Chapter 6
An Integrated GIS Approach for Sustainable Aquaculture Management Area Site Selection

6.1 INTRODUCTION

The aquaculture industry's desire to explore exposed open coast sites, together with recent central government requirements, has created the need for environmental managers to prescriptively zone for aquaculture through the creation of AMAs.

One of the most common reasons for the failure of aquaculture projects and for adverse environmental effects is locating developments on inferior sites (Boyd and Clay, 1998). 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 (Boyd and Schmittou, 1999; McKindsey *et al.*, 2006).

AMAs should be developed within the framework of an integrated coastal zone management framework, whereby any proposed aquaculture plan integrates into an adequate allocation system (GESAMP, 1996). Such a system should enable the selection of the most suitable aquaculture sites based on both environmental and institutional issues (Fridley, 1995), *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.

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 aquaculture operations maximised through rational use of the coastal space (GESAMP, 1996; Nath *et al.*, 2000).

6.2 MOTIVATION AND RELEVANCE TO THESIS OBJECTIVES

The GIS Decision Support System (DSS) approach increases clarity in selecting AMAs by addressing potential conflicts within and between industry, stakeholders, marine environment user groups, and society in general during the early planning stages. The method provides a reliable first indication of locations where sustainable shellfish aquaculture may best be achieved.

Currently, although there are no clear guidelines to follow in undertaking this task within the integrated management process (Pérez *et al.*, 2005), the use of GIS-based models is being recognised as a standard methodology (*e.g.* Nath *et al.*, 2000).

6.2.1 CHAPTER AIMS

This chapter aims to support the coastal zone management decision making process through the rational identification of the most suitable (and unsuitable) sites for sustainable open-coast AMA (*Perna canaliculus*) zoning within the Bay of Plenty, using GIS-based models and related technologies. This chapter puts to use and builds upon the benthic habitat mapping and benthic environment assimilative capacity work performed within chapter 3 by considering additional factors (*e.g.* productivity potential, water column currents) to gain a more complete indication of potential aquaculture sustainability.

The specific definition of 'sustainable aquaculture' has been the subject of some debate, with definitions often being worded such that environmental or social activists can declare unsustainable any development they wish to oppose (Boyd and Schmittou, 1999). To reflect the desire to focus on the aquaculture industry specifically and to maintain the sustainability of both environmental concerns and the economic operation of the industry, the definition of Boyd and Schmittou (1999) is adopted where sustainable aquaculture is defined as that '*where ecologic and economic viability persist indefinitely*'.

The study is, to the author's knowledge, the first of its kind undertaken within New Zealand, and also with specific reference to offshore bivalve aquaculture.

6.3 BACKGROUND

6.3.1 GIS BASED DECISION SUPPORT SYSTEMS IN THE MARINE ENVIRONMENT: APPLICATIONS TO AQUACULTURE PLANNING

Whilst planning is often cited as a priority for aquaculture development (Ross *et al.*, 1993), 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 (Valavanis, 2002). Poor site-selection can result in stressed ecosystems, stressed culture species, decreased production, and inferior economic performance (Preston *et al.*, 1997; Naylor *et al.*, 2000). 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 for both inland pond-based aquaculture (*e.g.* Meaden, 1987; Meaden and Kapetsky, 1991; Kapetsky, 1994; Kapetsky and Nath, 1997; Kapetsky *et al.*, 1988; Kapetsky *et al.*, 1990; Aguilar-Manjarrez and Ross, 1995a,b) and for the near-shore coastal culture of shellfish, shrimp, and fish (*e.g.* Kapetsky *et al.*, 1987; Paw *et al.*, 1992; Ross *et al.*, 1993; Parker *et al.*, 1998; Dubois and Habbane, 2002; Simms, 2002; Zeng *et al.*, 2003; Pérez *et al.*, 2005; Vincenzi *et al.*, 2006; Carrick and Ostendorf, 2007; Rajitha *et al.*, 2007). Study sites have included both developing (*e.g.* Ali *et al.*, 1991; Kapetsky, 1994; Abdus and Ross, 2000) and developed countries (*e.g.* Meaden, 1987; Levings *et al.*, 1995; Preston *et al.*, 1997; Rubec *et al.*, 1998; Arnold *et al.*, 2000). Despite the increasingly frequent applications, specific tools and methodologies for achieving the goals are still under development (Pérez *et al.*, 2003).

In this chapter, 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 (*e.g.* Nath *et al.*, 2000) focuses on specifying, creating, and aggregating comprehensive sets of evaluation criteria which reflect concerns relevant to the decision problem (Pérez *et al.*, 2005). 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 (Pérez *et al.*, 2005). 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), (*e.g.* Aguilar-Manjarrez, 1996; Arnold *et al.*, 2000; Zeng *et al.*, 2003; Vincenzi *et al.*, 2006). In order to define overall suitability, criteria are combined using either additive or multiplicative models, with or without individual weightings in order to define overall suitability.

The reliability of the model output is dependent on the accuracy of source data used (Ross *et al.*, 1993). Verification (ground-truthing) of data sources within such analyses is essential both for quality control of inferred or modelled datasets and also for the general applicability of the final model (Nath et al, 2000; Pérez *et al.*, 2005). 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.* (2000), who provide a comprehensive review of GIS principles and applications specific to aquaculture planning and the marine environment.

6.4 FACTORS INFLUENCING THE SUSTAINABILITY OF OFFSHORE SHELLFISH AQAUCULTURE

The identification of relevant datasets 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 (McKindsey *et al.*, 2006). 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).

6.4.1 ECONOMIC SUSTAINABILITY: FACTORS INFLUENCING THE GROWTH OF CULTURED SHELLFISH

Optimal sites for a sustainable AMA will be characterised by conditions leading to relatively enhanced growth rates. Rapid growth and high quality shellfish are desirable for the economic sustainability of the industry. Optimal sites allow similar economic returns at reduced stocking densities relative to poorer performing sites. Several common datasets 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 temperatures are ~14^{o}C (Longdill *et al.*, 2005b), not sufficiently low to severely restrict *P. canaliculus* growth (Jeffs *et al.*, 1999). 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 (Longdill *et al.*, 2005b) which can inhibit shellfish growth (Jeffs *et al.*, 1999). Consequently, the use of ‘raw’ temperature, salinity, and dissolved oxygen layers (*e.g.* Soniat and Brody, 1988; Levings *et al.*, 1995; Arnold *et al.*, 2000; Dubois and Habbane, 2002; Simms, 2002) 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 (Winter, 1978; Soniat and Ray, 1985). Cultured bivalves rely on natural food sources, which can become a significant constraint on production (Gibbs, 2007). Several studies have identified strong direct linkages ($R^2=0.77$) between upwelling indices and cultured shellfish production and quality (Blanton *et al.*, 1987; Figueiras *et al.*, 2002), 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 (Blanton *et al.*, 1987; Dame and Prins, 1998; Pitcher and Calder, 1998; Figueras *et al.*, 2002). Optimal AMA sites will be characterised by high productivity (Jeffs *et al.*, 1999).

