HYDRODYNAMIC AND WATER QUALITY MODELLING OF THE LOWER KAITUNA RIVER AND MAKETU ESTUARY

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by

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Abstract

The Maketu Estuary is a shallow intertidal estuary (2.3 km^2) located in the Bay of Plenty, North Island, New Zealand. The Kaituna River contributes the largest freshwater flow into the estuary through control gates. Lake Rotoiti and indirectly Lake Rotorua supply the base flow to the Kaituna River, with tributaries along the 50 km reach also significantly contributing to the flow. Water quality within the river is affected by elevated nutrients, faecal coliforms, high oxygen demand and algae concentrations derived from the lakes as well as contributions from tributaries and industrial and urban discharge. Through the use of a coupled hydrodynamic-biogeochemical numerical model ELCOM-CAEDYM, this study aims to examine the nutrient, phytoplankton and hydrodynamics of the Maketu Estuary and lower Kaituna River.

Water quality and hydrodynamic measurements were sourced from Environment Bay of Plenty's data archives as well as a number of instrument deployments to collect water velocity, tidal elevation and salinity and temperature measurements during the course of this study. Included in the field work was a survey of the lower river and estuary bathymetry.

Model simulations predicted that the maximum residence time in the Maketu Estuary is 1.5 days, occurring in the inner western region. Residence time in the lower river (mouth to 8.5 km upstream) is in the order of hours although some variations were predicted near the river mouth. Growth rates of four phytoplankton groups where assessed over a 15 day period in January 2004. In the Kaituna River ELCOM-CAEDYM predicted that the community growth rates were small with the exception of a slight increase in biomass of the two freshwater groups in a semi-detached river bend. The increase in the loop was correlated with an increase of residence time. In the estuary, marine diatoms showed the highest growth rates in the western region which is expected to relate to retention time and available nutrients. Dinoflagellates showed the smallest variation in predicted growth rates, most likely due to their broad salinity tolerance. The two freshwater species showed a reduction in abundance when mixed with marine water. A principle limiting factor to phytoplankton growth in both the river and estuary is the low residence time.

A number of scenarios were simulated in the river and estuary by altering the forcing conditions in the model. A simulation of the increased nutrient load associated with the Rotoiti diversion wall revealed that phytoplankton growth in the river and estuary will not be significantly affected. Because of the close proximity of the control gates to the river mouth, a proportion of water drawn through the structure can be marine. By opening the old river channel, model simulations predicted that a reduction in salinity would be possible, however the outcome of complete freshwater is probably not achievable. Increasing the discharge volume from the river into the estuary was also simulated. The results indicated that increasing the freshwater inflow at Fords Cut would reduce the salinity in the estuary while increasing the net (residual) flow towards the estuary mouth. Increasing the flow would also result in a greater range of salinity in regions of the estuary. Changing the inflow location to the historic Papahikahawai Channel also affected the salinity in the estuary. The most significant effect of an inflow at this location was a reduction of the residual currents in the western region of the estuary.

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Chapter One

Introduction

This thesis describes how a coupled hydrodynamic-water quality numerical model was applied to the Maketu Estuary and lower Kaituna River. The model was applied to predict the present hydrodynamic, nutrient and phytoplankton dynamics. Once this was achieved, the model was used to predict the likely hydrodynamic and nutrient/phytoplankton dynamics for a range of scenarios. The modelling scenarios address hydrodynamic and water quality concerns currently faced in the estuary and river.

1.1) Nature of the problem

The hydrodynamics of the Maketu Estuary and lower Kaituna River have been drastically altered over the past six decades. One of the most significant changes was the diversion of the Kaituna River out of the estuary in 1956, which is believed to have contributed to sediment infilling and general ecological decline of the estuary. Subsequent to the 1956 diversion, major realignment work was carried out on the lower river during the 1970s and 80s to reduce the effects of flooding, resulting in alteration of the hydrodynamics in the lower river. A re-diversion of the river flow back into the estuary has been advocated by Iwi, long-time users of the estuary and the local community. However, declining water quality, the threat of flooding and the closure of the new river mouth created during the diversion in 1956 have meant a re-diversion is currently not feasible. In 1998, resource consent was granted to allow 100,000 m^3 of Kaituna River water to enter the estuary through control gates. It was envisaged that the re-diversion would help reduce the sediment infilling and restore some the declining wetland marsh and kaimoana to the estuary. While to date the re-diversion has assisted in reducing the salinity in the upper estuary, the sedimentation, hydrodynamic and ecological improvements are yet to be observed. Moreover the already high nutrient load of the Kaituna River water may be further increased by the construction of a diversion wall in Lake Rotoiti. Presently, declining water quality in Lake Rotoiti is in part caused by nutrient rich water entering Lake

Rotoiti from Lake Rotorua. The diversion aims to channel this nutrient rich flow down the Kaituna River instead of into the main body of Lake Rotoiti.

1.2) Regional setting

The Maketu Estuary is located approximately 35 km south-east of Tauranga and 50 km north to north-east from Rotorua, within the Bay of Plenty on the east coast of the North Island (Figure 1.1). The estuary is situated on the eastern side of the Te Puke lowlands which were formed by tectonic warping during the middle to late Pleistocene (Healy *et al.* 1962). The geology of the Maketu comprises primarily of undifferentiated alluvium, peat and dune sand (Wigley, 1990) with a wedged shaped sandspit barrier that runs from its maximum width at Papamoa to the Maketu headland, enclosing the northern boundary of the estuary. The Maketu Headland located on the eastern side of the estuary, known as Town Point, consists of the Hamilton Ash Formation (Chappell, 1975) overtopped by a mixture of fluvatile silts, sands, gravels and terrace deposits (Wigley, 1990).

The Kaituna River spans approximately 50 km (White *et al.* 1978) commencing at the outlet of Lake Rotoiti at Okere arm and entering the sea at Te Tumu, just west of Maketu Estuary (Figure 1.1). The Kaituna River catchment includes drainage from both Lake Rotorua and Lake Rotoiti and has been in its present configuration for about 9000 years (Tortell, 1984). The entire catchment covers an area of 124,000 hectares with ~48 percent of this area occurring below the outlet of Rotoiti (McIntosh, 2005). After the Kaituna River leaves Okere Arm it passes through a steep, narrow gorge falling ~260 metres in elevation before meandering through the alluvial terraces of the lower Kaituna basin and onto the peat and sand deposits of the Te Puke lowlands. Lakes Rotorua and Rotoiti contribute the largest quantity of base flow to the Kaituna (EBOP, 2006); however, most flood run-off is generated by several tributaries from the catchment downstream of the lakes (McIntosh, 2005) including Mangorewa River, Waiari and Ohineangaanga Streams and Raparapahoe and Kopuroa canals. Mean annual discharge of the Kaituna River is ~39 m^3s^{-1} (McIntosh, 2005) with peak flood flows reaching in excess of 150 m^3s^{-1} (KRTA, 1986).

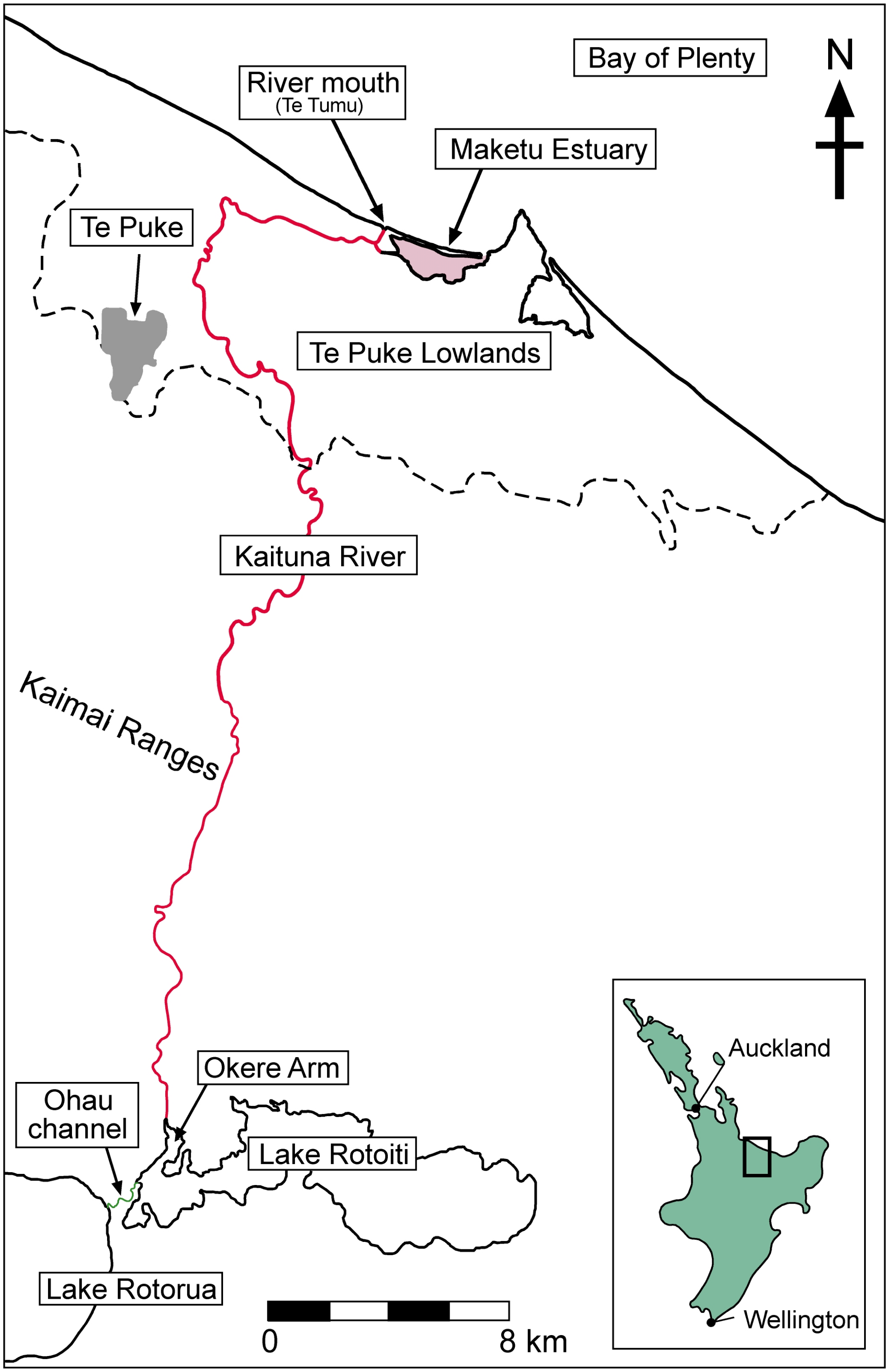

Figure 1.1. Location map illustrating the Maketu Estuary, Kaituna River, Lake Rotoiti, Lake Rotorua, Te Puke lowlands, Ohau channel, Okere Arm, Te Tumu and the Kaimai Ranges in the Bay of Plenty, North Island, New Zealand. (Source: LINZ, 2006)

1.3) Study area

1.3.1) Hydrodynamics

Burton (1987) and Domijan (2000) described the Maketu Estuary as a microtidal barrier-enclosed estuarine lagoon. The estuary is shallow (mean depth of one metre below mean sea level) covering a total area of ~2.3 km^2 and comprising sand and mud intertidal flats, tidal channels, salt marshes and wetlands. At low tide the intertidal sand and mud flats dominate the landscape, exposing an estimated 70-80% of the estuary bed (Domijan, 2000).

Kaituna River contributes the largest freshwater input into the estuary, entering through control gates at Fords Cut with an average inflow volume of 100,000 m^3 per tidal cycle (McIntosh, 1997). The tidal prism is estimated at 1,000,000 m^3 (Domijan, 2000) and is dominated by marine water entering through the estuary mouth located against the headland on the eastern side of the estuary. There are a number of defined channels within the estuary; however most are highly mobile and prone to shifting course.

1.3.2) Water quality

Currently the estuary waters are controlled by Environment Bay of Plenty's operative regional coastal plan (BOPRCP). This statutory plan sets guidelines on concentrations of water quality variables within Environment Bay of Plenty's regulatory region. The Maketu Estuary has faecal coliform concentration limits imposed on it. These limits are to protect the contamination of shellfish for human consumption. During compliance monitoring, Park (2003) reported that the water quality since 1996 had remained within the guidelines apart from one sample of shellfish with bacterial coliform concentrations above that of the guideline.

