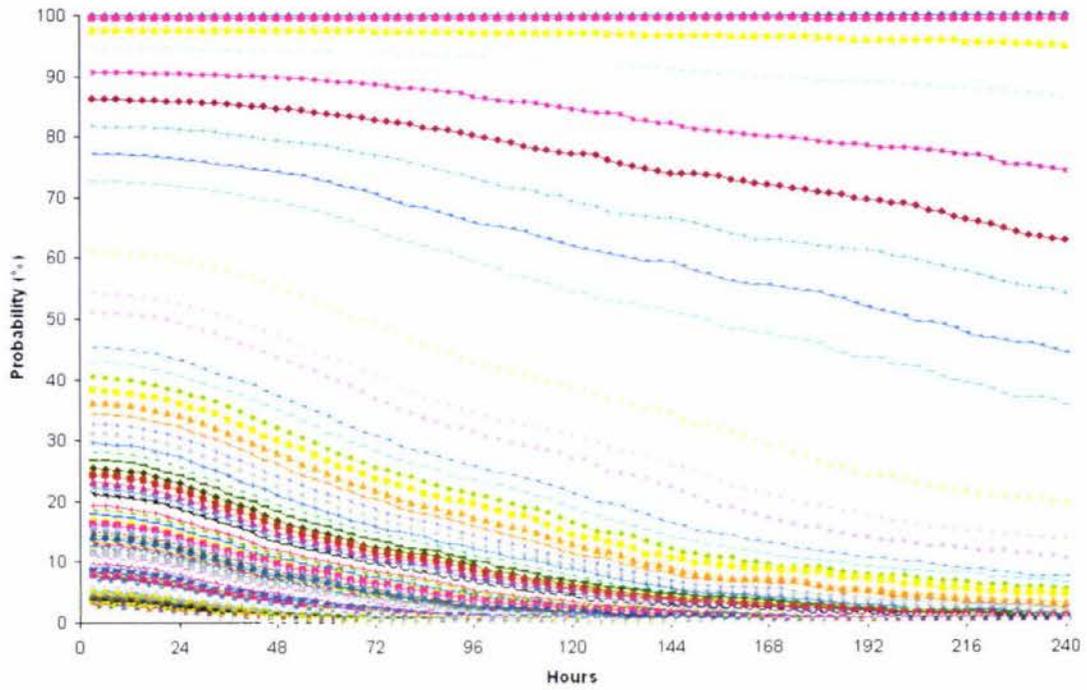


(e) Auckland



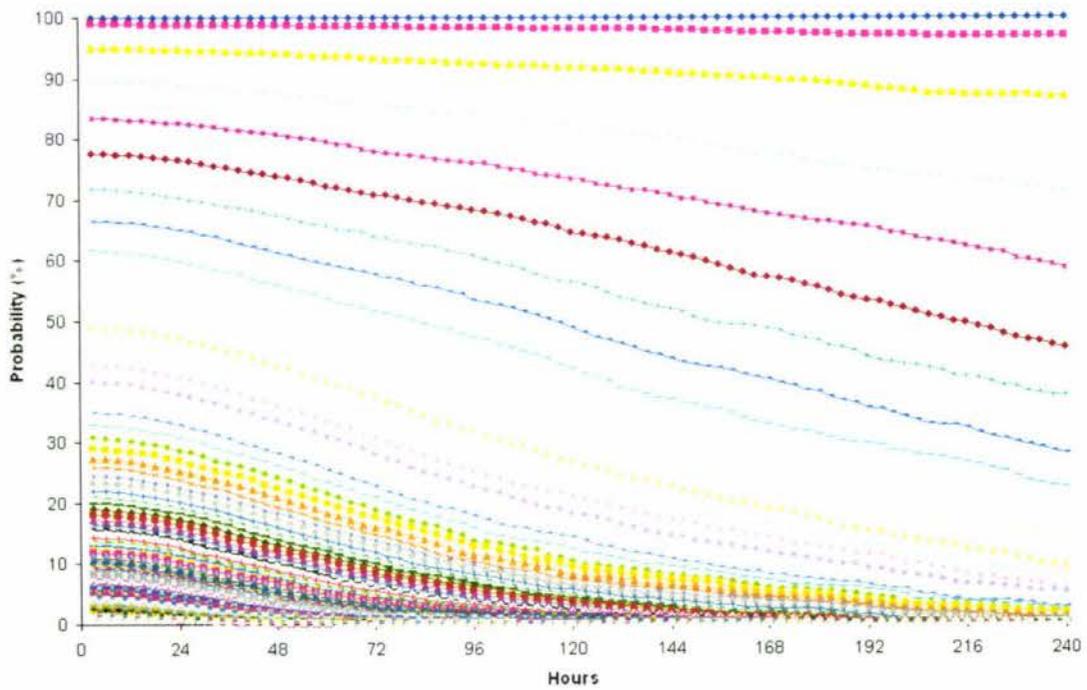
(f) Cape Egmont

Annual wave energy flux probability of exceedence and persistence for Greymouth

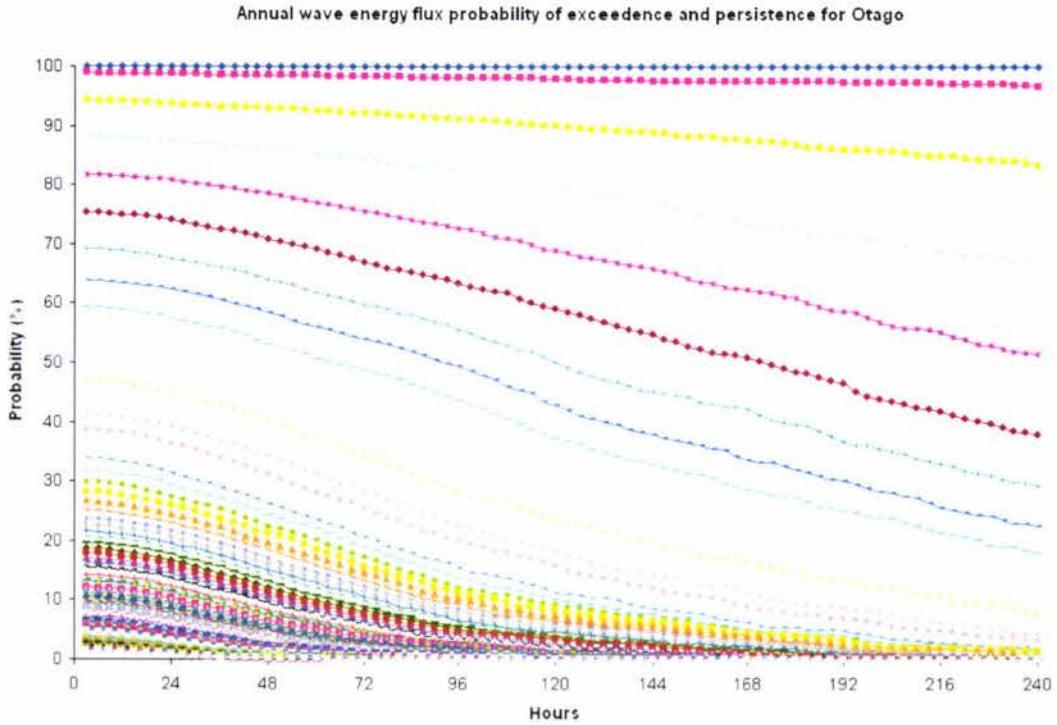


(g) Greymouth

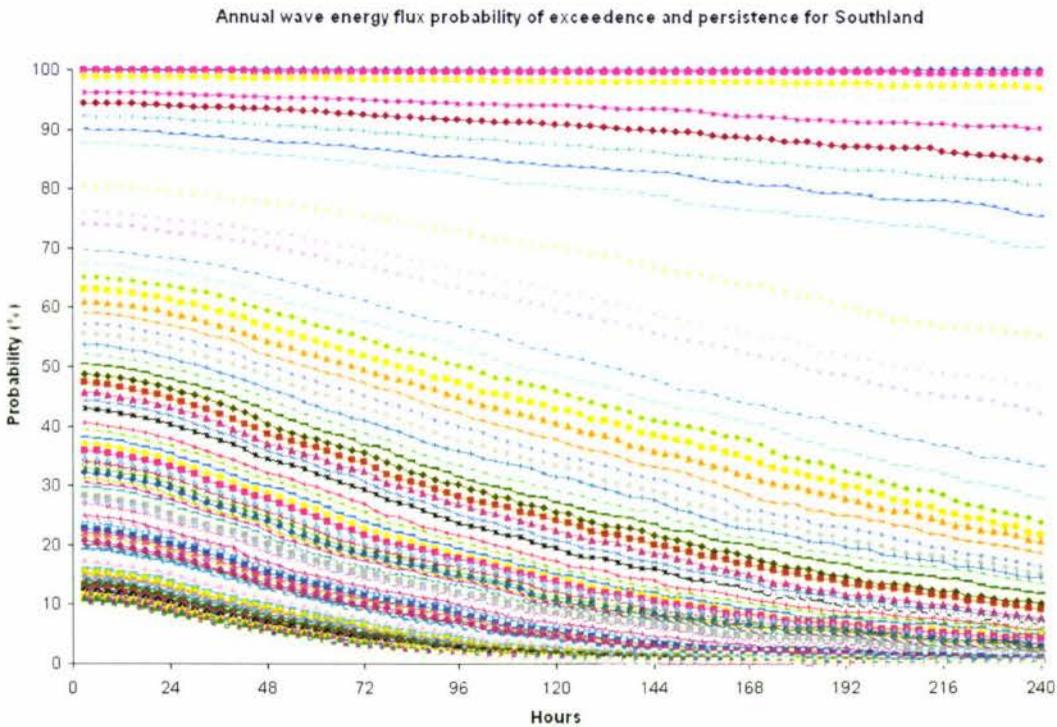
Annual wave energy flux probability of exceedence and persistence for Canterbury



(h) Banks Peninsular



(i) Otago Peninsular

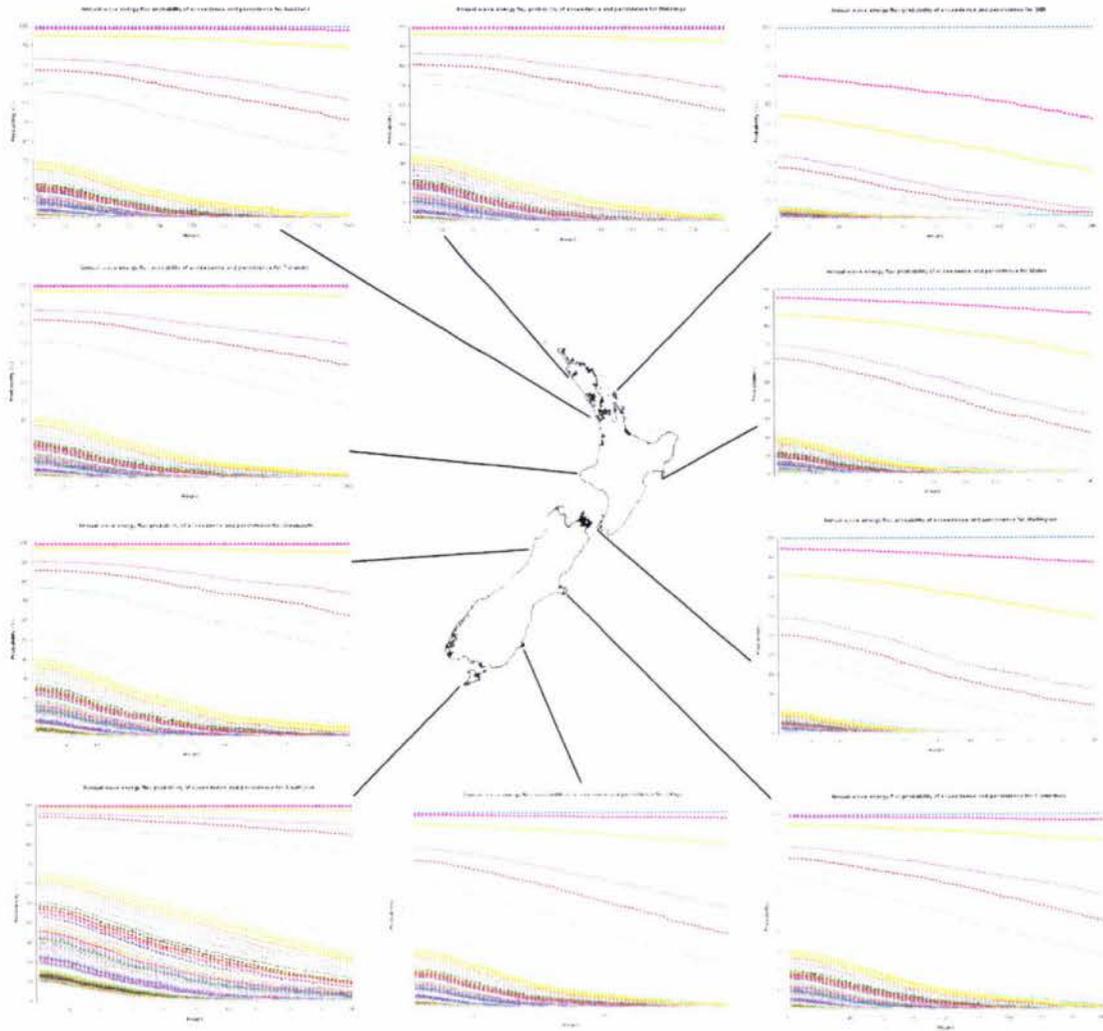


(j) South West Cape

Figure 6.11 (a-j). Comparison of ten day, annual, wave energy, exceedance-persistence charts for Great Barrier Island (a), Mahia (b), Wellington (c) Hokianga (d), Auckland's West Coast (e), Cape Egmont (f), Greymouth (g), Banks Peninsular (h), Otago Peninsular (i) and South West Cape (j).

The appearance of “bunching” of lines in the lower left hand side of each chart represents higher wave energy. The distance this bunching spreads towards the top right hand side provides a contrast for each site.

