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An integrated GIS approach for sustainable aquaculture management area site selection

Peter C. Longdill [a,*], Terry R. Healy [a,1], Kerry P. Black [b,2]

[a] Coastal Marine Group, Department of Earth and Ocean Sciences, University of Waikato, Private Bag 3105, Hamilton, New Zealand
[b] ASR Ltd, Marine Consulting and Research, P.O. Box 67, Raglan, New Zealand

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ABSTRACT

Within New Zealand, growth in the aquaculture industry has led to the diversification of aquaculture sites from more sheltered bays and harbours toward open coast locations. Coastal zone managers, along with the aquaculture industry, aim to ensure the long-term sustainability of any 'new' sites selected. Through targeted data collection programmes and the subsequent implementation of Geographic Information System (GIS) based models, the most suitable and sustainable locations for Aquaculture Management Areas (AMAs) can be identified. This approach is applied within the Bay of Plenty, New Zealand, with specific reference to suspended mussel (*Perna canaliculus*) aquaculture. Within the region, areas where maximum sustainability may be achieved make up 18% of the total area considered, with conflicting uses and other constraints accounting for 46%. Whilst further site and development specific studies are required to determine explicit carrying capacities, the effort required has been considerably reduced by eliminating unsuitable locations and identifying those where sustainability can be maximised.

1. Introduction

The New Zealand aquaculture industry has recently experienced a period of rapid growth. Specifically, greenshell mussel (*Perna canaliculus*) export volumes have doubled during the last decade (1995–2005) to reach 100,000 tonnes/yr [1]. Currently, there are more than 500 greenshell mussel farms totalling 30 km^2 [2]. Traditionally, these have been located within relatively sheltered estuaries and bays close to the coastline e.g. Firth of Thames and Marlborough Sounds. Rapid growth of the aquaculture industry coupled with the near saturation of traditional sites and recent advances in culture technologies, has led the industry toward alternate environments; notably offshore locations. The industry's desire to explore these areas, together with recent central government requirements, has created the need for environmental managers to prescriptively zone for aquaculture through the creation of Aquaculture Management Areas (AMAs).

One of the most common reasons for the failure of aquaculture projects and for adverse environmental effects is locating developments on inferior sites [3]. There is a clear need for sustainability issues to be considered during the early planning stages for all types of aquaculture. Site evaluations to determine locations where natural conditions are suitable, whilst also considering the needs of the operation and cultured species are essential for the development of sustainable operations [4,5].

The specific definition of 'sustainable aquaculture' has been the subject of some debate [4]. To reflect a desire to focus on the aquaculture industry specifically and also to maintain the sustainability of both environmental concerns and the economic operation of the industry, the definition of Boyd and Schmittou [4] is adopted where sustainable aquaculture is defined as that 'where ecologic and economic viability persist indefinitely'.

AMAs should be developed within the framework of an integrated coastal zone management scheme, whereby any proposed aquaculture plan integrates into an adequate allocation system [6]. Such a system should enable the selection of the most suitable aquaculture sites based on both environmental and institutional issues [7], i.e. considerations must extend to the environmental requirements of aquaculture, potential environmental impacts, other users and uses of the coastal and marine environment along with society's intrinsic values regarding coastal and marine areas. Currently, although there are no clear guidelines to follow in undertaking this task within an integrated management process [8], the use of Geographic Information System(s) (GIS) based models is being recognised as a standard methodology [9].

Through the use of GIS-based models, issues relating to competing demands on coastal space can be resolved, undesirable impacts minimised, and the profitability and sustainability of

* Corresponding author. Tel.: +64 95341252.
E-mail addresses: peter@longdill.co.nz (P.C. Longdill), t.healy@waikato.ac.nz (T.R. Healy), k.black@asrltd.co.nz (K.P. Black).
1 Tel.: +64 78585200.
2 Tel.: +64 78250380.

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aquaculture operations maximised through rational use of the coastal space [6,9]. It must be noted, however, that although GIS-based models can prove a useful tool for coastal managers, tough political choices will still remain. This study aims to support the coastal zone management decision making process through the identification of the most suitable sites for sustainable open coast AMA (*P. canaliculus*) zoning within the Bay of Plenty, New Zealand (Fig. 1), using GIS-based models and related technologies.

1.1. GIS use in aquaculture planning studies

Whilst planning is often cited as a priority for aquaculture development [10], the identification of sustainable aquaculture sites is a complex spatial problem requiring in depth knowledge of the marine environment as well as an understanding of numerous social and civil factors [11]. Poor site selection can result in stressed ecosystems, stressed culture species, decreased production, inferior economic performance, displeased neighbours and a disgruntled public [12]. The application of GIS-based models to the site selection task provides an efficient and effective tool under which a protocol for the structured analysis of spatial data for the purposes of resource assessment and management can be developed.

Since the late 1980s there has been an increased use of GIS in aquaculture site selection and suitability studies over a variety of spatial scales [13–20] and for the near-shore coastal culture of shellfish, shrimp, and fish [8,10,21–29]. Study sites have included both developing [15,30,31] and developed countries [13,32–34]. Despite the increasingly frequent applications, specific tools and methodologies for achieving the goals are still under development [35].

In this study, these applications are extended to the offshore culture of bivalve shellfish on an open coast incorporating the use of both numerical model output and the relative productivity of coastal regions, as identified from remotely sensed data.

The spatial decision making process begins with the recognition and definition of the problem; e.g. identifying suitable and sustainable sites for the open coast culture of shellfish. Once defined, the Multi-Criteria Evaluation (MCE) technique [9] focuses on specifying, creating, and aggregating comprehensive sets of evaluation criteria which reflect concerns relevant to the decision problem [8]. Evaluation criteria can be either contributing factors (a parameter which enhances or detracts suitability) or constraints (parameters limiting the use of locations). Integration of criteria into the GIS builds the spatial database on which the evaluation is performed.

Complications arise as a result of the variety of scales and units on which the criteria are measured; the MCE technique requires each criterion be transformed to comparable units [8]. Raw data are generally converted to standardised aquaculture suitability scores (normalised values between 0 and 1) through the use of Parameter-Specific Suitability Functions (PSSFs) [26,27,34,36]. In order to define overall suitability, the individual criteria are combined using either additive or multiplicative models, with or without individual weightings.

The reliability of the model output is dependent on the accuracy of source data used [10]. Verification (ground-truthing) of data sources within such analyses is essential both for quality control of inferred or modelled data sets and also for the general applicability of the final model [8,9]. Typically, individual data sources are verified by field sampling prior to the modelling stage.

For further background details the reader is referred to Nath et al. [9], who provide a comprehensive review of GIS principles and applications specific to aquaculture planning and the marine environment.

1.2. Study area

The Bay of Plenty is located on the east coast of New Zealand's North Island (Fig. 1). The region is relatively heavily utilised by both commercial (e.g. port operations, shipping, fishing, etc.) and recreational users. Transient wind forced upwelling episodes have been observed within the Bay during spring and summer, though the nutrient response is spatially variable due to variability in the shelf width and orientation (Fig. 1 and Ref. [37]).