The freshwater input that the estuary receives from the Kaituna River contains high concentrations of plant nutrients in the form of, nitrate (NO_3), ammonium (NH_4) and phosphate (PO_4). The elevated nutrients in the Kaituna River are sourced from Lake Rotoiti outflow as well as discharges occurring along the reaches of the Kaituna, including AFFCO meat works at Rangiuru

(Bruere *et al.* 1997; McIntosh, 2005), seepage from Te Puke sewage treatment wetlands and dairy farm runoff.

1.3.3) Climate

The Te Puke lowlands receive in the order of 1500 – 1700 mm yr^{-1} of rainfall. This is considerably less than the surrounding Kaimai ranges (Figure 1.1) which receive on average 2500 – 2600 mm yr^{-1} (Quayle, 1984). The reduced rainfall on the lowlands is due to the sheltering effect of the Kaimai Ranges from the dominant westerly winds. Temperature records at Te Puke show a mild annual average of 13.9 °C with an annual mean range of 9.5 °C. The predominant wind direction on the lowlands is west to south-westerly, but again due to the sheltering effect from the Kaimai Ranges, is considerably less than on the surrounding ranges (Quayle, 1984).

1.4) Research aim and objectives

The overarching aim of this thesis is to evaluate a range of hydrodynamic and water quality issues within the lower Kaituna River and Maketu Estuary using a three-dimensional coupled numerical model.

This outcome was achieved with four smaller objectives:

i. To create an up-to-date bathymetry for the Maketu Estuary and lower Kaituna River to be used in the numerical modelling.

ii. To predict the current nutrient and phytoplankton dynamics and hydrodynamic conditions in the Maketu Estuary and lower Kaituna River using a three-dimensional coupled hydrodynamic and ecological model, ELCOM-CAEDYM.

iii. To evaluate the potential ecological impacts of the proposed Rotoiti wall diversion on the Maketu Estuary and lower Kaituna River.

iv. Based on suggestions from the local community and Environment Bay of Plenty, assess a range of hydrodynamic scenarios using the numerical model ELCOM-CAEDYM.

1.5) Thesis outline

Following this introductory chapter, an account of the historic and cultural significance of the study area along with a brief outline of the major modifications and scientific reports on the estuary and lower river are presented in **Chapter Two**.

In **Chapter Three** a summary of recent literature on hydrodynamic and ecological numerical modelling is given. A review of eutrophication in estuaries and rivers is included along with a brief description of ELCOM-CAEDYM, the numerical model applied to the estuary and lower river in this study.

A description of the methods used in collecting and collating the data which were used to represent the bathymetry of the Maketu Estuary and lower Kaituna River is presented in **Chapter Four**. The derived bathymetry was used in the numerical modelling undertaken in this study.

In **Chapter Five,** a description of how the three-dimensional hydrodynamic numerical model ELCOM was applied to the estuary and lower river is presented. A description of the boundary conditions and results of model calibration and validation are given. The current hydrodynamic situation in the lower river and estuary are presented and the application of ELCOM is discussed.

In **Chapter Six,** a description of how the biogeochemical model CAEDYM was coupled with the hydrodynamic model ELCOM is presented. CAEDYM was used to simulate nutrient and phytoplankton dynamics in the lower river and estuary. The formulations of the boundary conditions are presented and the predicted nutrient / algae distributions in the estuary are illustrated.

ELCOM–CAEDYM was used to simulate a variety of hydrodynamic and nutrient scenarios in the river and estuary. The predicted results from the modelling scenarios are presented and discussed in **Chapter Seven.**

A summary of the key points from the thesis is presented in **Chapter Eight.** Included in this chapter are limitations of the thesis and suggestions for future work to be taken after this study.

Chapter Two

Historical accounts and changes within the Maketu Estuary and lower Kaituna River

2.1) Introduction

Maketu Estuary and the Kaituna River were settled in the 1300s and colonized by Europeans in the 1800s when deforestation and farming/agriculture practices increased steadily. Flooding issues resulted in significant restructuring of the lower river bed and substantial changes to the hydrology and ecology of the estuary.

2.1.1) Maori colonisation

The first Maori settlement in the Bay of Plenty (BOP) was around 1340 A.D (Tapsell, 2000). Te Arawa was one of nine canoes to arrive in the BOP. After navigating parts of the BOP coastline, Te Arawa entered the Maketu estuary where they may have anchored to two rocks named Taka-parore and Tuterangiharuru which are located inside the estuary mouth and are still present today (Tapsell, 2000).

The landscape at this time was vastly different from the present day. Numerous gullies and hillsides were most likely dominated by small fern bush. The swampy areas to the west (Kaituna swamp), east (Waihi swamp) and south (Kaawa swamp) were extensively covered by swamp grasses, flax (*phromium-tenax*), toe-toe, wi-wi (reed) and raupo (bullrush) (Tapsell, 2000). Tea tree also would have covered large areas of the surrounding expanse.

2.1.2) European settlement

The first European to settle within Maketu was Captain Phillip Tapsell in 1829 (Tapsell, 2000; Richmond *et al.* 1990). On Tapsell's arrival in the Maketu, he set up a flax trading post that exported flax via small ships entering the estuary. In the early to mid 19th century, before the mainstream European arrival, vast areas of swamp would have been covered by flax.

Mainstream European arrival occurred in the late 1800s after the Governor General of New Zealand issued a proclamation declaring the land known as Te Puke open for special settlement on the 27th January 1880 (BOPCC, 1970). The settlement region included the lower Kaituna River and Maketu Estuary. As more Europeans entered the area, development intensified resulting in vast areas of the native land being converted for agricultural use. The conversion involved draining and clearing of the swamps particularly during the 1890s (Tortell, 1984).

2.1.3) Kaimoana

The Maketu Estuary and Kaituna River presents a large source of Kaimoana to Maori and Pakeha alike. Residents described in oral interviews how traditionally seafood made up the greatest part of their protein diet and red meat was eaten rarely only for special occasions. In 1843 the explorer and Maori scholar Dr Edward Shortland described the people of Maketu as better fed and clothed than their neighbours due to their coastal location. The Maketu estuary and Kaituna River waters produced many edible species of finned fish, bivalve, white bait, crabs and plants that were important in the diet of local Iwi, long time users and residents alike. Table 2.1 summaries the types of seafood that have been harvested from within the estuary and lower river.

Table 2.1. List of food resources that are presently, or have been historically available from the Maketu Estuary and Lower Kaituna River.

Common name	Scientific name	Reference
Cockle	*Chione stutchburyi*	Richmond *et al.* 1990
Paddle crab	*Ovalipes punctatus*	Richmond *et al.* 1990
Pipi	*Paphies australe*	Richmond *et al.* 1990
Flounder	-	Donovan *et al.* 1976
Yellow eyed mullet	-	Donovan *et al.* 1976
Whitebait	*Galaxias genus*	KRTA, 1986
Snapper **Kaiwai** **Kingfish**	-	Murray, 1978;
Mussles (Green lip)	*Perna canaliculus*	Murray, 1978
Oysters (Rock)	*Crassostrea glamerata*	Murray, 1978

2.2) Engineering works in the lower Kaituna River and Maketu Estuary

Early farming developments in the Kaituna swamp area were costly and difficult due to flooding (BOPCC, 1970). A severe storm and subsequent flooding in 1907 resulted in a series of engineering reports to investigate ways of reducing flooding. The most comprehensive report was by Holmes and Blair Mason in 1922 which made a number of recommendations including diversion cuts and stop banking which were acted on as early as 1926 (BOPCC, 1970).

One of the earliest engineering works was to modify the estuary by channeling Fords twin cut in 1928. The aim of the cut was to divert part of the Kaituna River flow into the estuary and away from the existing channel (Papahikahawai channel) in an attempt to stop the Kaituna River breaching the Maketu spit (Murray, 1978).

2.2.1) 1956 diversion

The bypassing of the Kaituna River from Maketu Estuary to sea via Te Tumu occurred in February of 1958 (KRTA, 1986; Richmond *et al.* 1990). The diversion was commissioned to help reduce the frequency and severity of flooding on the Te Puke lowlands which were by now dominated by agricultural uses. The decision to divert through Te Tumu was against the recommendation of an engineering report by A. Murray in 1951. However the acting authority of that time 'The Kaituna River Board' proceeded with the diversion as a temporary measure until a suitable plan of action could be drafted to reduce the threat of flooding (KRTA, 1986). A report released by engineer A. Acheson in 1953 favoured the cut as 'in years to come it may enable the reclamation of the Maketu Estuary' (Tortell, 1984). This view was in stark contrast to the opinions of local Iwi, residents and long-time users of the estuary, who did not want the estuary flow regime altered (Te Puke Times, 8/11/1955; Tortell, 1984).

The 1956 diversion provided flood relief for 19,000 acres of low-lying land of which 60% was undeveloped at that time (Richmond *et al.* 1984). However the general opinion among farmers in the area was they had not gained anything from the works (Bay of Plenty Times, 28/8/1960). In the decade following the diversion it was apparent that only changing the river outflow would not significantly reduce the risk of flooding on the surrounding low-lying area (Tortell, 1984), as a considerable area of land still flooded twice yearly and most of the plain was inundated during the one in ten year flood event (BOPCC, 1970).

2.2.2) Kaituna Catchment control scheme

In 1973 the Kaituna Catchment control scheme was initiated (Richmond *et al.* 1984) following a report and recommendations by Bay of Plenty Catchment Commission (1970). The aim of the scheme was to straighten (Figure 2.1), widen and increase the depth in the lower reaches of the Kaituna River to allow easier flow to the sea and cope with a one-in-hundred year storm (BOPCC, 1970). Most works were not undertaken until 1981-1985 after the scheme became amalgamated into the upper catchment scheme. Included in the scheme were extensive stop banking (67 km), 88 km of canals and drains, 7 pump stations, 5 major floodgate structures, vegetation and rubble river bank protection and the construction of the groyne structure at Te Tumu (EBOP, 2006).

A component of the original diversion carried out in 1956 was the construction of a causeway at Fords Cut to allow freshwater to overtop into the estuary during high tide. However the causeway was raised to surrounding stop bank level as part of the Kaituna catchment scheme. This action practically sealed off any flow from the Kaituna into the Maketu Estuary (KRTA, 1986).

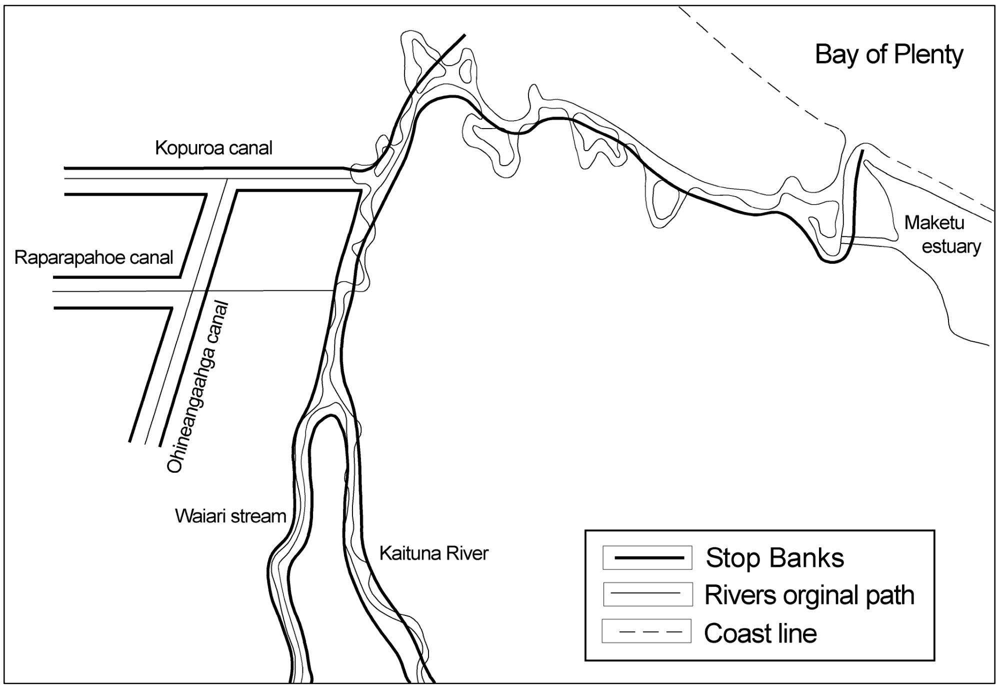

Figure 2.1. Map of the Kaituna River where stop banking and river realignment occurred as part of the Kaituna Catchment scheme. The original meandering river course is also shown. (Adapted from KRTA, 1986).