The exceedance-persistence diagrams (Fig. 6.11) provide a contrast of three differing wave climates for the locations surrounding New Zealand. These three divisions relate to the exposure to the Southern Ocean. The South West Cape (j) demonstrates the greatest wave energy resource with the high energy “bunching” spread over half the chart. Hokianga (d), Auckland’s West Coast (e), Cape Egmount (f), Greymouth (g), Banks Peninsular (h), and the Otago Peninsular (i) make up a second division with similar bunching. Great Barrier Island (a), Mahia (b), and Wellington (c) make up a third, lesser wave energy event, and division. The aspects of coastline these locations represent are demonstrated in Figure 6.12.



**Figure 6.12. New Zealand coastline and exceedance-persistence diagrams representative of major coastline aspects.**

The three location groupings are also demonstrated in the figures 6.13, 6.14, and 6.15. Individual persistence times (of 3, 48 and 96 hours) establish three groups with similar temporal wave energy characteristics. The concentration on specific probability of wave energy exceedance for set times (3, 48 and 96 hours) allowed the presentation and comparison all of the case study locations. These compassions provide a location ranking of the temporal characteristics of wave energy on the New Zealand coastline.

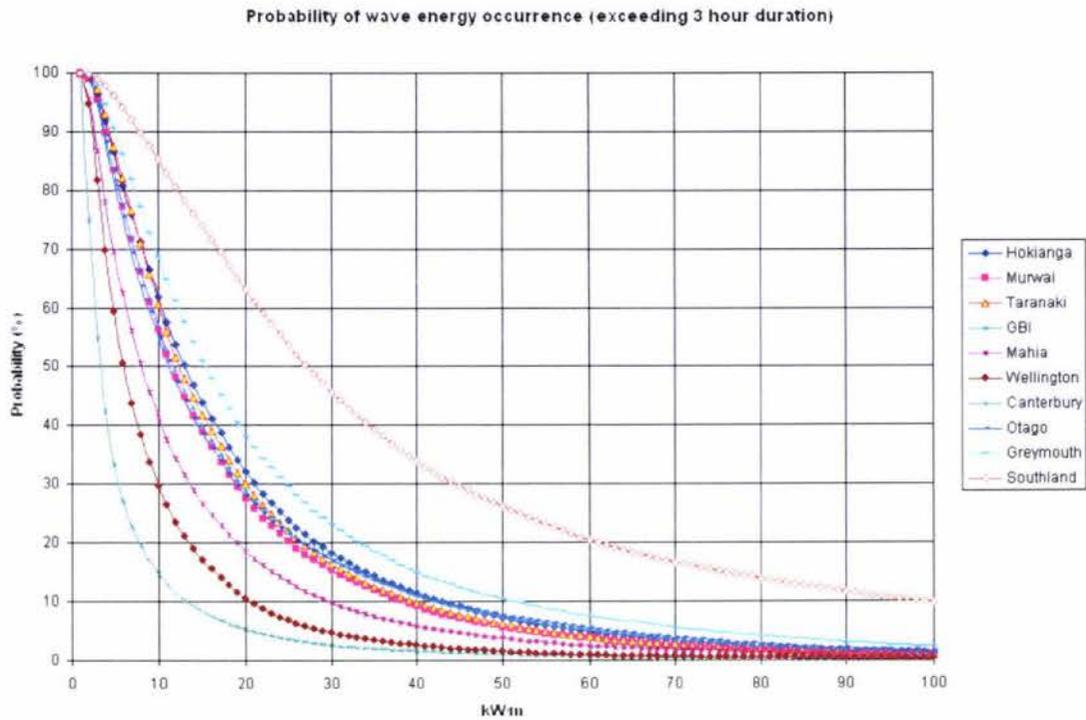


Figure 6.13. Comparison of the probability of wave exceedance for a persistence of 3 hours.

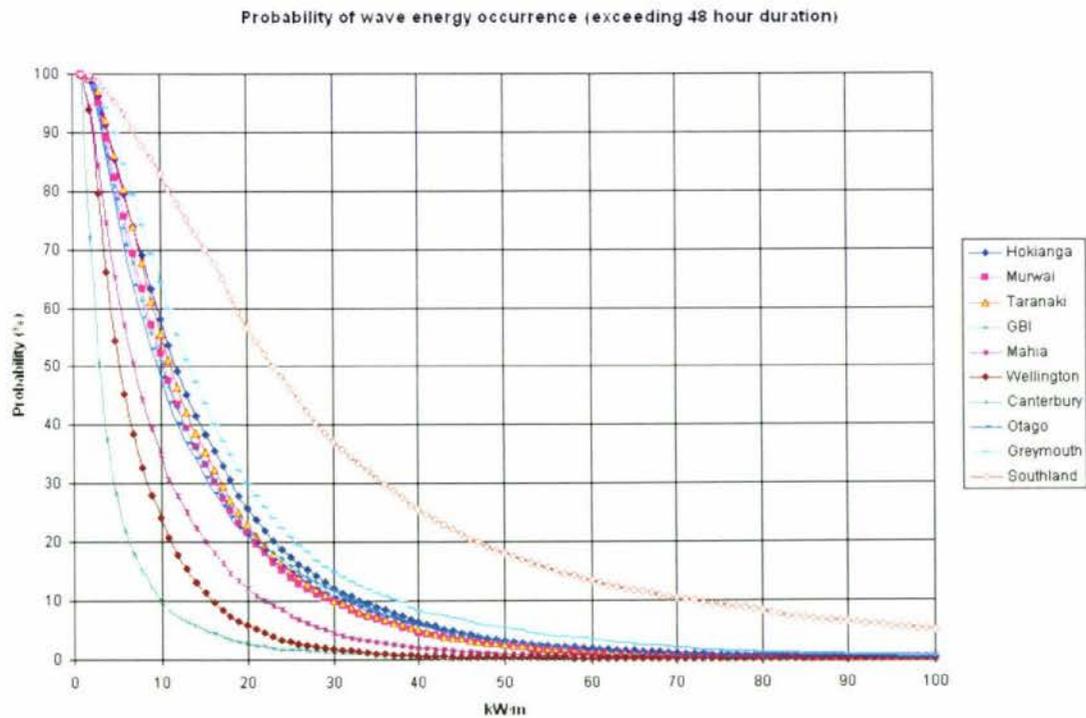


Figure 6.14. Comparison of the probability of wave exceedance for a persistence of 48 hours.

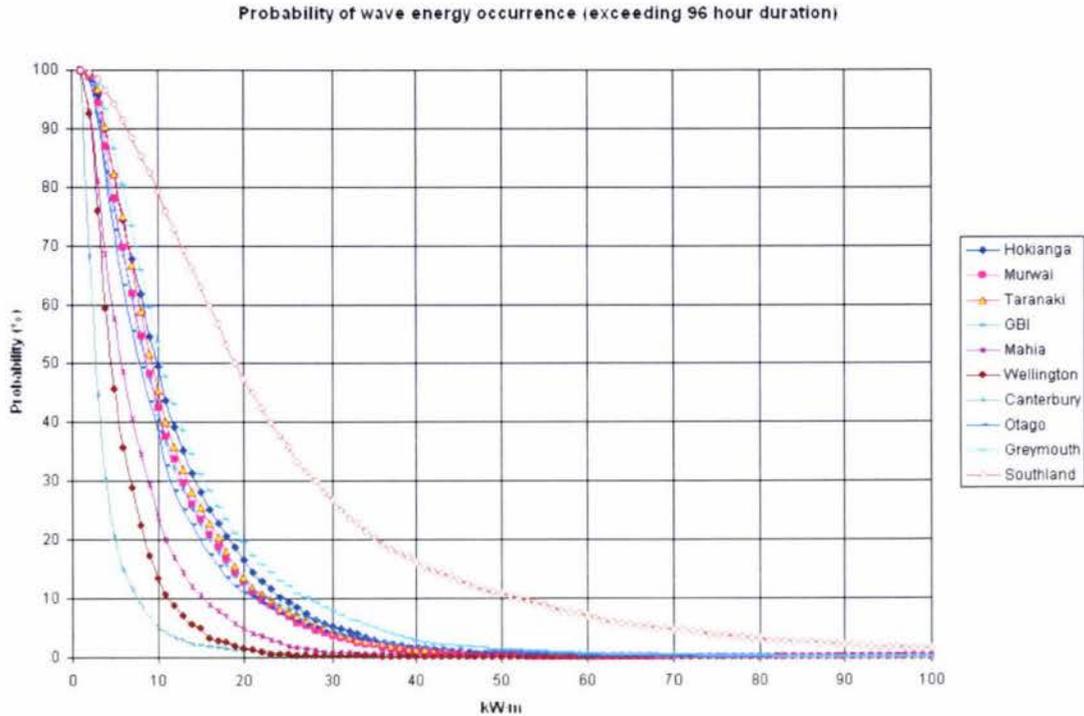


Figure 6.15. Comparison of the probability of wave exceedance for a persistence of 96 hours.

### 6.3 Predictability

The predictability of wave energy at a national scale and the reasons for the variability of predictability at the six locations was described in section 5.3.2. The root normalised mean square error (RNMSE) percentage results of predictability for wave height, period and direction for these locations are shown in Fig. 6.16.

The error intensifies from south to north, and west to east with the northeast coast having particularly significant errors compared to other sections of the New Zealand coastline. As described in section 5.3.2 there is greater variability of the wave generating storms in the sub-tropical waters to the north of New Zealand compared to the less variable parade of storms in the Southern Ocean to the southwest of New Zealand (Gorman *et al*, 2003b, Pickrill and Mitchell, 1979).

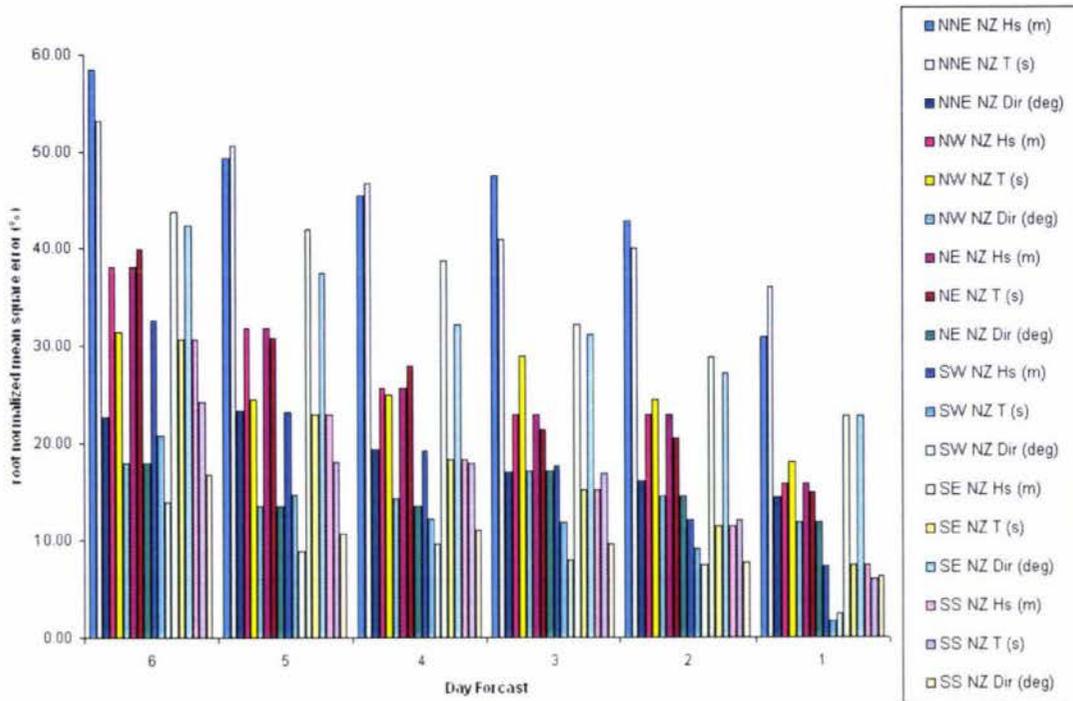


Figure 6.16. Wave height (metres), period (seconds) and direction (degrees) percentage root normalized mean square errors for 6 locations around New Zealand.

### 6.4 Wave energy possibilities

The hotspot, exceedance-persistence and predictability assessments at national scale provide for only the broad division of locations into the three groupings as outlined in the above sections. These relative associations could be termed excellent, good and poor wave resource locations (Table 6.2). Such generalisations are contrary to the theme of greater resolution and detailed understanding of the nature of the wave resource presented in this report, but as a nation scale summary, may be appropriate.

The “excellent” category refers to the Southland resource and with a complex bathymetry; specific locations may provide truly exceptional resource, anthropogenic considerations notwithstanding.

The large “good” resource refers to the locations of Otago, the west coast of the South Island, and many areas adjacent the coastline from Cape Egmount to North Cape. Specific locations may have intensified and remarkable hotspots, however the exceedance-persistence, and predictability will always lag the Southland example.

The poor resource applies to the remainder of the coastline, again specific location may have intensified hotspots, but the exceedance-persistence, and

predictability will always lag. Niche uses of wave energy in these locations may overcome these deficiencies.

