
Chapter 2

Aquaculture and the Bay of Plenty Region: A General Background

2.1 INTRODUCTION

In investigating the prospects for environmentally sustainable offshore aquaculture within the Bay of Plenty, and to begin addressing the objectives set out within Chapter 1, it is prudent to first cover the generalities of international and national (New Zealand) aquaculture, the environmental issues surrounding it, and the Bay of Plenty region. As such, this chapter aims to provide the reader with a broad background, and an informed initial viewpoint relating to the subjects dealt with within this thesis, including:

- the New Zealand greenshell mussel industry;
- legislative issues relevant to their culture;
- mussel feeding behaviour and ecology;
- cultivation systems used to date within New Zealand;
- environmental issues associated with their culture;
- the potential for, and determination of, a sustainable aquaculture industry; and
- the Bay of Plenty shelf environment oceanography.

2.2 AQUACULTURE: NARROWING THE FOCUS

Globally, aquaculture is a diverse industry encompassing marine finfish cage culture, freshwater finfish culture, shellfish cultivation, warm water culture in ponds and lagoons, along with tank and recirculating systems. Each method employs different species and cultivation techniques, leading to variable pressures and demands on the specific local environment. Since the early 1980s the domestic share of the greenshell mussel (also known as green-lipped, *Perna canaliculus*) industry have increased significantly (Ministry of Economic Development, 2007). Presently, within New Zealand, the aquaculture industry comprises greenshell mussels (64%), king salmon (27%), and pacific oysters (9%) (Ministry of Economic Development, 2007). Reflecting this dominance and importance, and also due to the specific interest shown within the Bay of Plenty, this thesis is concerned only with greenshell mussel aquaculture.

2.3 MUSSEL AQUACULTURE WITHIN NEW ZEALAND

2.3.1 THE BAY OF PLENTY EXPERIENCE

Within the Bay of Plenty marine area, aquaculture development has been somewhat typical of the general New Zealand situation. Currently there are three small (~2 ha) oyster farms established within the sheltered waters of Ohiwa Harbour. In November 2001 two applications were received by the regional council for open coast greenshell mussel farms of 4750 ha and 4009 ha offshore from Opotiki and Pukehina respectively (pers. comm. EBOP, Eastern Mussel Farms). These proposals were put on hold to allow the potential environmental impacts to be assessed. This thesis has been stimulated by these proposals, and aims to contribute to the understanding of their potential impacts.

2.3.2 LEGISLATIVE REQUIREMENTS: THE AQUACULTURE LAW REFORM

Following the remarkable increase in interest in open coast aquaculture development, the novelty of development within these sites in New Zealand waters, the large scale of the proposals, and the inability of the existing legislation (the Resource Management Act) to provide guidance, the New Zealand government placed a moratorium on new aquaculture development in late 2001 (Ministry for the Environment, 2003; New Zealand Government, 2004). This moratorium expired in December 2004.

The purpose of the moratorium was to allow central government time to develop and pass the Aquaculture Reform bill. A secondary benefit of the moratorium was the provision of time to investigate the proposals, the potential effects from development on such large scales, the suitability of open coast regions for aquaculture, any potential cumulative effects from aquaculture development, and to zone for sustainable aquaculture development through the creation of Aquaculture Management Areas (AMAs).

The completed law aims to “*enable the sustainable growth of aquaculture and to ensure the cumulative environmental effects are properly managed*” (New Zealand Government, 2004). The law places the requirement for ensuring the suitability and sustainability of operations on regional councils, the environmental management organisations within New Zealand. The law stipulates that aquaculture can only take place in designated AMAs, and that councils are required to prescriptively zone for these areas and then assess the impacts of any aquaculture proposals within them.

2.3.3 GREENSHELL MUSSELS

Greenshell mussels are an endemic New Zealand bivalve shellfish species. Initially identified as a member of the *Mytilus* genus (Gmelin, 1791 in Siddal, 1980), the species was more recently incorporated within the *Perna* genus based on hinge and ligament structures (Fleming, 1959).

The mussels are predominantly sub-tidal, growing to depths of ~50 m in a variety of habitats, ranging from solid substrates and algal holdfasts to clusters on sandy and muddy bottoms (Morton and Miller, 1973; Jeffs *et al.*, 1999). Whilst the mussels can tolerate aerial exposure, mussel condition indices reduce with increasing exposure (Hickman and Illingworth, 1980; Vakily, 1989; Jeffs *et al.*, 1999). They can also survive a wide range of temperature (5 – 27°C) and salinity (25-35 ppt) variation (Hickman, 1991; Jeffs *et al.*, 1999).

Greenshell mussels are filter feeders, extracting phytoplankton and other organic and non-organic material suspended in the water column. Mucus within the gills binds the particles for ingestion, those not suitable are expelled as mucus-bound pseudofaeces deposits (Alfaro *et al.*, 2001; Loyd, 2003). Suitable food particles are digested and excreted as faeces.

Growth rates of greenshell mussels are highly variable and are generally associated with variability in phytoplankton supply and water temperature (Jeffs *et al.*, 1999). Fully grown mussels can grow at a rate of 50 mm per year (shell length), and may reach over 240 mm once fully grown (Stead, 1971; Flaws, 1975). Individual adult mussels are capable of filtering water at rates of 350 L/day (James and Ross, 1996).

2.4 CULTIVATION SYSTEMS: HOW IT WORKS

Greenshell mussel culture within New Zealand has traditionally been undertaken using a modified Japanese long-line technique (Figure 2.1). Early efforts using a Spanish raft type technique were unsuccessful due to the instability of the rafts (Jeffs *et al.*, 1999). A typical 3 ha long-line farm comprises a series of ‘backbones’, often running shore parallel, supported by 30-40 plastic buoys over distances of ~100 m. Mussels are grown on droppers, suspended from the backbone, at densities of ~200 m⁻¹ and harvested after approximately 13 months when they reach ~80 mm in size (Hayden, 1995; Thomson, 1996; Jeffs *et al.*, 1999; Spencer, 2002; Mussel Industry Council, 2005).