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 (Levings *et al.*, 1995; Dame and Prins, 1998). 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 (Grant and Bacher, 2001). Indeed, amongst mussel aquaculture rafts on the coast of Spain, Navarro *et al.* (1991) 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 (*e.g.* Frechette and Bourget, 1985; Emmerson, 1990; Pérez-Camacho *et al.*, 1995; Strohmeier *et al.*, 2005). 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.

6.4.2 ENVIRONMENTAL SUSTAINABILITY: FACTORS INFLUENCING THE MAGNITUDE OF POTENTIAL IMPACTS FROM CULTURED SHELLFISH

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 (Pearson and Rosenburg, 1978; Dahlback and Gunnarsson, 1981; Grant *et al.*, 1995; Crawford *et al.*, 2003). 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 (Hartstein and Rowden, 2004; Pillay, 2004; Mitchell, 2006). Enhanced current speeds, in addition to affecting the rate of food supply, act beneficially to improve waste dispersal (Pearson and Rosenburg, 1978; Buschmann *et al.*, 1996; Kaiser *et al.*, 1998; Chamberlain *et al.*, 2001; Hartstein and Rowden, 2004; Pillay, 2004; Costa and Nalesso, 2006; Mitchell, 2006). 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 Chapter 3 and Longdill *et al.*, 2007a 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.* SST, 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 datasets.

6.4.3 EXISTING USES / USERS 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 (EBOP, 2006). 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 (EBOP, 2006).

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 avoided to minimise potential conflicts.

6.5 DATA SOURCES EMPLOYED

6.5.1 MARINE PRODUCTIVE REGIONS SUB-MODEL

Productivity ‘hotspots’ in the marine environment can be considered areas of increased sea surface Chl-a concentrations (Espinosa-Carreon *et al.*, 2004; Valavanis *et al.*, 2004), 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 (Agostini and Bakun, 2002). 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 (Chapter 4; Longdill *et al.*, in press).

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 (Li and Shao, 1998; Valavanis *et al.*, 1999; Demarcq and Faure, 2000; Espinosa-Carreon *et al.*, 2004; Valavanis *et al.*, 2004; Takahashi and Kawamura, 2005). The use of climatological (long-term) datasets allows the identification of persistently productive regions, independent of shorter-term variability (Valavanis, 2002).

6.5.1.1 SST ANOMALIES

Remotely sensed SST data, derived from the AVHRR, were obtained at 1 km spatial resolution from NIWA in netCDF format (Rew *et al.*, 2007). The instantaneous SST retrievals in the dataset have a standard deviation error of ~0.6^{o}C and a bias error less than ±0.1^{o}C (Richardson *et al.*, 2005). Climatological (inter-annual) monthly means, produced from monthly composites (1993 – 2004) of these data were processed using a Fourier decomposition method (Uddstrom *et al.*, 1999). Cloud detection algorithms, SST retrieval equations, compositing method and a broad scale validation are detailed in Uddstrom *et al.* (1999). An independent validation of the SST dataset using measured CTD and thermistor data, within the study region, found a correlation R^2 of 0.88 ($P < 0.05$, $n = 149$ at 18 sites) (Chapter 4, Figure 4.3).

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 datasets. 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 dataset.

The climatological monthly mean data can be compared with the corresponding coastal monthly mean value to identify temperature anomalies and areas of persistently higher or lower temperature. 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 (Figure 6.1), i.e:

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

$$A_{SST_{(x,y)}} = \sum_{m=1}^{m=12} A_{SST_{(x,y,m)}} \qquad \textbf{Equation 6.1}$$

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 coastal segment(s).

The determination of SST anomalies via this method differs from that of Hardman-Mountford and McGlade (2003) and Valavanis *et al.* (2004) who calculated anomalies from individual month SSTs rather than from monthly climatological (inter-annual) datasets as used here and also by Shevyrnogov *et al.* (2004). Climatological datasets 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 within the Bay of Plenty (Figure 6.1) 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.

Observed wind driven upwelling dynamics (Chapter 4, Longdill *et al.*, in press) and variability in the coast and shelf orientation can be used to explain the spatial pattern of anomalies within the central Bay of Plenty. The coastline and shelf orientation combines with Ekman dynamics to upwell cool water to the surface, however, as the coastline and shelf orientation is variable, the response is also variable, leading to the observed anomalies.

Observations of topographically induced upwelling close to East Cape have been made by both Garner (1959, 1961) and Heath (1984b). The shelf width at East Cape is very narrow (~2 km) relative to elsewhere within the Bay (~25 km), a key factor in combination with along-shelf currents which can lead to bathymetrically induced upwelling dynamics (Hsueh and O'brien, 1971; Crépon *et al.*, 1984; Oke and Middleton 2000).

No explanation can be offered for those anomalies identified to the north east of Coromandel Peninsula without additional locally specific data. A strong positive temperature anomaly exists in the nearshore regions of the eastern Bay of Plenty (Opotiki – Te Kaha), in a similar location to where a persistent 'tongue' of warm water was identified during summer from the monthly mean SST data (Section 4.5.1 and Figure 4.9).