**Table 6.2. Case study assessment summaries**

Case Study	Hotspot	Exceedance-persistence	Predictability
Hokianga	Good	Good/Excellent	Good
Auckland	Good	Good	Good
Taranaki	Good (requires further mapping)	Good	Good
Wellington	Good	Poor	Good
Canterbury	Poor	Good	Good
Otago	Excellent	Good/Excellent	Good
Southland	Excellent	Excellent	Excellent

**Table 6.3. Summary of case study wave energy possibilities including preliminary anthropocentric considerations**

Hokianga	Natural focusing, longevity of swell events and predictable swell generating zone result in a significant wave resource, situated at the mouth of this harbour. A large wave power plant may not be suitable for this location. However a solitary device or small array may be advantageous to the local community. The small distance to shore from the high wave energy environment of the harbour mouth; simple access from the harbour; and possible “ownership” by local iwi, or community of either a gifted or purely altruistic nature, may make this location partially useful as a preliminary wave energy site. It not anticipated that manufacture or assembly of wave energy converter devises would be realistic locally, but a degree of maintenance infrastructure may be possible.
Auckland	Auckland is a large agglomeration of people industry and commerce. The region has high-energy demands and relies on transmission of electricity from outside the area. Large-scale construction and maintenance of wave energy converters would adapt to the city’s present industrial community. An exact location would require further investigation of empirical wave data collection and high-resolution bathymetry. This case study however identifies the diminished wave energy along the Waitakere coastline (the “west coast beaches”), an effect influenced by the Manukau Harbour bar. This effect is pronounced during south swells and explains an anecdotally identified effect of similar sized waves braking at Manu Bay Raglan and the west coast beaches, when Manu Bay appears to be significantly less exposed. This shadowing means that the high wave energy areas adjacent to the southern side of the harbour and north of Muriwai may represent good locations for large-scale wave energy plants. Alternatively wave focusing of the harbour bar may be utilised..
Taranaki	Taranaki, and particularly New Plymouth are well suited to industry of the scale and niche requirements of construction and maintenance of wave energy converters. The possibility exists to

	<p>utilise the infrastructure developed for the hydrocarbon extraction industry, such as vessels, surveying pipeline/ cable easements, and empirical wave climate data. The local community is well used to offshore energy developments and may provide a more sympathetic perspective.</p> <p>The spatial hotspot map is dominated by low wave energy in the Southern Taranaki region. This may mean a limiting of utilisation of wave energy to the western Cape Egmount surrounds and to the west of New Plymouth. The resolution of the hotspot mapping is such that the variability of the bathymetry does not show the focusing of wave energy. Nested models of resolution similar cell sizes to the Auckland and Hokianga case studies would alleviate this deficit of information.</p> <p>The prediction and exceedance assessment of the Taranaki area are very positive and make this area an excellent candidate for wave energy utilisation, provided sufficient effort is made into identifying the spatial, hotspot mapping.</p>
Wellington	<p>The wave energy hotspot mapping appears promising for this area with significant wave focusing close to a shoreline nodal point. The wave probability of exceedance and persistence charts shows a poor resource for the winter and autumn and an extremely placid ocean for summer and spring. The focus south of the Oterangi node may however be useful as prototype developmental location, as the short-lived swells provide opportunity to access developmental wave converters and the existing easements for the inter-island electricity cables, reducing consenting obstacles.</p>
Canterbury	<p>The exceedance-persistence graph for this location shows a good, consistent resource of swell that persists for a good period when it arrives. The predictability is also promising, especially for a coastline that is open to a large window of swell directions. It might be expected that interpretation of directional expectations, may improve predictability figures. The hotspot mapping however shows no significant wave energy resource close to shore. The bathymetry also appears to be quite planar, hence lacking in features that would influence significant wave energy focusing. Any wave power development would most likely be required to be a significant distance off the Banks Peninsular. There is significant electricity grid infrastructure in the area, but little protruding on the Banks Peninsular.</p> <p>Construction and maintenance infrastructure may be possible as Christchurch has both a large harbour (Lyttelton) and significant industry. Wind energy industry development upon the Peninsular may provide a link of grid infrastructure. This region may on day provide sites for wave energy, but the tyranny of distance demonstrated by the hotspot mapping, make this not an immediate choice for wave energy development.</p>
Otago	<p>The Otago assessment shows very favourable wave energy potential for this area. The higher wave energy close to shore in</p>

	<p>the northern and southern sections of the hotspot map, good exceedance and persistence of wave events, and low error of predictability warrant confidence in this location as suitable for wave energy conversion. The closeness of Dunedin to the coast and the natural harbour with industrial infrastructure enhance this conclusion.</p> <p>The planning of wave energy infrastructure would require significant mapping as the same variable bathymetry that creates hotspots, also creates areas of divergence such as those found in the hotspot mapping directly in front of the city.</p> <p>Otago would be a useful location for both large and small-scale wave energy plants. However the energy needs of the area is already well covered and Otago is an exporter of energy, and this would need to be considered particularly the infrastructural requirements and interconnectedness of the generation plant.</p>
<p>Southland</p>	<p>The physical wave resource for this location is the best in the country by a significant margin. The location for wave energy is inconclusive on a localised scale from this case study, however it is expected that closer inspection with finer resolution bathymetric data and refraction modelling would identify wave energy intensification. This is due to the bathymetry appearing to be of a variable nature and containing “shoaling” features.</p> <p>A wave power plant in this location might be required to be of a massive scale to be economic (due to the abundance of electricity already locally generated). Using the current state of development wave energy devices this would involve many hundreds of devices. This type of development would require extensive construction of devices that may be local fabricated, as well as various mooring and maintenance issues.</p>

## **7 Future developments**

Limitations of the methodology presented in the case studies (section 6) are due to:

- the quality of the input data available (hindcast data, digitised bathymetric xyz co-ordinates, buoyweather.com forecasts)
- compromises made to apply processes to the constraints of software applications (ArcMap, MapInfo, Matlab, 3DD suite);and
- a lack of validation of each of the three assessments with empirical data.

The case studies were compiled and presented to demonstrate the methodology of assessment. Presenting seven locations, varying in wave energy expectations (as derived from the general method results of Fig. 6.1), provided a judgment of the merits of the wave energy assessment methodology through comparisons of outputs (hotspot maps, exceedance-persistence charts, and the RNMSE of predictability). Presented here are possible improvements to these assessment outputs and also possible techniques to expand and refine the assessment methodology

### **7.1 Hotspots**

The development of a geo-registered weighted average wave energy map, that is able to quickly describe the spatial variation of wave energy for a location and can be utilised within a GIS to further analyse relationships with other spatial data (such as grid nodes in the case studies), represents a desired outcome (section 1.2). The methodology described to produce this output (section 5.1) may be improved using more sophisticated bathymetric input data and the use of full spectrum nested models. Full spectrum models would be capable of identifying the multiple swells from many directions and wave periods. Wave energy converter device outputs calculated from a full spectrum would provide for greater accuracy provided the characteristics of the devices under the influence of possible sea states is known. For most devices in the

developmental stages (i.e. pre full scale prototype) this is not necessarily understood (Black, 2007).

### 7.1.1 Bathymetric data

The resolutions of the WAVEWATCH III forecast (buoyweather.com), the 20 year WAM hindcast (1.25° latitude x 1.25° longitude) and the various nested WBEND bathymetry grids (3000m x 3000m – Southland, 200m x 200m -Hokianga), produced output hotspot maps that provided an indication of wave energy intensification. Greater certainty of the location of hotspots, as well as the size of the area of intensification and the spectral shape of the wave resource (Fig. 2.4) required higher resolution.

Multibeam surveys of the ocean floor (Fig. 4.5) are becoming an industry standard and provide bathymetric data of the highest quality with resolutions several orders of magnitude beyond the computational capabilities of most PC based modelling. Simplification of this data is presently overcome through averaging of data. Use of higher resolution multibeam bathymetric surveys may become of greater importance as near exponential growth of computing capacity allows higher resolution grid inputs for numerical modelling.

### 7.1.2 Wave generation and propagation modelling

This report used two types of model to product the hotspot maps. WAM hindcast spectral modelling and wave characteristics (wave height, peak period, and peak direction) were used as a boundary condition for WBEND nearshore wave transformation modelling. This provided acceptable outputs for the case studies and was a realistic degree of sophistication given the bathymetric resolution and the numerical modelling competence available. The outputs of this modelling were further manipulated into a geo-registered weighted average wave energy map.

This combination of nested nearshore wave transformation models from boundary conditions provided by global WAM forecasts is an accepted method of defining location wave characteristics. A further step is to utilise surf zone modelling (Boussinesq modelling) to determine more exacting wave refraction. This approach has been compiled and simplified by the United States Navy in a PC based package called “The Distributed Integrated Ocean Prediction System “(DIOPS) (Allard *et al*,

2005)(Fig. 7.1). Expansion of the wave energy resource assessment methodologies hotspot mapping should provide a similar pattern of model interaction.

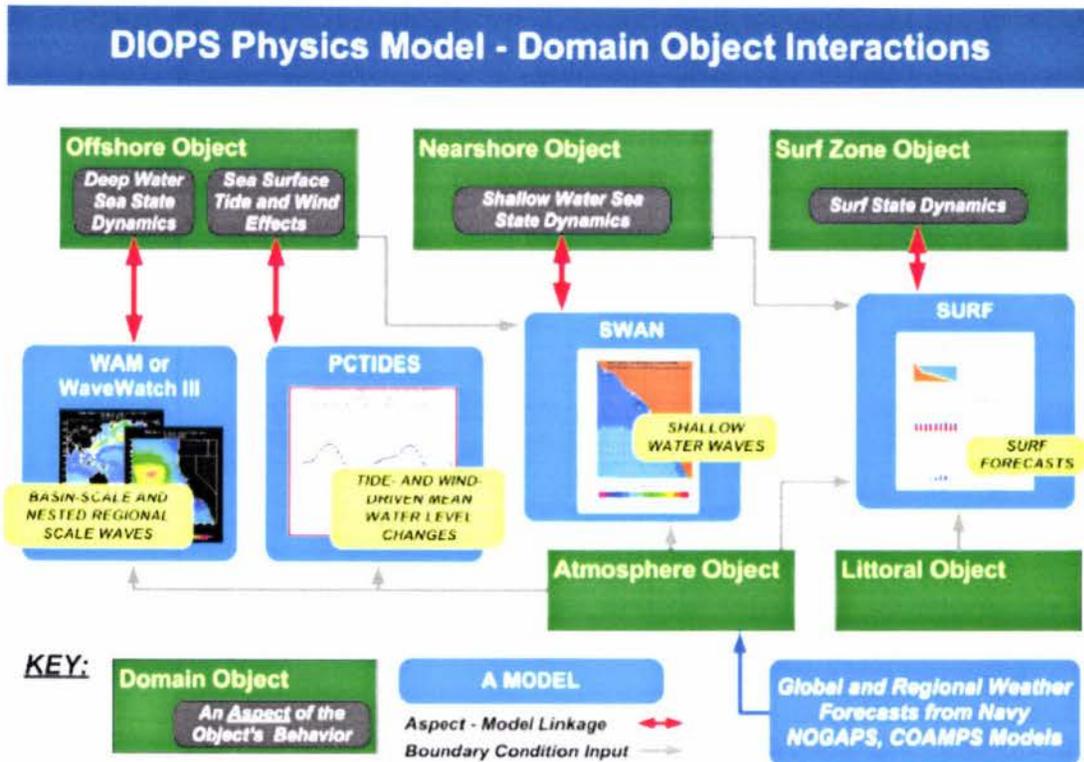


Figure 7.1. The Distributed Integrated Ocean Prediction System (DIOPS). Interaction of several wave models (described here by domain objects) is a pattern that the mapping of hotspots should attempt to emulate beyond the “offshore” and “nearshore” models (WAM, and WBEND respectively) of the case studies.

The use of spectral modelling rather than monochromatic waves would further provide greater mimicking of the real world situation. Whenever possible, this higher “resolution” of wave information should be adopted and resonated through the respective scales of wave models. Spectral modelling however is (when compared to the methods used in this study) very computing and labour intensive. Spectral modelling is therefore recommended for a specific site rather than the broad assessment presented here with seven locations.

## 7.2 Exceedance-Persistence

The WAM hindcast data used for this report provided a calculation of energy flux. This characteristic has been used to determine the usefulness of the wave energy

resource for a location, regarding the occurrence of an exceedance of wave energy that persists for length of time.

This gross measure of wave energy does not account for the particular usefulness of the energy once converted. Calculation of the actual energy expected from a particular device would be advantageous. Therefore calculation (for each iteration) of wave energy output of the hindcast time series (for a generic or specific wave energy converter device) would provide a greater assessment of applicability of development for interested parties.

### 7.3 Predictability

The data collected from the Internet wave-forecasting site, buoyweather.com was limited because:

- the data set was for a short period of time, June 21<sup>st</sup> 2004 to 10th August 2004; and
- the data was collected daily whereas the forecasts are updated every four hours).

A longer period of collection, and a greater number of collection times (i.e. the same four hourly update as the website), would resolve these issues.

The predictability assessment for the Westgate port of Taranaki by ASR Ltd used a 100-day spectral forecast and compared to empirical data. As stated in section 5.3.2 the use of empirical data is not necessary (apart from calibration the forecast model) as the determination of this assessment is the predictability of the location of wave generating climatic conditions. The use of spectral forecasts would add significantly to the assessment.

The speculation as to the location and variability of the climatic conditions for each of the aspects considered (Fig. 4.12) would be significantly enhanced with a spectral comparison of error as the differing wave frequencies of the spectrum can be traced to a generation location.

## **8 Summary and Conclusions**

### **8.1 Key findings of this investigation:**

- Waves can be predicted for a specific stretch of coastline dependant upon the predictability of the climatic conditions of the location.
- Wave energy resource assessment is often presented as a single figure (averaged kW/m) that fails to adequately incorporate the temporal, spatial and predictive aspects of the resource.
- A methodology was compiled to create areas of intensified wave energy (hotspots) mapping of a location utilising ASR Ltd's wave transformation models. These maps were then able to access spatial relationships to other digital information (electricity grid nodal locations, marine protected areas, navigation requirements, etc).
- Processing of wave climate data (utilising Matlab© script developed by ASR Ltd) identified the probability of wave energy being exceeded and persisting for a given location.
- Forecasts of wave characteristics are published on the Internet. Calculation of error between a "now forecast" and the previous day's forecast for today (up to six days out), can give an assessment of the predictability of an aspect of a location provided the wave forecast model utilises significant climatic variables.
- Case studies of wave energy resource assessment (using the developed hotspot, exceedance-persistence, and predictability methods) conducted for seven locations encircling New Zealand, identified three classes of wave resource; excellent (Southland), good (Otago, Taranaki, Auckland, Hokianga), and poor (Canterbury, Wellington).