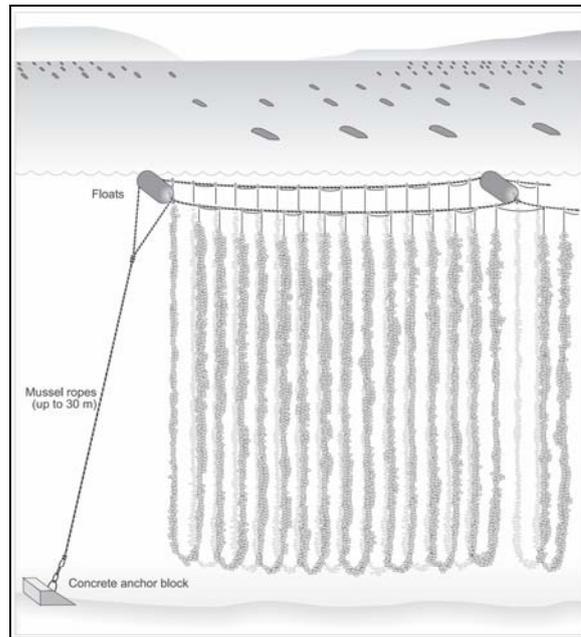


Figure 2.1 Diagram of typical New Zealand mussel farm found in sheltered water ways with surface floats and continuous mussel droppers suspended from ‘backbone’ ropes (source, Loyd, 2003).

Recent technologies have led to a system capable of culturing mussels in more exposed open coast locations (e.g. Thomson, 1996; Figure 2.2). Rather than being suspended from the surface, mussels are grown on dropper lines suspended from backbones which themselves are submerged below the surface (Figure 2.2). By submerging the structure the physical stresses from surface waves are reduced (Thomson, 1996; Hampson *et al.*, 1999). Such structures and technologies have stimulated interest in open coast aquaculture surrounding New Zealand, including that within the Bay of Plenty.

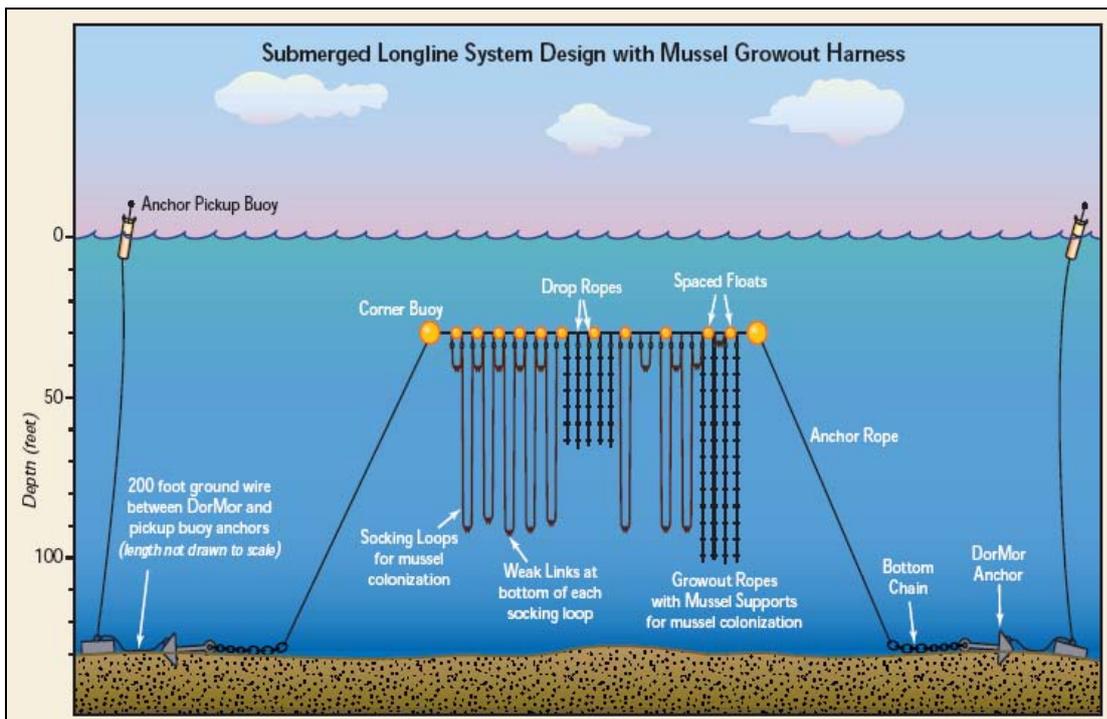


Figure 2.2 Suspended cultivation system used in open coast aquaculture. (source: Hampson *et al.* 1999).

Bivalve culture, unlike most finfish aquaculture, does not require the addition of artificial feeds or stimulants to the marine environment (Kaiser, 2001; Pillay, 2004). Recent research, however, has suggested that in some sheltered environments, productivity gains may be achieved by artificially increasing water column nitrogen concentrations (Ogilvie *et al.*, 2000), though this has not progressed further than the conceptual phase and is not common place.

2.5 AQUACULTURE: THE ENVIRONMENTAL ISSUES

Aquaculture modifies its receiving environment. The potential impacts from aquaculture can be divided into those of an ecologic, physical, social, and economic nature (*e.g.* Burbridge *et al.*, 2001; Kaiser, 2001; Plew *et al.*, 2005). In this section a summary highlighting those environmental issues of relevance to a planning study is provided. A more in-depth analysis of selected issues is covered in the following chapters.

Effects on Planktonic Communities

Mussels are filter feeders and gain their energy requirements by filtering phytoplankton from the water column. The filtering action of dense bivalve populations effectively diverts primary production energy from pelagic areas towards benthic food webs.

High densities of mussels can cause localised phytoplankton depletion due to the large amount of water being filtered (*e.g.* Inglis *et al.*, 2000; Grant and Bacher, 2001; Broekhuizen *et al.*, 2002; Gibbs, 2007). The exact nature of the depletion is dependent on a number of influences, including farm size, crop density, water depth, currents, productivity, and season (*e.g.* Grant and Bacher, 2001; Broekhuizen *et al.*, 2002). Reductions of up to 60% may occur within farm boundaries (Waite, 1989), and a 50 ha farm may consume >20% of all phytoplankton passing through it (Broekhuizen *et al.*, 2002). Additionally, decreases in zooplankton abundances are possible either directly by mussel filtering and subsequent excretion as pseudofaeces, or indirectly as a result of phytoplankton depletion (Davenport *et al.*, 2000).

