GREMO: A GIS-based generic model for estimating relative wave exposure

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Abstract: Wave exposure plays a major role in shaping the ecological structure of nearshore communities, with different community types able to survive and/or thrive when typically exposed to different levels of wave energy. This can be quantified by taking direct field measurements with wave buoys over time and then manipulating the data to derive typical conditions. However, taking these measurements is only feasible for very limited areas due to logistical constraints, and generating them with numerical wave models can also be expensive to run and may require data inputs that are either lacking or are highly uncertain. Instead, the relative differences in wave exposure between places (relative wave exposure) may be sufficient to distinguish between different community types. It is possible to approximate relative wave exposure using a cartographic approach. Typically this involves measuring the relative shelter or openness of a particular location based on the distances from it to the nearest potential wave blocking obstacle in all directions with provides an approximation of fetch. Given that dominant wind speed and direction data is available for a particular site, these fetch distances can be manipulated to estimate the potential wave climate at that site, with some models going as far as to link this to linear wave theory in order to calculate wave power. This works because the extent to which large waves can form, and to which seas are 'fully developed', is constrained by wind velocity, time and fetch. Mapping relative wave exposure in this relatively simple way could be used to predict the spatial distribution of broad categories of ecological community types, especially where this information is difficult to collect using more direct methods.

Despite its relative efficiency and simplicity, running a cartographic-based relative exposure model for more than a local study area quickly becomes computationally intensive, which drives the need to set up the model to run as quickly as possible while minimizing the risk of not detecting potential wave blocking obstacles, and thus underestimating the wave exposure. Yet surprisingly, no studies have tested the sensitivity of the relative wave exposure estimates that these models produce to variation in how key factors, such as the density of points from which fetch distances are measured (point spacing), the angle increment at which the fetch lines are drawn around each point (fetch angle spacing), and the adjustment of fetch line lengths based on bathymetry, are set in the model. This paper presents a preliminary analysis that shows the extent to which estimated relative wave exposure changed when the above model settings were varied for four case study areas within the Great Barrier Reef selected for their characteristic spatial arrangement (number and density) of obstacles. This was done using a new GIS-based generic model for estimating relative wave exposure (GREMO) which integrates many existing techniques into a single modeling platform.

Keywords: relative wave exposure, GIS, modeling

1. INTRODUCTION

Wave energy plays a major role in driving ecological processes in the coastal zone (Ekebom *et al.* 2003; Tolvanen & Suominen 2005; Burrows *et al.* 2008), and thus, over time, wave action helps shape the structure and composition of biological communities (Zacharias *et al.* 1999; Valesini *et al.* 2003; Wernberg & Thomsen, 2005; Harborne *et al.* 2006). Because of this, measures of routine wave conditions over time (wave exposure) can be used as a proxy for ecological structure - for example, to map the distribution of biotopes in the Strait of Georgia, British Columbia (Zacharias *et al.* 1999). Routine wave conditions over time are defined based on typical wave heights, periods, and directions (Denny 1988), which can be measured directly in situ using wave buoys. However, direct measurements are only feasible for very limited areas due to logistical constraints (Burrows *et al.* 2008). Though numerical models based on wave theory can also be used to generate highly precise wave statistics, they requir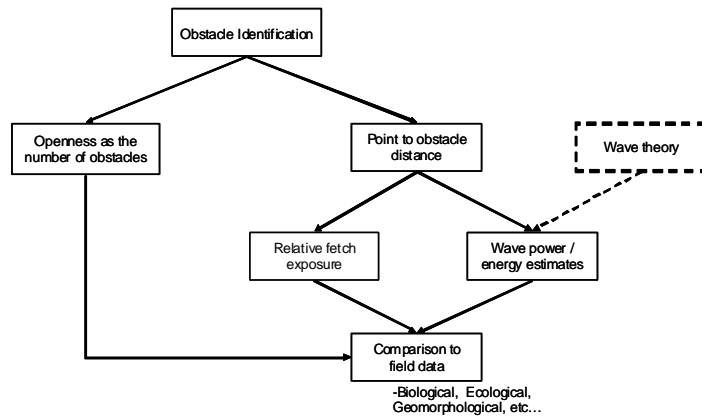e considerable data inputs which may or may not exist, and are computationally intensive. And detailed wave statistics are not required to distinguish between different community types, at least at an ordinal level – for this purpose, the relative differences in typical wave conditions between places (relative wave exposure) is sufficient. Relative wave exposure can be approximated relatively quickly and cheaply using a cartographic approach. For a given site of interest, relative wave exposure is based on wind speed, wind duration, and fetch. Fetch is defined as the water over which wind blows uninterrupted for a given direction or set of directions. These factors combine to determine the sea state likely to exist under those conditions (Denny 1988), which – in combination with estimated