The wave energy industry is maturing. A methodology of resource assessment that includes the spatial, temporal, and predictive nature of the wave resource, and presents this information in an intuitive and simplistic manner is desirable. This project has developed such a methodology with a three-point assessment requiring a

description of the nature of a wave's generation and propagation (section 2.1); analysis of the wave energy assessment methods employed to date (section 2.2); and an understanding of the problems facing renewable energy (section 2.3). The state of wave energy converter devices (section 3.1), and use of geographic information systems (section 2.2.7) to combine information for analysis, was also investigated. These reviews of knowledge were assessed (section 4) to provide a practical application for case studies surrounding New Zealand.

Data and the method of analysis of the data was collated and processed (section 5). The case studies (section 6) provided an elementary assessment of how this three-part analysis could be used to evaluate a region's wave energy potential. The shortfalls of the methodology are presented, and an indication of possible improvements and refinements described (section 7), which could be applied to specific sites.

By incorporating the three resource assessment aspects (hotspots, exceedance-persistence, and predictability) it was found that the New Zealand wave resource is good to excellent for a vast area of the country's coastline. Bathymetric features close to many main centres provide hotspots of intensified wave energy. The procession of storms of the Southern Ocean provides highly predictable wave events that persist for sufficient time to make significant contributions to New Zealand's electricity. The potential to utilise this resource is dependant upon a maturing energy conversion devices. The wave climate and wave resource of New Zealand differs from the northern hemisphere where many devices are being developed. New Zealand enjoys a constant barrage of swell from the Southern Ocean throughout the year, compared to the seasonality of the Northern Pacific and Atlantic Oceans. The exceedance-persistence characteristics of New Zealand negate any reliance upon the single averaged kW/m figures for determining the usefulness of the wave resource, as has been often presented by northern hemisphere based evaluations.

This study condensed the characteristics of a complex, erratic, alien environment, whose forces and energies are foreign and peculiar, into a form that is, elegant, intuitive, and informative. The case studies provided a comparison of wave energy locations that demonstrate the resource evaluation effectiveness.

This study set out to “produce a methodology of wave energy resource assessment incorporating the spatial, temporal, and predictive variables of the wave resource”. This has been achieved through the mechanisms of hotspot maps, exceedance-persistence charts and predictability error graphs. The outputs of the assessment methodologies are comparable, uncomplicated, graphic representations of the wave resource. The qualifier to these outputs is ...”which is relevant to electricity generation entities.”

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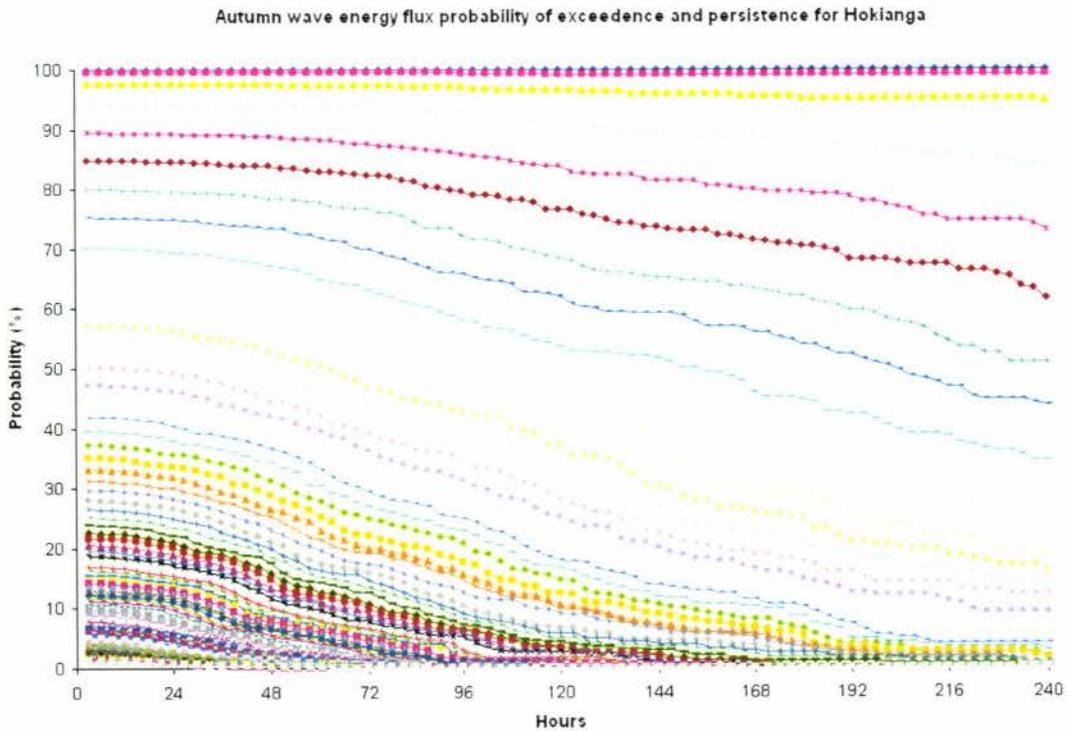
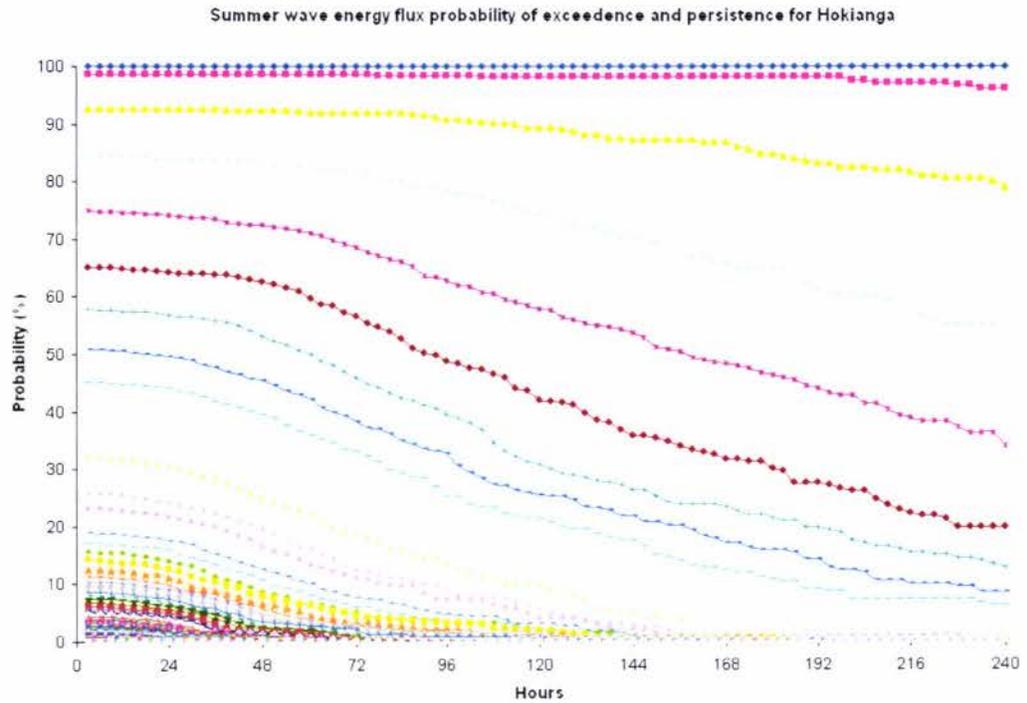
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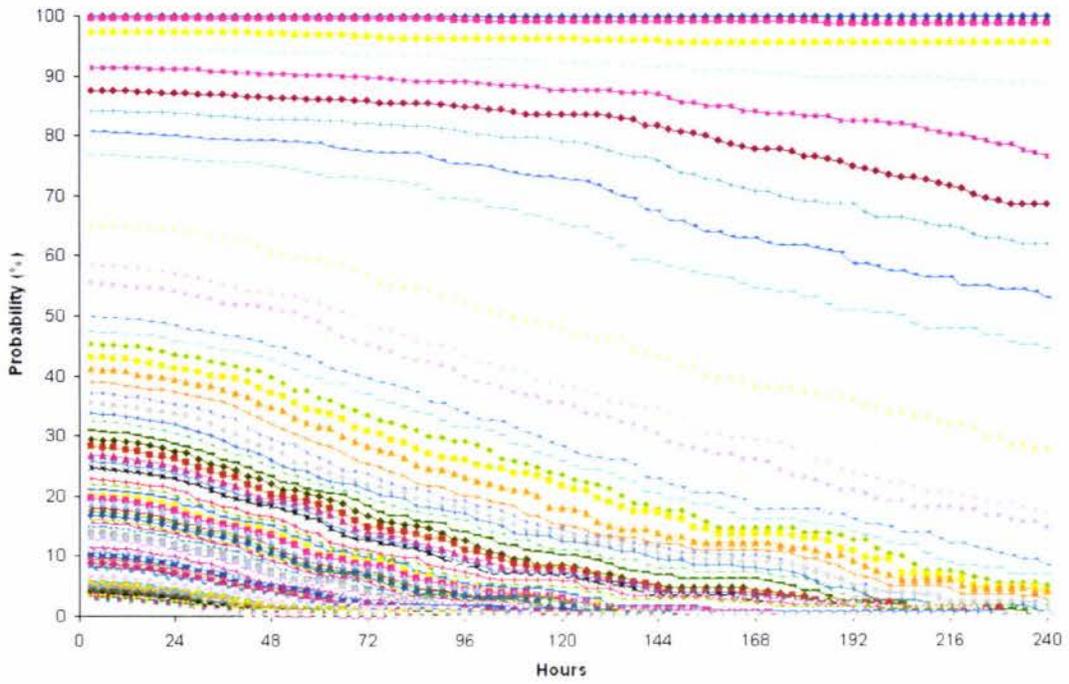
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## 10 Appendix A, seasonal exceedance-persistence