Extensive mussel cultivation may induce complex changes in phytoplankton community structure (Broekhuizen *et al.*, 2002); an increased dominance by fast growing phytoplankton species is possible, fuelled by ammonia excreted by the cultured mussels (Kaiser *et al.*, 1998). However, despite these possibilities, little research has focussed on such changes to pelagic food webs (Cole, 2002).

Benthic Effects and Nutrient Cycling

Mussel farms can modify the benthic environment through the settling of live mussels, broken shells, farm debris, faeces and pseudofaeces on the seabed (Pearson and Rosenberg, 1978; Dahlback and Gunnarsson, 1981; Kaspar *et al.*, 1985; Stenton-Dozey *et al.*, 1999). The relative impacts of these inputs can be influenced by the size

and age of the farm, stocking densities, water depth, and the local current regime (Chamberlain *et al.*, 2001; Crawford *et al.*, 2003; Hartstein and Rowden, 2004; Mallet *et al.*, 2006; Mitchell, 2006).

The settling of faeces and pseudofaeces beneath mussel farms leads to the organic enrichment of sediments (Kaspar *et al.*, 1985; Kaiser *et al.*, 1998). This enrichment can affect benthic nutrient cycling and in some situations lead to the build up of acidic conditions and anaerobic sediment layers (Dahlback and Gunnarsson, 1981; Tenore *et al.*, 1982; Grant *et al.*, 1995). In extreme cases, organic sedimentation rates of $2.4\text{-}3.1\text{ gCm}^{-2}\text{day}^{-1}$ have been observed beneath mussel farms (Dahlback and Gunnarsson, 1981; Mattson and Linden, 1983). However, in other cases the additional organic inputs have actually been observed to enrich local nutrient supply and promote algal growth and productivity (Tenore *et al.*, 1982; Gibbs *et al.*, 1992; Prins *et al.*, 1997; Ogilvie *et al.*, 2000).

An increase in sediment organic content (or the settling of broken shells etc.) can induce successional effects on benthic species assemblages and/or on the benthic biodiversity (Pearson and Rosenberg, 1978; Kaspar *et al.*, 1985; Grant *et al.*, 1995; Crawford *et al.*, 2003). Observed changes have included adjustments from suspension feeding communities to those favouring deposit feeders (Grant *et al.*, 1995; Inglis *et al.*, 2000), and opportunistic feeding on fallen shellfish by fish species, gastropods, and crustaceans (Tenore *et al.*, 1982; de Jong, 1994; Grant *et al.*, 1995; Stenton-Dozey *et al.*, 1999; Kaiser, 2001).

Unwanted Organisms

The farming of shellfish can lead to the introduction of unwanted organisms, such as parasites and pathogens through the transfer of farming equipment and shellfish spat (Inglis *et al.*, 2000; Kaiser, 2001; Cole, 2002). Mussel farming has been identified as the likely cause of the spread of invasive seaweeds such as *Undaria* within New Zealand waters (Kaiser, 2001; Cole, 2002). Further, it has also been suggested that increased ammonia concentrations, resulting from excretions by farmed shellfish, have in some situations accelerated the spread of harmful algal blooms (Inglis *et al.*, 2000; Kaiser, 2001).

Hydrodynamic Effects

Bivalve aquaculture in the marine environment requires the introduction of structures from which to suspend or support the cultured shellfish. The introduction of such features affects the local hydrodynamics (Grant and Bacher, 2001; Plew *et al.*, 2005), often by aligning flows passing through the farm to the local structural orientation (Boyd and Heasman, 1998), and can attenuate through farm currents by up to 30% (Gibbs *et al.*, 1991). In these cases, observed impacts were restricted in spatial extent to the local farmed area. In addition to the direct effects of farm structures on local flows, shell deposits on the seabed beneath farms can act to reduce near-bed flows by

increasing the roughness length (de Jong, 1994), and thus inhibit the transport of any enriched organic matter deposited by the mussels.

There is some evidence for damping of high frequency wave action (short wind chop) by mussel farm structures (5-20%), though the attenuation effect is variable with wave frequency; low frequency, long period waves pass through with little reduction in wave height (Grant and Bacher, 2001; Plew, 2005).

2.6 SUSTAINABILITY AND THE CARRYING CAPACITY CONCEPT

The recent growth of the aquaculture industry has increased both national and global concerns regarding the long-term sustainability of both individual operations and of the industry as a whole. Quantifying and predicting sustainabilities, carrying capacities, and cumulative impacts are therefore becoming key considerations in the expansion of the industry (Dame and Prins, 1998; Smaal *et al.*, 1998; Black, 2001; Broekhuizen *et al.*, 2002; Pillay, 2004).

Initially, the carrying capacity of aquaculture was defined as the maximum standing stock which could be supported by a given ecosystem for a given time (Odum, 1983; Dame and Prins, 1998; Smaal *et al.*, 1998). Inglis *et al.* (2000) revised this definition, with specific relevance to coastal aquaculture, and developed a widely adopted scheme separating carrying capacity into component parts:

- physical carrying capacity – the total area of farms which can be accommodated in the available space given factors such as planning restrictions, geography, and infrastructure;
- social carrying capacity – the level of farm development which causes unacceptable social impacts, factors may include access restrictions or visual amenity;
- production carrying capacity – the stocking density of bivalves at which harvests are maximised; and
- ecological carrying capacity – the stocking or farm density which causes ecological impacts beyond that deemed acceptable (often this limit takes the form of a socially imposed threshold).

This separation of the original definition is significant. Different stakeholders are generally concerned with different aspects of the environment or the aquaculture operation; hence, they are concerned with different aspects of sustainability and carrying capacity.