2.2.3) Effects of the diversion

Within a decade of the diversion, changes in the estuary had started to be observed (Richmond *et al.* 1990; Tortell, 1984). Many locals and long time users were unhappy with the changes with newspaper articles documenting how it was affecting their livelihood (Bay of Plenty Times, 28/8/1960). Since 1970, there have been more than 15 reports recommending a revision of the management in the estuary and lower Kaituna River (Domijan, 2000; Richmond *et al.* 1990) Over the four decades following 1956, major changes had taken place in the estuary as a direct or indirect effect of the diversion. The three most significant changes to the estuary are described below.

Sedimentation and shallowing of the estuary

Domijan (2000) reported that between 1985 and 1996 inter-tidal storage volume within the estuary had been reduced by 0.15 x 10^6 m^3 (17.3 %). This reduced tidal storage was attributed to sedimentation in the estuary at a rate of ~13,640 m^3 per year (Domijan, 2000). Historical reports and accounts show the estuary channels were much deeper, with boats as great as 60 tonne and drafts of up to one meter entering the estuary (Rutherford *et al.* 1989) as illustrated in Figure 2.2. Many long-time users of the Maketu Estuary estimate that its depth has been reduced by up to 5 meters in some places (Bay of Plenty Times, 30/10/1991). Bay of Plenty Times (11/4/1981) reported that before the Kaituna was diverted, 22 fishing boats were able to use the estuary as a port and yachts could sail within the estuary at low tide.

There has been debate over whether the 1956 diversion has caused these high rates of sedimentation. It had been suggested that high sedimentation rates had been occurring before the cut was put in place (1956) as records show blasting to deepen the entrance occurred as early as 1926 (Murray, 1978). There were also several spit breach events during large storm events which could have bought additional sand into the estuary (Richmond *et al.* 1990). Nevertheless it is generally acknowledged that the 1956 diversion has played a role in increasing the sedimentation rate by reducing flood tide dominance and its ability to scour out sediments (KRTA, 1986; Richmond *et al.* 1990; Domijan, 2000).

Figure 2.2. A small coastal vessel inside the estuary in 1886 illustrating the size of vessels that once navigated parts of the estuary (Source: Murray, 1978).

Salt marsh reduction

It is estimated that in the period from 1939 to 1979, 95% of the maritime salt marsh in the estuary disappeared (KRTA, 1986) as illustrated in Figure 2.3. Most loss resulted from stop banking which occurred between 1963 and 1977. However there is evidence that the remaining decline could be attributed to the river diversion (KRTA, 1986). The diversion affected the salt marsh by reducing freshwater inflows, which significantly increased the salinity in the upper reaches of the estuary. Donovan *et al.* (1976) identified the salt marsh vegetation as the rush *Juncus maritmum* and *Leptocarpus simplex* and extensive beds of *Scirpus caldwelli* fringing the old Kaituna inlet (Papahikahawai channel). The decrease in salt marsh habitat has also been attributed to the reduction in whitebait yield as the salt marsh is the principal breeding ground of several species of white bait (KRTA, 1986).

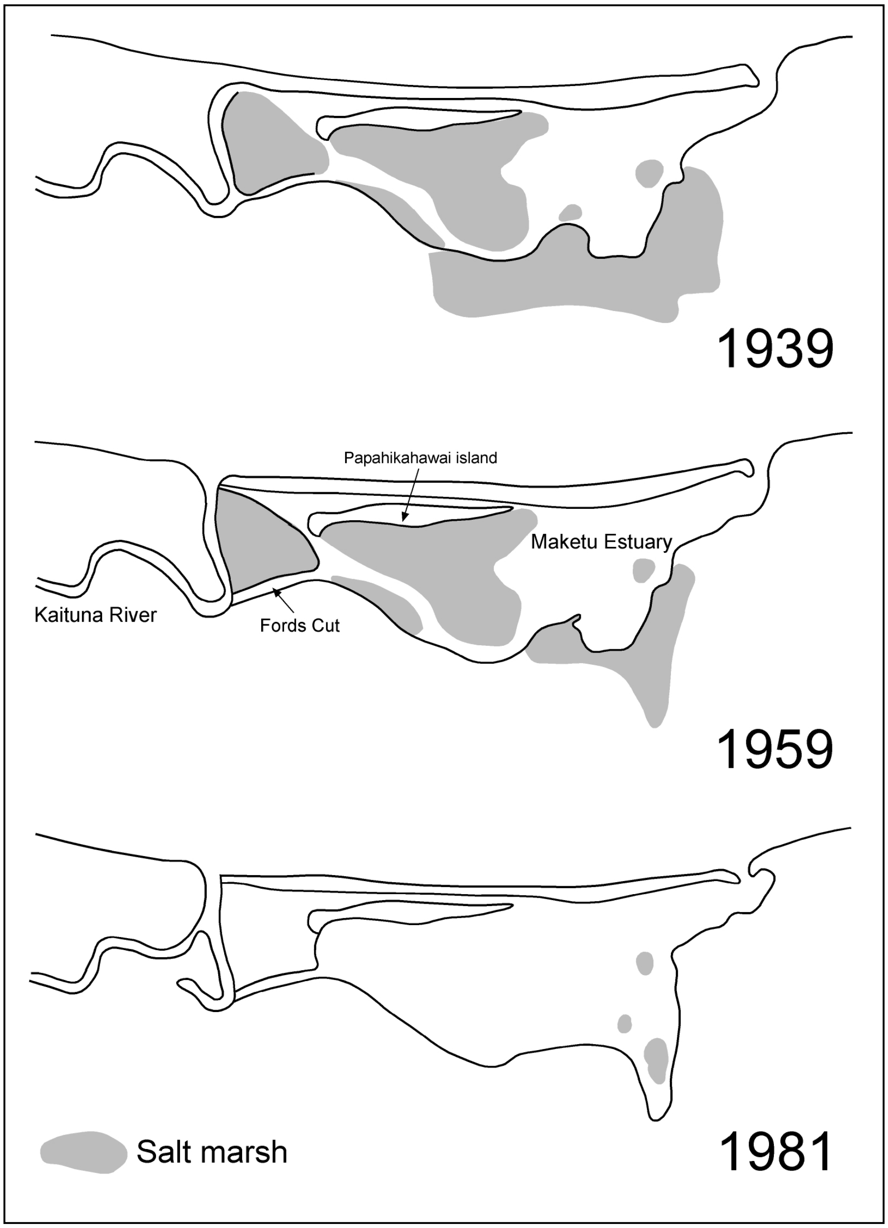

Figure 2.3. Decline of salt-marsh beds in the Maketu Estuary from 1939–1981. (Adapted from KRTA, 1986)

Reduced fishing and shellfish gathering

One of the greatest concerns to many locals and long time users of the estuary is the demise of the pipi beds (Richmond *et al.* 1990). The most likely cause for the reduction in yield is high rates of sedimentation resulting in smothering of the active beds (Park, 2003). The reduction in bed size combined with high harvest rates has seen the confinement of the pipi to very small area of the estuary. In contrast to the pipi, the cockle has thrived on the higher saline environment present since the 1956 diversion.

From historical accounts many fish species have been present in the estuary as listed in Table 2.1. The most recent reports of finned fish in the estuary (Donovan *et al.* 1976; Murray, 1978) identified only two species of finned fish present in abundance, the yellow eyed mullet and flounder. This change can probably be explained by two possible causes: a regional decline in fish stocks and reduction in feeding and breeding grounds in the Estuary. Murray (1978) also suggests that illegal fishing practice in the estuary which he observed would have an effect of fish populations in the estuary.

2.3) Returning the Kaituna River to the Maketu Estuary

As a result of changes to the estuary a number of activities have diminished or are now limited to a much narrower region than pre-diversion. A social report (Loomis, 1984) found recreational and commercial fishing, swimming, recreational boating and the estuary as an ecological resource (birds, marine life, marine and terrestrial plants) had been effected by the diversion.

Local Iwi, residents and many long time users of the Maketu Estuary have sought the return of the Kaituna to the Maketu even as early as the 1960s. In 1984, opposition from locals and long-time users resulted in a petition supported by 3000 signatures that was put forward by the Maketu action group demanding the return of the Kaituna River to the Maketu Estuary (New Zealand Herald, 6/5/1984).

In response to the continual pressure, the Commission for the Environment was requested to report on environmental issues and options for the Maketu Estuary. The reports which followed (Lomis, 1984; Tortell, 1984) were highly critical of the original 1956 diversion and led to the commissioning of a technical study (KTRA, 1986) to investigate the options for returning freshwater flow into the Maketu Estuary. The KRTA (1986) report was followed by a number of others investigating the potential options for returning the Kaituna River to the Maketu (Rutherford *et al.,* 1989; Richmond *et al.* 1990). The critical findings of these reports concluded that the entire flow of the Kaituna River in its current state could not be returned to the estuary for reasons outlined below.

2.3.1) Water quality

Of principal concern in any attempt to re-divert Kaituna River flow back into the estuary is the effect on water quality. Since the 1956 diversion, water quality in the lower Kaituna River has become degraded with respect to nutrient levels, faecal coliforms, chemical oxygen demand and algae. This is due in part to poorer water quality exiting Lake Rotoiti as well as discharges from AFFCO meat works and seepage into Waiari Stream from the Te Puke sewage wetland (McIntosh, 2005). Pastoral intensification in the Kaituna catchment over this time period has also led to increased nutrient, sediment and coliform concentrations entering the river from farm drains and diffuse runoff.

Maketu Estuary is reliant on high water quality to sustain its recreational use and shellfish gathering. Of principal concern are the high concentrations of fecal coliforms present in the Kaituna River (Park, 2003), which could render the estuary waters unsafe for shellfish consumption (Richmond *et al.* 1990) and recreational contact. Additionally an increase in plant nutrients, largely in the form of nitrogen and phosphorus, would elevate the trophic status of the Maketu and could lead to increases in nuisance algae growth such as *Ulva* (sea lettuce) which is common in Bay of Plenty estuaries (Rutherford *et al*. 1989).

2.3.2) Navigation at Te Tumu

The mouth of the Kaituna River at Te Tumu is currently used for boat access to the Bay of Plenty. A reduction in flow through the mouth could cause the mouth to silt up to a point of rendering it too shallow for boats to safely cross. Rutherford *et al.* (1989) reported that any flow less than 20 m^3s^{-1} at the river mouth could result in the mouth no longer being a viable boat access to the sea. Flows less than 10 m^3s^{-1} could mean the closure of the mouth at Te Tumu.

2.3.3) Flooding

In 1956 the Kaituna River was diverted out of the Maketu Estuary to reduce the effects of flooding on the surrounding land. It is likely that a re-diversion will result in an increased risk of flooding on the surrounding lands. To reduce this risk more stop banking around the estuary and lower river would have to occur at a considerable cost.

2.4) Consent granting to DOC for a partial re-diversion

On 7 February 1994, the Department of Conservation was granted consent by Environment Bay of Plenty to discharge 20,000 m^3 from the Kaituna River into the Maketu estuary via control gates at Fords cut (McIntosh *et al.* 1996). The main objectives of the partial diversion were for:

i. *The restoration of the spiritual and traditional values of the Maketu estuary to the Te Arawa people.*
ii. *Decrease of the salinity in the upper estuary to help restore the declining marsh area.*
iii. *Change the net tidal flow to help prevent the recent and rapid infilling of the estuary.*

(McIntosh *et al.* 1996)

In June 1998, monitoring showed that the classification (in respect to faecal coliform and shellfish samples) of the estuary waters had not been exceeded by the current consent so a new consent was granted allowing 100,000 m^3 per tidal cycle to be discharged (Park, 2003). The new consent required monitoring of bacteria (total coliforms, faecal coliforms, enterococci), nutrients (ammonium, nitrate, total nitrogen, dissolved reactive phosphorus, total phosphorus) and salinity over a tidal cycle during February of each year (Park, 2003). The consent also required a bacteriological quality of five shellfish samples to be measured annually. Currently, the only sample to exceed guidelines is a single sample of cockle in both 2001 and 2002 (Park, 2003).

Results of McIntosh *et al.* (1995), McIntosh *et al.* (1996), McIntosh *et al.* (1997) and Park (2003) show through measured data the diversion has reduced the salinity in the upper part of the estuary. However any post re-diversion reports were unable to conclude on whether the diversion was achieving its aims of reducing the infilling of the estuary or restoring the wetlands.

2.5) The future of the Maketu Estuary and lower Kaituna River

Environment Bay of Plenty (EBOP) is currently drafting a strategy plan for the Maketu Estuary and lower Kaituna River. Through community involvement, this plan aims to address how the lower river and estuary should be managed. As part of this strategy it allows the community and any interested parties to have input into the management. The proposed Rotoiti diversion wall also has implications for the estuary and river through changes to the nutrient and algae load flowing in the receiving waters of the upper Kaituna River.