Responding to the need to identify suitable and sustainable AMAs within the region, the coastal zone managers have implemented an extensive scientific programme to characterise the

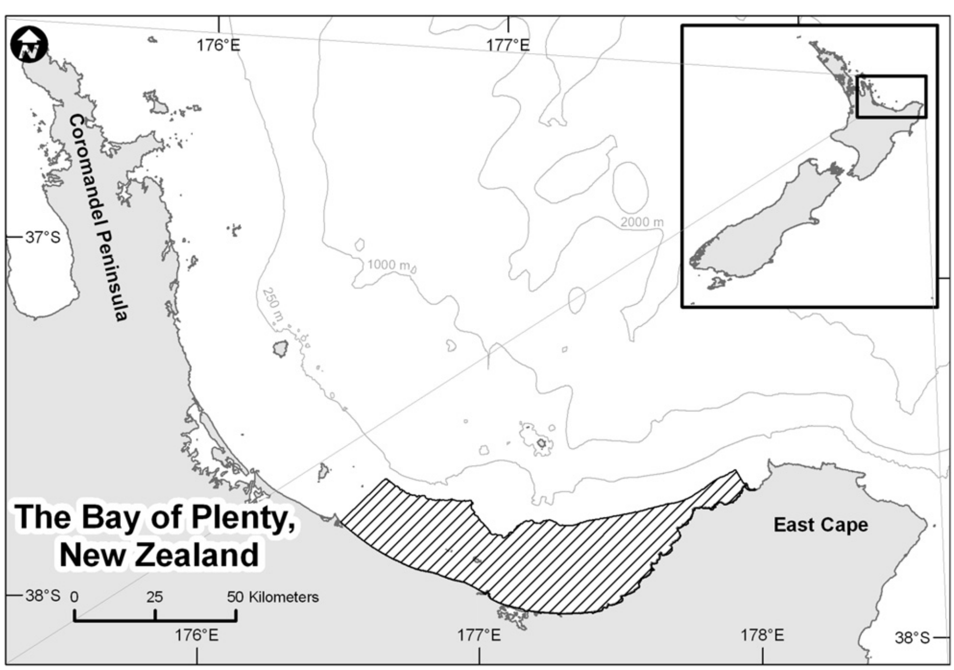

Fig. 1. The Bay of Plenty is located on the east coast of New Zealand's North Island. The shaded area indicates the common extent of all data applied during the study.

region, identify potential AMA sites, and assess sustainabilities and carrying capacities [37–41]. This study contributes to this programme.

2. Factors influencing the sustainability of offshore aquaculture

The identification of relevant data sets is an integral step in the GIS MCE technique. In determining suitable areas for sustainable aquaculture consideration must be given to the available natural conditions, the needs of an aquaculture operation, and the shellfish to be cultured [5]. A planning analysis aiming to identify sustainable offshore AMA sites, must recognise development independent factors which influence:

1. the growth and quality of cultured shellfish (economic sustainability),
2. the magnitudes of potential impacts from cultured shellfish (environmental sustainability), and also recognise,
3. existing uses and users of, along with societal values relating to, the coastal marine region (conflicting uses and constraints).

2.1. Factors influencing growth and quality

Optimal sites for a sustainable AMA will be characterised by conditions leading to relatively enhanced growth rates. Rapid growth and high quality shellfish are essential for the economic sustainability of the industry. Similar economic returns can be achieved at optimal sites with relatively low shellfish stocking densities (and hence less environmental stress) as at less optimal sites with higher stocking densities. Several common data sets have traditionally been applied to assist the identification of such locations. However, these factors influencing the growth of cultured shellfish, can be cultured species, or culture technique specific (e.g. temperature and salinity variability).

Within the Bay of Plenty, lowest observed monthly mean water temperatures are $\sim 14\,^{\circ}$C [40], not sufficiently low to severely restrict *P. canaliculus* growth [42]. Additionally, the open coastal regions of the Bay of Plenty are not subject to a high degree of salinity variation or to depressed dissolved oxygen concentrations [40] which can inhibit shellfish growth [42]. Consequently, the use of 'raw' temperature, salinity, and dissolved oxygen layers [24,25,32,34,43] is redundant for this specific region and cultured species.

The growth of suspension feeding bivalves (e.g. *Perna* sp.) is largely controlled by food availability and phytoplankton dynamics [44,45]. Cultured bivalves rely on natural food sources, which can become a significant constraint on production [46]. Several studies have identified strong direct linkages ($R^2 = 0.77$) between upwelling indices and cultured shellfish production and quality [47,48], highlighting the importance of physical dynamics to the potential productivity of the industry. Upwelling typically provides a rich source of nutrients to enhance phytoplankton growth, and indeed large volumes of shellfish are cultured in areas with relatively high phytoplankton concentrations [47–50]. Optimal AMA sites will be characterised by high productivity [42].

Increased current speeds can act to decrease flushing times through aquaculture developments, thus enhancing the rate of supply of particulate food, and enabling the support of denser populations than if water exchange was more limited [32,49]. Large groupings of bivalve suspension feeders (as in aquaculture developments) can locally deplete ambient water of particulate food, and in some situations, become self limiting [51]. Indeed, amongst mussel aquaculture rafts on the coast of Spain, Navarro et al. [52] noted a pattern of mussel rafts on the borders of groupings tending to grow faster than those from the inner parts. Further, several authors have correlated bivalve growth directly to current speeds [53–56]. Optimal AMA sites will be characterised by rapid flushing rates and efficient water exchange, i.e. persistently 'high' current speeds in open coast locations, though infrastructural issues obviously limit areas of extreme hydrodynamism.

2.2. Factors influencing impact magnitudes

For a given stocking density and culture method, there are several factors capable of influencing the magnitudes of potential impacts from aquaculture, and hence its environmental sustainability. In selecting sustainable AMA sites, potential negative impacts must be considered and sites selected where these are minimised, prevented, or mitigated effectively.

The build up of organic and other waste material (e.g. faeces, pseudo-faeces, shell-litter, ammonia) beneath and surrounding shellfish aquaculture sites can potentially lead to distinct changes in nutrient cycling characteristics, benthic species assemblages, and benthic bio-diversity [57–60]. The magnitude of these impacts can be influenced by the dispersion of waste material from the farm and also by the assimilative capacity of the receiving sediments [62–64]. Enhanced current speeds, in addition to affecting the rate of food supply, act beneficially to improve waste dispersal [57,61–67]. The natural benthic environment (e.g. high organic content fine sediments, coarse sand, rocky reef) and its assimilative capacity, relating to the specific additional inputs, plays a further role in determining the impact magnitude (see Longdill et al., [41] for further discussion).

In addition to generic water speeds, predominant flow directions (residual over a long time period) can also be used to prescriptively zone for sustainable aquaculture. The Bay of Plenty coast is a site of active recreational fishing and shellfish gathering and, along with New Zealand's entire coastline, is of particular significance to the country's population. The potential transmission of localised depleted (phytoplankton and/or nutrients) water masses or waste material toward near-shore zones should be avoided to minimise potential impacts close to the coast. It can be viewed as beneficial, therefore, to have predominant water velocities through an AMA directed offshore and away from the coast.

Whilst some influential factors can be considered constant in time (e.g. sediment-type) others may exhibit considerable temporal (daily, seasonal, annual and inter-annual) variability (e.g. Sea Surface Temperature (SST), Chlorophyll-*a* (CHL-*a*), current speeds). The use of long-term means (e.g. decadal-scales for SST and CHL-*a*, annual scales for currents) allow this shorter-term variability to be integrated within individual data sets.

2.3. Existing uses and societal values

An enduring and sustainable aquaculture industry must minimise conflict with other users and uses of the marine environment. Though some conflicts may be solved through dialogue, compromise, or compensation, avoidance is often the simplest and most sustainable solution. This is best achieved during the planning stages.

There are significant commercial fisheries within the Bay of Plenty. Important species include snapper, skipjack tuna, mackerel, kahawhai, and crayfish (pers. comm. Ministry of Fisheries staff); typically caught by bottom trawling, purse seining and danish seining [68]. Additionally, recreational activities (including fishing) are popular throughout the region, with significant quantities of finfish being landed as a result of vessel and land based recreational fishing [68].