Physical and Social Carrying Capacity

The concept of a physical carrying capacity is to define the area which is both geographically available and physically adequate for aquaculture. Generally the capacity depends on an overlap between the requirements of the cultured species and the physical properties of the area under consideration (McKindsey *et al.*, 2006). The concept involves habitat suitability indices with multiple relevant factors being analysed within a Geographic Information System (GIS) framework (*e.g.* Preston *et al.*, 1997; Arnold *et al.*, 2000; Nath *et al.*, 2000; Perez *et al.*, 2005; Vincenzi *et al.*, 2006). Surprisingly, McKindsey *et al.* (2006) note that biological and organo-chemical datasets should not be used in such analyses. However, the use of physical, biological, chemical, or ecological indices representing factors which correlate to bivalve growth or minimise adverse impacts, when used during the planning stages aids the identification of optimally sustainable sites from physical, ecological, and production viewpoints.

Assessments of social carrying capacities comprise influences from the other three categories, along with tradeoffs by stakeholders and the population in general (Inglis *et al.*, 2000; McKindsey *et al.* 2006). Whilst detailed assessments of social carrying capacities are beyond the scope of this thesis, and best undertaken within the framework of an Integrated Coastal Zone Management (ICZM) plan, several of the more simple concepts (*e.g.* avoiding conflicting uses of the marine environment) can be undertaken within the same GIS framework as that of the physical carrying capacity.

Production and Ecologic Carrying Capacity

A dominant factor determining the production carrying capacities of bivalve aquaculture is primary production (Gibbs *et al.*, 1992; Small *et al.*, 1998; Jeffs *et al.*, 1999; Figueras *et al.*, 2002; McKindsey *et al.*, 2006), though several other factors such as water residence and bivalve clearance times also play key roles (Dame and Prins, 1998; Pillay, 2004; Gibbs, 2007). Sustainable bivalve aquaculture requires that either phytoplankton grow at a rate equal to or faster than that at which bivalves can feed on them, or that 'new' phytoplankton be advected into the system. This concept highlights the influence of both ecological and physical processes on the sustainability of bivalve aquaculture. Clearly, an adequate understanding of both the physical and ecological workings and interactions within a given environment is vital for optimum aquaculture site selection and sustainability. Poor site selection may result in stressed ecosystems, stressed or diseased culture species, invasive species problems, decreased production, and inferior economic performance (Preston *et al.*, 1997; Naylor *et al.*, 2000).

Historically, carrying capacities have been determined by trial and error (as a result of species collapse and/or reduced returns, Raillard and Menesguen, 1994; Smaal *et al.*, 2001; Frankic and Hershner, 2003; Handley and Jeffs, 2003), and more recently through the application of numerical models (Dame and Prins, 1998; Smaal *et al.*, 1998; Henderson *et al.*, 2001). Modelling aquacultural systems allows for more

efficient production from the available space, and also provides a tool with which to gauge effects on the wider ecosystem to achieve a sustainable outcome (Jefferies *et al.*, 1999; Doonan, 2001; Silvert and Cromey, 2001).

A wide variety of modelling approaches has been applied to the task of determining production and ecologic carrying capacities. Nutrient-Phytoplankton-Zooplankton (NPZ) type models are the most prevalent (Carver and Mallet, 1990; Campbell and Newell, 1998; Ross *et al.*, 1999; Bacher *et al.*, 2003; Duarte *et al.*, 2003). Often however, their spatial resolution is greatly restricted by the application of a box-model type approach, where the studied region is separated into large boxes (generally < 5) with only fluxes into and out of these boxes being considered (*e.g.* Raillard and Menesguen, 1994; Bacher *et al.*, 1998; Ferriera *et al.*, 1998; Ross *et al.*, 1999; Chapelle *et al.*, 2000; Grant *et al.*, 2007). NPZ type models of bivalve aquaculture have generally been focused on predicting bivalve growth and optimising stocking densities over local-scales (*e.g.* Carver and Mallet, 1990; Dowd, 1997; Ferriera *et al.*, 1998; Grant *et al.*, 2007). Increasingly the trend is toward integrated ecosystem models with bivalve energetics sub-models fully coupled to simulations of physical hydrodynamic processes (Dyke, 2001; Duarte *et al.*, 2003; Menesguen *et al.*, 2007). Over regional-scales these integrated ecosystem models allow the identification of ecosystem level impacts over long time periods (Dowd, 2005; Menesguen *et al.*, 2007). Local-scale (~farm-sized) models, while providing greater spatial resolution over smaller areas, often simplify ecosystem level processes to boundary conditions and hence fail to incorporate several important feedback processes (Smaal *et al.*, 1998; Smaal *et al.*, 2001), limiting their application over seasonal time scales.

The underlying basis of NPZ simulations is a model of general hydrodynamic circulation. These hydrodynamic models allow the simulation of passive transport and dilution of nutrients, phytoplankton, zooplankton, and waste material through advective and dispersive processes (*e.g.* Chapelle *et al.*, 2000; Henderson *et al.*, 2001). The scale and resolution of the underlying hydrodynamic model is intimately linked to the NPZ model, *i.e.* box models require fluxes in and out of boxes; regional-scale models require regional scale replication of the hydrodynamics.

Other carrying capacity modelling approaches have included current speeds (Incze *et al.*, 1981; Aure *et al.*, 2007), energy flows (Grant *et al.*, 1998; Ren and Ross, 2005) and mass balance food web models (Wolff, 1994; Brando *et al.*, 2004; Jiang and Gibbs, 2005). Food web models and some energy flow models attempt to overcome the major shortfall of NPZ-type models; that of failing to account for higher trophic levels (than zooplankton) in ecosystem functioning, and hence any top-down control of lower trophic levels. Dense populations of bivalves may control phytoplankton to such an extent that they fill the 'natural' role of zooplankton, hence reducing their concentrations and a potential food source for higher trophic levels (Gibbs, 2007). NPZ-type models cannot offer insights into any potential impacts of these effects. The incorporation of higher trophic levels within food web and energy flow models,

however, by their very nature greatly limits their spatial and temporal resolution relative to NPZ models (Jiang and Gibbs, 2005).