2.6) Possible options for the ongoing restoration of Maketu Estuary

From the range of petitions and communication with local people, potential ideas of how to help restore the Maketu Estuary and work towards the aims intended for re-diversion (Section 2.4) have been suggested. From a numerical modeling perspective it is possible to evaluate a number of of these ideas. Option A, B and C are three options that through this study have been evaluated. Chapter Seven includes an in-depth methodology, results and discussion for each option. An overview of each option is given below.

2.6.1) Option A

The local community and long time users have long advocated the restoration of the Maketu Estuary to its 1956 pre-diversion condition. Many of these people believe that the only way for this to be achieved is for the entire flow of the Kaituna to be returned to the estuary. This option has been dismissed for a number of reasons, mainly because of concerns with water quality, flooding and closure of the mouth at Te Tumu (Richmond *et al.* 1986). Accompanying the returning of the river flow, it is also advocated that the location of the inflow needs to be returned to the historic location of Papahikahawai channel. Altering the location of the inflow has been modeled in this study.

2.6.2) Option B

In 1994, the re-diversion was granted resource consent to increase the freshwater flow into the estuary. However because of the close proximity of the structure to the tidal mouth of the river, Te Tumu, a varying proportion of the water flowing through the structure is of marine origin (McIntosh *et al.* 1996). It has been suggested that one way of increasing the ratio freshwater to marine going through the diversion structure may be to remove the island barrier in the lower river allowing more fresh water to flow around the old channel and into the Maketu.

2.6.3) Option C

The objective of this option would be to increase the flow through the control structure by increasing the number of culverts. This would bring about greater flushing of freshwater through the estuary. However it may cause water quality guidelines to be exceeded in the estuary, and cause boat navigation issues at the river mouth because of the reduced flows. The effects of increasing the freshwater discharge on the salinity and residual flows in the estuary are assessed.

2.7) Conclusion

In summary, historically the Maketu estuary was vastly different from its present configuration. Originally it received a high volume of freshwater from the Kaituna River and supported a wide range and marine life that was important in the diet of the local people. Now the estuary is much shallower and while freshwater flows have been partially returned to the estuary via control gates, the sediment is not being flushed out of the estuary and ecological variables such as salt marsh and pipi beds have yet to establish in the reduced saline environment. The changes in and around the estuary that have occurred since the 1920s are source of much local discontent and discussion with many people judging that the entire river flow needs to be returned to the estuary to achieve the goal of restoring the Maketu Estuary to its pre twentieth century state. However due to water quality, flooding and navigation issues a complete re-diversion is currently un-feasible.

Chapter three

Literature Review

3.1) Introduction

This study aims to assess a range of hydrodynamic and ecological issues in the lower Kaituna River and Maketu Estuary through the application of a coupled hydrodynamic-ecological model, ELCOM-CAEDYM. This chapter briefly reviews examples of applied hydrodynamic models in New Zealand estuaries and harbours together with several international applications of coupled models. A brief description of the numerical model ELCOM-CAEDYM is given, including a summary of previous applications. Eutrophication issues faced in New Zealand water bodies are discussed, including the common effects of eutrophication in rivers and estuarine environments. Emphasis is placed on the current understanding of primary controls on phytoplankton abundance in rivers and estuaries and how the model predictions of ELCOM-CAEDYM relate to these processes.

3.2) Eutrophication in New Zealand water bodies

Eutrophication is an increasing problem with serious implications for New Zealand's fresh, brackish and coastal waters. In recent years concerns have mounted over the increase in nutrients, sediment and other pollutants entering New Zealand water bodies. These contaminants are often derived from the surrounding catchment (Quinn *et al.* 2002) and associated with the expansion of human population in these zones (Hume *et al.* 1986; Cloern, 2001). Contaminants can be derived from various sources including farm runoff, human sewage, soil erosion, industrial waste and urban runoff (Quinn *et al.* 2002; Paerl, 2005). General implications of eutrophication on a water body include, fish kills, benthos smothering, increase in invasive aquatic weeds, algae blooms, shift from macrophyte to phytoplankton dominance (Hilton *et al.* 2006) reduced aesthetic values, the rendering of water unsafe for drinking and recreational use

(Chau, 2004) and increased oxygen demand which can lead to deoxygenated water (Vincent *et al.* 1984).

Contaminants entering an estuary or river from the surrounding catchment can vary from plant nutrients to heavy metals. Furthermore, it is acknowledged that elevated nutrients (White *et al.* 1978), sediment and faecal coliforms (Deely, 1997) all adversely affect the water quality and alter the ecology in the Kaituna River and Maketu Estuary. However through the use of a numerical model this study aims to quantify the macronutrients available for plant uptake, in the form of nitrate (NO_3), ammonium (NH_4) and phosphate (PO_4) and determine how these nutrients, plus the major hydrodynamic processes (residence time, temperature and salinity), influence phytoplankton growth in the lower Kaituna River and Maketu Estuary. Consequently water quality throughout this study is discussed in terms of plant nutrients and phytoplankton growth.

The effects of eutrophication in New Zealand's freshwater lake systems are well documented in the literature (Rutherford, 1984; Vincent, 1984; Rutherford *et al.* 1989b and Edgar, 1999). However, rivers and estuaries present a different set of hydrodynamic processes from that of a lake. Typically, rivers and estuaries found in New Zealand are characterised by low residence times and high turbulence. To give an example, the Waikato River which is the longest river in New Zealand has a residence time of ~26 days (Lam, 1981). Similarly the large (368 km^2) Manukau Harbour has an estimated residence time of 12–26 days depending on the harbour channel (Bell *et al.* 1998). In contrast, Lake Rotoiti has a residence time of 1.5 years (Vincent *et al.* 1984). Residence time has been shown to be important in pollutant and ecological studies (Hilton *et al.* 2006; Gibbs, 1993) as a low residence time may allow a system to flush out the nutrients/pollutants before adverse effects occur.

Some observed changes to New Zealand's rivers and estuaries can be attributed to human influence. Negative impacts include high rates of sedimentation, increase of aquatic weed, faecal contamination (Deely, 1997), loss of native vegetation, e.g. salt-marsh (Donovan, 1976) and changes in benthic sediment structure (Gillespie, 1990).

In a study of lowland rivers of New Zealand, Larned *et al.* (2004) revealed that water quality (plant nutrients, faecal coliform and clarity) was significantly reduced in rivers that received waters from developed catchments. Moreover negative impacts can persist well beyond the point that contaminants stop entering the river or estuary and in some systems the effects may not be reversible (Hilton *et al*. 2006).

3.3) Hydrodynamic process in estuaries and rivers

In addition to short residence times, estuaries also have their own unique set of hydrodynamic processes. Estuarine circulation is complex and a large number of external factors are important for determining the hydrology and circulation. These factors include rate of freshwater supply, tidal current speed, wind forcing and topography (Stigebrandt, 1988). Prichard (1955) devised one of the earliest classification schemes for estuarine circulation. This scheme was based on the relative ratio of freshwater inputs and classified an estuary from well mixed (low freshwater inputs) to highly stratified (large freshwater inputs). These conditions refer to the extent that the marine and fresh water mix. However, mixing in estuaries in not just controlled by the ratio of fresh to marine water but can also be influenced by wind, topography, current velocities and bottom friction (Kreeke, 1988). The extent of mixing in an estuary is not just important for determining the salinity; density gradients between the denser marine and fresh water can also cause residual circulation (Li *et al.* 1998). Typically, density driven residual circulation is characterised by net seaward flow of freshwater over top and a return flow of marine water underneath. The term given to flow imposed by density gradients is **baroclinic.** Forcing by tides, wind or freshwater inflows are termed **barotropic.**

Residual currents are the net circulation after tidal currents have been removed (Kreeke, 1998) and can be important for determining the health of an estuary (Stacy, 2001). This is because residual circulation in estuaries determines the net exchange of salt, water and other biological and chemically important materials (Kjerfve *et al.* 1981). Due to their significance, much effort has gone into predicting the strength and cause of estuarine residual flows from both a scientific and management point of view. Residual circulation can also be separated into baroclinic and barotropic flows. Studies have focused on using measurements to determine the role of these two terms, for example Sutton *et al.* (1997) and Li (1998). The cause of residual currents range from wind forcing (Bell, 1989; Geyer, 1997), density driven currents, bottom topography (Li *et al.* 1997) and freshwater inflows causing a seaward flow due to the imbalance in volume between flood and ebb tides (Kreeke, 1998). In most cases a combination of the described factors will result in an estuary's over all residual flow patterns (Kjerfve *et al.* 1988). The shallow environment of an estuary can also distort the tidal wave (O'Callaghan, 2005). This distortion, also known as 'overtides', can cause the ebb tide to persist over a greater period of time than that of the flood (Brown *et al.,* 1999) once again setting up a residual flow. Overtides can be identified by sawtooth or non-sinusoidal shape of the water elevation.

Flow dynamics in a river are characterised by high turbulence and strong velocities. These processes are import for keeping the large amount of sediment that rivers transport in suspension. In lowland rivers the strong velocities can cause a river to meander. Meandering is produced by the uneven distribution of cross river velocity causing erosion on one bank and deposition on the other (Yalin, 1992). The lower Kaituna River showed a typical meandering path prior to the river realignment in the 1980s (Figure 2.1). Intrusion of marine water up a river at the mouth is common. Because of the high volume of freshwater, stratified conditions at a river mouth will typically occur (Brockway *et al.* 2005). The extent of the intrusion and stability of the stratification depends on various factors including river flow, tidal range and river bed topography (Brockway *et al.* 2005; Liu *et al.* 2006; Peters, 1997).

3.4) Hydrodynamic numerical modelling

There are a wide range of numerical models available to simulate the hydrodynamics of various aquatic systems including: rivers, estuaries, lakes, reservoirs, coastal bays and the open ocean. Model complexity ranges from being able to solve in one-dimension (1D) through to three-dimensional (3D) models (refer Figure 3.1). Most common hydrodynamic applications use a two-dimensional (2D) model, either depth or width averaged for example Bell *et al.* (1998) and Heuff *et al.* (2005).

ELCOM, the hydrodynamic numerical model that has been applied to the Maketu Estuary and lower Kaituna River in this study uses a Cartesian 3D grid. The obvious advantage of a 3D grid over a 1D or 2D model is their capability to resolve in all three-dimensions. In geomorphologically complex areas where it is not appropriate to average in the longitudinal or lateral direction, then being able to resolve in the third-dimension (depth) is critical if the water body has a vertical structure (Drago *et al.* 2001). For instance, in a lake or coastal area where a thermocline (temperature driven stratification) is present. Estuaries and river mouths provide another particular situation where vertical structure is important due to density gradients that salinity differences impose (Pritchard, 1955).

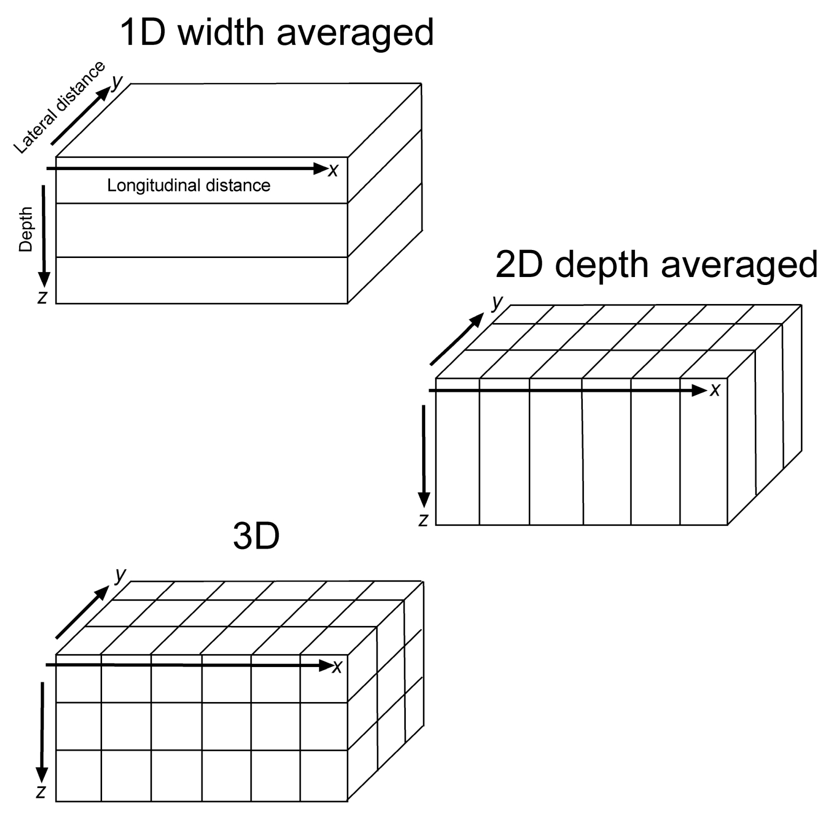

Figure 3.1. Illustration of the various configurations of grids for numerical models, ranging from being able to solve in one-dimension (1D) through to three-dimensions (3D). ELCOM, used in this study, employs a 3D Cartesian grid. Note: there are also various other configurations including 1D depth-averaged and 2D lateral-averaged and various ways of representing cells (i.e. do not need to be squares or evenly spaced).