Figure 1. Flow diagram illustrating key steps in cartographic fetch modeling. All models include some method for obstacle identification, but vary in which additional steps they include and how they are achieved.

frequencies for a given set of conditions – can be used to estimate routine wave exposure. The fundamental basis for all of these models is to identify the potential wave-blocking obstacles, such as the coastline, islands, reefs, and areas where water is sufficiently shallow for waves to 'feel' the bottom, in the vicinity of each site of interest. These obstacles have the potential to dissipate incoming waves and thus limit the wave exposure in the vicinity of a given site to that which can be generated by local winds blowing over the expanse of water from the obstacle to the site. Cartographic relative wave exposure models assume that an obstacle acts as a complete barrier to incoming waves, which is generally true for short period waves approaching obstacles like islands and reefs unless located quite distant from one another (Young and Hardy 1993). It does not hold for long period swell, the effect of which is not presently considered. Regardless, a range of methods have been developed based on this basic idea (Figure 1).

The simplest of these models defines the potential for wave exposure at a site based on the degree of 'openness' around it as defined by the number of obstacles located within a set of compass sectors around the site – the Baardsdeth index (Ruuskanen et al 1999, Wernberg and Thomsen 2005). Most cartographic relative wave exposure models go beyond this to measure the actual distances from points of interest to the nearest wave blocking obstacle along lines constructed to radiate out in all directions around each point, based on an angle spacing that ranges from 7.5 to 45 degrees. This is
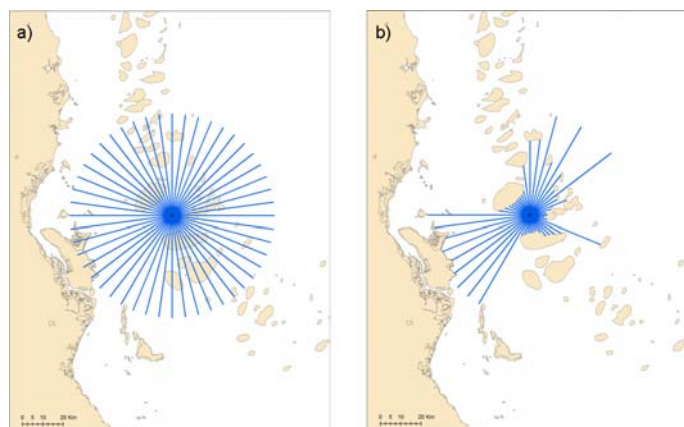

Figure 2. Construction of fetch lines around a site of interest.