Sustainability and Carrying Capacity Indicators

In practice the measurement of aquaculture sustainability through carrying capacity limits is difficult due to the variety of concepts and influences. Recently, sustainability performance indicators, carrying capacity ‘mile-stones’ (Gibbs, 2007) and ‘acceptable limits of change’ (Oliver, 1995; Zeldis *et al.*, 2006) have each been suggested for the purposes of defining sustainability and preventing negative impacts. These approaches attempt to quantify limits and ‘trigger points’, indicative of an environment under stress, in order to prevent significant or long-term impacts (Crawford, 2003). These indicators are, however, often limited by a lack of consideration of larger scale physical exchange processes which may enhance water, nutrient, and phytoplankton exchange. In their present form both the sustainability indicator and ‘acceptable limits of change’ approaches are aimed at measuring existing developments rather than maximising sustainability and minimising and mitigating negative impacts during the planning stages. However, with appropriate modelling efforts as employed in this study (e.g GIS sustainability planning models and regional-scale NPZ models) these indicators can be applied to model output to determine potential sustainability.

2.7 UNDERSTANDING THE BAY OF PLENTY REGION OCEANOGRAPHY

The physical environment and its inherent hydrodynamics play a key role in regulating shelf phytoplankton abundances through their role as an implicit controller of nutrient supply and exchange in shelf waters. Due to these influences and the observed connections between phytoplankton production, aquaculture production carrying capacity and sustainability (Gibbs *et al.*, 1992; Smaal *et al.*, 1998; Jeffs *et al.*, 1999; Figueras *et al.*, 2002; McKindsey *et al.*, 2006), we can deduce that physical dynamics are also an important influence on coastal aquaculture sustainability. A summary of knowledge relevant to the Bay of Plenty (Figure 2.3) region’s oceanography is provided to reflect the importance of these influences and a background to the study region.

Potentially the most influential oceanographic feature within the greater Bay of Plenty is the East Auckland Current (EAUC), an extension of the western boundary current, manifested as the East Australian Current and part of the South Pacific gyre driven by the predominant SE trades.

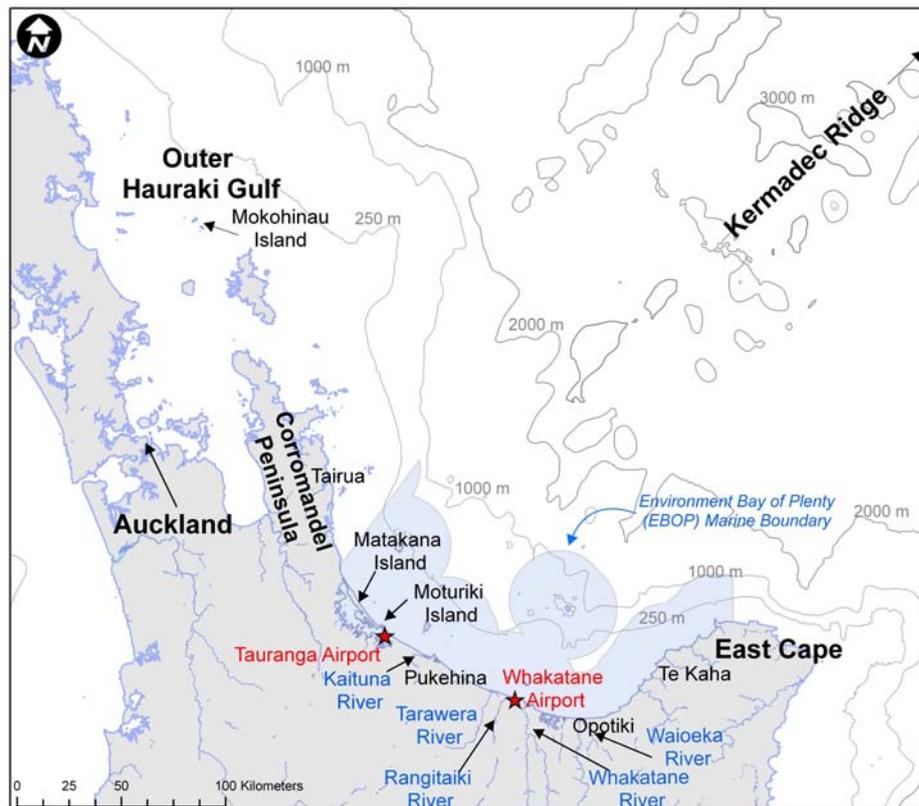


Figure 2.3 Locations and place names in the upper North Island and Bay of Plenty used throughout the text.

2.7.1 THE EAST AUCKLAND CURRENT

The mean SE wind field over the South Pacific Ocean forms the South Pacific gyre as an anti-clockwise current of subtropical water westward (the South Equatorial Current) from the Eastern Pacific towards the Coral Sea, then southward along the Australian coast as the East Australian Current (EAC) (Tomczak and Godfrey, 1994; Sharples, 1997). The EAC partially separates from the Australian coast between 30 and 34°S (Laing *et al.*, 1996; Uddstrom and Oien, 1999; Tilburg *et al.*, 2001), turns left and meanders across the Tasman Sea forming the Tasman Front (TF, Figure 2.4). Although flows through this region are both spatially and temporally variable (Stanton, 1981; Mulhearn, 1987; Tilburg *et al.*, 2001), mean transports are in the range of 12 - 13 Sv for the TF (Stanton, 1981). On reaching the northern tip of New Zealand, this eastwards flow turns to the southeast and becomes the EAUC (Heath, 1985).

The EAUC flows southeastwards, generally following the coastline (Heath, 1985; Tilburg *et al.*, 2001, and Figure 2.4) and transports relatively warm (~19-20.5°C) and saline (~35.7 psu) subtropical water along the northeast coast of New Zealand (Sharples, 1997; Uddstrom and Oien, 1999; Chiswell, 2001; de Lange *et al.*, 2003). Whilst the majority of the flow gradually separates from the coast and continues northeastwards off the outer Hauraki Gulf (Figure 2.4), a small fraction remains attached to the coast past the Bay of Plenty and continues on towards East Cape (Heath, 1985; Stanton *et al.*, 1997; Tilburg *et al.*, 2001). This remaining portion of the

current rounds East Cape in a clockwise direction and becomes the East Cape Current (ECC).