3.4.1) Numerical modelling applications in New Zealand estuaries and harbours

Numerical modelling of New Zealand estuaries and harbours is limited to a small number of published studies. Heuff *et al.* (2005) investigated the effects of wind driven circulation and vertical mixing in Akaroa Harbour using a 2D laterally-averaged hydrodynamic model. Their model predictions compared well with 3 months of temperature and current data, and demonstrated the relationship between wind driven circulation and vertical mixing. However the Akaroa Harbour is much larger (44 km^2), deeper (maximum 25 metres), and has very little freshwater input compared to the Maketu Estuary. The Manukau Harbour is closer to the configuration of Maketu as it has large intertidal flats and significant contributions from freshwater inflow. Bell *et al.* (1998) set up and calibrated a depth averaged 2D hydrodynamic model of the Manukau Harbour to establish the dominance of tidal-over wind-driven circulation. Their study included a four-month field deployment to measure water elevation and current velocity at various locations inside and outside the harbour. The key findings of their modelling were that in the Manukau Harbour wind-driven circulation is greater on intertidal flats, and that tidal currents are too strong to allow any thermal stratification. However, again, the area and range of depths between Manukau (368 km^2 : 50 m) and Maketu (2.3 km^2 : 3 m) is large.

Three-dimensional numerical models have not been widely applied to New Zealand estuaries, harbours and rivers. An example of a 3D model applied to the open coast is Black *et al.* (2005). The aim of this modelling was to simulate the dynamics of a headland eddy. Model results were compared to temperature and velocity measurements at multiple locations over a six week period. To calibrate the the 3D model, a large amount of temperature and velocity data needed to be collected in both the horizontal and vertical directions over the model domain. This involved using Acoustic Doppler Current profiles and thermistor strings and represents a more intense field data programme than what would be needed for calibrating a 2D model. The 3D grid was vital in re-creating the observed current and temperature data, as the eddy had a large vertical as well as horizontal structure. Another New Zealand modelling application where a 3D grid was critical was the Procter *et al.* (1998) study in which they determined horizontal and vertical residual currents forced by baroclinic and barotropic circulation in the Pelorus Sound. Because the Pelorus Sound has a large freshwater input, creating vertical salinity stratification, both baroclinic and barotropic forces are numerically important, therefore in a geomorphologically complex region such as Pelorus Sound, the three-dimensional grid was critical in accurately modelling the circulation patterns.

3.4.2) Modelling applications in Maketu Estuary

In the past, four numerical hydrodynamic models have been applied to predict tidal and residual flow in the Maketu Estuary. The most complex of these models was a 2D depth-averaged model to determine the tidal and wind residual circulation associated with the 1996 partial re-diversion of the Kaituna River. The modelling undertaken in my study represents the first three-dimensional hydrodynamic model that can solve both baroclinic and barotropic terms, to be applied in the estuary and lower river.

One-dimensional MIKE 11 model

A 1D model was applied to the Maketu Estuary to assist in the interpretation of the effects associated with the 1996 re-diversion. The critical findings of this study included: that a diversion of up to 200,000 m^3 per tide was feasible; the diversion would increase net outflow at the Maketu Estuary mouth, salinity was likely to reduce in the upper estuary and cause stratification at times; the diversion would probably increase the salinity in the lower Kaituna River (Domijan, 2000; BOPRC, 1991).

Two-dimensional 3DD model

Incorporated in Domijan's (2000) thesis was a 2D depth-averaged hydrodynamic modelling (3DD) study of the Maketu Estuary. The aim of the model simulation was to compare tidal circulation in the estuary prior to and post the 1996 partial re-diversion. Model results were compared to water elevation and current speed at five locations throughout the estuary. This study provided the first good numerical investigation into the tidal and residual circulation of the estuary. Although the current configuration of the estuary mouth has changed since the 1995-1997 survey data used in Domijan's (2000) numerical modelling, which is likely to have affected the hydrodynamics.

3.4.3) Coupled hydrodynamic–biogeochemical models

The coupling of a hydrodynamic numerical model to ecological, chemical or water quality models is becoming more common for evaluating a range of management issues in estuaries and rivers. Globally 3D coupled models have been applied to a number of estuaries, harbours, lakes and rivers in an effort to predict a range of hydrodynamic, physiochemical and biological variables such as, Korpinen *et al.* (2004) The major advantage of coupling an ecological or water quality model to a hydrodynamic model is that it allows the user to link transport processes with biogeochemical cycles. In many situations the water quality is directly controlled by the system's hydrodynamics. Several examples of the application of coupled models where hydrodynamic variables have been important for determining water quality include: the effects of flushing times and salinity on phytoplankton growth (Robson *et al.* 2004), thermal stratification and nutrient dynamics (Burger, 2006), underflow of nutrient rich plumes in a freshwater reservoir (Romero *et al.* 2003) and effects of estuarine hydrodynamics on pollutant transport (Shen *et al.* 2004; Drago *et al.* 2000).

Increasing model complexity (3D and coupled models) introduces difficulties and complications to the user (and model developer) due to the added number of equations, parameters, rates and input variables needed. A range of problems associated with the application of 3D and coupled models include: the large range and amount of data needed to calibrate the model (Drago *et al.* 2001); a practical approach to sensitivity analysis of all ecological parameters may be virtually impractical (Romero *et al.* 2004) and the model simulation period is reduced due to the increase in model cells associated with three-dimensions. During the application of ELCOM-CAEDYM to the Maketu Estuary and Kaituna River, a key concern was the slow runtimes that occurred. ELCOM uses a Cartesian grid, meaning that the horizontal bathymetry is represented by fixed squares or rectangles (Figure 3.1). Cartesian grids typically need more cells than boundary fitted (curved) grids (Hodges *et al.* 2001), resulting in a reduction of the model speed. One technique developed to increase the model speed of Cartesian grids is to straighten the bathymetry (Hodges *et al.* 2001) allowing the user to use bigger grid sizes. This technique applied to ELCOM has worked well in a number of applied cases, for example Romero *et al.* (2003), Robson *et al.* (2004) and Romero *et al.* (2004). However 'straightening' of the bathymetry can only be applied when longitudinal channels dominate, i.e. a 'long and thin' model domain like the Kaituna River.

3.4.4) Estuary and Lake Computer Model (ELCOM)

The following description of ELCOM is referenced from Hodges *et al.* (2000) and Hodges *et al.* (2001b). ELCOM is an example of a 3D hydrodynamic model that through this research has been applied to the Maketu Estuary and lower Kaituna River. ELCOM is made up of a hydrodynamic and thermodynamic model which can simulate the temporal behaviour of stratified water bodies with environmental forcing. ELCOM solves the unsteady hydrostatic, Navier-Stokes, Boussinesq, Reynolds-averaged and scalar transport equations. The hydrodynamic algorithms in ELCOM are based on the Euler-Lagrange method for advection of momentum with a conjugate-gradient solution for the free-surface height. The passive and active scalars (i.e. tracers, salinity and temperature) are advected using a conservative ULTIMATE QUICKEST discretization. Heat exchange through the water's surface is governed by standard bulk transfer models. The grid used in ELCOM is based on rectangular Cartesian cells with fixed Δx and Δy (horizontal) grid spacing, whereas the vertical Δz spacing may vary as a function of z but must be horizontally uniform.

3.4.5) Computertation Aquatic Ecosystem Dynamics Model (CAEDYM)

The following description of CAEDYM is referenced from Hipsey *et al.* (2006). An advantage of ELCOM is its ability to be easily coupled with CAEDYM. CAEDYM is an aquatic biogeochemical model and can be run independently or coupled with the hydrodynamic model DYRESM (1D) or ELCOM (3D). CAEDYM consists of a series of mathematical equations representing the major biogeochemical processes influencing water quality. CAEDYM can simulate up to seven phytoplankton groups and includes comprehensive process representation of nitrogen, phosphorus, carbon, silica and oxygen dynamics/transport. In addition to this CAEDYM can model a wider range of biological parameters including macrophytes, zooplankton, jellyfish, finned fish and benthic invertebrates making CAEDYM more advanced than traditional nitrogen-phosphorus-zooplankton models.

CAEDYM's configuration is flexible so that the user can focus on the processes of interest and at a level of complexity that is suitable. This makes CAEDYM universally applicable to many situations and this is reflected in the hundreds of lakes, reservoirs and estuaries it has been applied to globally. Publications using ELCOM-CAEDYM have included modelling water quality, pollution transport and phytoplankton. For examples refer to Chan *et al.* (2002), Romero *et al.* (2003), Romero *et al.* (2004), Robson *et al.* (2004) and Spillman *et al.* (2007).

3.5) Phytoplankton dynamics in river and estuarine systems

In this study the relative growth rate of four phytoplankton groups in the lower river and estuary are predicted by the numerical model ELCOM–CAEDYM. The phytoplankton groups were chosen to represent the species that would be typical of temperate marine water (marine diatoms and dinoflagellates), and present in an outflow from a eutrophic lake (freshwater diatoms and cyanobacteria). Phytoplankton are autotrophic (primary producers), and are present in almost every fresh, marine and brackish water body globally, consequently they contribute substantially to overall primary production (Day *et al.* 1989). However rapid growth of phytoplankton can cause nuisance blooms to occur. Blooms of phytoplankton are an aesthetically negative impact of eutrophication (Hilton *et al.* 2006) and can be hazardous to human and animal health (Hamill, 2001) and occur in the Rotorua Lakes. A general prerequisite for high phytoplankton growth rates is elevated plant nutrients and calm (low turbulence) weather conditions (Pinckney *et al.* 1999). However nutrient concentrations alone can provide a poor predictor of phytoplankton biomass in an estuary as other factors contribute to growth rates (Pinckney *et al.* 1999). Before considering ELCOM-CAEDYM's predicted growth rates, it would be useful to understand the variables that control phytoplankton growth in river and estuary environments and which of these processes are represented in the coupled numerical model ELCOM-CAEDYM.

The river and estuarine hydrodynamic processes that can dominate nutrient and pollutant dynamics (low residence time) also influence the phytoplankton abundance in these systems (Ferreira *et al.* 2005). Reynolds (1984) estimated that if a river has residence time of less that 2–3 times that of an algae cell's doubling rates, then the chance of nuisance concentrations of algae will be minor as the algae will be flushed out more quickly than they can grow. If we take Reynolds's (1984) assumption to an extreme case in New Zealand rivers, the Waikato River (residence time of 26 days), then we may expect some relatively high phytoplankton concentrations by the time the water reaches the river mouth. Lam (1981) reported a correlation between phytoplankton numbers and downstream distance in the Waikato, but nothing near the concentrations expected using Reynold's (1984) assumption. This is because, variables other than nutrients and residence time present in an estuarine or river environment can add complexity to phytoplankton growth in a river (Hilton *et al.* 2006) or estuary (O'Higgens *et al.* 2005). Other variables that can influence growth rates include: available light and euphotic depth (Vant *et al.*, 1993); predication on phytoplankton by predatory zooplankton and bivalves (top-down grazing) (Lewituz *et al.*, 1998; Gallegos, 1996) and temperature.

The variables that effect phytoplankton dynamics in a river also influence phytoplankton abundance in an estuarine environment. However, in an estuarine environment there is one other important variable – salinity. Variation in salinity can have a profound effect on the phytoplankton growth rates and biomass (Day, *et al.* 1989; Kirst, 1990; Floder, 2004). In general, freshwater species cannot tolerate saline conditions and marine species cannot tolerate reduced salinities associated with freshwater inflows as illustrated in Figure 3.2. Because estuaries are essentially the boundary where freshwater meets marine water, salinity limitations on both marine and freshwater species of phytoplankton can be significant (Day *et al.* 1989). For marine species of phytoplankton the mixing of marine and freshwater presents a conundrum in many estuarine environments. This is because marine species growth rates often demonstrate a good correlation with nutrient rich coastal plumes derived from riverine inputs for example, Haywood (2004) and Spillman (2007). However in an estuary with significant freshwater inflows, some degree of mixing will occur, resulting in salinity limitations on marine phytoplankton. Estuarine species of phytoplankton have a broader salinity tolerance (Dey *et al.* 1998). The phytoplankton group dinoflagelattes represent the estuarine species used in this study that have broader salinity tolerance. For the phytoplankton salinity parameters used in CAEDYM for this study refer to Appendix 1.