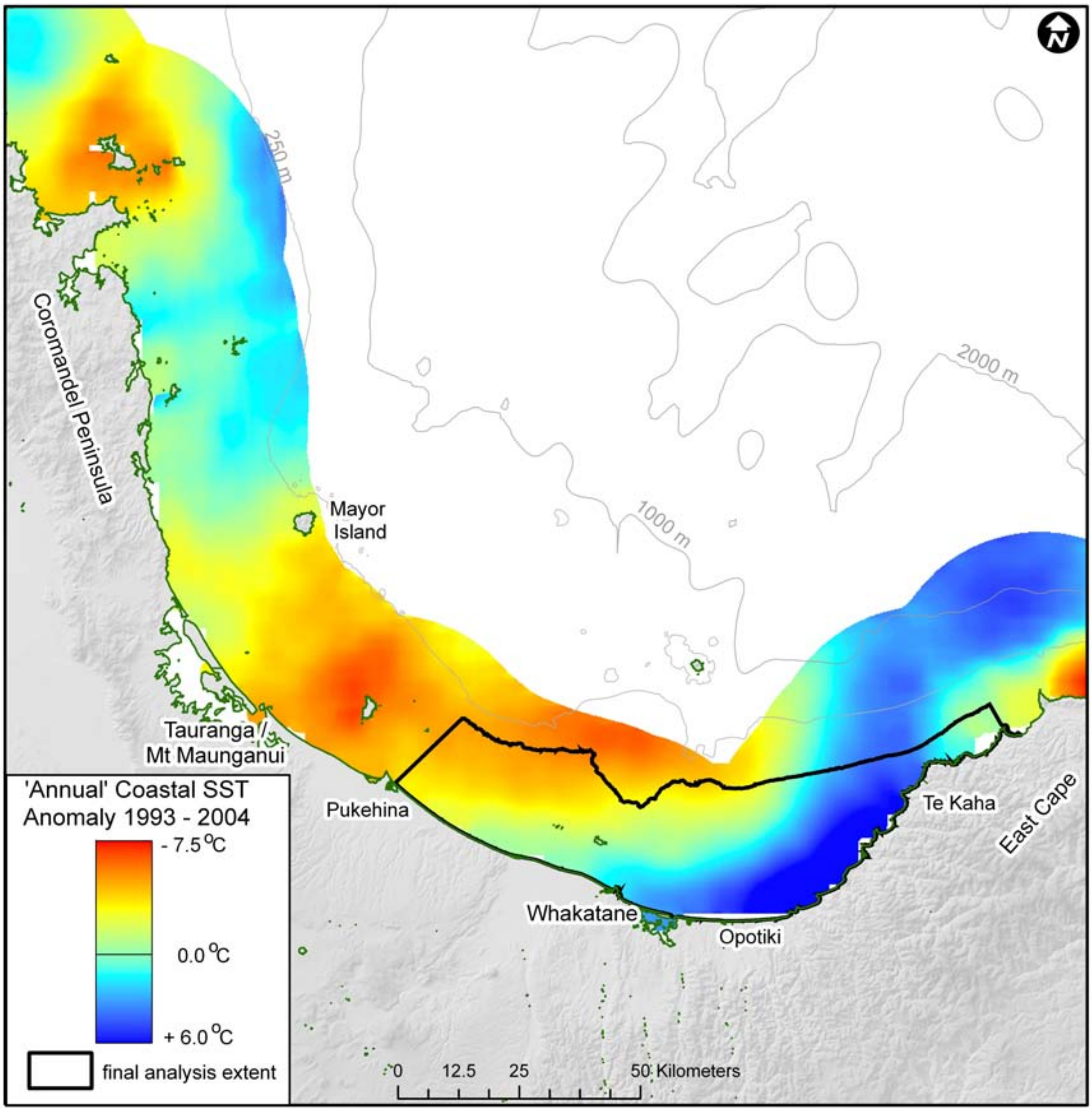

Figure 6.1 Coastal climatologlical SST anomaly in the Bay of Plenty from 1993 to 2004 (to 30 km offshore). A negative anomaly indicates lower than typical (for the coastal segment) sea surface temperatures. Effects due to persistent cross-shore temperature gradients have been removed. Colour scale is set to allow comparisons to CHL-a anomaly and best identify marine productive regions. Original AVHRR data sourced from National Institute of Water and Atmospheric Research Ltd (NZ).

6.5.1.2 CHL-A ANOMALIES

Remotely sensed climatological monthly mean Chl-a data (1997-2004), derived from SeaWiFS were obtained at both 4 km and 1 km resolutions from NIWA in netCDF file format (Rew *et al.*, 2007). Case 2 Chl-a products were generated using the NIWA IOP algorithm to iteratively solve a set of non-linear equations in order to both correct for non-phytoplanktonic sediment concentrations and to retrieve IOP from corrected water leaving radiances (Richardson, 2005).

Though Pinkerton *et al.* (2005) conclude that these data (and their associated error, ± 35%, Lavender *et al.*, 2004) '*do not differ at the 95% confidence level*' from in-situ measurements; an independent validation of the dataset highlighted several weaknesses in these data (Figure 4.4). 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 (Chapter 4). 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 datasets available for the region. Though smaller scale close nearshore trends and details (<1 km^2) may not be well represented (Section 4.46) it is believed these data do reflect the general trends in Chl-a distribution (Pinkerton *et al.*, 2005).

Long term (1997 – 2004) coastal Chl-a anomalies (Figure 6.2) within the Bay of Plenty were generated in an identical manner to that of SST.

Chl-a anomalies within the Bay of Plenty (Figure 6.2) indicate a relatively highly productive region between Pukehina and Whakatane. The location of this more productive region is consistent with a variable along-shelf upwelling response and the along-shelf transport to the east of upwelled material from near Pukehina (Chapter 4 and Longdill *et al.*, in press).

Notably a less productive region is indicated along the shoreline of East Cape and there is no indication of an increase in relative productivity resulting from the cool upwelled water present here (Figure 6.1). This can be explained by the relatively rapid transportation of the upwelled water to the east and south around East Cape by the ECC (Stanton *et al.*, 1997; Tilburg *et al.*, 2001) along with the lag times required for phytoplankton to bloom following the upwelling of high nutrient water (Barber and Smith, 1981; Mann and Lazier, 1996; Chang *et al.*, 2003). Indeed, farther along the ECC (and beyond the extent of the current data), a region of persistently elevated Chl-a concentration has been observed (Bradford *et al.*, 1982; Murphy *et al.*, 2001).