While the pathways of the EAUC and ECC can be variable (Laing *et al.*, 1996), two persistent anticyclonic eddies have been identified in the EAUC off the northeast coast of New Zealand, the North Cape Eddy (NCE) and the East Cape Eddy (ECE), (Stanton *et al.*, 1997; Roemmich and Sutton, 1998) (Figure 2.4). While both these eddies have been identified from dynamic topography (Stanton *et al.*, 1997; Roemmich and Sutton, 1998), analyses utilising remotely sensed sea surface temperatures found no evidence of the ECE (Uddstrom and Oien, 1999) indicating that they may be temporally and/or spatially variable features.

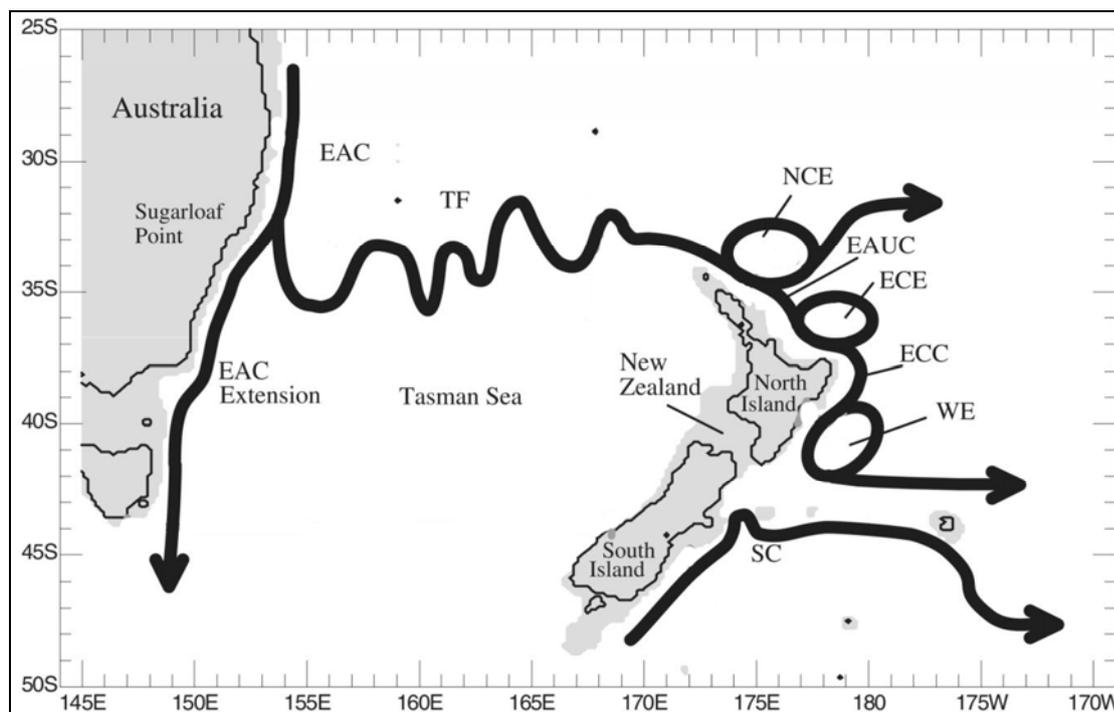


Figure 2.4 Major oceanic flows surrounding New Zealand showing approximate positions of the East Australian Current (EAC), Tasman Front (TF), North Cape Eddy (NCE), East Auckland Current (EAUC), East Cape Eddy (ECE), East Cape Current (ECC), Wairarapa Eddy (WE), and the Southland Current (SC). (Source: Tilburg *et al.*, 2001).

Assessments of the mean transport of the EAUC on the southern side of the NCE revealed volumes of 11 and 34 Sv (Stanton *et al.*, 1997), and ~9 Sv (Roemmich and Sutton, 1998). The variations were explained by temporal variability in the current and also in the location and strength of the NCE (Stanton *et al.*, 1997; Roemmich and Sutton, 1998). Temporal variability in the EAUC transport and location, whilst still being actively researched, is thought to occur more over inter-annual cycles (Morris *et al.*, 1996; Stanton, 2001; Stanton and Sutton, 2003) as opposed to the seasonal cycle initially proposed (Roemmich and Cornuelle, 1990; Laing *et al.*, 1996).

The EAUC has been observed to periodically encroach onto the Hauraki Gulf shelf (Sharples, 1997) delivering relatively warm (~19-20.5°C) and saline (> 35.5 psu) subtropical oceanic water to the coastal areas of northeastern New Zealand during the austral summer. These intrusions are generated by Ekman forcing of the EAUC front

and were initially thought to require both southeasterly winds ($10 - 12 \text{ m.s}^{-1}$) and shallow stratification of the water column (Sharples, 1997; de Lange *et al.*, 2003). However, more recent analyses (Zeldis *et al.* 2004a) suggest that only strong stratification and an absence of winds from the northwest are prerequisite for such intrusions. Despite the significance of these events (*e.g.* the 1992-1993 toxic bloom of *Gymnodinium cf. breve* in the Hauraki Gulf, Chang *et al.*, 1995; Sharples, 1997) large gaps occur in the knowledge of coastal upwelling and oceanic intrusions surrounding New Zealand (de Lange *et al.*, 2003). The marine environment of the Bay of Plenty is no exception.

Impacts of the EAUC on the Bay of Plenty

Whilst the majority of the EAUC flow separates and turns away from the coast at $\sim 34^\circ\text{S}$, a weak remnant of the original flow continues flowing southeastwards (Figure 2.4, Heath, 1985; Stanton *et al.*, 1997; Tilburg *et al.*, 2001). Weak southeasterly geostrophic flows (flows extending to at least 200 m with surface speeds of $\sim 0.14 \text{ cm.s}^{-1} = 44 \text{ km.yr}^{-1}$) have been measured across the oceanic regions of the Bay of Plenty (Ridgeway and Grieg, 1986; Stanton *et al.*, 1997; Sutton and Chereskin, 2002), generated from the inshore side of the EAUC and from the southern side of a ridge associated with the ECE (Figure 2.5).