3.5.1) Phytoplankton representation in ELCOM-CAEDYM

The particular combination of factors explained above, affecting phytoplankton growth rates and biomass is unique for any estuary (O'Higgens *et al.* 2005) and can vary within an estuary producing measurable spatial variations or 'patchiness' of phytoplankton biomass (e.g. Gibbs, 1993; Vant, 1993; MacKenzie *et al.* 2004). Through this study ELCOM-CAEDYM predicts variations in the phytoplankton concentrations of four phytoplankton groups caused by temporal and spatial variations in light intensity, water temperature, salinity, hydrodynamics (residence time and turbulence) and nutrients (NO_3, NH_4 and PO_4). Equation 3.1 demonstrates a simplified version of how these variables are represented in CAEDYM to determine the growth of phytoplankton (μ_g) per day, where μMAX is the maximum growth normalised to 20^{o}C (Appendix 1) and $f(I)$, $f(N)$, $f(P)$, $f(Si)$ and $f(T)$ represent limitation by light, nitrogen, phosphorus, silica[1] and temperature respectively. Simply put, the growth rate is determined by the maximum growth rate scaled by the limiting factor and multiplied by a temperature function. R is the loss term in the model and includes the combined effects of respiration, natural mortality and excretion, and includes a respiration function for salinity $f(S)$. For model simulations in the estuary and river, nitrogen (*N*) is represented by ammonium (NH_4) and nitrate (NO_3), and phosphorus (*P*) is represented by phosphate (PO_4). A simple relationship of growth rate and nutrients, salinity and temperature is given in Figure 3.2 derived from Dey *et al.* (1989).

$$\mu_g = \mu MAX\left(\min[f(I), f(N), f(P), f(Si)]\, f(T)\right) - R \qquad (3.1)$$

[1] Only applies when simulating diatoms

The other major expression affecting phytoplankton abundance are vertical migration, settling and resuspension. Vertical migration and settling rates are important for defining where a phytoplankton cell is in relation to the compensation depth (illustrated on Figure 3.3), as respiration (loss) will exceed photosynthesis (growth) below this depth. Types of vertical migration can be set differently within the model and are important for two reasons (a) defining where a cell is in relation to the compensation depth (b) settling of phytoplankton out of the water column into the sediment. CAEDYM has different algorithms to represent these processes which can vary between species, for example cyanobacteria can be modelled with a buoyancy term and diatoms have negative buoyancy so rely on mixing to keep them suspended in the water column. Residence time affects growth rates by simply limiting the amount of time a phytoplankton cell spends in the model domain. Included in the CAEDYM sub routines, but ignored in simulations in the Maketu Estuary and Kaituna River, is grazing pressure by predatory zooplankton and bivalves, and forms of detrital particulate organic nitrogen and phosphorus. A simplified estuarine or river environment is illustrated in Figure 3.3, which shows how CAEDYM variables interact with a phytoplankton cell as part of the computation of phytoplankton biomass. For a more complete reference of CAEDYM processes refer to Hipsey *et al*. (2006).

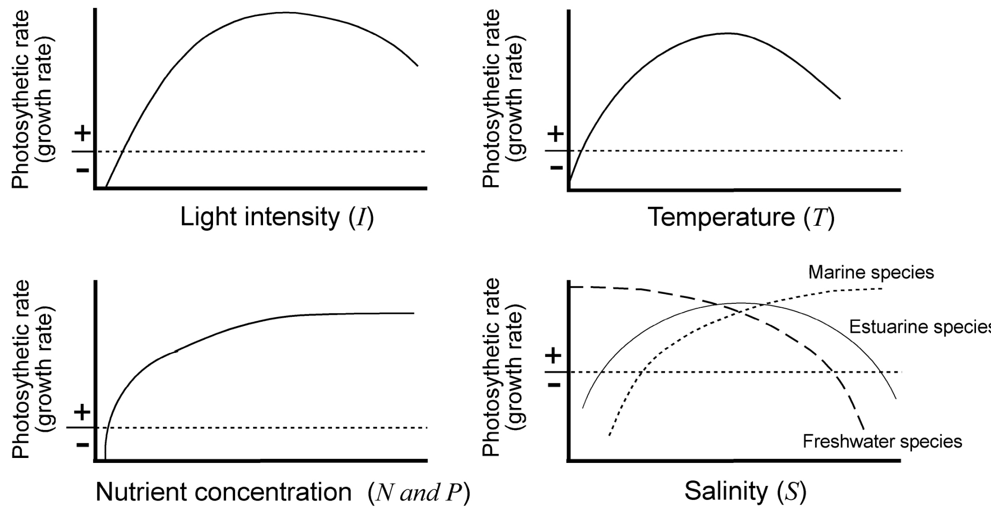

Figure 3.2. Relationship between light intensity, temperature, nutrient concentrations, salinity and phytoplankton growth. The four variables (and others) were simulated in CAEDYM runs in the Maketu Estuary and Kaituna River to predict the phytoplankton growth.

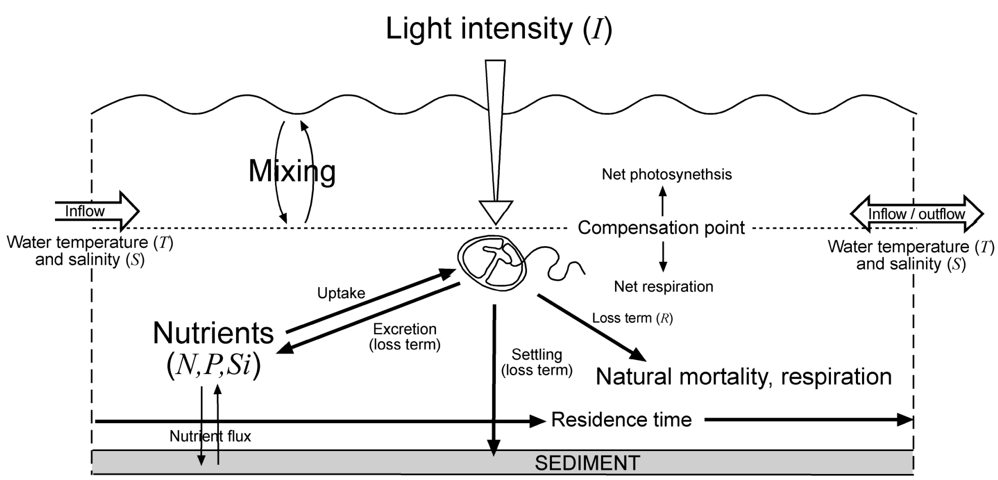

Figure 3.3. Variables affecting the growth and loss of phytoplankton in an idealised estuarine or river environment. Grazing is the only process shown but not included in simulations in the Maketu Estuary and lower Kaituna River.

Chapter Four

Bathymetry

4.1) Introduction

Precise bathymetry measurements are one of the most important elements for the accurate solution of numerical models (Ramming *et al.* 1980). Not defining correct bathymetry data for a given domain can lead to large errors in the hydrodynamics and cause endless difficulties in the calibration and validation. A number of techniques were used to collect and process bathymetry data for the lower Kaituna River and Maketu Estuary and these techniques are described in this chapter.

4.2) Kaituna River

The region of interest for this study extended from Te Matai gauging station (NZMS 260 U14 064773) to the river mouth at Te Tumu (NZMS 260 V14 110773) covering a total length of ~11 km (Figure 4.1). Prior to this work the most recent bathymetry data for this region were a number of cross sections made in the river over three years up to January 1995 (Tichmarsh *et al.* 1996). To accurately represent the lower river bathymetry in the numerical modeling undertaken in this study, a series of depth sounding and corresponding horizontal coordinates were measured over two days in June 2006. After obtaining the bathymetry data, the modeling domain was condensed to ~8 km (Figure 4.1) to increase the model's speed.

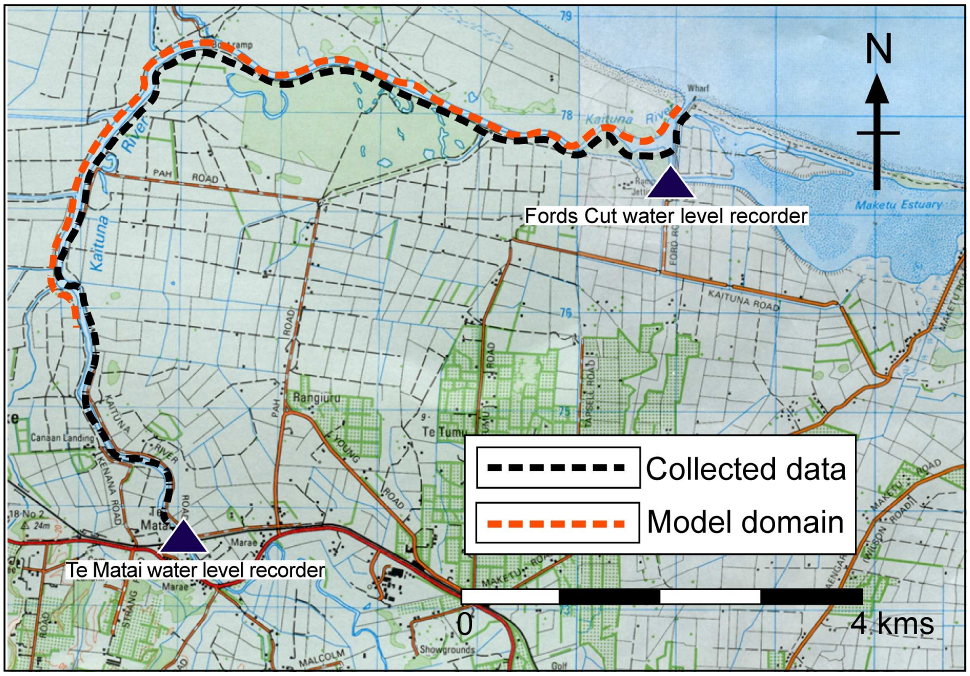

Figure 4.1. Map of the lower Kaituna River illustrating where bathymetry data was collected (dashed black line) and the final modeling domain (dashed red line). Also illustrated is the water level recorders at Te Matai and Fords Cut. (Source: LINZ, 2006).

Depth soundings for the Kaituna River were collected on the 8th and 20th of June 2006. Horizontal location measurements where obtained using a Garmin Etrex™ GPS and depth measurements relative to instantaneous water level were obtained with an Eagle Cuda™ echo sounder. A small power boat was used to navigate the river as measurements were collected along transverse lines as the boat progressed up the river (Figure 4.2). To define the boundaries of the river, a series of regular spaced horizontal position coordinates on the edge of the river bank were also collected using the GPS.

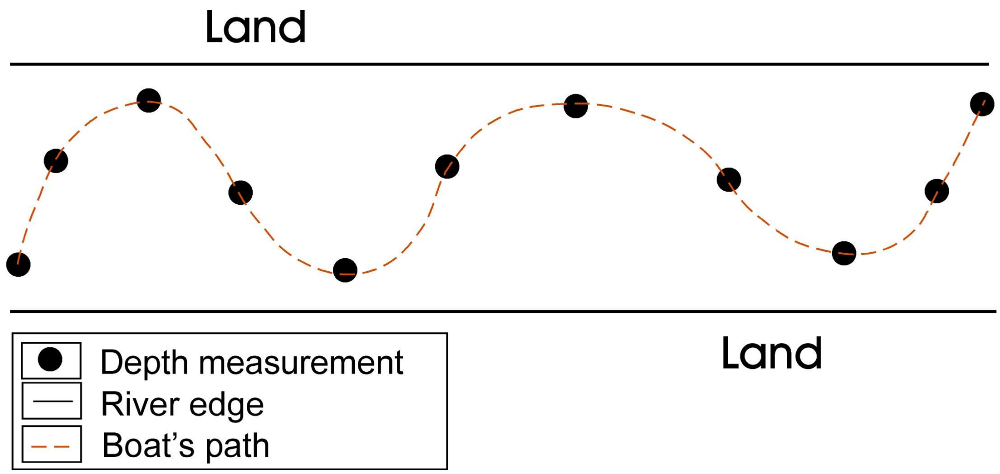

Figure 4.2. A schematic illustrating the sampling strategy for collecting depth soundings in the lower Kaituna River.