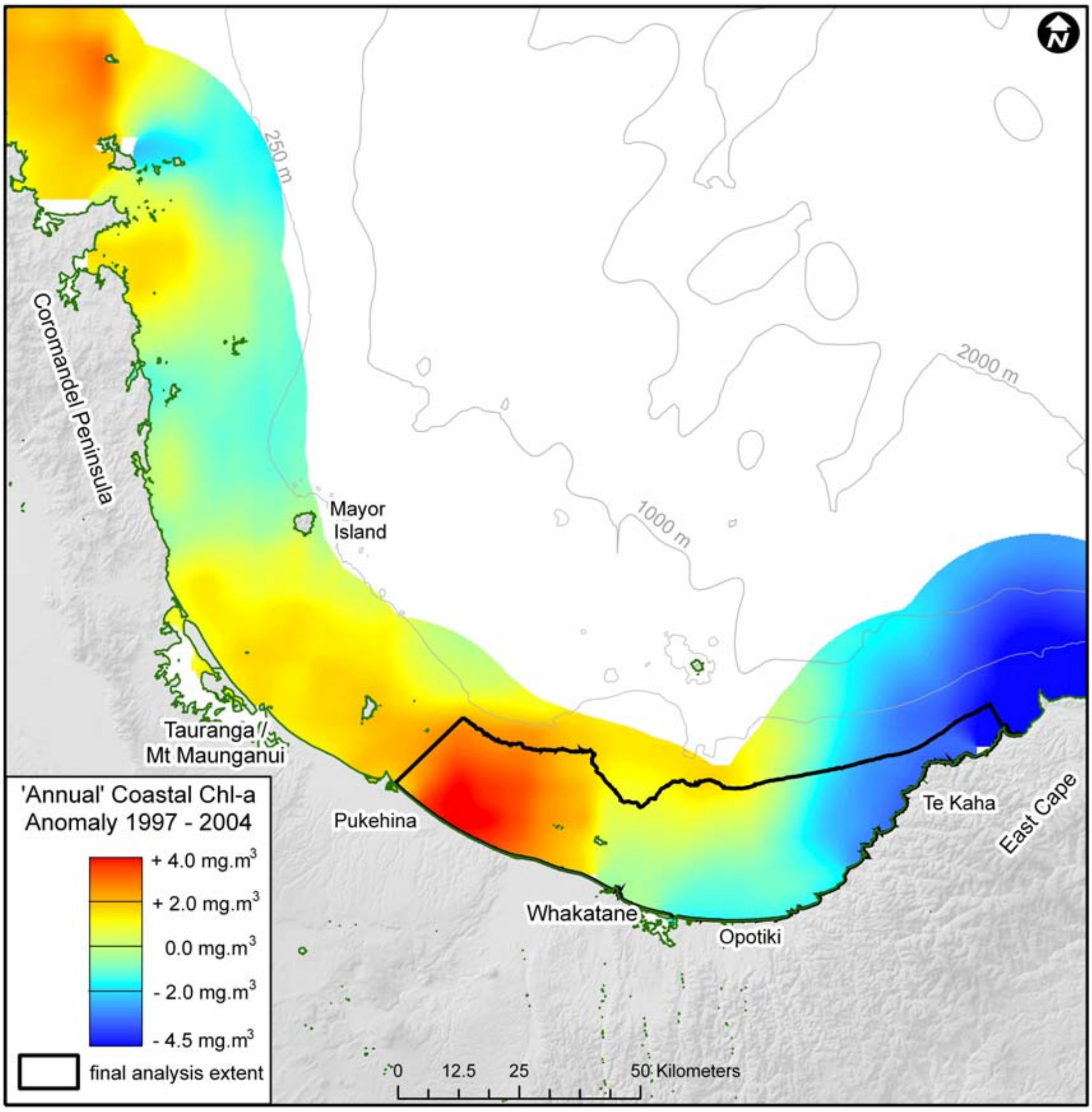

Figure 6.2 Coastal climatological case-2 Chl-a anomaly in the Bay of Plenty from 1997 to 2004 (to 30 km offshore). A negative anomaly indicates lower than typical (for the coastal segment) Chl-a concentrations. Original SeaWiFS data and locally calibrated Inherent Optical Properties (IOP) algorithm sourced from National Institute of Water and Atmospheric Research Ltd (NZ).

6.5.1.3 MARINE PRODUCTIVE REGIONS

Normalised (0-1) climatological SST and Chl-a anomalies were multiplied together (unweighted) to identify regions with persistently low SST and high Chl-a (Figure 6.3). Combined normalised anomalies (Figure 6.3) suggest that the most productive coastal regions within the Bay of Plenty are centrally located between Mt Maunganui and Whakatane. Relative productivity is lowest near the coast in the eastern Bay of Plenty, near Te Kaha. The results suggest that, in light of the relationships between cultured shellfish production and quality and upwelling indices (Blanton *et al.*, 1987; Figueiras *et al.*, 2002), cultured bivalve growth may be best offshore from Pukehina.

It is worthwhile noting the apparent eastward shift of the water mass; in Figure 6.1, the coolest water, indicative of the most persistent upwelling, occurs on the shelf between Tauranga and Pukehina. In the SeaWifFS imagery (Figure 6.2), the peak

Chl-a is observed to the east of Pukehina which is consistent with the prevailing along-shelf (eastwards) transport of upwelled nutrients.

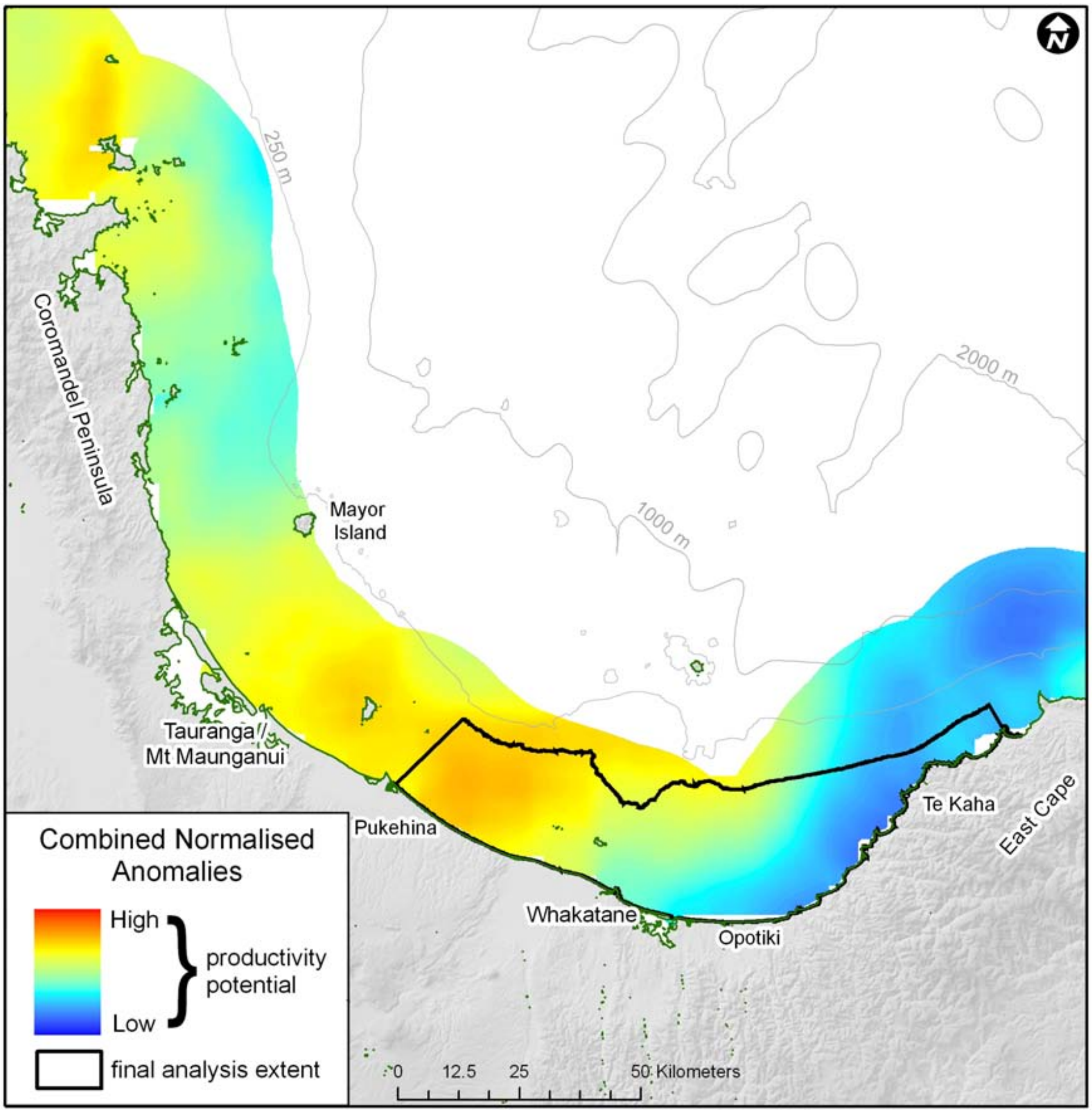

Figure 6.3 Spatially integrated combined normalised anomalies in SST (1993-2004) and Chl-a (1997-2004) used as an indication of the relative productivity potential of coastal areas within the Bay of Plenty, New Zealand. A high value indicates persistently lower than typical SSTs and higher than typical Chl-a concentration, indicative of a productive area.