Additional uses of the marine environment within the Bay of Plenty include commercial shipping, commercial anchorages, dredge dump grounds, Marine Protected Areas (MPAs), local fisheries management areas and sites of cultural, ecological, historical and geologic significance. All such sites where there is high commercial or recreational use, and those with special significance to large groups of the population should be either avoided or a detailed assessment of potential impacts undertaken and integrated within the plans in order to minimise potential conflicts.

3. Data sources employed

3.1. Marine productive regions sub-model

Productivity 'hotspots' in the marine environment can be considered areas of increased sea surface CHL-*a* concentrations [69,70], the result of a localised increase in available nutrients to photosynthesisers. The increase in available nutrients is generally the result of oceanographic processes such as upwelling, gyres or eddies [71]. Such processes can act to transport cold, nutrient-rich water from below the pycnocline to the euphotic zone. The cold water signature of the nutrient-rich water results in these productivity hotspots typically being associated with low SSTs. Indeed, within the Bay of Plenty the connection between upwelling circulation, the surface expression of cold water, and enriched nutrient concentrations has previously been identified [37].

The spatial integration (addition or multiplication) of normalised SST and CHL-*a* anomalies indicates areas of productive processes such as upwelling, gyres, and frontal formations [69,70, 72–75]. The use of climatological (long-term) data sets allows the identification of persistently productive regions, independent of shorter-term variability [11].

3.1.1. SST anomalies

Remotely sensed SST data, derived from the Advanced Very High Resolution Radiometer (AVHRR), were obtained at 1 km spatial resolution from the National Institute of Water and Atmospheric Research Ltd (NIWA). Instantaneous SST retrievals in the dataset have a standard deviation error of $\sim 0.6\,^{\circ}$C and a bias error less than $\pm 0.1\,^{\circ}$C [76]. Climatological (inter-annual) monthly means, produced from monthly composites (1993–2004) of these data were processed using a Fourier decomposition method [77]. Cloud detection algorithms, SST retrieval equations, compositing method and a broad scale validation are detailed in Uddstrom and Oien [77]. An independent validation of the SST data set using measured CTD and thermistor data, within the study region, found a correlation R of 0.94 ($P < 0.05$, $n = 149$ at 18 sites).

Coastal monthly mean SSTs can be defined as the mean temperature of the entire coastal segment (at a specified distance from the coast), obtained from the climatological monthly mean data sets. Due to the complexity of the SST pattern within the Bay of Plenty (typically warmer water offshore and cooler water onshore), monthly mean coastal SSTs were generated for polygons buffered consecutively from the coastline at 2 km intervals to a distance of 30 km from the coast for each climatological monthly mean data set.

The climatological monthly mean data can be compared with the corresponding coastal monthly mean to identify temperature anomalies and areas of persistently higher or lower temperature than that of the coastal mean. Monthly anomalies were created within ArcGIS through the subtraction of coastal monthly means from the climatological monthly means. For example, Oct93_04 – coastal_mean_Oct93_04 = Oct93_04_anomaly. Monthly anomalies ($A_{SST(x,\,y,\,m)}$) were then summed over the year to provide a spatial perspective of persistent SST anomalies ($A_{SST(x,\,y)}$) in the coastal segment, i.e.:

$$A_{SST_{(x,y,m)}} = \left[\overline{SST}_{(x,y,m)} - SST_{(x,y,m)}\right]$$

$$A_{SST_{(x,y)}} = \sum_{m=1}^{m=12} A_{SST_{(x,y,m)}}$$

for x and y belonging to the 'coastal-segment', where ($A_{SST(x,\,y,\,m)}$) is the spatially variable (x and y) inter-annual SST anomaly in the coastal-segment for each month (m) of the year, $SST_{(x,\,y,\,m)}$ is the climatological monthly mean temperature and $\overline{SST}_{(x,y,m)}$ is the mean of these data over the buffered coastal segment(s).

The determination of SST anomalies via this method differs from that of Hardman-Mountford and McGlade [78] and Valavanis et al.

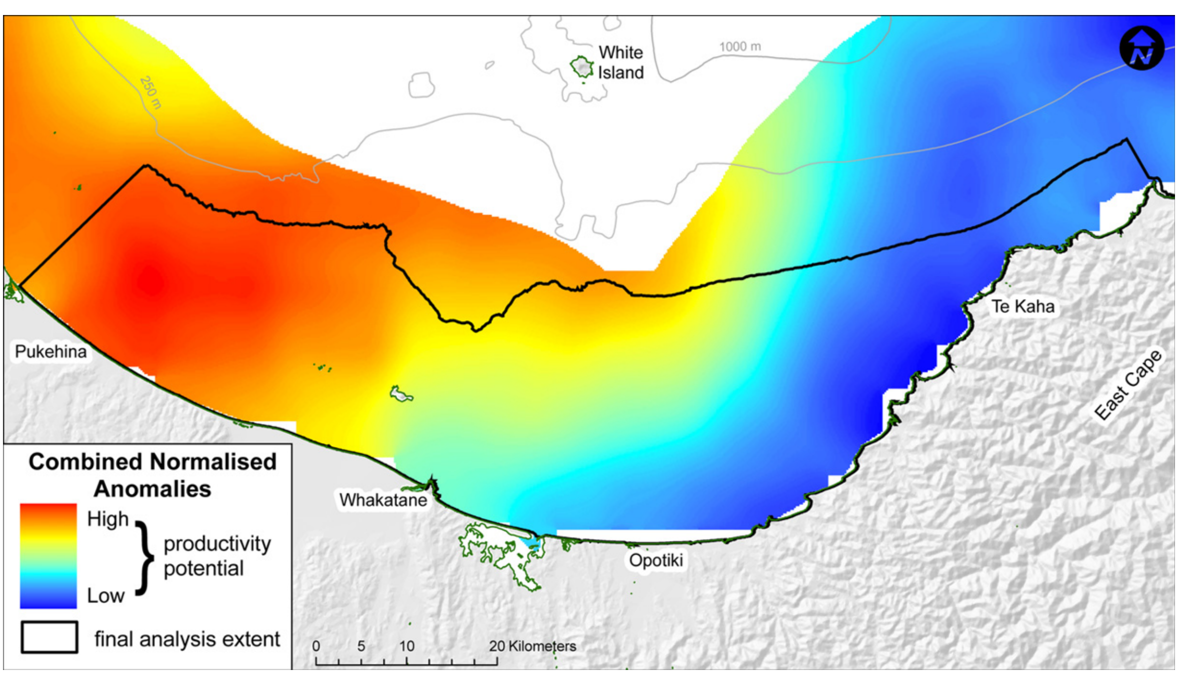

Fig. 2. Spatially integrated combined normalised anomalies in SST (1993–2004) and CHL-*a* (1997–2004) indicating the relative productivity potential of coastal areas within the Bay of Plenty, New Zealand. A high value indicates persistently lower than typical SSTs and higher than typical CHL-*a* concentration, indicative of a productive area.

[70] who calculated anomalies from individual month SSTs rather than from monthly climatological (inter-annual) data sets as used here and also by Shevyrnogov et al. [79]. Climatological data sets provide clear advantages over more short-term (e.g. single year) data in their (at least partial) representation of inter-annual variability.

Coastal SST anomalies (not shown) within the Bay of Plenty exhibit considerable variation along the coast. Strong negative anomalies (an indicator of upwelling) occur on the north east of the Coromandel Peninsula, between Mt Maunganui and Pukehina, in deeper water (80–200 m) offshore from Whakatane, and near East Cape. Notably, SST anomalies are consistent with observed wind driven upwelling dynamics [37] and variability in the coast and shelf orientation.