To obtain accurate river bed bathymetry relative to a datum, the measured water depths needed to be corrected for changes in water level. The water level in the lower Kaituna River is controlled by two factors (a) the tidal level forced at the river mouth and (b) river flow. Environment Bay of Plenty (EBOP) operates two water recorders referenced to Moturiki datum in the lower Kaituna River. The recorders are positioned at either end of the river domain at Fords Cut (NZMS 260 V14 110773) at (x_0), where x is up-river distance, and Te Matai gauging structure (NZMS 260 U14 064773) at (x_{us}) (Figure 4.3). It was assumed that spatial changes in water level between the two recorders were linear therefore the adjustment (ζ) needed to correct the measured water depth $(\hat{d})$ at time (t) to a common datum $(d = 0)$ can be calculated by equation (4.1). Figure 4.3 illustrates the parameters used in equation (4.1), (4.2) and (4.3).

$$d(x_i) = \hat{d}(x_i, t) + \varsigma(x_i, t) \tag{4.1}$$

$$\varsigma(x_i, t) = m(t)x_i + \varsigma(x_0, t) \tag{4.2}$$

$$m(t) = \frac{\varsigma(x_0, t) - \varsigma(x_{us}, t)}{x_{us} - x_0} \tag{4.3}$$

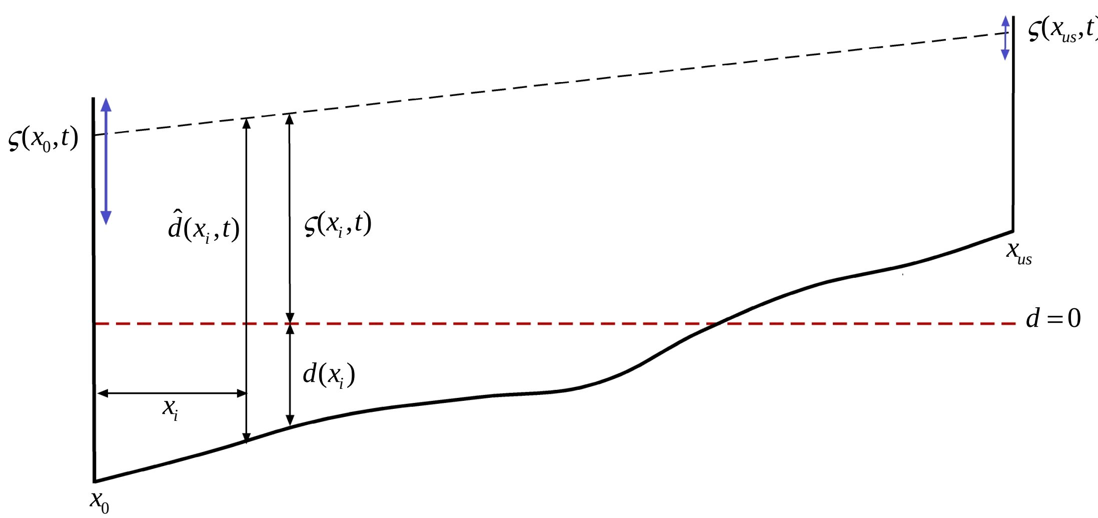

Figure 4.3. Schematic illustrating the variables in equation (4.1), (4.2) and (4.3) used to correct the instantaneous water depths in the lower Kaituna River to a common datum (Moturiki).

Golden Software's SURFER™ was used to grid the bathymetry of the river domain. The major advantage of using SURFER™ over similar gridding routines such as MATLAB was the ability to easily blank out-of-water or non-useful cells. The blanking cell function enables the user to automatically exclude (or include) all points within a given boundary. A blanking cell was created from the river boundary coordinates collected during the field program. SURFER™ allows various configurations and gridding methods. The kriging method was chosen with a search radius of 150 metres to grid the Kaituna River bathymetry. In a study of river gravel beds kriging was considered the best method as it aims to minimize the residual variance of the grid (Carter *et al.* 1997).

The optimal grid size is a compromise between model runtime and spatial resolution. Because of the high length to width ratio of the river and the Cartesian grid, if grid cells are too large, they may only be connected by grid corners at locations were the river bends sharply. This results in a flow blockage in the model and ultimately sets a maximum limit on the grid size. There is a method available to straighten out river bathymetry (Hodges *et al.* 2001) but is a mathematically difficult and time consuming process because the flow dynamics at the river bends must be conserved. A 20 × 20 meter grid was chosen for model simulations of the lower Kaituna River as it gave the best resolution while allowing acceptable runtime ratios. The final bathymetric data are illustrated in Figure 4.4 at a 20 × 20 meter horizontal resolution.

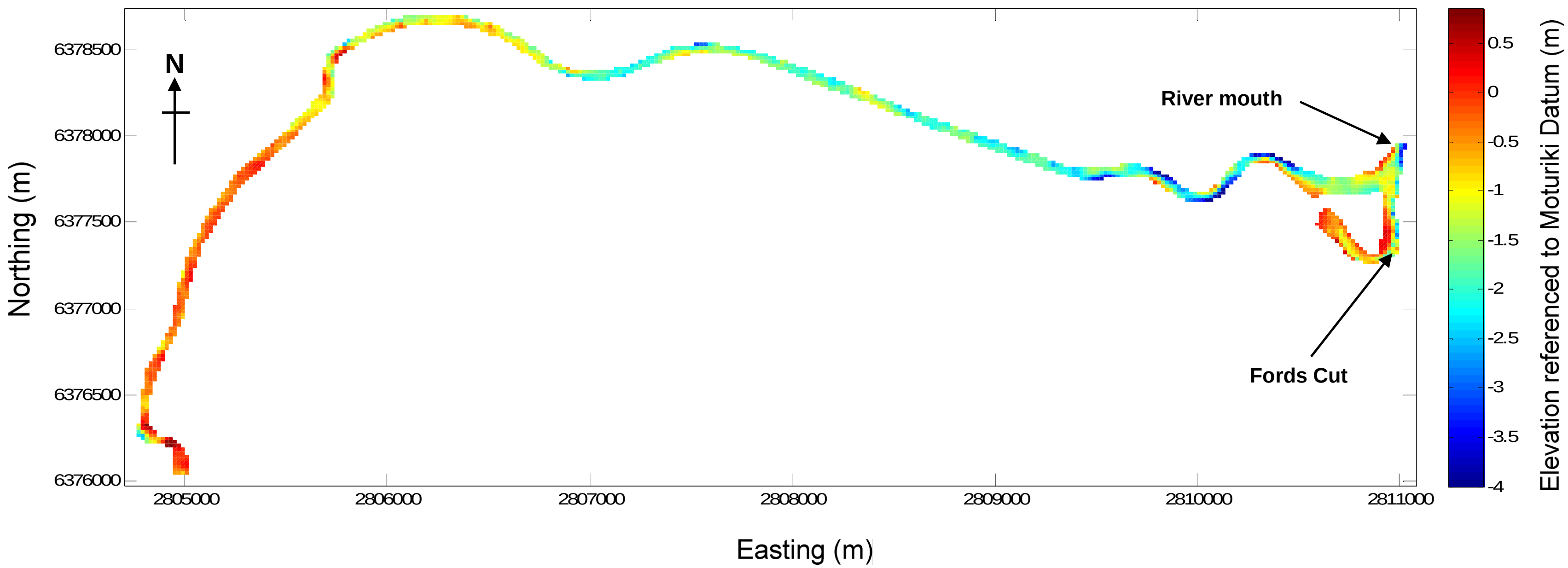

Figure 4.4. Kaituna River bathymetry. 20 × 20 meter grid referenced to Moturiki datum (mean sea level).

4.2.1) Error estimates

In collecting and adjusting the data to create a bathymetry map of the Kaituna River a number assumptions were made and a number of systematic errors introduced. The associated errors are briefly outlined below.

Accuracy of the Garmin Etrex GPS

The Etrex GPS which was used to collect the horizontal coordinates displays an approximate accuracy when turned on. Regular checks of the error were made during field work with an estimated error of 4–7 metres.

Accuracy of the echo sounder

Echo sounders rely on accurate representation of the speed of sound in water. The speed of sound is affected by density therefore an error is introduced when measurements are taken in saline and fresh water due to salinity differences. The echo sounder displays depth readings to one decimal place (0.1 m). Therefore an estimate of the accuracy during the field measurements is ± 0.2 metres.

Linear assumption

When correcting the measured values to the Moturiki datum, it was assumed that the water level changes between Ford Cut and Te Matai were linear.

4.3) Maketu Estuary

The most recent and comprehensive bathymetry survey of the Maketu Estuary was completed by Domijan (2000) in October 1995 and February 1997. The survey involved using both a jet ski and logging echo sounder (1997) and land based (1995) surveying techniques. EBOP has also surveyed a number of cross sections through the Maketu Estuary, but this information was not retrievable from the EBOP archives.

The Maketu Estuary channel morphology is known to change over short time scales. Visually comparing areas of the present morphology to a chart of the 1995/97 survey revealed some major differences. The most notable change is the position of the estuary mouth, from 1995-97 the mouth was located ~300 m to the west. By 2004 the mouth had advanced back to the headland where it is currently located as shown in Figure 4.5.

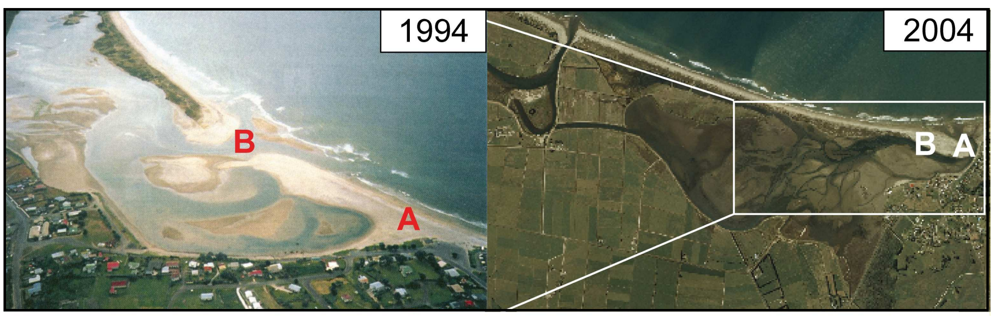

Figure 4.5. Aerial view of the Maketu Estuary depicting the changes in mouth location. (A) The current location of the mouth. (B) The 1995–97 location of the mouth. Also note the associated changes in sand banks around the estuary mouth. (Photo source: Domijan (2000) and EBOP RDAM (2004))

4.3.2) Bathymetry survey for this research

Due to the overall shallowness and complex nature of the intertidal channels present in the Maketu Estuary, a full boat or land based survey would have been outside of the scope of this study. Therefore the bathymetry data for this research were comprised of the historic bathymetry data collected during 1995/97, a RTK survey and video-based survey.

4.3.2.1) Previous bathymetry data

Two distant areas in the southern and western side of the estuary dominated by broad sand flats and low tidal velocities were identified (Figure 4.7). At the commencement of this study, visual comparison of these two areas to a chart of the previous survey revealed little change in channel morphology. Therefore, in these two regions, the 1995/97 survey data was integrated into the bathymetry used in this research.

4.3.2.2) RTK survey

RTK (Real Time Kinetic) is a GPS (Global Positioning System) survey based system that allows very accurate horizontal and vertical measurements to be acquired. During data collection, each point must be referenced to the estuary bed. For shallow or intertidal water bodies such as the Maketu Estuary, this can be achieved by two methods:

i. Approximately 2 hours either side of low tide, access to the intertidal sand flats was obtainable, at which time it was possible to mount the RTK antenna on the backpack and walk over the sand flats.
ii. Approximately 2 hours either side of high tide, water depth was sufficient to deploy a small boat in the estuary to measure the estuary bed morphology with the RTK antenna mounted on a pole (Figure 4.6).

Surveying the entire estuary using RTK would take weeks and was beyond the scope of this research. Therefore to best use the time available with RTK, it was limited to two key areas: (a) the estuary entrance and main channels located around the entrance; (b) The main western channel from Fords Cut to where it detaches from the southern bank as shown in Figure 4.7.

Figure 4.6. Obtaining an RTK-GPS survey point on a sand flat in the estuary using a small boat an hour after high tide.