done by first constructing lines of a length equal to the distance at which fetch no longer limits the ability to build waves at wind speeds and durations characteristic of the study area (Figure 2-A). These lines are then shortened to include only the segment that extends from the site of interest to the nearest potential wave blocking obstacle (Figure 2-B) and the length of the lines are measured. Some models take bathymetry into account, either by defining shallow areas as obstacles a priori, or by shortening fetch lines based on the proportion of samples along a fetch line that are considered to be 'shallow'. A location is defined as shallow based on the depth at which waves would feel the bottom for a given wind speed (Malhotra & Fonseca, 2007). The above process yields a set of fetch distances around the site that represent the amount of water over which wind can blow uninterrupted to build waves. For these fetch distances to be of any use, meteorological data for dominant wind speeds and directions is then used to combine them to estimate the potential wave climate at that site. This can be as simple as an 'effective fetch' measurement, which describes the average distance available for a wave to collect energy before meeting the shore (see Ruuskanen et al., 1999; Zacharias et al., 1999 or Malhotra & Fonseca 2007). Other alternatives have included the calculation of an average fetch line distance (Burrows et al., 2008), the sum of fetch line distances (Tolvanen & Suominen, 2005), averaging (Lewis 2001, Puotinen 2005) or discounting and adding (Puotinen 2005) fetch line distances in a dominant sector defined from meteorological data. Some models have gone so far as to use linear wave theory to estimate wave power and energy (Ekebom et al. 2003, Harborne et al. 2006, Bekkby et al 2008). However, use of these models is limited to deep water where the assumptions of linear wave theory apply. The implementation of more complex shallow water wave theories within a GIS has stalled due to the difficulty of representing the requisite higher-order mathematics adequately. This is a common issue with GIS which recent research is attempting to address (Haklay, 2004). In the meantime, work has focused on developing relatively simple GIS-based models for shallow water. These attempt to consider nearshore processes like refraction and diffraction by incorporating bathymetry (Bekkby et al., 2008; Malhotra & Fonseca, 2007).

Despite the considerable progress that has been made, there is much scope for continued research into cartographic wave exposure. For example, for even a small number of points of interest, manually measuring the distance from each point to the nearest obstacle in each of at least eight intercardinal directions, even when done using a GIS, is very time consuming and potentially error prone. Automation of these techniques within GIS using programming has led to increases in model efficiency, particularly for large study areas (Burrows et al., 2008; Malhotra & Fonseca, 2007; Puotinen, 2005, Ekebom et al 2003). Despite this, relative wave exposure modeling is computationally intensive. One way to address this is to implement more efficient analysis algorithms within the GIS modeling framework, such as a point to polygon distance calculation that has recently been developed (Murtojärvi et al., 2007). Another is to attempt to optimize the settings of the model – in this case, setting model parameters to minimize processing time while also minimizing the likelihood of failing to detect wave blocking obstacles (which would overestimate wave exposure). Interestingly, given how computationally intensive these models are to run, no published literature reports any attempts to measure the sensitivity of a relative wave exposure model to its parameter settings. Presumably, parameter settings such as the density of points around which fetch distances are measured (point spacing), the angle increment at which the fetch lines are drawn around each point (fetch angle spacing), and the adjustment of fetch line lengths based on bathymetry could significantly affect both the processing time and results of a relative wave exposure model. Clearly, the ideal settings for these parameters will vary depending on the number and spatial arrangement of obstacles within a study area. For example, the processing time required to use a 7.5 degree angle spacing needed to adequately estimate wave exposure for an archipelago (Ekebom et al 2003) or a dense matrix of coral reefs (Harbourne et al 2006, Puotinen 2005) may not be justified for a geographic area with few obstacles and simple bathymetry. Similarly, some models may be suited primarily to deep water environments (Ekebom et al 2003), while others may be designed specifically for shallow water (Malhotra and Fonseca 2007). A first step is to test whether model results are sensitive to parameter settings. If so, a tool or set of tools designed to assist a researcher in determining optimal, or at least acceptable, settings of a model for a given study area would be extremely useful. Towards that end, this paper describes: 1) the development of a generic relative wave exposure modeling framework (GREMO) which brings together tools from across the published literature, and 2) a preliminary use of GREMO to test model sensitivity based on four case studies within the Great Barrier Reef chosen as representative of four characteristics spatial arrangements of wave blocking obstacles.

2. GENERIC RELATIVE EXPOSURE MODEL (GREMO)

Implemented within ArcGIS 9.2 using Visual Basic for Applications (VBA), GREMO integrates tools from a number of existing cartographic fetch models within a single user-friendly interface (in ESRI's ArcMap), and

includes four basic components (Figure 3): 1) fetch line construction and alteration, 2) bathymetry interrogation, 3) fetch results, and 4) relative wave exposure normalisation and classification.