3.1.2. *CHL-*a *anomalies*

Remotely sensed climatological monthly mean CHL-*a* data (1997–2004), derived from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) were obtained at both 4 km and 1 km resolutions from NIWA. Case 2 CHL-*a* products were generated using the NIWA Inherent Optical Properties (IOP) algorithm to iteratively solve a set of non-linear equations in order to correct both for non-phytoplanktonic sediment concentrations and to retrieve IOP from corrected water leaving radiances [76]. The NIWA IOP algorithm [80] was calibrated and validated for the Bay of Plenty region based on an extensive field survey of bio-optical parameters within the study area [81]. Details regarding the calibration of the algorithm for the study region are recorded in Pinkerton et al. [81].

Though Pinkerton et al. [81] conclude that these data (and their associated error, $\pm$ 35%, [82]) 'do not differ at the 95% confidence level' from in-situ measurements; an independent validation highlighted several weaknesses in these data [40]. These weaknesses may, however, have been the result of spatially 'patchy' phytoplankton distributions and the comparison of point based (fluorometer and water sample) data with area based (1 km^2) remotely sensed data. Whilst it is accepted that there are some limitations in the use of case 2 CHL-*a* products in coastal waters, these data represent the best available spatially and temporally dense data sets available for the region. Though smaller scale trends and details (<1 km^2) may not be well represented it is believed that these data do reflect the general trends in CHL-*a* distribution [81].

Long-term (1997–2004) coastal CHL-*a* anomalies within the Bay of Plenty were generated in an identical manner to that of SST.

3.1.3. *Marine productive regions*

Normalised (0–1) climatological SST and CHL-*a* anomalies were multiplied together to identify regions with persistently low SST and high CHL-*a* (Fig. 2). Combined normalised anomalies (Fig. 2) suggest that the most productive coastal regions within the Bay of Plenty are located offshore from Pukehina. Relative productivity is lowest near the coast in the eastern Bay of Plenty, adjacent to Te Kaha. The results suggest that, in light of the relationships between cultured shellfish production and quality and upwelling indices [47,48], cultured bivalve growth may be best offshore from Pukehina.

3.2. *Current speeds and directions*

Wind and tidally forced current speeds throughout the Bay of Plenty were determined from a 3-dimensional baroclinic numerical hydrodynamic model (3DD; [83]) of the shelf environment. The model was calibrated against measured sea levels and current components ($R = 0.82$ and ≈ 0.74, respectively, $P < 0.05$, $n = 1699$ h) to ensure replication accuracy.

The model was run for an entire year (1/8/2003–31/7/2004) and mean flow speeds, independent of direction (i.e. a scalar quantity), determined within each model cell (3×3 km grid). Mean flow speeds ($\overline{S}_{(x,y,z)}$) can be defined by

$$\overline{S}_{(x,y,z)} = \frac{\sum_{t=0}^{T} \left| S_{(x,y,z,t)} \right|}{n}$$

where $S_{(x,y,z,t)}$ is the flow magnitude within the grid cell *x, y, z* at time *t*, and *n* is the number of time steps between 0 and *T*, the final model time step. Note that *S* is a scalar quantity, flow magnitude, and is independent of direction.

As the model replicates currents in 3-dimensions, those in the depths where offshore bivalve aquaculture is likely to be located (5–25 m; [84]) are utilised for the zoning analysis (Fig. 3).

Some generic guidelines for water speeds required for sustainable mussel (*P. canaliculus*) aquaculture have been suggested previously for the purposes of prescriptive zoning (Table 1). These velocities, proposed by Inglis et al. [85], represent 'typical speeds' rather than long-term averages, which may be somewhat lower than those deemed 'typical' at the same site. Where flow directions are variable (as they are over much of the Bay of Plenty shelf [37,38]), due to the action of tides and/or variable wind stress, the direction changes usually cause intermediate periods of slack currents which are subsequently incorporated into the long-term means.

This effect can be clearly seen from a long-term ADP current meter deployment (off Pukehina) where velocities frequently oscillated by ± 40 cm s^{-1} in the along-shelf direction during the 70 day deployment [37,38], yet the yearly mean speed at the same site is 7.5 cm s^{-1}. To represent and account for these differences, the guidelines of Inglis et al. [85] have been decreased by 50% (Table 1).

Hydrodynamic model output is also used to determine residual velocity vectors ($\overline{U}_{(x,y,z)}$ and $\overline{V}_{(x,y,z)}$), and then its shore-normal component, within each model cell:

$$\overline{U}_{(x,y,z)} = \frac{\sum_{t=0}^{T} u_{(x,y,z,t)}}{n}$$

$$\overline{V}_{(x,y,z)} = \frac{\sum_{t=0}^{T} v_{(x,y,z,t)}}{n}$$

where *u* and *v* are velocity components at each model cell (*x, y, z*) at time *t*. The residual velocity vector indicates the net general movement of water over the averaging interval, *T* (1/8/2003–31/7/2004).

Variability in the orientation of the Bay of Plenty coastline results in a more complex situation to determine shore-normal residual currents than for a straight coast. Within ArcGIS the coastline was buffered at regular intervals offshore (3 km). Each buffered coastline (as a polyline layer) was subsequently split into regular segments (each being 3 km long) and the orientation of each segment determined. The shore-normal component of residual velocity was then determined from the buffered shoreline orientation (Fig. 4).

3.3. *Benthic environments*

A benthic suitability index for aquaculture within the Bay of Plenty has been developed previously [41] (Fig. 5). This suitability index considers the character of the natural environment (sediment-type, organic content, shell content, reef type, habitat complexity, and both in-faunal and epi-faunal species assemblages) and its influence on the benthic assimilative capacity with respect to the potential inputs from suspended shellfish aquaculture [41].

The index is directly incorporated into the GIS MCE model to assist in the identification of sustainable AMAs within the Bay of Plenty.

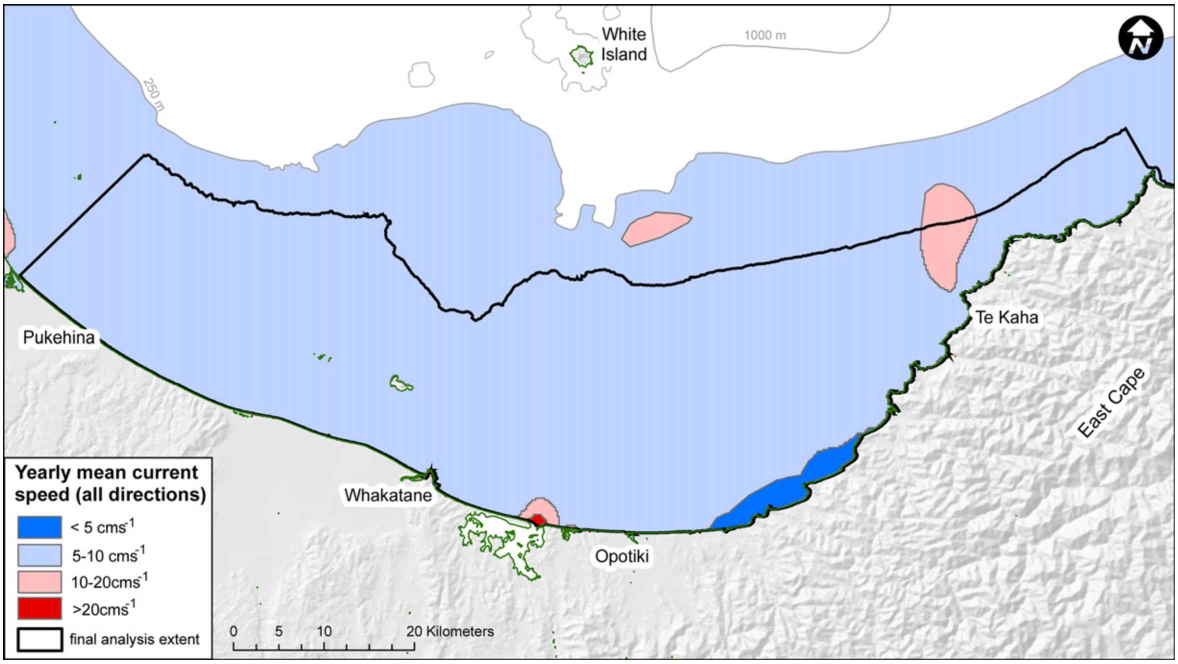

Fig. 3. Year long mean shelf current speeds at 5–25 m depths between the shoreline and the 250 m contour from calibrated numerical hydrodynamic models forced by winds and tides. Mean speeds determined by averaging current speeds (scalar) from throughout the simulations.