6.5.2 CURRENT SPEEDS

Wind and tidally forced current speeds throughout the Bay of Plenty were determined from a 3-dimensinal baroclinic numerical hydrodynamic model (3DD; Black, 1995) of the shelf environment. The model was calibrated against measured sea levels and current components (R=0.82 and ≈0.74 respectively, $P < 0.05$, $n = 1699$ hrs) to ensure replication accuracy (Chapter 5).

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 x 3 km grid). Mean flow speeds ($\overline{S}_{(x,y,z)}$) can be defined by,

$$\overline{S}_{(x,y,z)} = \frac{\sum_{t=0}^{T} \left| S_{(x,y,z,t)} \right|}{n}$$ **Equation 6.2**

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; Thomson, 1996) are utilised for the zoning analysis (Figure 6.4).

Some generic guidelines for water speeds required for sustainable mussel (*Perna canaliculus*) aquaculture have been suggested previously for the purposes of prescriptive zoning (Table 6.1). These velocities, proposed by Inglis *et al.* (2000), represent 'typical speeds' rather than long-term averages, which maybe 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, Chapter 4), due to the action of tides and/or variable wind stress, 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 cms^{-1} in the along-shelf direction (Figure 4.20) during the 70 day deployment, yet the yearly mean speed at the same site is 7.5 cms^{-1}. To represent and account for these differences, the guidelines of Inglis *et al.* (2000) have been decreased by 50% (Table 6.1).

Table 6.1 Generic guidelines for water speed for sustainable mussel culture, modified from Inglis *et al.* (2000).

'Typical' water speed (cms^{-1})	**Year long mean speed (cms^{-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

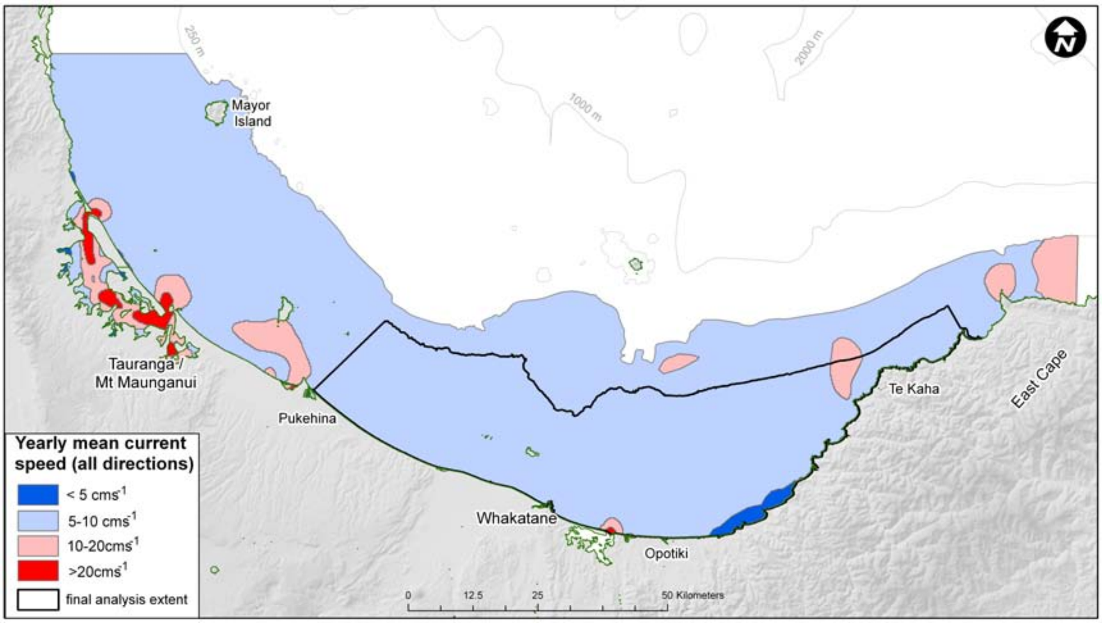

Figure 6.4 Year-long mean shelf current speeds at 5-25 m depths between the shoreline and the 250 m contour from calibrated numerical hydrodynamic models forced by winds and tides. Mean speeds determined by averaging current speeds (scalar) from throughout the simulations.

6.5.3 CURRENT DIRECTIONS: THE BENEFITS OF OFFSHORE TRANSMISSION

It can be viewed as beneficial for water, once it has travelled through the mussel farm and is likely depleted in nutrients and phytoplankton, to be transmitted offshore rather than toward the coast.

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:

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

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

Equation 6.3

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 relatively 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 (Figure 6.5).

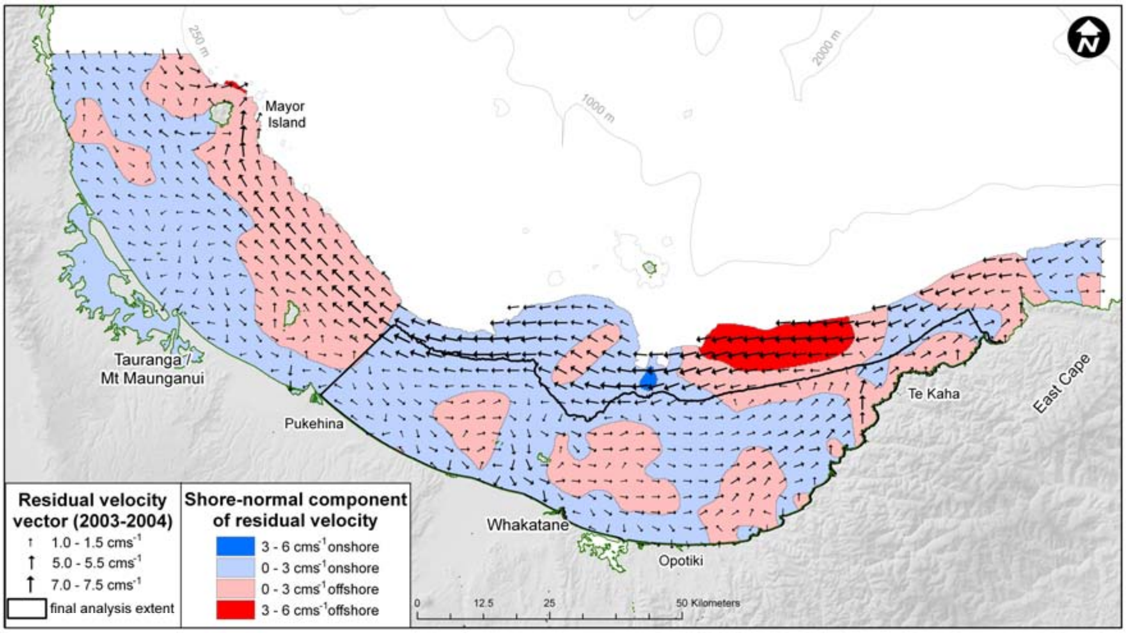

Figure 6.5 Residual shelf velocities (2003-2004) at 5-25 m depths between the shoreline and the 250 m contour from a calibrated numerical hydrodynamic model. Residuals determined by vector averaging current components from throughout the simulation.