2.1. Fetch line construction and alteration

A wave exposure index assesses a site's relative exposure based on the fetch length. Clearly it is not feasible to measure the distance from a site to the nearest wave blocking obstacle in an infinite number of directions – instead a fetch angle spacing must be chosen (usually this ranges between 7.5 and 90 degrees). The number of lines built around a site is based on the equation:

$$L_n = \left(360 / \theta\right) \quad \text{eq.1}$$ where L_n is the total number of lines and θ is the fetch angle specified.

The distance from the site to the nearest wave-blocking obstacle is measured along each fetch line. The key difference between GREMO and older models (i.e. Ekebom et al 2003, Puotinen 2005) is how these distances are calculated. GREMO reduces the processing time by orders of magnitude by doing calculations within memory instead of clipping the lines to the obstacles to create new files.
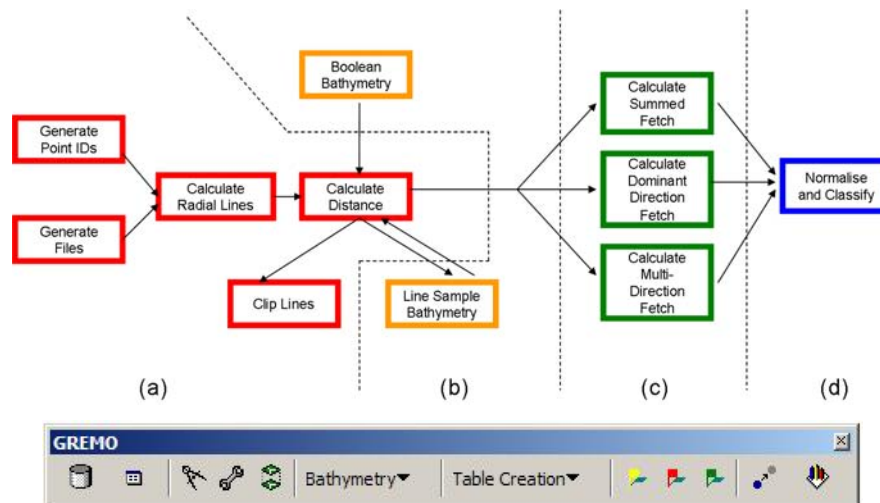

Figure 3. Basic structure of GREMO (top) and the GREMO toolbar (bottom). The GREMO process is divided into four sections: (a) Construction and alteration (red), (b) bathymetric interrogation (yellow), (c) generating fetch results (green), and (d) normalisation and classification of fetch results (blue). Dashed lines delineate model processes into these four sections. Arrows indicate the order in which tasks within the model take place.

2.2. Bathymetry interrogation

Two approaches to bathymetric interrogation are included in GREMO: 1) Boolean, and 2) line sampling bathymetry. With the first scenario, shallow water regions within an area, as indicated by applying a threshold value to a digital depth model (DDM), are assumed to act as complete obstacles to waves. For the second scenario, the length of a given fetch line is reduced based on how depths vary along the line, by adapting a technique described by Malhotra & Fonseca (2007):

$$f_i = \sum_{j=0}^{L/n} \left[1/(D_j)^{P_w} \; (1 - D_j / L_i) \right] Z_j \qquad \text{Eq. 2}$$

where F_i = adjusted length for ith radiating fetch line, D_j = jth distance along the fetch line from the site, L_i = length of the ith fetch line, Z_j = depth at the distance D_j along the ith fetch line, n = fixed distance for raster sampling, and P = power function controlling the degree of weighting bathymetry at the distance D_j along a fetch line.

In GREMO, the P values are specified by extrapolation from a table originally developed to represent the relationship between fetch lengths, average water depth and power values over a limited depth range (Malhotra and Fonseca 2007).