3.4. Constraints and conflicting uses

Commercial fishing trawl paths within the Bay of Plenty were obtained from the New Zealand Ministry of Fisheries over the following intervals:

- Bottom trawl 1995–2001.
- Purse seine 1993–2001.
- Danish seine 1996–2001 [68].

Individual trawl path vectors were converted to raster format (1 km^2 cells) by intersecting the vector polylines with raster cells. Cells were then spatially summed and divided by the number of years of data to provide a fishing effort data set, with units of visits per year, for each method. Areas of high effort (>50% of maximal) were identified for each fishing technique and mapped as constraints (Fig. 6). Highest efforts were in the range of 40–50 visits per year, in water of 30–50 m depth near Opotiki.

Generally, comprehensive data on recreational vessel movement patterns is difficult to obtain. However, within New Zealand, for safety reasons recreational vessels generally call in to the local coastguard to report their departure time, intended location and activity, and intended return time. Analyses of coastguard radio log books from the three local coastguards within the region (Whakatane, Tauranga, and Waihi Beach) over the year 2003–2004 enabled the derivation of vessel visits per year for general locations within the Bay of Plenty [68].

As only general locations are available from the log books some interpretation was required to represent these as definitive areas. Offshore island and reef locations were buffered with a 2 km radius, creating representative polygons. Where near-shore locations were reported, polygons were created between the coast, the 30 m depth contour, and for a representative distance either side of the reported location (Fig. 6). Logged visit data were summed within each location.

Despite the limitations of the data set (e.g. not all vessels reporting, misreported locations, etc.), it represents the best available data of recreational vessel patterns and densities within the Bay of Plenty. For the purposes of this study, the data set adequately describes recreational vessel locations.

In addition to vessel based recreational activities, fishing from beaches and rocky headlands (e.g. by long-lines deployed by Kite/kontiki and surf-casting) is popular throughout the region. These long-lines can typically extend to a distance of 2 km from the coast. A constraint layer, as a coastal buffer zone, has been applied to represent this use within the MCE model (Fig. 6).

Conflicting uses and constraints to AMA zoning have been identified and data on their spatial extents obtained from a variety of sources (Table 2). Constraint layers include uses/users such as commercial shipping, commercial anchorages, dredge dump grounds, marine protected areas, local fisheries management areas, recreational access ways, significant sites (ecological, historical, cultural, and geological), and visual amenity areas (Table 2 and Fig. 7).

Where constraints were point based locations e.g. commercial anchorages or a shipwreck, a polygon buffer (2 km radius) was created to prevent the nearby siting of AMAs.

Table 1
Generic guidelines for water speed for sustainable mussel culture, modified from Inglis et al. [85]

'Typical' water speed (cm s^{-1})	Year long mean speed (cm s^{-1})	Generic guide
<5	<2.5	Very weak currents, poor mass flux and inconsistent direction. Depletion likely at the centre of farms
5–10	2.5–5	Weak currents of generally variable direction, leading to some depletion at the centre of farms
10–20	5–10	Moderate-low depletion that may be more marked at downstream end of farm. Depletion is more likely to be observed in centre of farmed area
>20	>10	Strong current flow. Little depletion but cumulative effect of many ropes/longlines in the direction of flow could result in flow reduction

3.5. Resolution and interpolation

All layers were converted to raster format with a spatial resolution of 200 m. SST, CHL-*a* (1 km resolution) and hydrodynamic

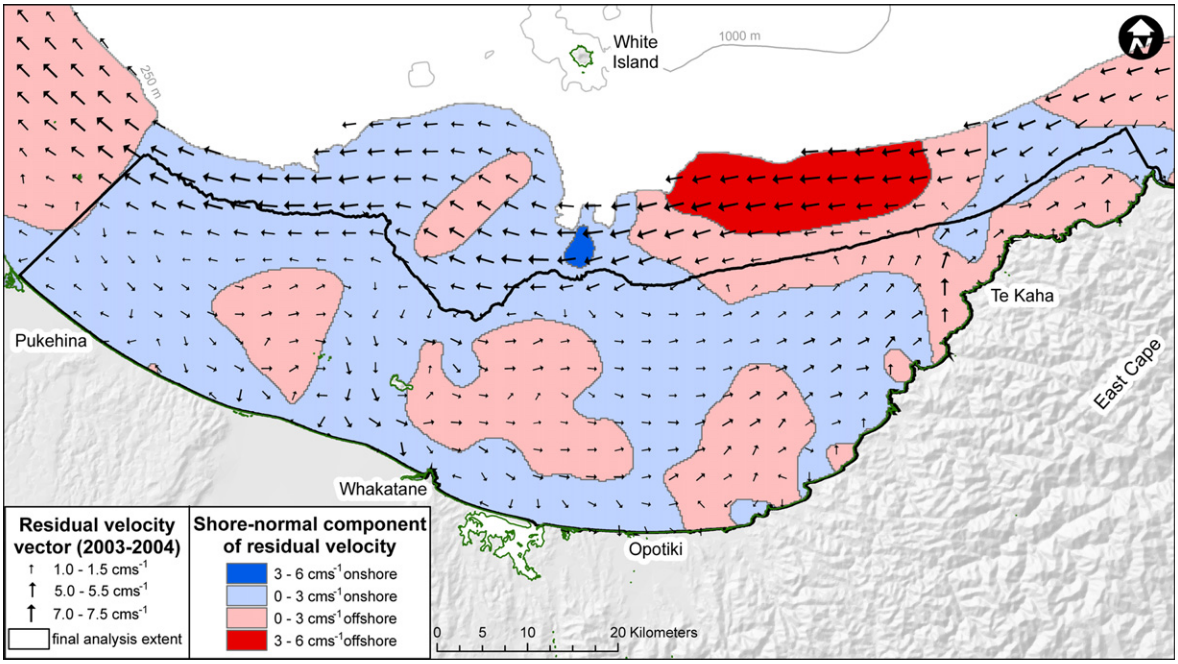

Fig. 4. Residual shelf velocities (2003–2004) at 5–25 m depths between the shoreline and the 250 m contour from a calibrated numerical hydrodynamic model. Residuals determined by vector averaging current components from throughout the simulation.

numerical model output (3 km resolution) were interpolated to the 200 m grid using Inverse Distance Weighting (IDW) techniques. To focus on areas of maximum interest for AMA development and on those within the bounds of existing technology, locations greater than 30 km from the coast (SST, CHL-*a*) or deeper than 100 m, were excluded from the final analysis. This crudely, though effectively, constrains the analysis using infrastructural factors, such as distance to market and existing technology restrictions.

4. Analytic framework

Combining selected data sets using MCE techniques requires that each parameter be transformed to comparable and consistent units. Parameter-Specific Suitability Functions (PSSFs) can be defined for each variable (parameter) which convert the raw data to standardised aquaculture suitability scores with reference to the specific biogenic or physical parameter [26,27,34,36]. Typically, suitability scores are defined on an arbitrary scale between 0 and 1, where 0 defines a non-suitable area, and 1, the most suitable. The PSSF method provides a distinct advantage over traditional Boolean logic where an element must belong to a ‘crisp’ set (0 or 1) as it allows the discrimination of levels of suitability as opposed to a simple binary classification.