6.5.4 BENTHIC ENVIRONMENT SUB-MODEL

A benthic suitability index for aquaculture within the Bay of Plenty has been developed previously (Chapter 3, Longdill *et al.*, 2007a, Figure 6.6). 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 their influence on the benthic assimilative capacity with respect to the potential inputs from suspended shellfish aquaculture (Chapter 3 and Longdill *et al.*, 2007a).

The index is directly incorporated as a layer in the GIS MCE model to assist in the identification of sustainable AMAs within the Bay of Plenty (Table 6.2).

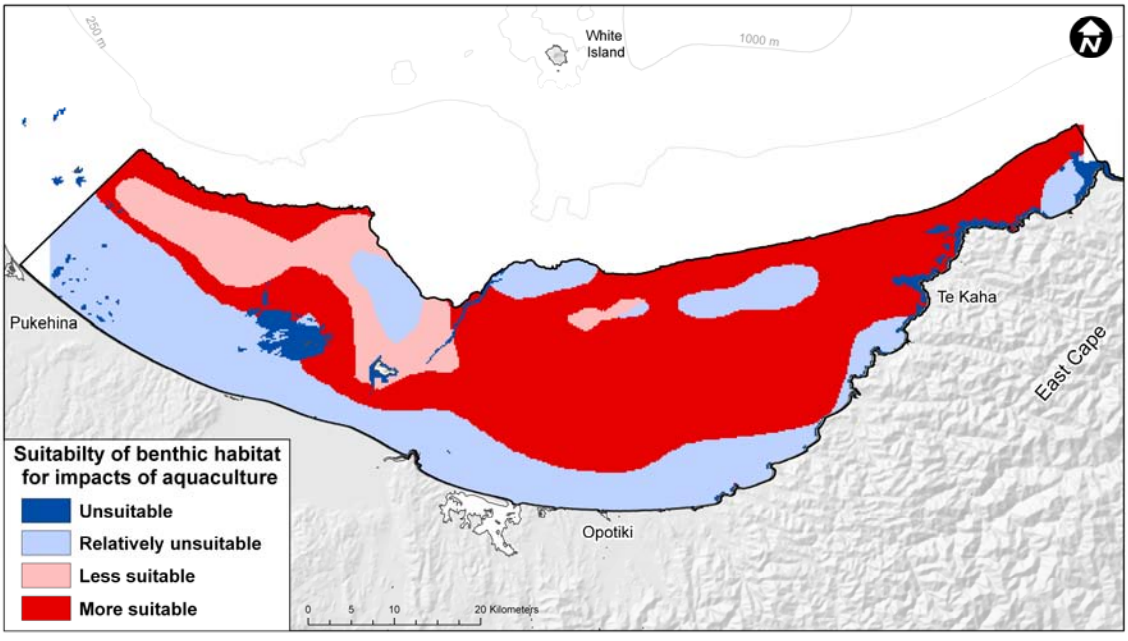

Figure 6.6 Assessed suitability of benthic habitats within the Bay of Plenty to be sited beneath suspended bivalve aquaculture (from Chapter 3 and Longdill *et al.*, 2007a).

6.5.5 AQUACULTURE DEVELOPMENT CONSTRAINTS AND CONFLICTING USES/USERS

6.5.5.1 ASSESSING COMMERCIAL FISHING EFFORT

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

(EBOP, 2006).

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 dataset, with units of visits/year, for each method. Areas of high effort (> 50% of maximal) were identified for each fishing technique and mapped as constraints (Figure 6.7). Highest efforts were in the range of 40-50 visits per year, in water of 30-50 m depth near Opotiki.

Additionally, though no detailed data is available, the locations of significant commercial scallop dredging has been identified (EBOP, 2006), and are also incorporated into the commercial fishing effort constraint layer (Figure 6.7).

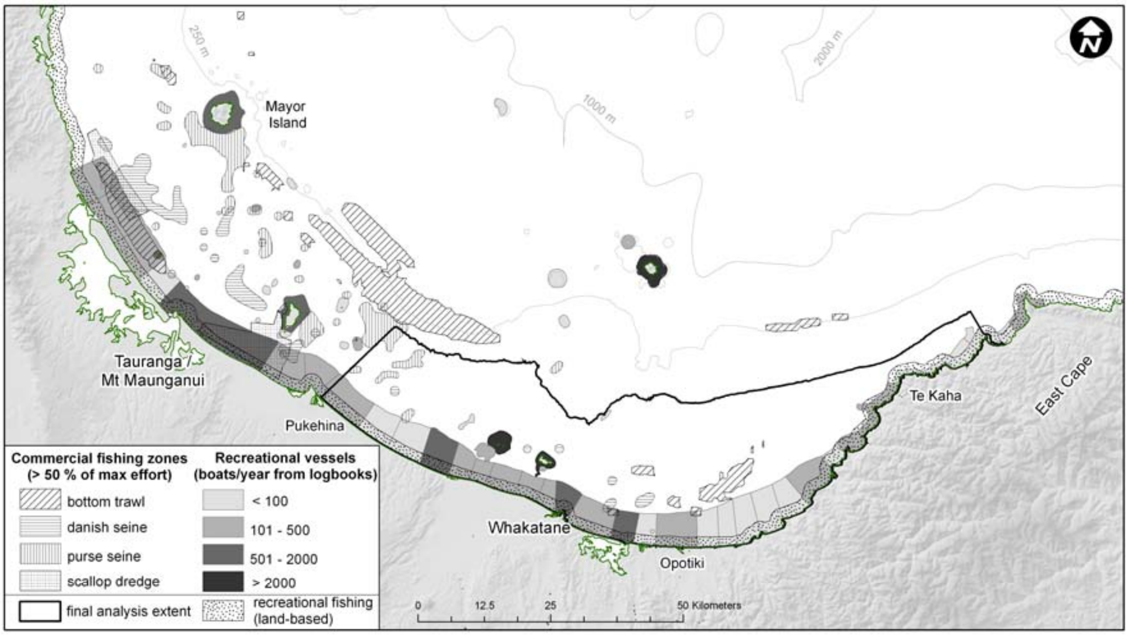

Figure 6.7 Commercial fishing hotspots and recreational fishing density within the Bay of Plenty.

6.5.5.2 RECREATIONAL FISHING AND MARINE USE

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 (EBOP, 2006).

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 (Figure 6.7). Logged visit data were summed within each location.

Despite the limitations of the dataset (*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 dataset 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 (Figure 6.7).

6.5.5.3 CONSTRAINTS

Conflicting uses and constraints to AMA zoning have been identified and data on their spatial extents obtained from a variety of sources (Table 6.2). 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 6.2 and Figure 6.8).

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 6.2 Sources, requirements, values, and Parameter-Specific Suitability Functions (PSSFs) of datasets used in the suitability analysis of the Bay of Plenty region for AMAs.