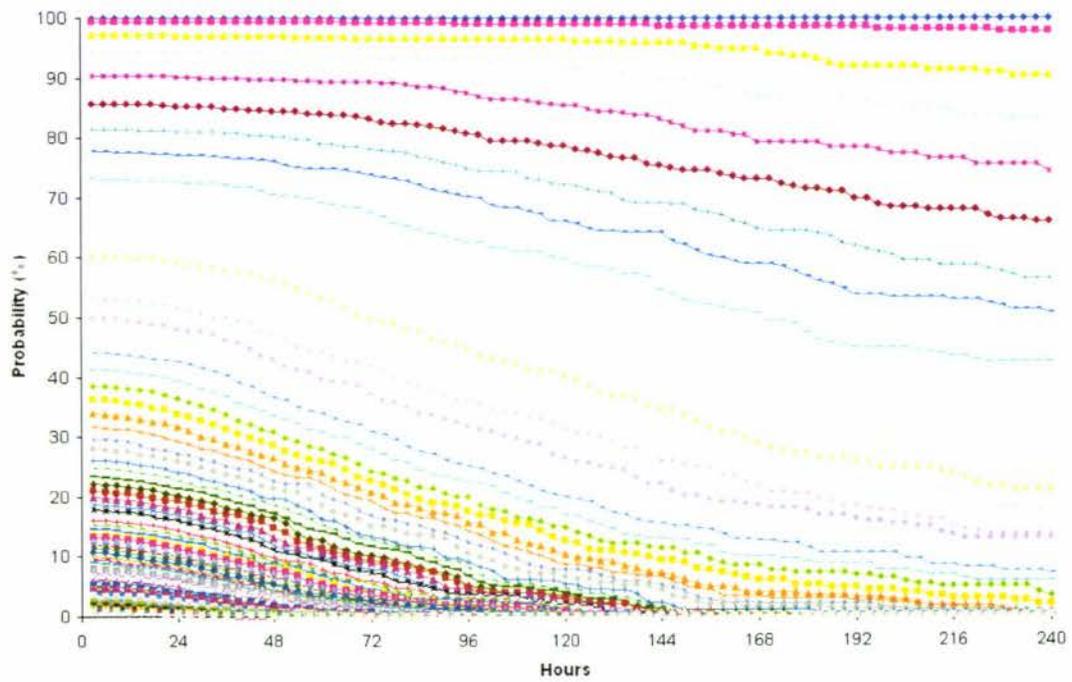
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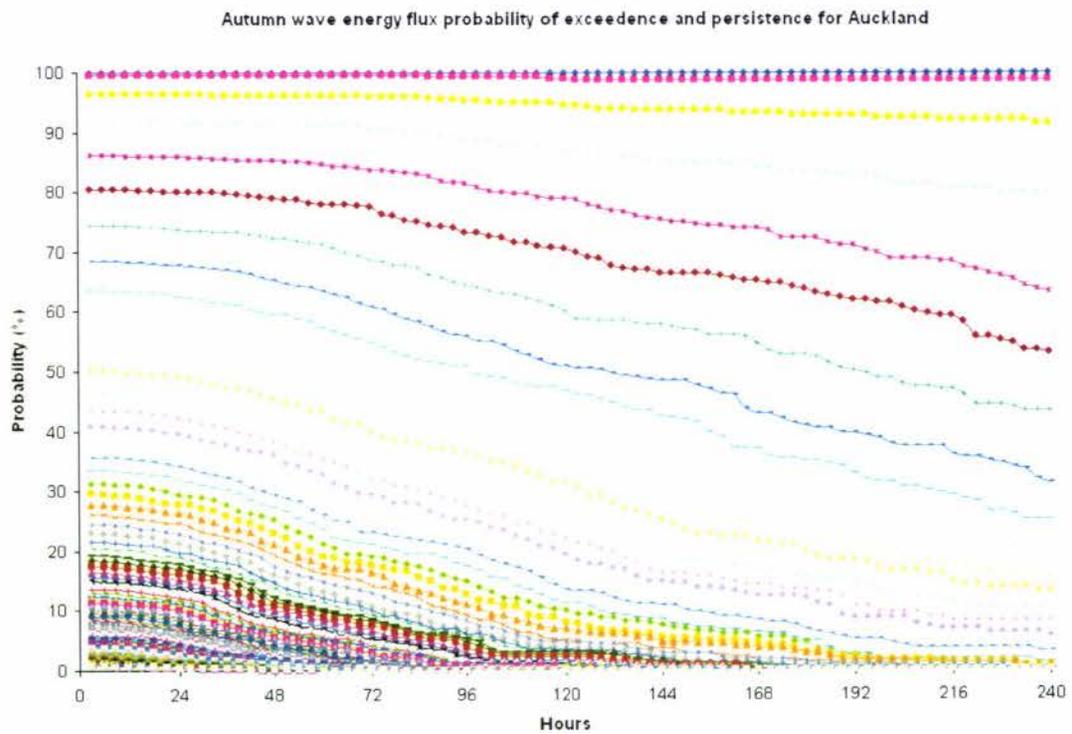
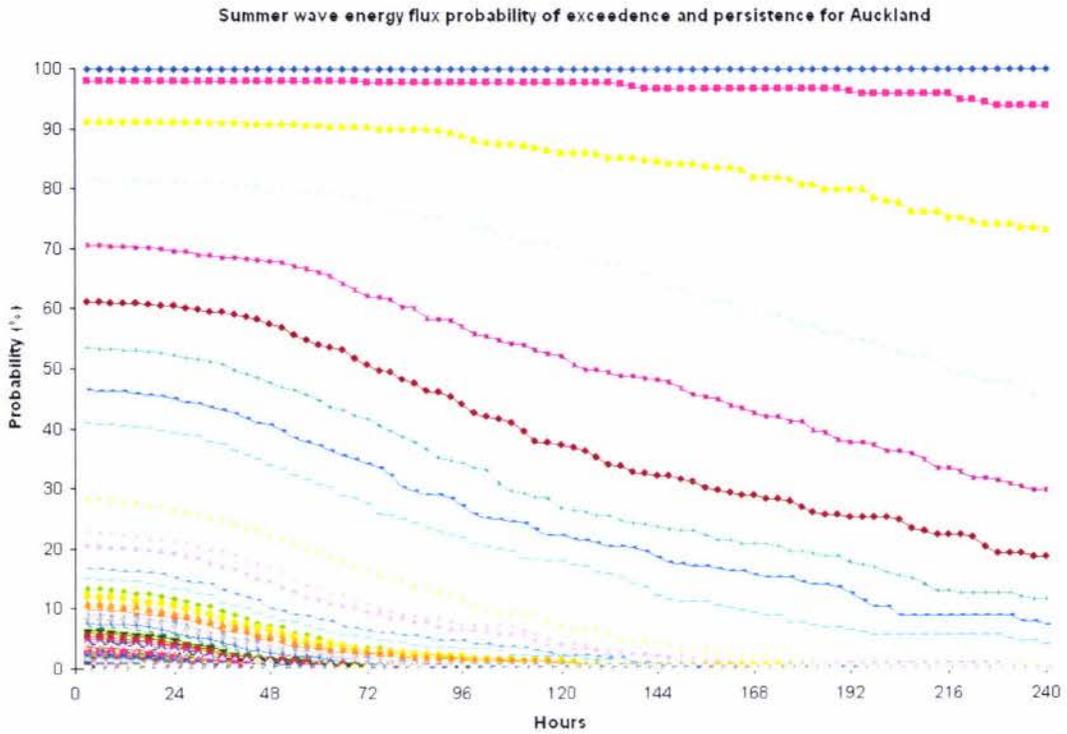
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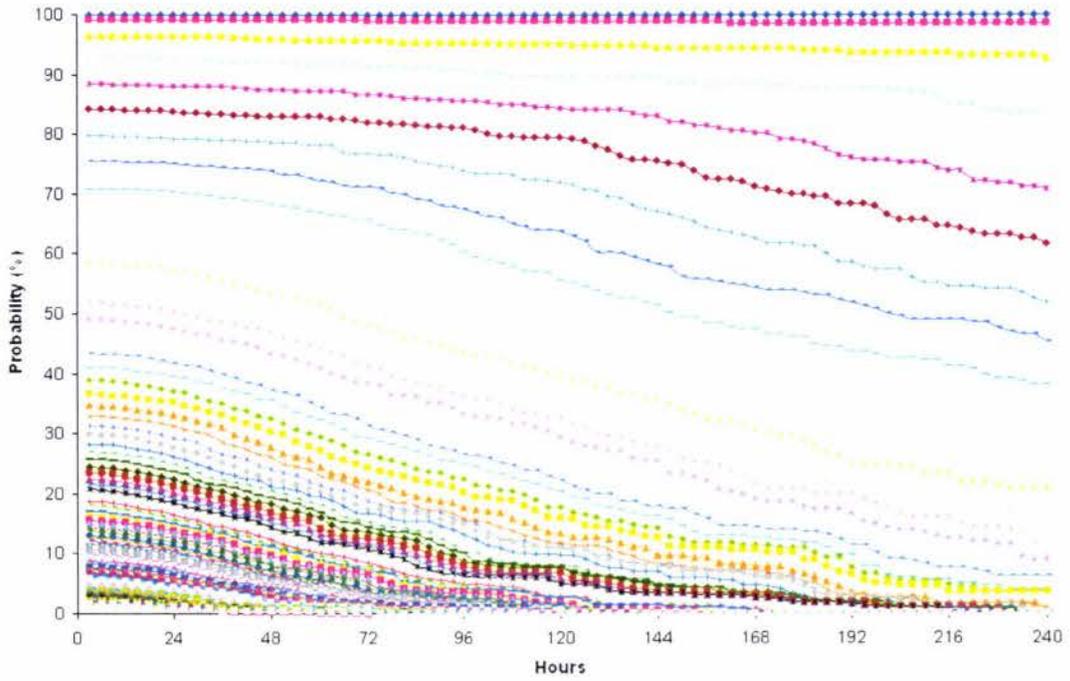
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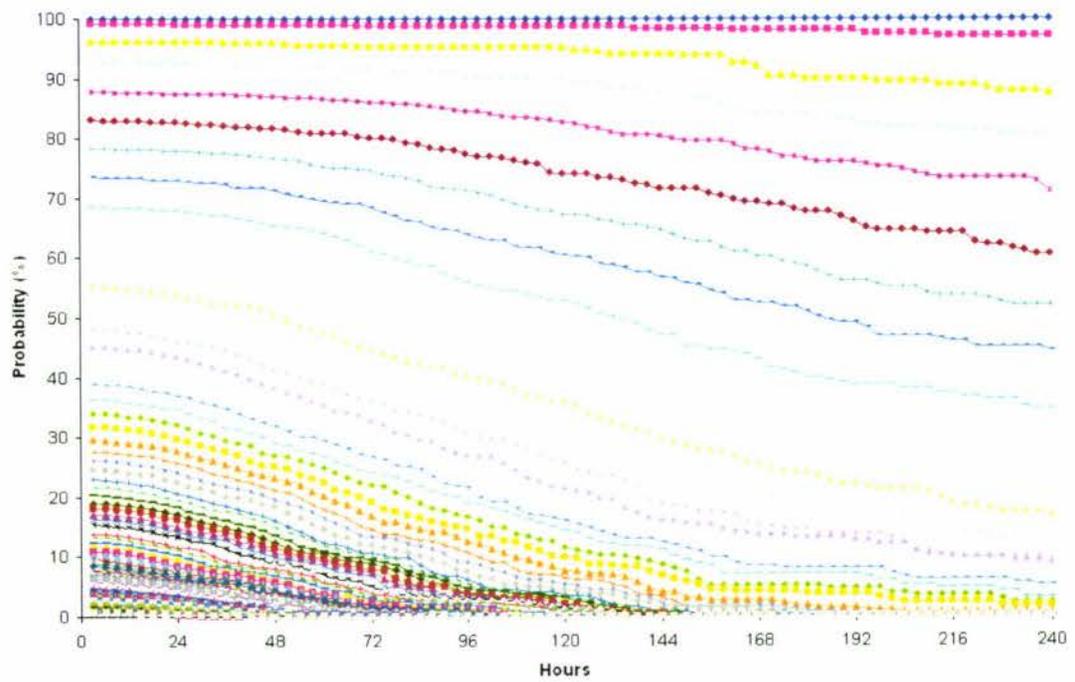
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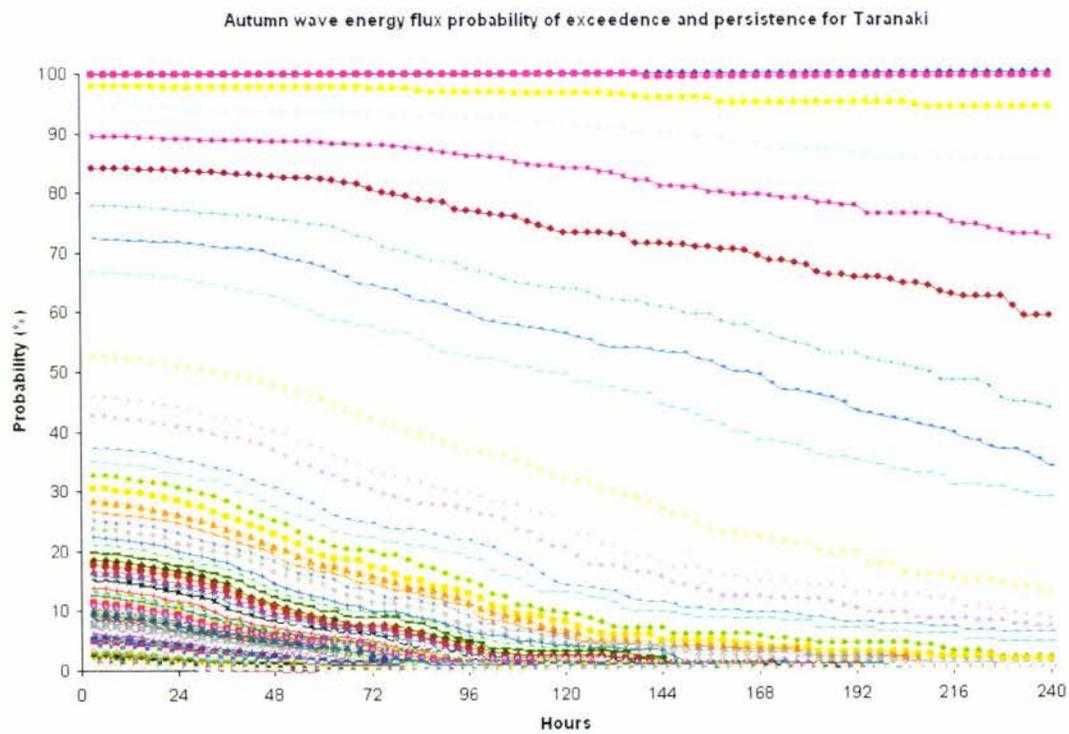
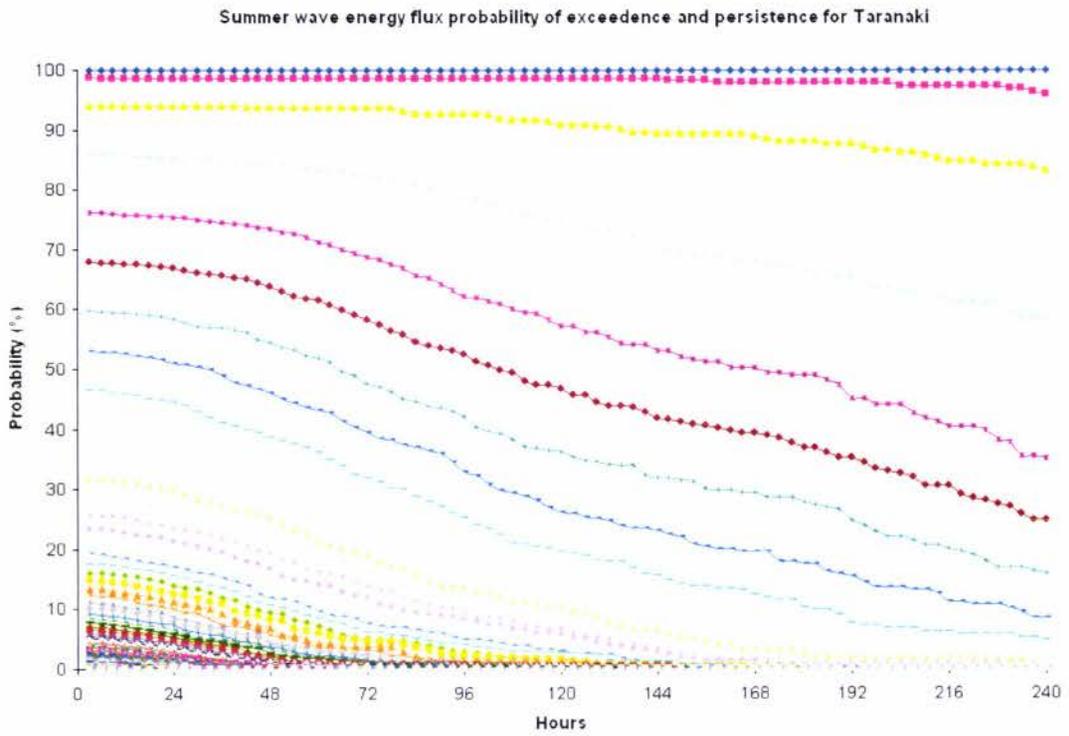
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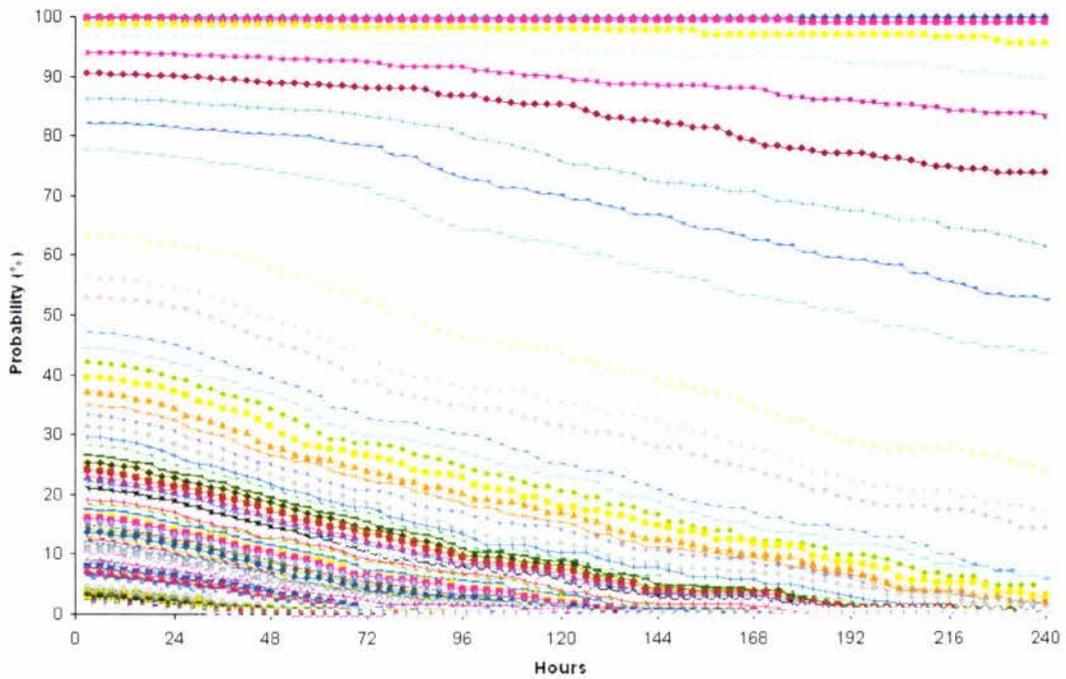
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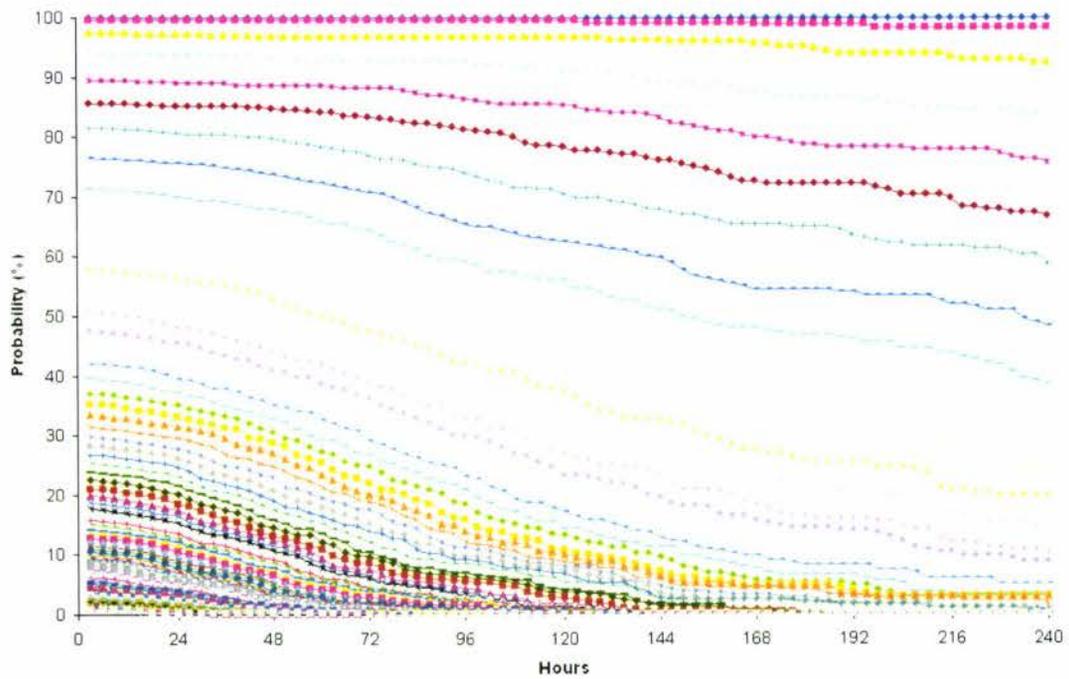
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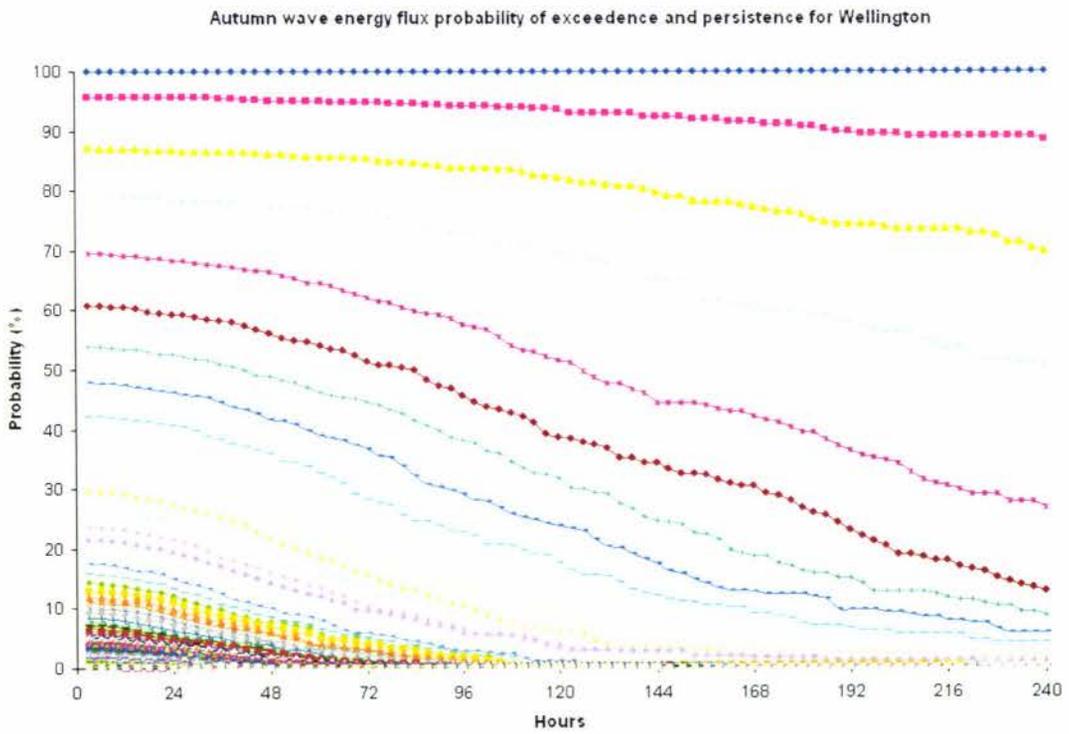
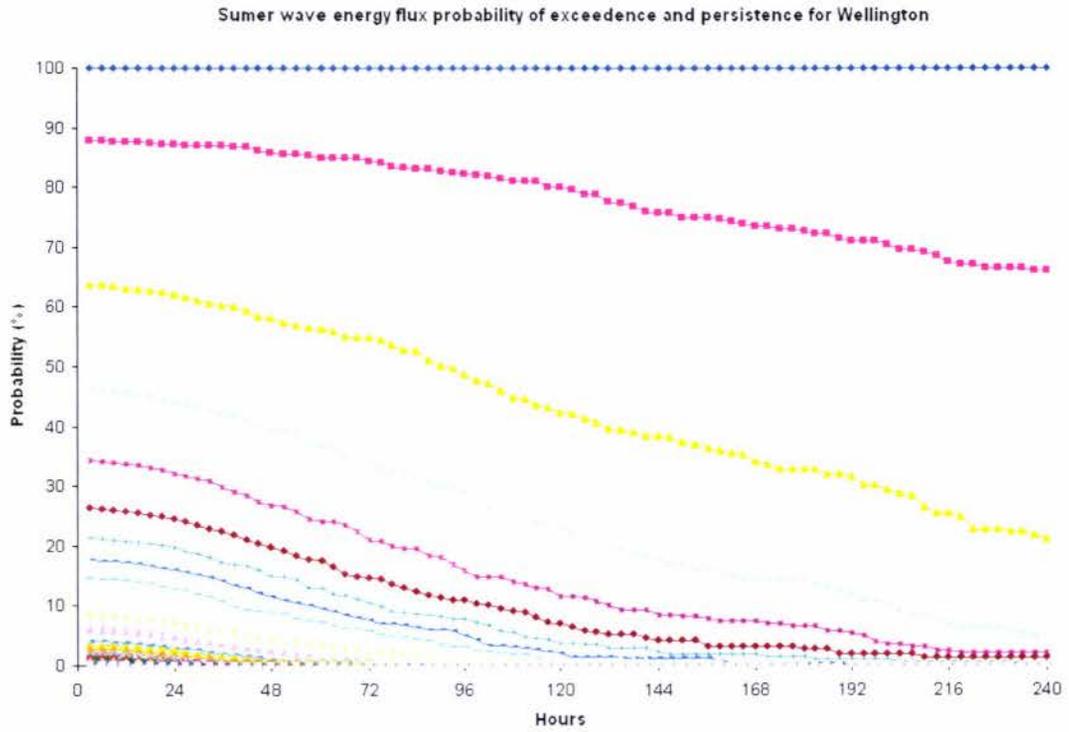
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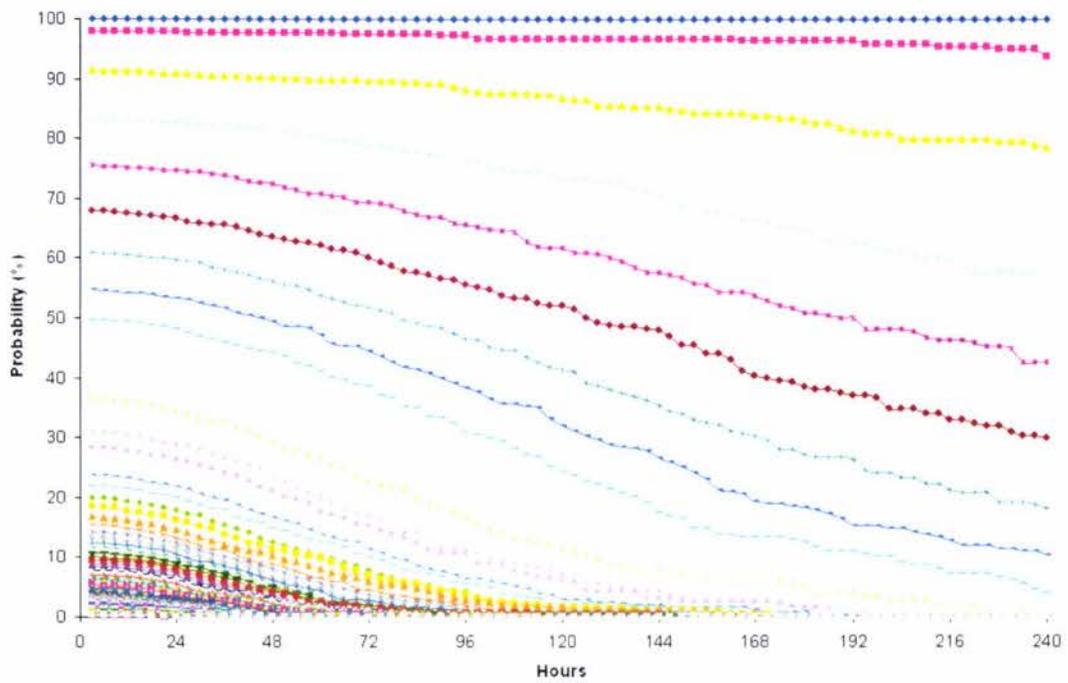
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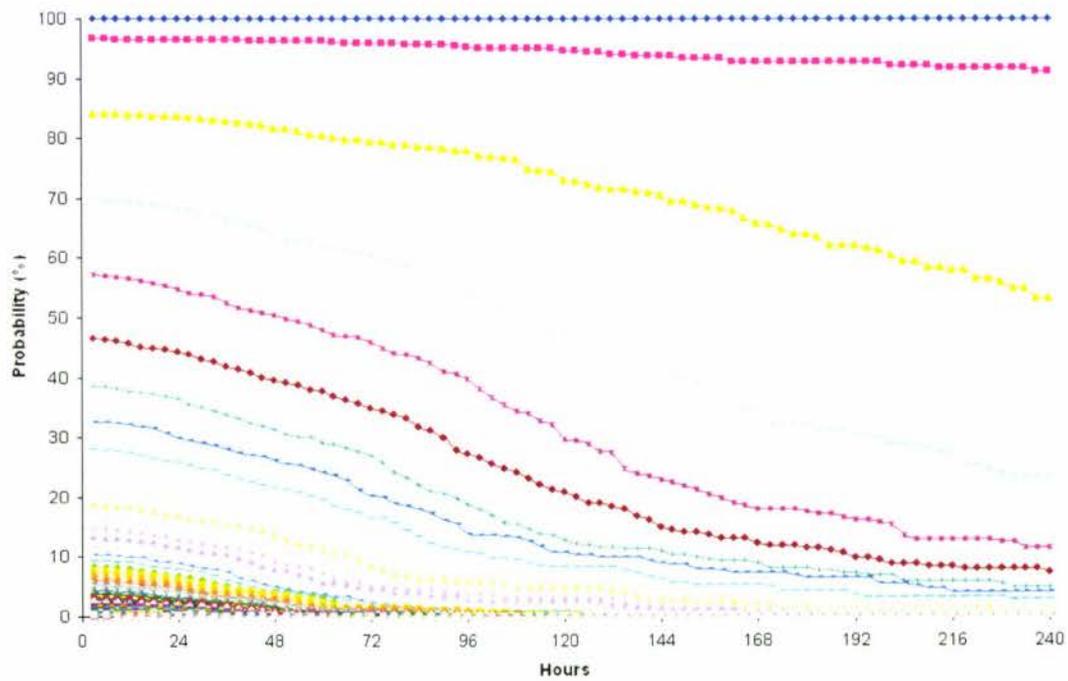
## 10.4 Wellington