Here, consistent with other applications of PSSFs for aquaculture site selection [26,27], functions are assigned based on a combination of species specific research, those applied by other researchers,

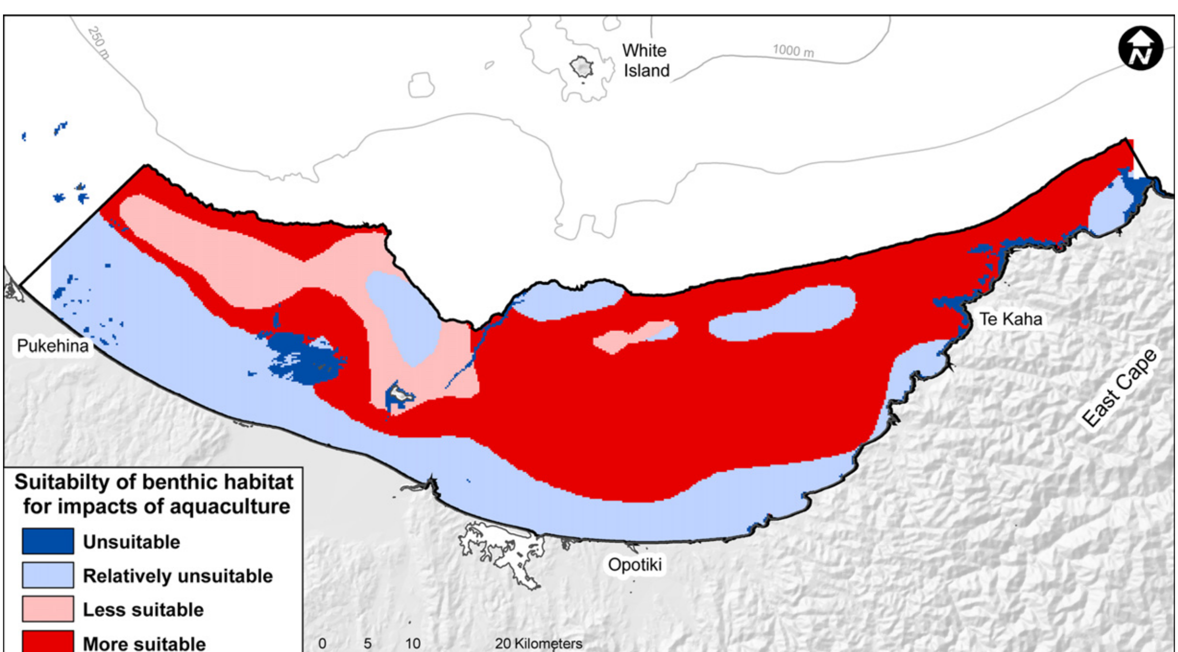

Fig. 5. Assessed suitability of benthic habitats within the Bay of Plenty to be sited beneath suspended bivalve aquaculture (from Longdill et al. [41]).

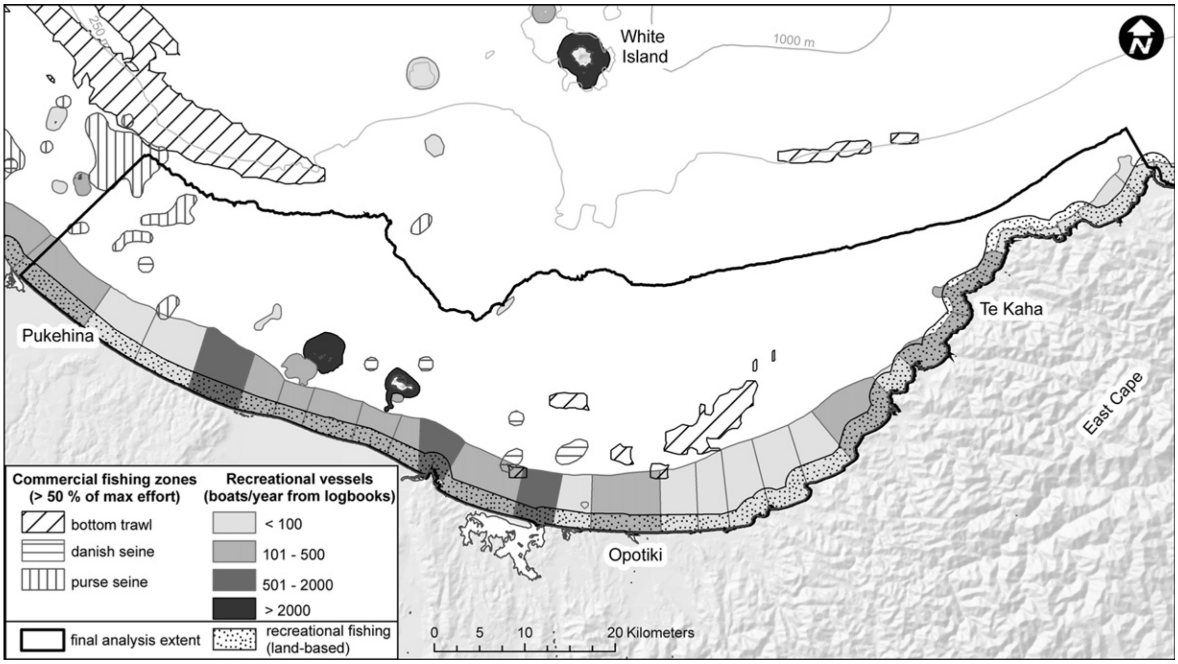

Fig. 6. Commercial fishing hotspots and recreational fishing density within the Bay of Plenty.

and expert opinion (Table 2). The somewhat subjective approach to PSSF definition and allocation effectively converts the initial quantitative data to that of a semi-qualitative nature. The method is, however, essential to allow the consideration and direct comparison of such diverse data sets.

MCE techniques are used to aggregate contributing factors (Fig. 8) into a spatially variable (x and y co-ordinates belonging to the study region) Suitability Index ($\mathrm{SI}_{(x,\ y)}$), providing a comprehensive assessment of the suitability for sustainable aquaculture.

The SI is calculated as the geometric mean of all parameters (modified by their PSSF) and subsequent restriction by the Boolean constraints layer:

$$\mathrm{SI}_{(x,y)} = \left(\prod_{i=1}^{5} \mathrm{PSSF}_{(x,y,i)}\right)^{1/\sum i=1,\ldots,5} \quad \text{where } C_{(x,y)} = 1,$$

and

$$\mathrm{SI}_{(x,y)} = 0 \quad \text{where } C_{(x,y)} = 0$$

where $\mathrm{PSSF}_{(x,y,i)}$ is the spatially variable parameter (co-ordinates x and y) modified by its Parameter-Specific Suitability Function into suitability levels (Table 2); $i=1,..5$ is an index identifying the 5 corresponding input parameters (Table 2); and $C_{(x,y)}$ is the spatially variable constraints layer (Fig. 7). $\mathrm{SI}_{(x,y)}$ is bounded between 0 and 1.

A weighted geometric mean can also be applied [27], where each parameter is assigned a 'weight' to indicate relative importance, often determined subjectively by 'experts'. However, Aguilar-Manjarrez [36] has shown, with specific reference to aquaculture, that a group of experts from similar backgrounds can vary in their ranking of importance. Further, subject matter experts with differing backgrounds (e.g. aquaculturists, planners, conservationists) bring differing viewpoints, resulting in a range of outcomes [9,32]. As a result, and to maintain generality and objectivity for the present case no variable weightings are applied, and the 'unweighted' geometric mean used.