Dataset	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 • Sediment organic contents • In-faunal and epi-faunal organism counts • Underwater videography / photography • Multi-beam bathymetric surveys • Assessment of potential impacts of aquaculture on identified habitats	Unsuitable	0	Chapter 3 and Longdill *et al.* (2007a)
		Relatively unsuitable	0.33	
		Less suitable	0.67	
		More suitable	1	
Mean flow speeds (10-25 m depth)	• Calibrated 3-d numerical hydrodynamic model run over an extended time period	>2.5 cms^{-1}	0	Chapter 5 (HD model) and Inglis *et al.* (2000) (class. scheme)
		2.5-5 cms^{-1}	0.33	
		5-10 cms^{-1}	0.67	
		<10 cms^{-1}	1	
Residual current direction (onshore-offshore component)	• Calibrated 3-d numerical hydrodynamic model run over an extended time period • Buffered and split coastline orientations extending over study region	>3 cms^{-1} onshore	0.33	Chapter 5 (HD model)
		0-3 cms^{-1} onshore	0.5	
		0-3 cms^{-1} offshore	0.67	
		>3 cms^{-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 • Scallop dredging zones	effort > 50% maximal	0	Ministry of Fisheries data
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	Maritime New Zealand (2006)
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	• 5 km 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 (2005)
Significant sites	• Cultural sites, *e.g.* Customary fishing sites, sites of local significance • Ecological sites, *e.g.* migratory bird nesting areas, habitat of endangered species • Other sites *e.g.* special geologic sites, historical features, marine mammal habitats	n/a	0	consultation with tangata whenua (indigenous tribes) and regional council coastal plan
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

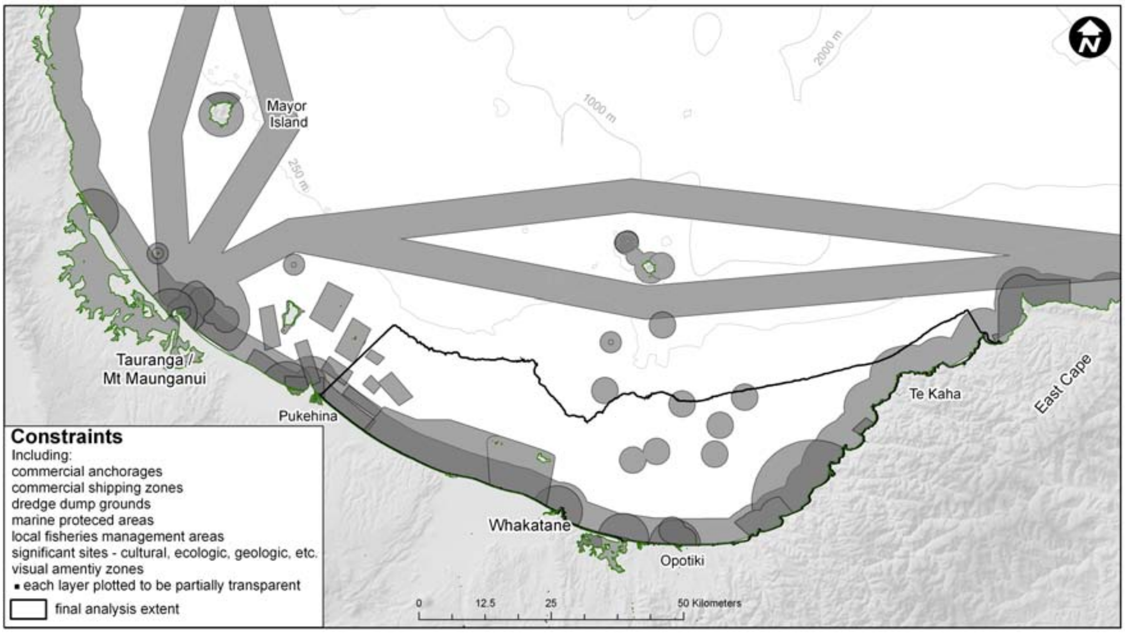

Figure 6.8 Constraints to the zoning of AMAs within the Bay of Plenty shelf. See Table 6.2 for sources of datasets used as constraints.

6.5.6 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 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.

6.6 ANALYTIC FRAMEWORK: A GIS BASED MODEL TO DETERMINE SUITABILITY

6.6.1 PARAMETER-SPECIFIC SUITABILITY FUNCTIONS (PSSFS)

Combining selected datasets using MCE techniques requires that each parameter be transformed to comparable and consistent units. 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 (Aguilar-Manjarrez, 1996; Arnold *et al.*, 2000; Zeng *et al.*, 2003; Vincenzi *et al.*, 2006). 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 (*e.g.* Zeng *et al.*, 2003; Vicenzi *et al.*, 2006), functions are assigned based on a combination of species specific research, those applied by other researchers, and expert opinion (Table 6.2). 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 datasets.

6.6.2 SUITABILITY INDEX MODEL

MCE techniques are used to aggregate contributing factors (Figure 6.9a) into a spatially variable (*x* and *y* co-ordinates belonging to the study region) Suitability Index ($SI_{(x,y)}$), 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:

$$SI_{(x,y)} = \left(\prod_{i=1}^{5} PSSF_{(x,y,i)} \right)^{\frac{1}{\sum i=1,\ldots 5}} \text{ where } C_{(x,y)} = 1\text{, and}$$

Equation 6.4

$$SI_{(x,y)} = 0 \text{ where } C_{(x,y)} = 0$$

where $PSSF_{(x,y,i)}$ is the spatially variable parameter (co-ordinates *x* and *y*) modified by its Parameter-Specific Suitability Function into suitability levels (Table 6.2); *i*=1,..5 is an index identifying the 5 corresponding input parameters (Table 6.2); and $C_{(x,y)}$ is the spatially variable constraints layer (Figure 6.7). $SI_{(x,y)}$ is bounded between 0 and 1.

A weighted geometric mean can also be applied (Vincenzi *et al.*, 2006), where each parameter is assigned a 'weight' to indicate relative importance, often determined subjectively by 'experts'. However, Aguilar-Manjarez (1996) 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 (Levings *et al.*, 1995; Nath *et al.*, 2000). As a result, 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 ($PSSF_{(x,y)} = 0$), the overall suitability index ($SI_{(x,y)}$) is 0 regardless of the $PSSF_{(x,y)}$ value for other parameters (Soniat and Brody, 1988; Vincenzi *et al.*, 2006). This provides a distinct advantage over additive type models (Dubois and Habbane, 2002; Pérez *et al.*, 2005) 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; Figure 6.9b). The structure of class definitions and labels (Figure 6.9b) are consistent with those applied elsewhere (*e.g.* Cross and Kingzett, 1992; Pérez *et al.*, 2005).

The spatial extent of the final output suitability index is limited by the least extensive dataset, 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.

6.7 SUITABILITY FOR OFFSHORE SHELLFISH AQUACULTURE

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 60 and 80 m depths offshore from Whakatane and Matata (Figure 6.9). 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 (Figure 6.9). 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.