2.3. Fetch results

The lengths of fetch lines must then be combined in a manner that yields a measure of relative wave exposure. GREMO provides three basic methods of doing this: 1) sum of all fetch lines, 2) sum of weighted fetch lines in a dominant direction and 3) sum of weighted fetch lines in multiple dominant directions. Following Ekebom et al 2003, option 1 assumes that winds of equal strength blow towards the site of interest for an equal length of time. Where meteorological data indicates that most winds blow towards the site from a particular direction (or contiguous range of directions), then option 2 is applied. Following Puotinen 2005, fetch lines are weighted based on their distance from the dominant direction using 'directional discounting'. As fetch lines are located increasingly far from the dominant direction, their lengths are multiplied by an increasingly smaller fraction of 1, thus reducing their contribution to the final summed fetch. Where meteorological data indicates that multiple dominant directions are appropriate, option 3 is applied.

2.4. Relative wave exposure normalization and classification

Finally, GREMO provides tools to normalize the relative wave exposure estimates to a common measurement framework that can be compared across study areas. This is done by defining a maximum routine exposure possible and then dividing a given fetch exposure value by this maximum. Doing so yields a number between 0 and 1, with 1 being the most exposed. The maximum exposure value is based on a set of 650 km long fetch lines arrayed with a 7.5 degree angle spacing that are uninterrupted by obstacles and assumes continuous gale force winds (17 m.s^{-1}).

3. SENSITIVITY ANALYSIS

With any model, it is important to assess the extent to which model results vary with changes in the specification of input parameters (sensitivity). If a model is sensitive to a particular parameter setting, then errors in setting it are particularly important to avoid. Because relative exposure models are based on estimating the openness of the sea around a site of interest, estimates of wave exposure will vary primarily based on the spatial arrangement and size of potential wave blocking obstacles with respect to the model parameters. For instance, setting the fetch angle spacing or the fetch length incorrectly for a given spatial arrangement of obstacles can dramatically alter the result by missing obstacles (Figure 4). Further, there is an associated danger of increasing computer processing times with little gain by setting parameter values inappropriately. Thus, it is important to assess how sensitive a model like GREMO is to parameter settings – if it is sensitive, then effort should be directed towards identifying appropriate settings for a given study area.
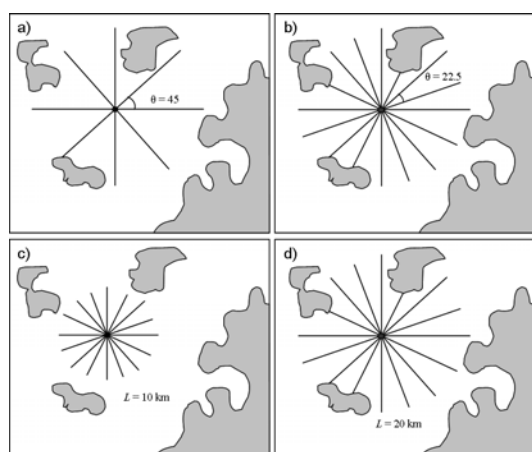
Figure 4. Consequences of setting relative wave exposure models incorrectly: (a) a fetch angle spacing of 45 degrees misses all obstacles but one, (b) a fetch angle spacing of 22.5 degrees detects all obstacles, (c) a fetch angle length set to 10 km under-estimates exposure, and (d) a fetch length set to 20 km more accurately represents exposure at the site.

3.1. Design

For four case study areas in the Great Barrier Reef (Figure 5), a preliminary sensitivity analysis of GREMO was conducted by running it multiple times, varying key parameter settings systematically and recording the relative wave exposure result. The case study areas represent four characteristic spatial arrangements of wave blocking obstacles: 1 – few obstacles that are closely packed, 2 – many obstacles that are closely packed, 3 – many obstacles that are spread out, and 4 – few obstacles that are spread out. Sensitivity was assessed by examining the results statistically using a full factorial design. A full factorial design was chosen over the more simple One At a Time (OAT) approach in order to measure factor interactions as well as each factor's main effect. For the full factorial design, the experimental unit was each site of interest within a