The use of the geometric mean implies that, if a site is unsuitable with respect to one parameter ($\mathrm{PSSF}_{(x,\ y)}=0$), the overall suitability index ($\mathrm{SI}_{(x,\ y)}$) is 0 regardless of the $\mathrm{PSSF}_{(x,\ y)}$ value for other parameters [27,43]. This provides a distinct advantage over additive type models [8,24] which fail to similarly account for a 0 score in a single parameter.

To clearly delineate suitability regions from the model output distinct classes within the SI are defined (good, medium, poor, unsuitable; Fig. 9). The structure of class definitions and labels (Fig. 9) are consistent with those applied elsewhere [8,86].

The spatial extent of the final output suitability index is limited by the least extensive data set, in this case benthic suitability. These data (benthic suitability) are expensive to obtain in terms of time, effort, and cost, although they represent essential information for the ongoing environmental sustainability of an AMA. A balance must be met between the spatial extent of sampling, sampling density, and the requirements of the task.

5. Results

Final output from the suitability model indicates that 421 km^2 (18%) of the survey region is classed as the most suitable for sustainable AMA development. These areas were generally located between 30 and 100 m depths offshore from Whakatane, and Matata (Fig. 9). Constraints, along with other unsuitable areas, accounted for 1099 km^2 (46%) of the region under consideration. Within the analysis area, the majority of constraints were restricted to near-shore regions, where, for the purposes of AMA zoning, they effectively maintain a coastal buffer zone with width varying between 5 and 10 km. Significant factors constraining AMA zoning include culturally significant sites (371 km^2, 15% of total), significant conservation areas (299 km^2, 13%), commercial fishing (105 km^2, 4%), and unsuitable benthic habitats (90 km^2, 4%). Much of the remaining constraint area comprises the coastal visual amenity buffer.

Circular buffer zones surrounding culturally significant sites offshore from Opotiki represent a substantial obstacle for AMA zoning (Fig. 9). These sites may represent traditional fishing grounds, ancestral sites, or areas of Waahi tapu (sacred sites), etc. Cultural sensitivities prevent the specific nature of these sites being published.

Table 2
Sources, requirements, values, and Parameter-Specific Suitability Functions (PSSFs) of data sets used in the suitability analysis of the Bay of Plenty region for AMAs

Data set	Data requirements	Data value	PSSF value	Source
Marine productive regions	• Inter-annual monthly means of remotely sensed SST and CHL-*a*	Normalised	0–1 linear	SST and CHL-*a* anomalies
Benthic suitability index	• Sediment composition	Unsuitable	0	[41]
	• Sediment organic contents • In-faunal and epi-faunal organism counts	Relatively unsuitable	0.33	
	• Underwater videography/photography			
	• Multi-beam bathymetric surveys	Less suitable	0.67	
	• Assessment of potential impacts of aquaculture on identified habitats	More suitable	1	
Mean flow speeds (10–25 m depth)	• Calibrated 3-d numerical hydrodynamic model run over an extended time period	>2.5 cm s^{-1}	0	[85] (class. scheme)
		2.5–5 cm s^{-1}	0.33	
		5–10 cm s^{-1}	0.67	
		<10 cm s^{-1}	1	
Residual current direction (onshore–offshore component)	• Calibrated 3-d numerical hydrodynamic model run over an extended time period	>3 cm s^{-1} onshore	0.33	HD model
	• Buffered and split coastline orientations extending over study region	0–3 cm s^{-1} onshore	0.5	
		0–3 cm s^{-1} offshore	0.67	
		>3 cm s^{-1} offshore	1	
Recreational fishing zones (vessel and land based)	• Coastguard log books of reported recreational vessel location (boats per year, bpy)	<100 bpy	0.75	Regional council and coastguards
		101–500 bpy	0.5	
		501–2000 bpy	0.25	
		>2000 bpy	0	
		land based	0	
Boolean constraints				
Commercial fishing zones	• Trawl paths of commercial fishing boats	Effort $>$ 50% maximal	0	Ministry of fisheries data
	• Scallop dredging zones			
Commercial anchorages	• Sites designated for large commercial vessels awaiting entry to port, buffered by 1 km.	n/a	0	Navigation bylaws
Commercial shipping zones (+ 3 km buffer)	• Existing large vessel shipping routes, 3 km buffer	n/a	0	[89]
Dredge dumping grounds	• Consented sites where dredge tailings are dumped	n/a	0	Resource consent files
Marine protected areas (existing and proposed)	• Protected areas (by law) where disturbing the natural environment is prohibited.	n/a	0	Ministry of fisheries
Taiapure (local fisheries management area)	• Existing locations where local management of fisheries is in place, and recognised by law	n/a	0	Ministry of fisheries
Recreational access ways	• Five kilometer buffer surrounding popular entry/exit points to the open coast by recreational vessels, e.g. river mouths, estuary mouths, boat ramps.	n/a	0	Regional council and maritime New Zealand [88]
Significant sites	• Cultural sites, e.g. Customary fishing sites, sites of local significance	n/a	0	Consultation with tangata whenua (indigenous tribes) and regional council coastal plan
	• Ecological sites, e.g. migratory bird nesting areas, habitat of endangered species • Other sites e.g. special geologic sites, historical features, marine mammal habitats			
Visual amenity zones (horizon line buffer)	• Buffered from coastline (5 km), to prevent an observer at sea level from seeing aquaculture structures	n/a	0	Buffered from coastline

6. Discussion

AMA site selection requires the consideration of numerous, seemingly incompatible data sets. With the use of GIS technologies and MCE techniques to assess evaluation criteria and integrate data sets, useful databases and outputs can be generated for coastal managers.

In general, the Bay of Plenty region offers relatively suitable conditions for aquaculture development. However, consistent with other regions worldwide [8,10,30], existing users and uses of the coastal environment severely restrict potential sites where development can take place with minimal mediation between conflicting user groups.

The 421 km^2 (18% of area considered) evaluated to be of good suitability for aquaculture provides environmental managers with enough scope to be somewhat flexible in their allocation of AMAs within an integrated coastal zone management strategy. The analysis utilised 'traditionally applied' data sets (e.g. constraint layers, benthic environments, current speeds) and also introduced several novel data sets to aquaculture planning analyses. The identification of marine productive regions from long-term SST and CHL-*a* anomalies using GIS principles, though relatively common [69,70,72–75], has not previously been applied to aquaculture site selection (to the authors' knowledge). Additionally, the application of a layer representing long-term shore-normal residual velocities is a new concept with merit in minimising potential impacts to coastal and near-shore zones from offshore aquaculture.

Despite the extent of favourable locations, the GIS-based model does not imply actual estimates of carrying capacity (either physical, production, ecological, or social) within the region, but rather identifies locations where these may be maximised while maintaining sustainability. It is logical that separate developments need to be located some distance apart to minimise potential cumulative impacts [8]. An analysis to determine such specifics requires much more detailed information regarding actual development extents, locations, and stocking densities. Whilst beyond the scope of the