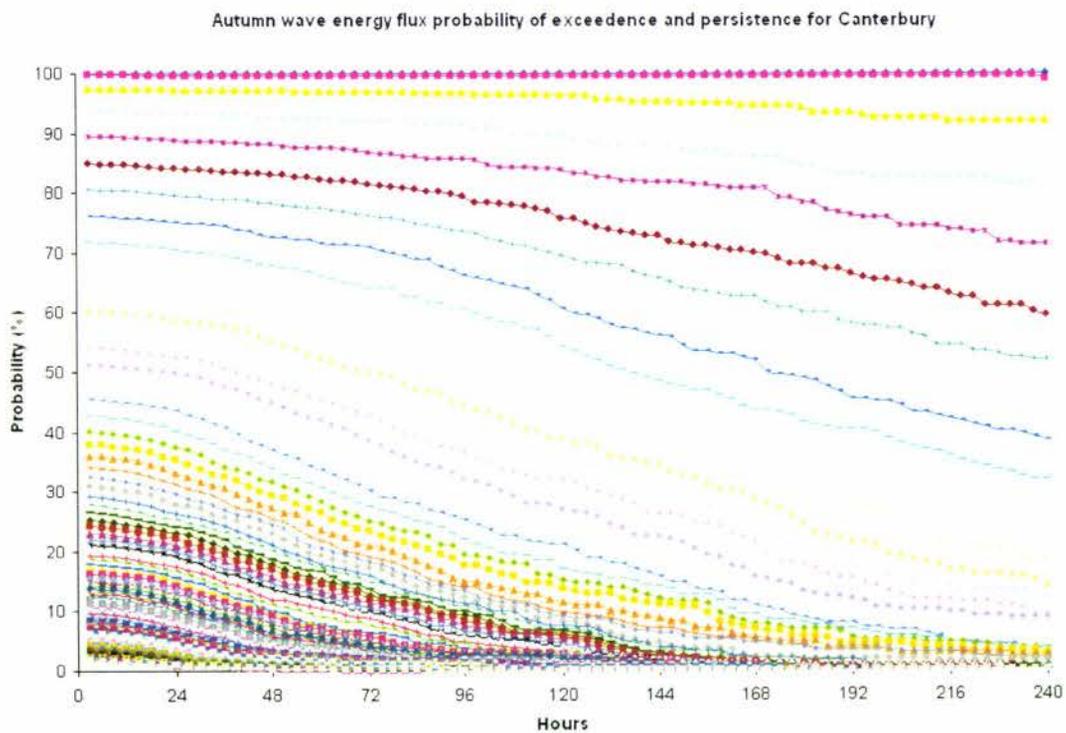
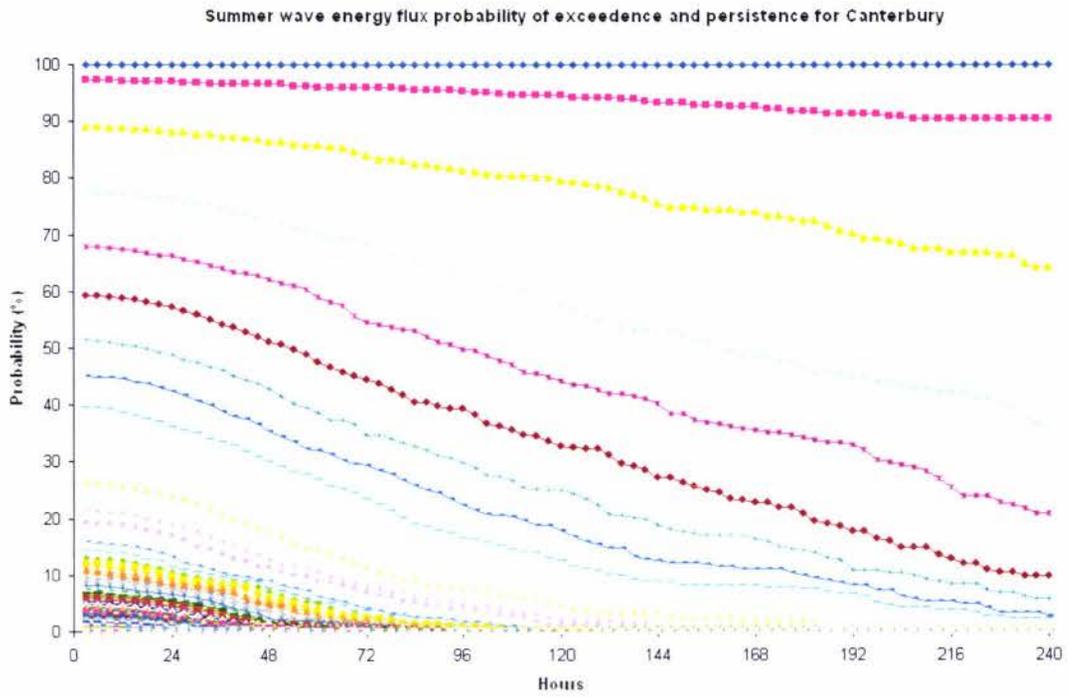
Winter wave energy flux probability of exceedence and persistence for Wellington