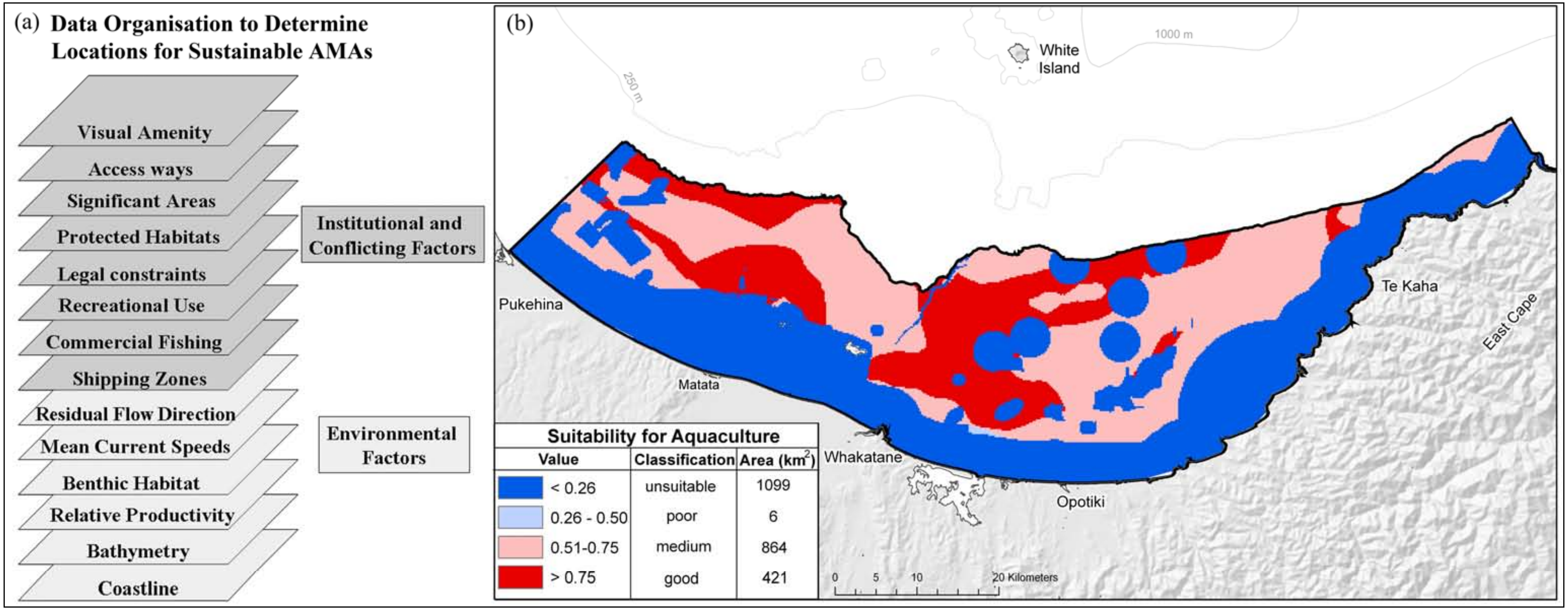

Figure 6.9 Data layers and organisational structure (a) to determine locations for sustainable AMAs and (b) output suitability index classes for suspended offshore bivalve aquaculture within the Bay of Plenty, New Zealand.

6.8 DISCUSSION

This chapter has focussed on the identification of the most suitable and sustainable locations for allocating 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.

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

SST anomalies within the Bay of Plenty are consistent with observed wind driven upwelling dynamics (Chapter 4, Longdill *et al.*, in press) and variability in the coast and shelf orientation. The coastal regions of the Bay of Plenty are variable in their potential marine productivity, with near-shore areas off Pukehina being highest, and those to the East and off Te Kaha being the least. In general, the Bay of Plenty region offers relatively suitable conditions for aquaculture development. However, consistent with other regions worldwide (*e.g.* Ross *et al.*, 1993; Abdus and Ross, 2000; Pérez *et al.*, 2005), existing users and uses of the coastal environment can 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' datasets (*e.g.* constraint layers, benthic environments, current speeds) and also introduced several novel datasets to aquaculture planning analyses. The identification of long-term SST and Chl-a anomalies using GIS principles, though relatively common as a study by itself (*e.g.* Li and Shao, 1998; Valavanis *et al.*, 1999; Demarcq and Faure, 2000; Espinosa-Carreon *et al.*, 2004; Valavanis *et al.*, 2004; Takahashi and Kawamura, 2005), has not previously been applied to aquaculture site selection (to the author's 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 <u>does not</u> imply actual estimates of carrying capacity (either physical, production, ecological, or social) within the region, but rather assists the identification of 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

(Pérez *et al.*, 2005). 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 present chapter, 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 datasets. Though 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 (Boyd and Schittou, 1999). There are no standardised sets of suitability or sustainability indicators for coastal aquaculture, although there is a clear need for their establishment and implementation (Frankic and Hershner, 2003). Currently, improvements are being made in this regard (*e.g.* Gibbs, 2007), 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 dataset, 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 (Pérez *et al.*, 2003). Their use in aquaculture site selection supports and assists the decision making process.

6.9 SUMMARY

Numerous factors may influence the environmental sustainability of an aquaculture development within the Bay of Plenty, including:

- relative productivity;
- current speeds;
- current directions;
- the assimilative capacity of the benthic environment to waste material;
- the numerous other uses and users of the BOP region; and
- cultural and social values relating to the area;

SST and Chl-a anomalies indicate that optimal food sources for cultured mussels are located on the shelf offshore from Pukehina. From a coastal ecological impact perspective, open coast aquaculture is preferentially sited where mean water currents are moderate and persistently directed away from the coast. Such locations are found in deep water between Mayor Island and Pukehina and also within mid-shelf cells between Pukehina and Te Kaha.

In general, the Bay of Plenty offers suitable and productive regions for environmentally sustainable aquaculture development. Eighteen percent (421 km^2) of the area surveyed was determined, using a rule based hierarchical scheme, to be the most suitable to locate a sustainable aquaculture operation. These areas were located on the shelf at depths of 60-80 m and offshore from Whakatane and Matata. The high use of the coastal marine area, however, restricts the zoning of AMAs. The areas identified as most suitable for sustainable AMAs represent initial areas to be considered by both environmental managers and industry.

As demonstrated in this research project GIS-based models can be used in the first instance to effectively and efficiently manage and manipulate the wide variety of datasets required for initial planning analyses to determine suitable and sustainable locations for offshore AMAs. A weakness of the method is that further development-specific studies are required to allow a quantitative assessment of the carrying capacity and specific sustainability of individual and collective farm developments.

The limitations of the applied GIS approach with respect to providing quantitative sustainability or carrying capacity estimates means alternate techniques must be used to more comprehensively consider aquaculture potential. The obvious way forward is the application of a model of ecosystem behaviour which can be used to quantitatively predict ecosystem level changes resulting from aquaculture development.