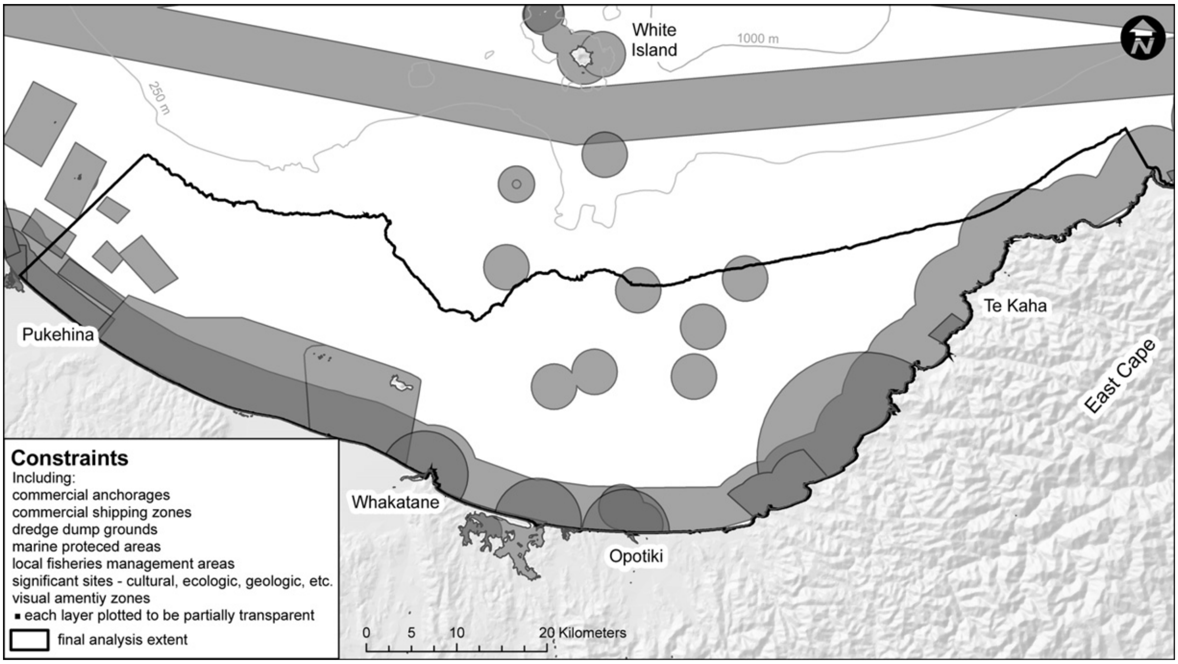

Fig. 7. Constraints to the zoning of AMAs within the Bay of Plenty shelf. See Table 2 for sources of data sets used as constraints.

present study, such investigations are appropriate once aquaculture development applications have been received.

Although the present model represents the usefulness of GIS as a planning tool for AMA zoning, the final model output is limited by some level of ambiguity in the application of semi-qualitative PSSFs. This is, however, a necessity for the implementation of the MCE technique and for the integration of the various data sets. Although these types of models are applied in an effort to protect the environment and allow for the sustainable use of resources, individual perceptions of environmental quality differ and sustainable use can be difficult to define [4]. There are no standardised sets of suitability or sustainability indicators for coastal aquaculture, although there is a clear need for their establishment and implementation [87]. Currently, improvements are being made in this regard [46], although these are more generally aimed at existing developments rather than for site suitability studies during the planning stages. Locally specific factors are likely to complicate their development.

Despite the model's limitations (restricted incorporation of infrastructural factors, known issues with CHL-*a* data set, PSSF allocation) it operates effectively as a planning aid indicating suitable locations for sustainable AMAs. GIS analyses do not provide definitive answers to a given problem; rather they generate outputs from a range of input data [35]. Their use in aquaculture site selection supports and assists the decision making process. This investigation identified those areas most suitable for sustainable AMAs within the Bay of Plenty, and also the restrictions and limitations on their placement.

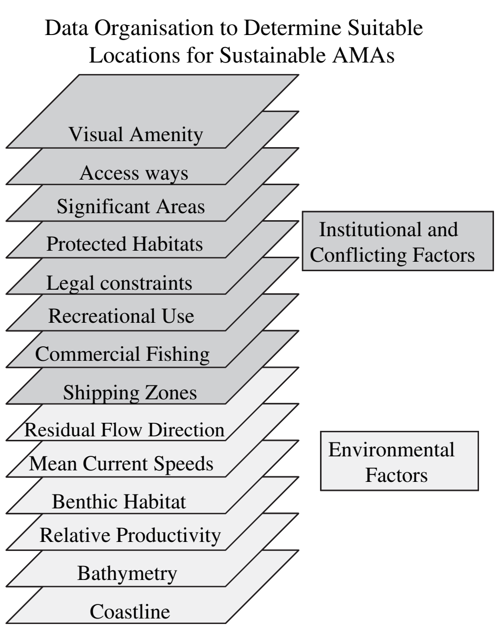

Fig. 8. Data layers and organisational structure used to determine locations for sustainable AMAs.

7. Conclusion

This study has focussed on the identification of the most suitable and sustainable locations for offshore AMAs within the Bay of Plenty, New Zealand. The analysis considered the available natural conditions, existing uses and users of the environment, and the needs of an aquaculture operation and the shellfish to be cultured. Identifying suitable and productive sites is essential for the environmental sustainability and economic viability of aquaculture ventures as it considers issues and resolves conflicts between users (and uses) at the planning stage, enabling rational use of the coastal space.

The usefulness of GIS-based tools and models for the task of planning for sustainable aquaculture has been highlighted. The introduction of novel concepts to GIS-based assessments of aquaculture suitability in the form of layers representing marine productive regions and long-term shore-normal components of residual velocities assisted the identification of productive and sustainable offshore AMAs.

The GIS-based model is useful in its identification of areas where the sustainability of AMAs may be maximised, though limited by the fact that it is unable to estimate actual carrying capacities.

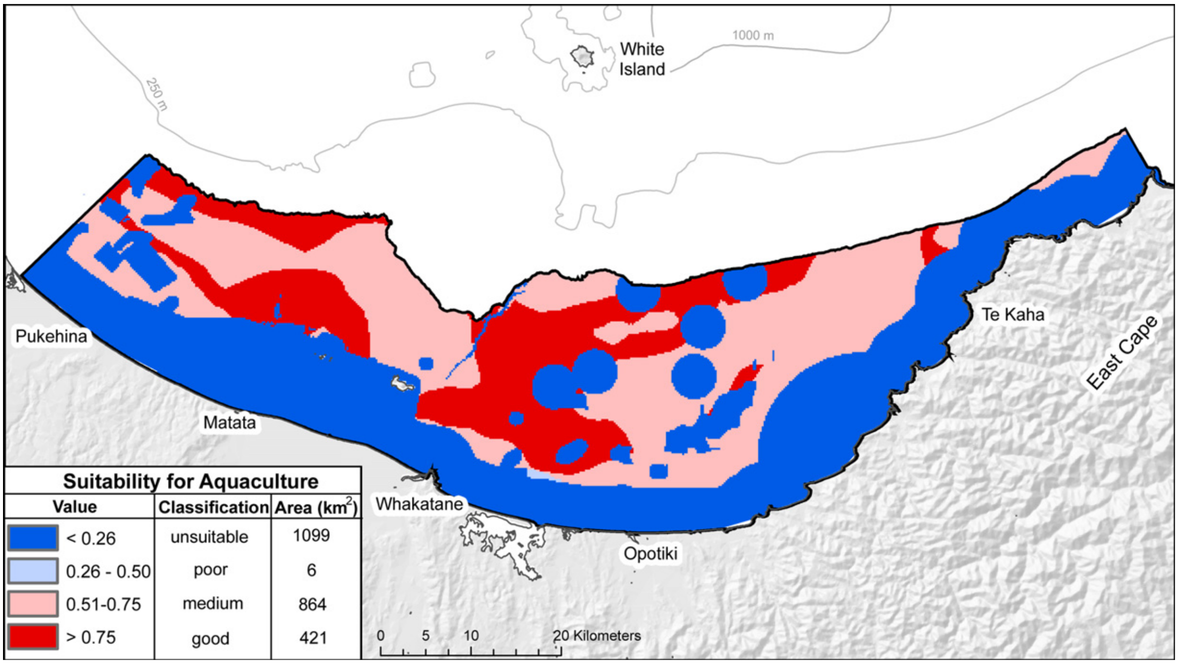

Fig. 9. Suitability index classes for suspended offshore bivalve aquaculture within the Bay of Plenty, New Zealand.

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