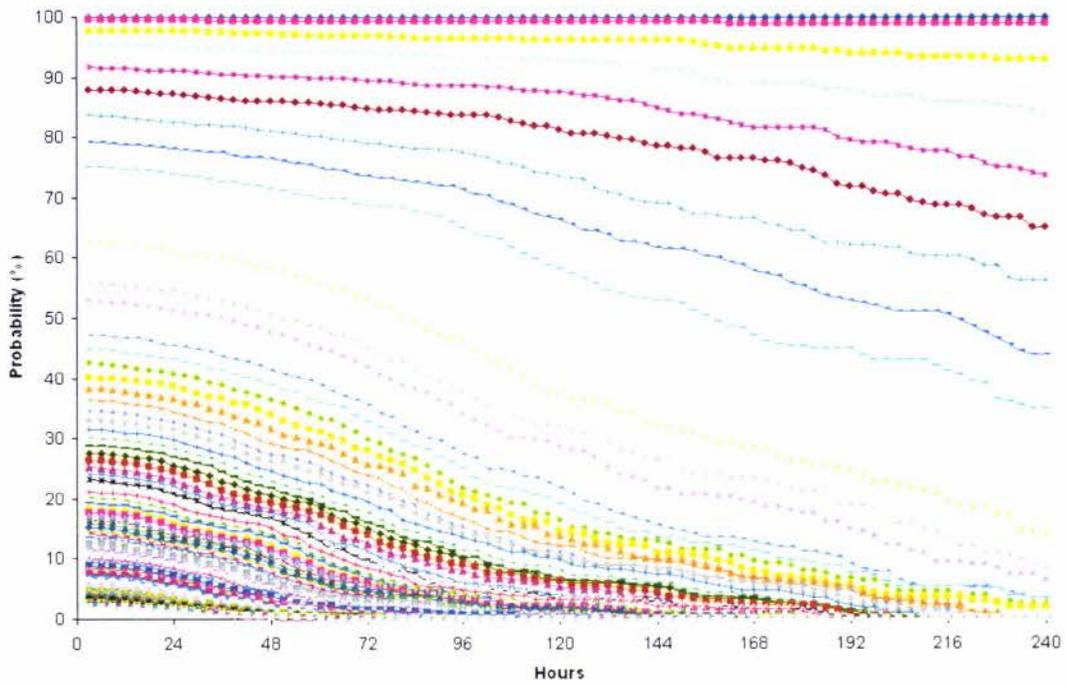
Spring wave energy flux probability of exceedence and persistence for Wellington