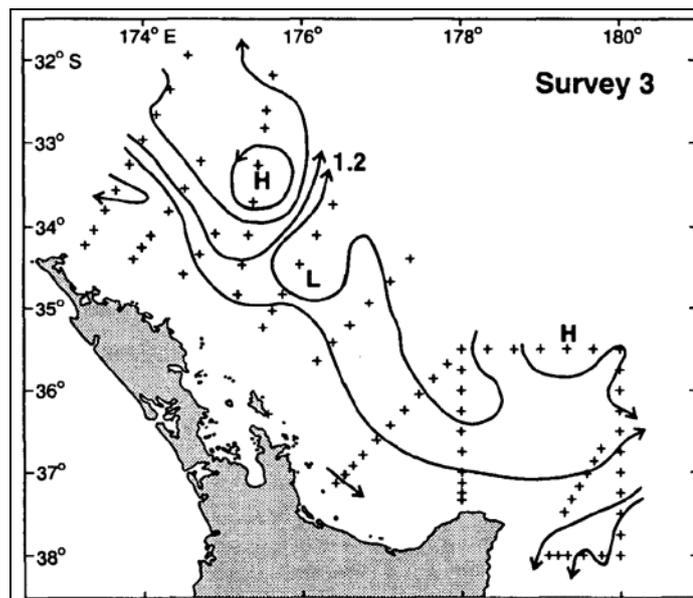


Figure 2.5 Dynamic topography and implied geostrophic currents northeast of New Zealand (November –December 1995). Flows over the shelf within the Bay of Plenty are weak, and the main source of water for the East Cape Current is from the north east, not from within the Bay of Plenty. (Source: Stanton *et al.*, 1997).

Conservative calculations using these figures (200 km wide stream, 1000 m deep, 0.0014 m.s^{-1}) lead to estimates of $\sim 0.28 \text{ Sv}$ ($28 \times 10^4 \text{ m}^3.\text{s}^{-1}$) for the geostrophic transport through the greater Bay of Plenty, though the EAUC may transport greater volumes farther offshore than 200 km. This represents a significant reduction from the 9-34 Sv calculated in the EAUC off the Hauraki Gulf (Stanton *et al.*, 1997; Roemmich and Sutton, 1998).

The ECC, flowing south along the coast from East Cape, sources its water from the 'northeast' (Stanton *et al.*, 1997) (Figure 2.5), providing further evidence for only weak flows through the Bay of Plenty. Analyses of climatological Sea Surface Temperatures (SSTs) surrounding New Zealand found greater variability in the ECC than the EAUC (Uddstrom and Oien, 1999), potentially indicating that the two are somewhat disconnected by the Bay of Plenty region (though they may indeed be connected further offshore). Calculations by Stanton *et al.*, (1997) led to the conclusion that, of the water entering the ECC, only around 1 Sv (~5 % of ECC total) is sourced from flow across the greater Bay of Plenty. The pathway for these flows around East Cape was between 100 and 200 km from shore with westward flowing counter-currents being found within 100 km of shore (Stanton *et al.*, 1997).

There is strong evidence therefore that the EAUC has limited impact on the Bay of Plenty shelf relative to that of the outer Hauraki Gulf.

2.7.2 SITE CHARACTERISTICS

Temperature and Salinity Characteristics

The typical annual range in SST surrounding New Zealand varies from 4°C through to 8-9°C, with the larger ranges being observed in shallow embayments or harbours (Heath, 1985; Grieg *et al.*, 1988; Bell and Goring, 1998). SST maxima typically occur in February and minima in August, whilst salinities can vary seasonally by ~0.3-0.4 psu (Heath, 1985; Grieg *et al.*, 1988). Specific to the Bay of Plenty region, data from Tauranga Harbour indicate seasonal temperature variation between 23°C (Feb) and 14°C (Aug) (Grieg *et al.*, 1998). A more spatially comprehensive investigation within the greater Bay of Plenty in February 1981 found surface temperatures and salinities increasing in an offshore direction (Ridgeway and Grieg, 1986). The isolines of both properties also deepened away from the coast, indicating an increase in the mixed layer depth in an offshore direction. Surface temperatures ranged between 23 and 20°C (offshore and nearshore), with surface salinities between 35.0 and 35.5 psu (Ridgeway and Grieg, 1986; Park, 1991; Park, 1998).

Though little oceanographic research has been focussed directly within the Bay of Plenty the outer Hauraki Gulf (north of the Bay of Plenty, Figure 2.3) has a relatively large body of literature describing its marine environment and dynamics. Within the outer Hauraki Gulf increasing temperatures and salinities away from the coast are to be expected as a result of the subtropical EAUC water (19-20.5°C, ~35.7 psu, Sharples, 1997). The front separating neritic waters from those of the EAUC is a distinct feature with temperature gradients > 2°C over short distances (Sharples, 1997). Within the outer Hauraki Gulf a seasonal thermocline develops from October to depths of 35-50 m in late summer (de Lange *et al.*, 2003). There are no published data of thermocline depths specific to the Bay of Plenty. SSTs surrounding New Zealand vary over inter-annual time scales in response to the El Niño Southern Oscillation (ENSO), which acts to lower SSTs throughout New Zealand's coastal waters during strong oscillation events (Grieg *et al.*, 1988).

Wave Climate

Waves within the Bay of Plenty are typically generated by enclosed synoptic-scale meteorological systems, either in the mid-latitudes or more local depressions moving west to east. Local wave heights are a function of the speed of the storm along with its intensity (Heath, 1985). Frequently, these storms do not persist long enough for a ‘fully arisen sea’ to generate (Heath, 1985).

The wave climate within the Bay of Plenty can be defined as that of ‘a low energy lee shore’, where typical wave heights are 0.5–1.0 m with periods of 5–7 s, travelling from northerly and easterly directions (Pickrill and Mitchell, 1979; Healy *et al.*, 1997). The wave climate has a weak seasonality with more activity during the winter; wave steepness is variable throughout the year (Pickrill and Mitchell, 1979). More recent data, offshore from Tauranga, have indicated a persistent swell with heights of ~0.3 m and periods between 12–16 s, with locally generated seas superimposed (de Lange, 1991). While no seasonal trends were identified in these data, the possibility exists of forcing in-line with ENSO, with a greater incidence of northeasterly winds during La Niña phases (de Lange, 1991).