GBR study area for which wave exposure was modelled with a particular fetch angle spacing (7.5 vs 45 degrees), fetch length (20 vs 650 km), bathymetry technique (None, Boolean, Line Sampling), and fetch line combination technique (Sum, Dominant direction, Multiple direction). The response variable was a normalised wave exposure index value. The design is a 2 (fetch angle spacing) × 2 (fetch length) × 3 (bathymetry technique) × 3 (fetch line combination) factorial design with no blocking and single replication with a total of 36 treatment combinations. Point spacing was not included as a factor in order to reduce the potential for spatial autocorrelation in the results. Instead, the statistical model was run once for each spatial resolution (5 and 10 km) in each study area. Factor levels were chosen to represent reasonable extremes in feasible parameter settings (for example, it is unlikely that a fetch angle spacing of <7.5 or >45 degrees would ever be used). A future, possibly more useful approach, would be to define thresholds for parameter settings based on plateaus of performance, and test sensitivity across the full range within the thresholds. The model assumes that the response variable and error terms form a normal distribution and are independent. To meet these conditions, it was necessary to log transform the data and use average fetch results across each study area. For each of the two spatial resolutions, 36 runs of the model were required. This was repeated for each of the four study areas, yielding a total of 288 model runs. Measurements of normalised relative wave exposure from each model run were then compared to test whether they differed significantly using an ANOVA at 0.05 significance level by exporting model run results to JMP statistics software.

Figure 5. Study areas for GREMO model runs, designed for four characteristic spatial arrangements of obstacles: 1 – few obstacles that are closely packed, 2 – many obstacles that are closely packed, 3 – many obstacles that are spread out, and 4 – few obstacles that are spread out.

Table 3. ANOVA test of how normalised wave exposure differed for model runs that varied four model setup factors. * indicates significance at the 0.05 level.

| Factor(s) | Closely packed | | | | Spread out | | | |
| | GBR1 | | GBR2 | | GBR3 | | GBR4 | |
	5 km	10 km	5 km	10 km	5 km	10 km	5 km	10 km
1 only	*	*	*	*	*	*	*	*
2 only	*	*	*	*	*	*	*	*
3 only	*	*	*	*	*	*	*	*
4 only	*	*	*	*	*	*	*	*
1*2			*					
1*3	*	*	*	*		*	*	*
2*3	*	*	*				*	*
1*2*3	*		*			*	*	
1*4						*		
2*4	*	*	*	*		*	*	*
1*2*4								
3*4	*							
1*3*4						*	*	*
2*3*4						*	*	*

3.2. Results

All four model settings tested (bathymetry, fetch angle, fetch length and fetch line combination) were sensitive to normalized wave exposure predictions for all study areas (Table 3). This means that wave exposure estimates will differ depending on how these parameters are set when the model is run. For all study areas except GBR3 at 5km resolution, higher order interactions were also significant, limiting the ability to assess the relative importance of individual factors to model results. Some of these interactions may be reduced by more careful choice of case study areas. For example, GBR1 consists of largely shallow areas which meant that considering bathymetry made a disproportionately large difference to the results.

4. DISCUSSION AND CONCLUSIONS

A preliminary experiment was conducted to test the sensitivity of GIS-based cartographic relative wave exposure models to the setup of key input parameters using a new modeling framework (GREMO), which incorporates tool and models from a range of published studies. From this experiment, it is clear that more work is needed to explore model sensitivity as wave exposure estimates varied significantly for different

settings of all key model parameters tested. Because model results will differ given how the model is set up, care must be taken to set these appropriately. At present this is done on an ad hoc basis. However because the factors interact and the effects are driven by the spatial arrangement of obstacles, optimal model settings will not always be obvious. Ultimately, it would be useful to develop a set of automated tools with which to examine the spatial arrangement of obstacles within a given study area to determine optimal model settings. Before this can be done, however, a more detailed set of experiments is needed. One way to simplify the task could be to run sensitivity tests on manufactured rather than real data, such that the obstacles and their spatial arrangement can be controlled to represent end points of the continuum of spatial arrangements possible. Only once a model is run with an optimal set up does validation with in situ wave exposure make sense.

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