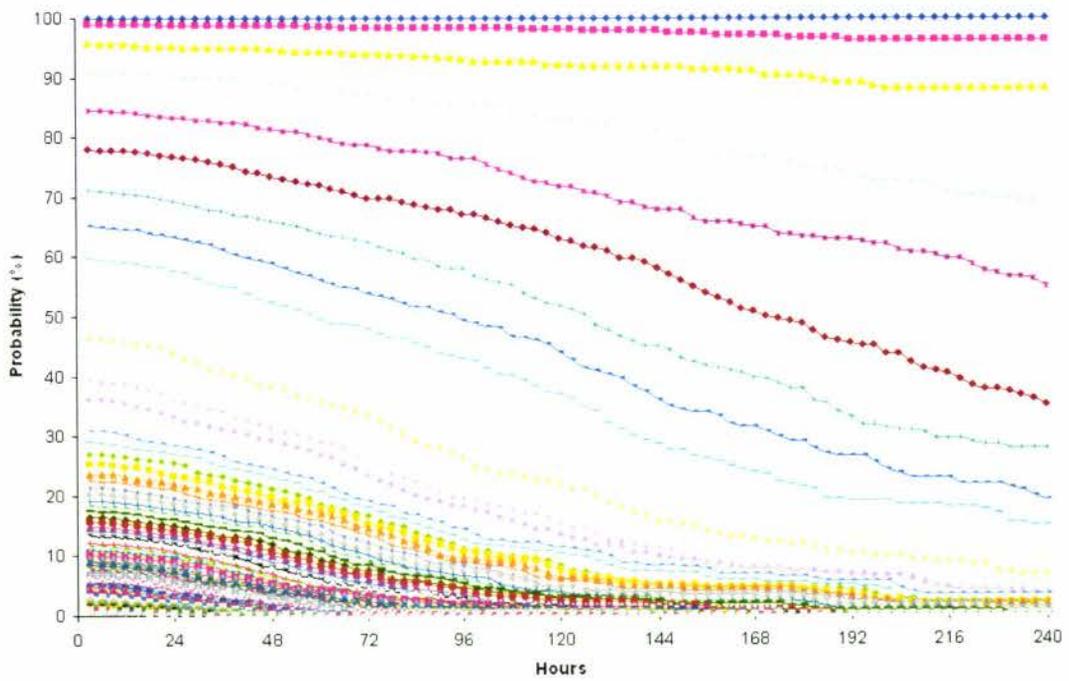
## 10.5 Canterbury



Winter wave energy flux probability of exceedance and persistence for Canterbury

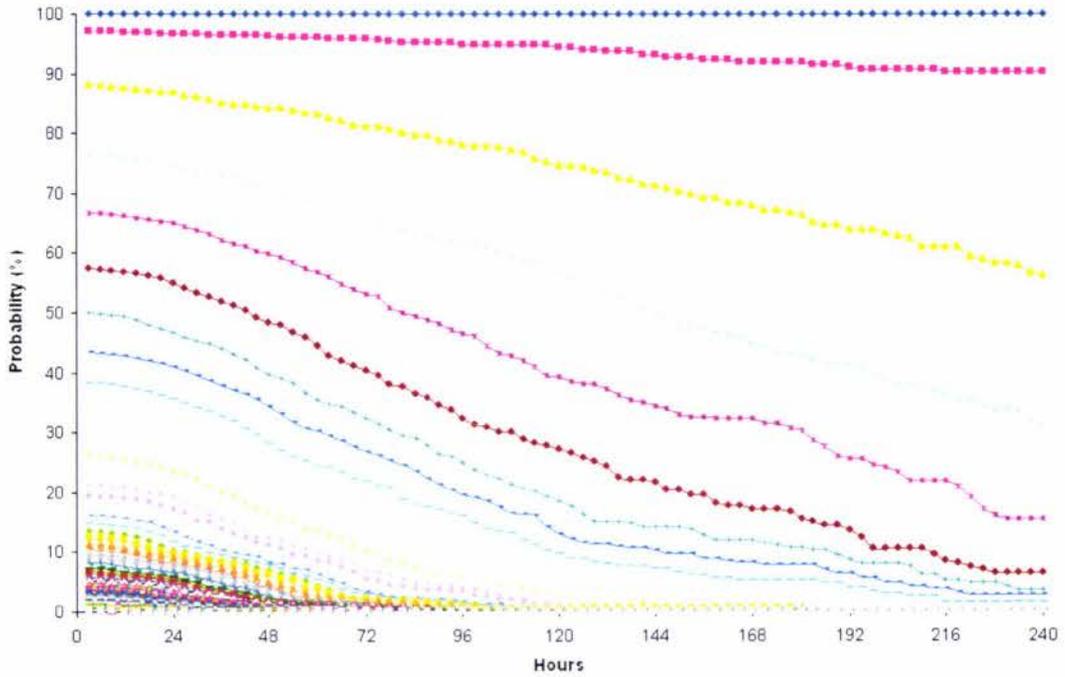


Spring wave energy flux probability of exceedance and persistence for Canterbury

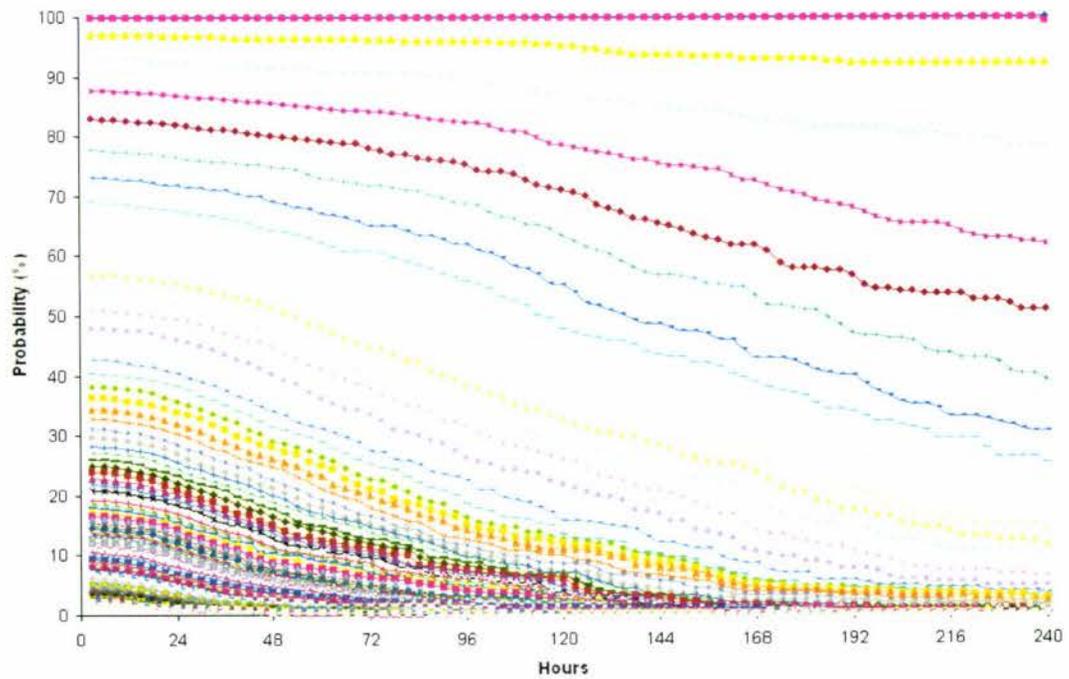


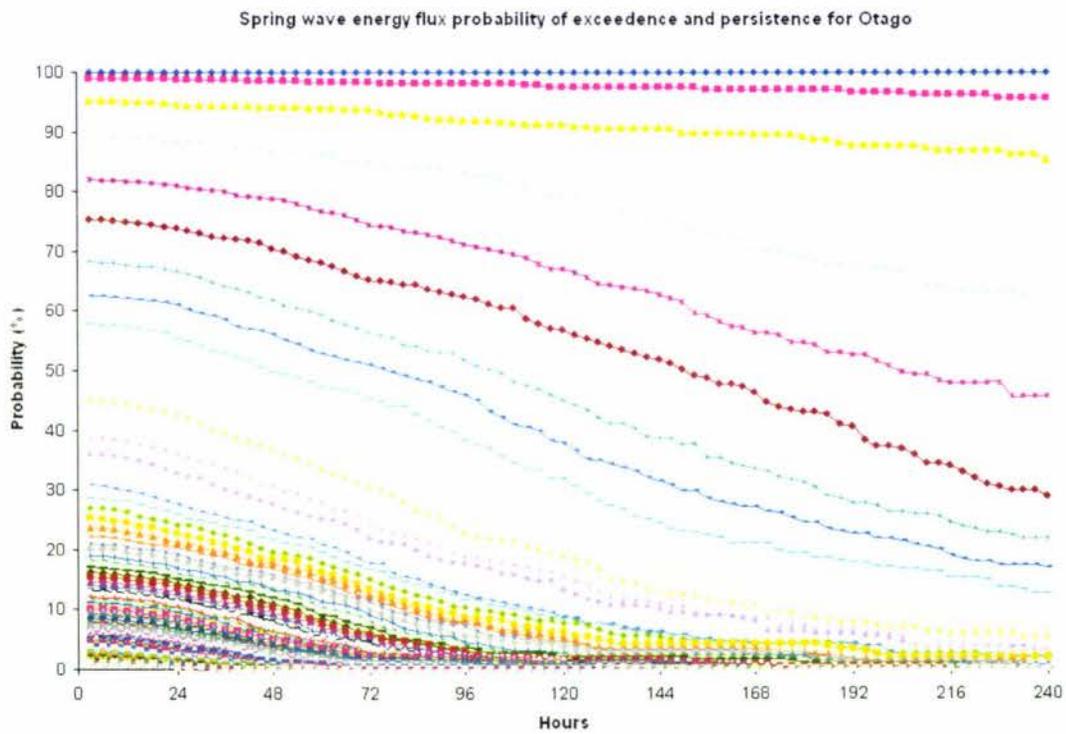
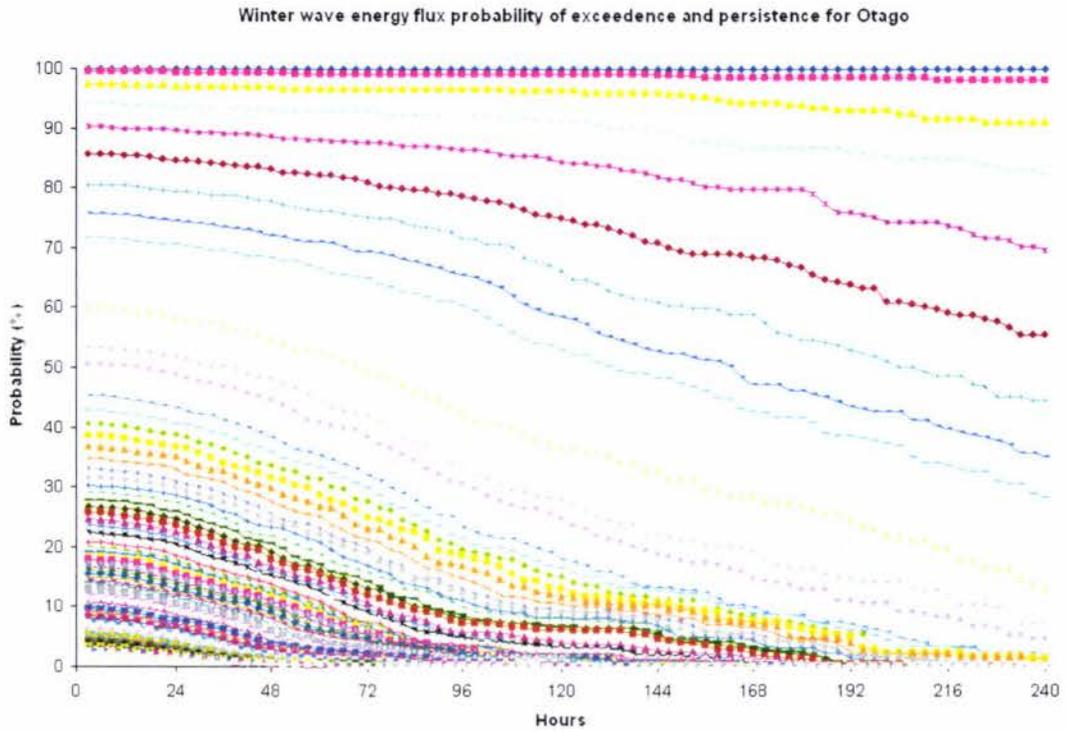
## 10.6 Otago

Summer wave energy flux probability of exceedance and persistence for Otago

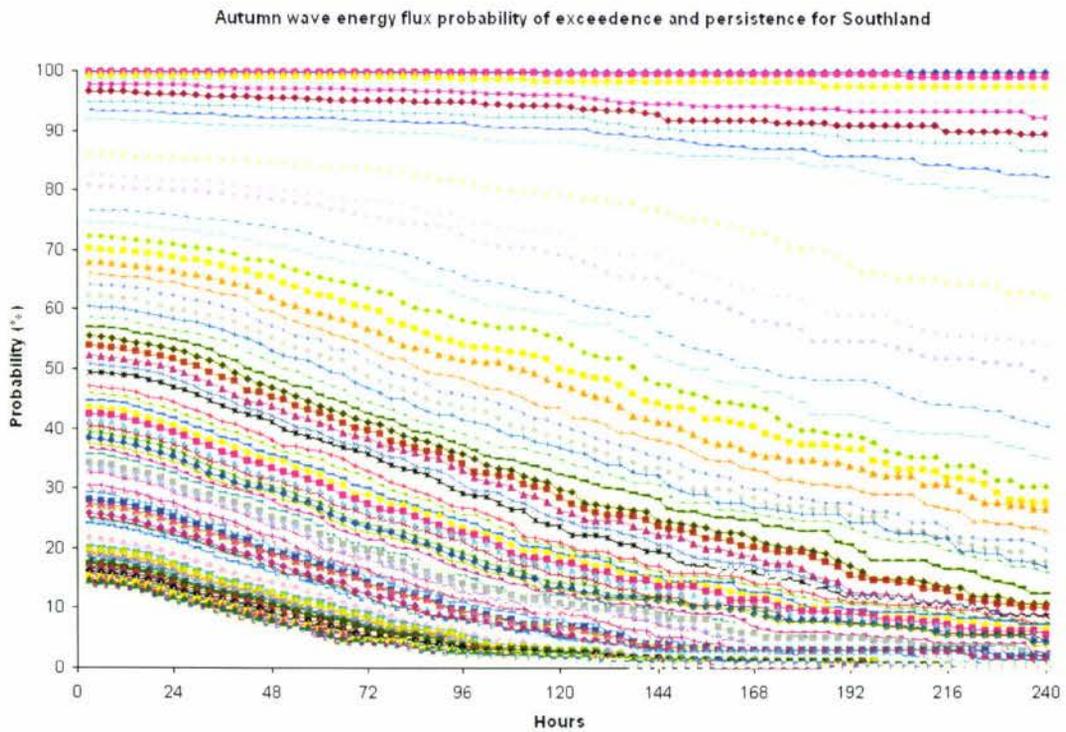
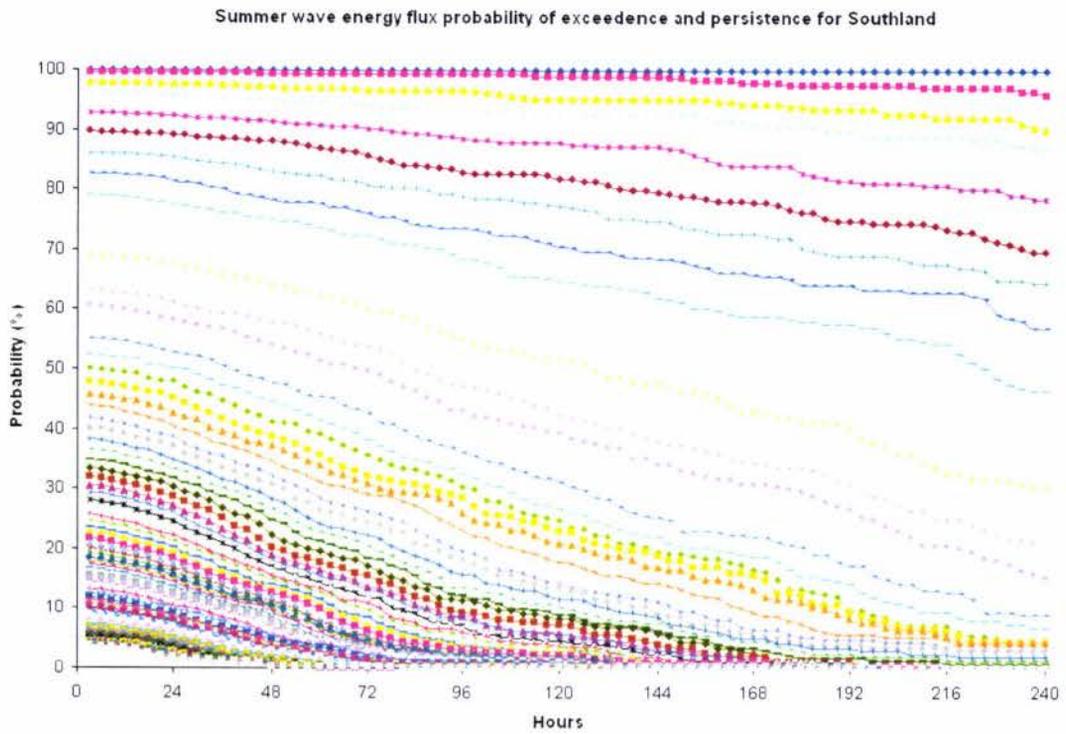


Autumn wave energy flux probability of exceedance and persistence for Otago

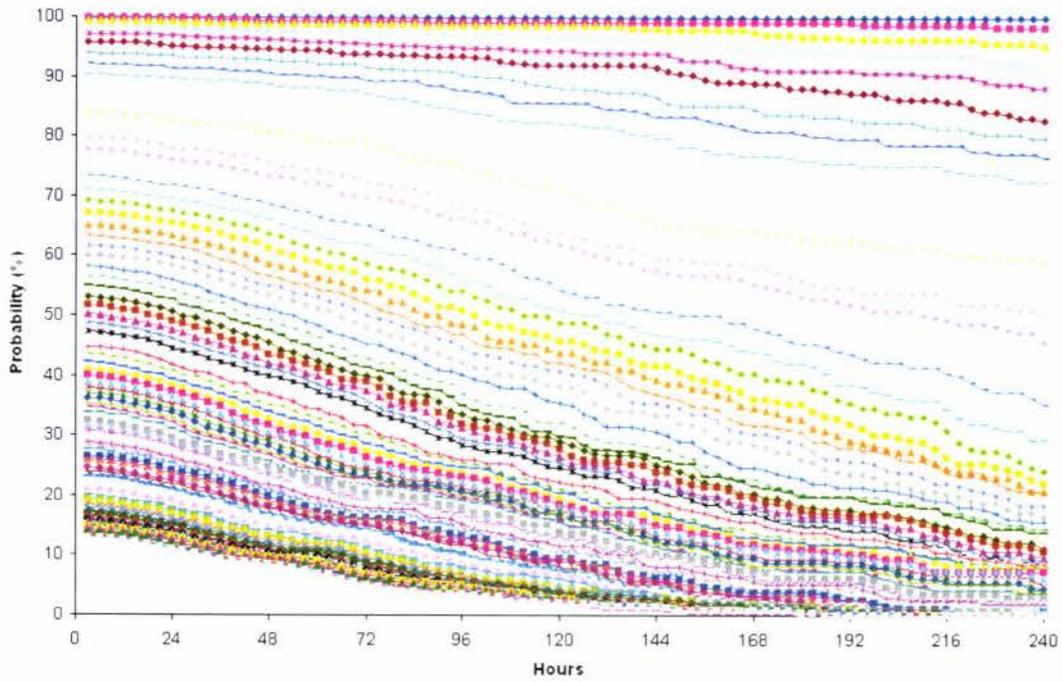




## 10.7 Southland



Winter wave energy flux probability of exceedance and persistence for Southland



Spring wave energy flux probability of exceedance and persistence for Southland