Shelf Currents

Little is known of continental shelf currents within the Bay of Plenty. The east Coromandel shelf has two main mutually exclusive shore parallel current regimes, a calm weather, weak ($0.1 - 0.2 \text{ m.s}^{-1}$) southward current associated with westerly winds, and a stronger ($\sim 0.4 \text{ m.s}^{-1}$) northward current associated with storms and winds from the east and northeast (Bradshaw *et al.*, 1994).

Tidal Sea level Variability

The New Zealand coast is generally meso-tidal and strongly semi-diurnal (de Lange *et al.*, 2003). The semi-diurnal tide (lunar M_2 , 12.42 h period and solar S_2 , 12.0 h period components) completely rotates around New Zealand as a propagating Kelvin wave in an anti-clockwise direction (Bye and Heath, 1975; Hume *et al.*, 1992; Sharples and Greig, 1998; Walters *et al.*, 2001; Goring and Walters 2002). Typically the tidal range is 1–3 m with associated currents of $0.1 - 0.2 \text{ ms}^{-1}$ (Sharples and Greig, 1998; Stanton *et al.*, 2001), however, it should be noted that in these tidal current modelling efforts, there was a general lack of calibration and verification points within the Bay of Plenty. Peak tidal currents in open shelf areas occur around the times of high and low water, due to the propagating M_2 tidal wave circling New Zealand (de Lange *et al.*, 2003). Tidal forcing accounts for 97% of the total variance in a long term dataset of open coast sea levels from within the Bay of Plenty (Bell and Goring, 1998).

Non-tidal Sea Level Variability

Sea levels at Moturiki Island within the Bay of Plenty were found to vary both seasonally (< 20 cm) and inter-annually (~9 cm) between 1972 and 1989 (Bell, 1985; Hay *et al.*, 1991). The inter-annual variability showed significant correlations with the Southern Oscillation Index (SOI), with a lag period of 11 months (Hay *et al.*, 1991). The annual cycle of heating and cooling coupled with the inter-annual

variability in water temperatures, in-line with the SOI and resulting in steric adjustments (density) are the largest influences on non-tidal sea level variation within the Bay of Plenty (Bell and Goring, 1998). Tertiary level influences could arise from along-shelf wind stresses creating pressure gradients and initiating coastal trapped waves, influencing sea levels with periods between 5 and 20 days, and from barometric influences (Bell and Goring, 1998; de Lange *et al.*, 2003). Though there are no direct observations of coastal trapped waves within the Bay of Plenty (Bell and Goring, 1996), current velocity measurements off Tairua (Coromandel Peninsula) have shown characteristics typical of these features (de Lange *et al.*, 2003).

Characteristic Wind Conditions

Analyses of long term (1985-94) wind forecasts within the central Bay of Plenty (37.5°S, 177.5°E) indicated a net vector averaged wind stress over the decade from the west (Bell and Goring, 1998). The monthly averaged cross-shelf component was consistently directed offshore and was strongest in late autumn and winter and weakest during spring (Figure 2.6, Bell and Goring, 1998). The along-shelf wind stress is dominated by northwesterly (NW) winds (negative values), which are strongest in spring and weakest during late summer (Figure 2.6, Bell and Goring, 1998).

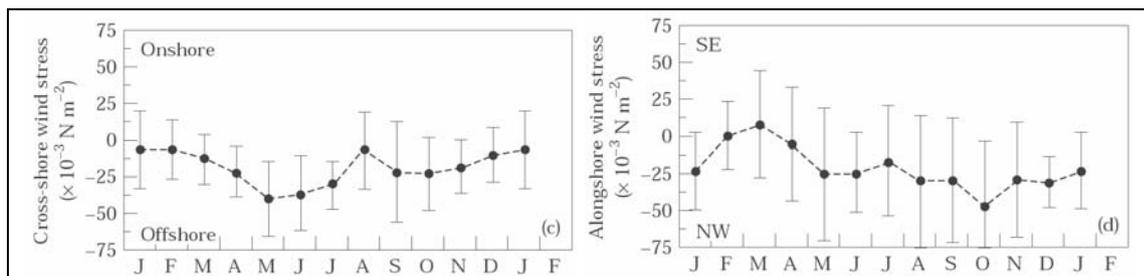


Figure 2.6 Average monthly values (dashed lines) of cross-shore (NE onshore winds +ve) and alongshore (SE winds +ve) wind stress from European Centre for Medium-range Weather Forecasts (ECMWF) winds (1985-94, mean = -0.02 Nm^{-2} for both), vectors aligned to coastline at 135° . Error bars are ± 1 SD bands (source: Bell and Goring, 1998).

2.8 SUMMARY

Greenshell mussels have been farmed within New Zealand for some time and more recently applications have been received for large open coast farms, including within the Bay of Plenty. Progress on these applications has been slow as the government and scientific community attempt to determine the sustainability of and flow on impacts from such farms. Specific to this situation key knowledge gaps include:

- The state of the Bay of Plenty marine environment e.g. sediments, water properties;
- The Bay of Plenty physical dynamics and nutrient delivery mechanisms;
- The lack of ecosystem boundary processes for predictive models; and
- The lack of detailed information on feedback interactions of farmed mussels with their environment.

The oceanography of many areas of the eastern Australia–Tasman Sea–New Zealand east coast region is dominated by the EAUC. There is evidence, however, to suggest that this large current system has only a limited impact upon the Bay of Plenty shelf. This is in sharp contrast to the outer Hauraki Gulf, some 200 km farther north of the Bay of Plenty. Nonetheless, some impact of the EAUC system is thought to be present due to positive offshore temperature and salinity gradients. The Bay of Plenty is a lee coast shelf with a relatively mild wave climate c.f. New Zealand’s west coast. Tidally and non-tidally induced sea level changes within the Bay of Plenty are generally consistent with other New Zealand east coast locations.