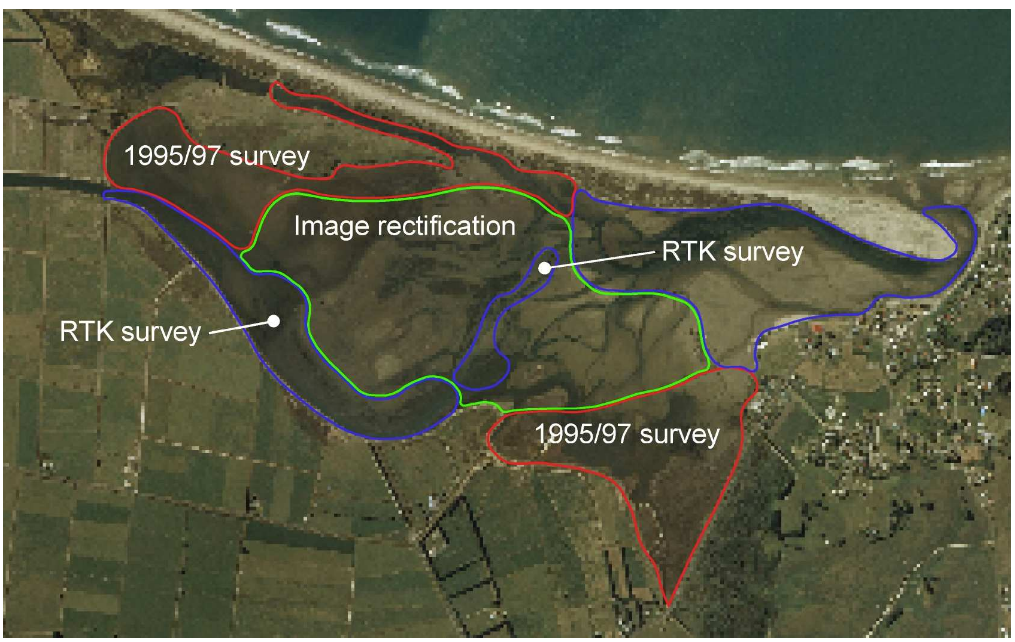

Figure 4.7. Regions over which different techniques were applied to collect bathymetry data of the Maketu Estuary. (Photo source: EBOP RDAM (2004))

4.3.2.3) Image rectification

For the morphologically complex central area of the estuary, image analysis techniques were applied to obtain some proxy depth points of the intertidal flats that could then be integrated into the bathymetry grid used in this study. Image analysis entails taking to take a two-dimensional digital picture correcting it for distortions caused by lens imperfections and then converting it into real-world three-dimensional co-ordinates (Aarninkhof *et al.* 2003) from which measurements can be made. This technique has been successfully applied to the near shore environment to measure, for example wave run up and bar dynamics (Lippmann *et al.* 1990; Alexander *et al.* 2004).

Generating bathymetry data using image rectification involves taking a series of pictures over a tidal cycle from an elevated point above the region of interest (Morris *et al.* 2007). By digitizing and rectifying the water–sand bank interface on each image, and knowing the water elevation at the time the image was taken, a series of proxy depth soundings can be built over the tidal cycle. These points can then be gridded using standard techniques.

Image rectification was used to acquire the bathymetry for parts of the estuary where the sand bank geometry was too shallow and complex to make more traditional methods feasible. The most elevated point surrounding the estuary is located to the west of the estuary (Figure 4.8). However, from this location areas of the western, northern and southern regions of the estuary are obscured by vegetation and houses in the foreground. The eastern region of the estuary would also be difficult to obtain accurate definition between land and water boundaries because of the diminished angle between the camera and estuary. Therefore image techniques could only give realistic results for the middle section of the estuary where an un-obstructive view and high resolution was achievable (Figure 4.7).

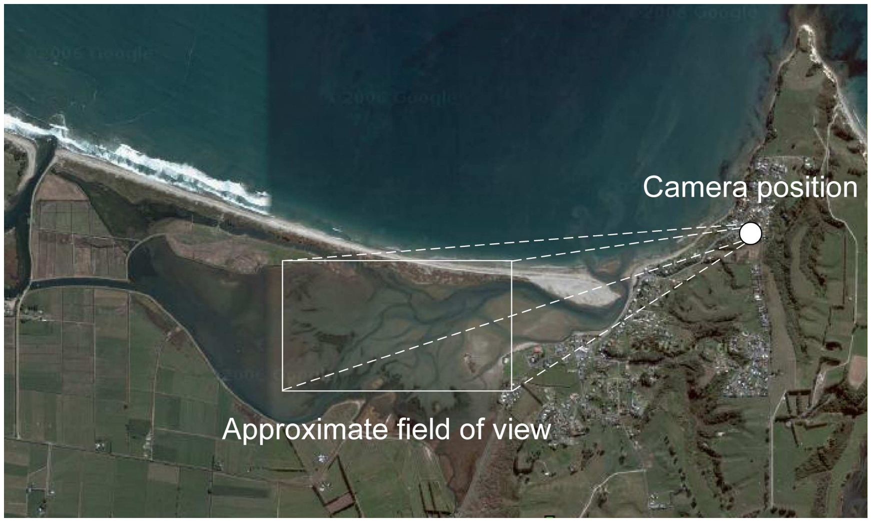

Figure 4.8. Aerial photo of the Maketu Estuary depicting the camera position and approximate area of estuary were image rectification was plausible. (Source: Google Earth, 2006)

To convert the oblique two-dimensional images into real world ground co-ordinates a number of transformations and distortion corrections needed to be made as outlined below:

Ground Control Points

Precise rectification of the images requires accurate ground control points (GCPs) spread over the frame of reference that can be later identified in the images (Siegle *et al*. 2006). For this study the GCPs were obtained using RTK survey system (Section 4.3.2.2) allowing an accurate fix on a number of points visible in each image. The GCPs consisted of Maimais in the estuary, corners of houses and large trees; in total at least 9 points where used for each image rectified.

Lens calibration

To rectify the images, a number of internal camera parameters must be known, the focal length, optical centre of image and lens distortion coefficients. Focal length and distortion coefficients can be estimated by calibrating the camera lens. Lens calibration involves taking images of a uniform 'checker board' grid pattern from multiple angles and heights. The images are then loaded into a MATLAB routine[1] which automatically extracts the grid coordinates from the images to estimate the

[1] MATLAB toolbox. Downloaded from www.vision.caltech.edu/bouguetj/calib_doc/index

focal length, optical centre and distortion of the lens. Figure 4.9 illustrates the lens distortion and optical centre of the camera used in this study.

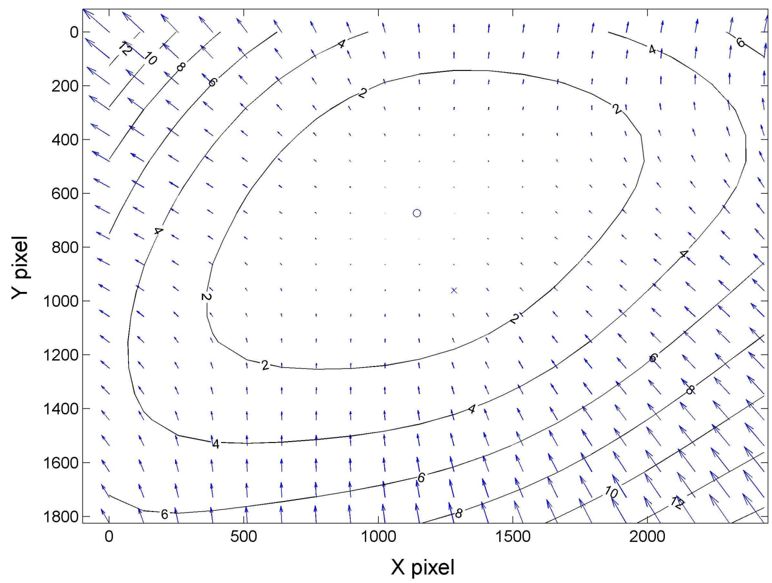

Figure 4.9. Illustration of lens distortion and optical centre of the camera used to take images of the Maketu Estuary. Optical centre is illustrated as a ring and differs from the central pixel coordinate (×). The length and direction of each arrow corresponds to the size and direction of the discrepancy between pixels before and after the un-distortion routine has been applied. The contours correspond to the magnitude of the distortion in pixels.

4.3.3) Errors and error estimates

For the image rectification it was assumed that the water surface in the region being rectified was level and relative to Moturiki datum. However assuming a spatially level water surface is often an invalid assumption in tidal inlets where pressure gradients are present (Siegle *et al.* 2006). To define the water elevation relative to the datum for each rectified image, pressure measurements were converted into depth using the hydrostatic assumption. The pressure sensor was located approximately in the centre of the image rectification area. Analysis of our water elevation measurements from the spring tide deployment (not presented) suggested that in the region we were rectifying, water elevation could vary spatially by up to 0.2 metres due to estuary channel and mouth flow restrictions. Therefore a vertical error in the rectified images of ± 0.2 m could be assumed.

A horizontal error can be estimated by the differences between the rectified pixel coordinates and the actual locations of ground coordinates (GCPs). A worse fit indicates a larger error and more uncertainly in the accuracy of the final rectification. All our rectified images had an average error of ~10 metres.

4.3.4) Gridding method

The bathymetry data for this study consisted of three different methods of collection over a range of time scales with different degrees of accuracy (Section 4.3.2.1, 4.3.2.2, 4.3.2.3). Due to points from different collection methods spatially overlapping, priority in gridding needed to be given to points that were the most recent and had the greatest accuracy. The order of priority was RTK >> image rectification >> 1995/97 survey, Figure 4.10 shows the distribution of the points used in gridding the final bathymetry map. The points were gridded in SURFER™ using a blanking cell for regions that were above the high water mark. The final bathymetry is illustrated in Figure 4.11 as a 15 × 15 meter grid used in model simulations.

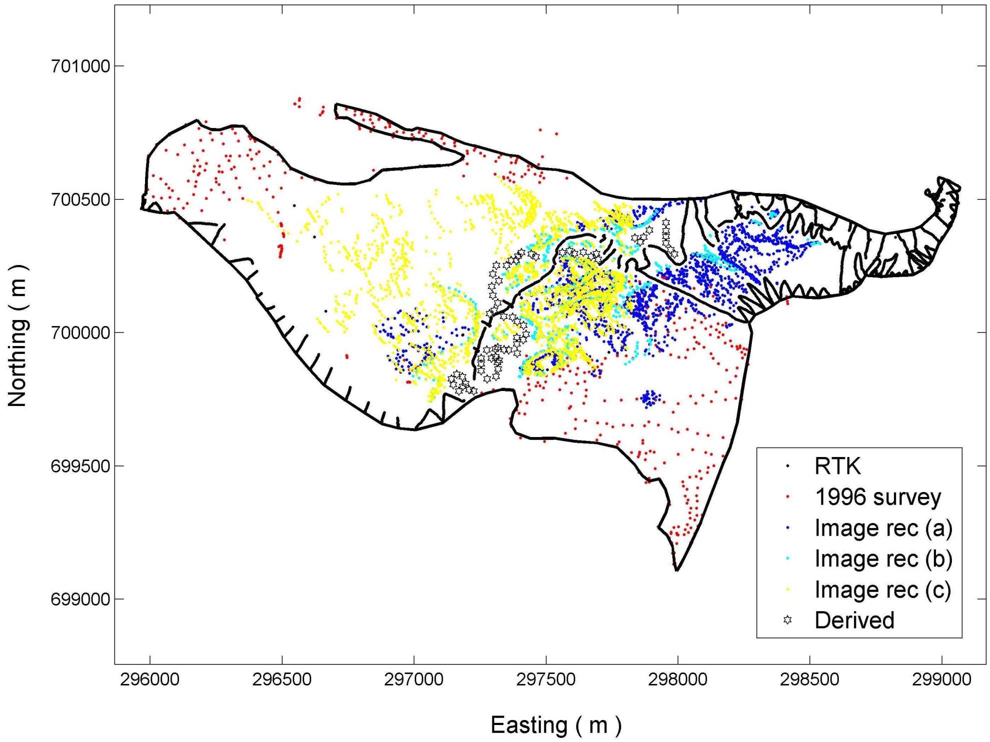

Figure 4.10. The horizontal coordinates of the points used in gridding the final bathymetry map of the Maketu Estuary. Three sets of image rectification points are shown (a, b, c). Images for points (a) were taken on the 18th August. Images for points (b) and (c) were taken on the 4th September over two camera angles. Derived points are from the centre of the major channels which are below low water mark on the day the images were obtained and therefore in these areas the channel bed was not exposed in any of the images. The depth at these points was set to the closest RTK point. Note: horizontal coordinates are referenced to Bay of Plenty Meridional Circuit Geodetic Datum 1949.

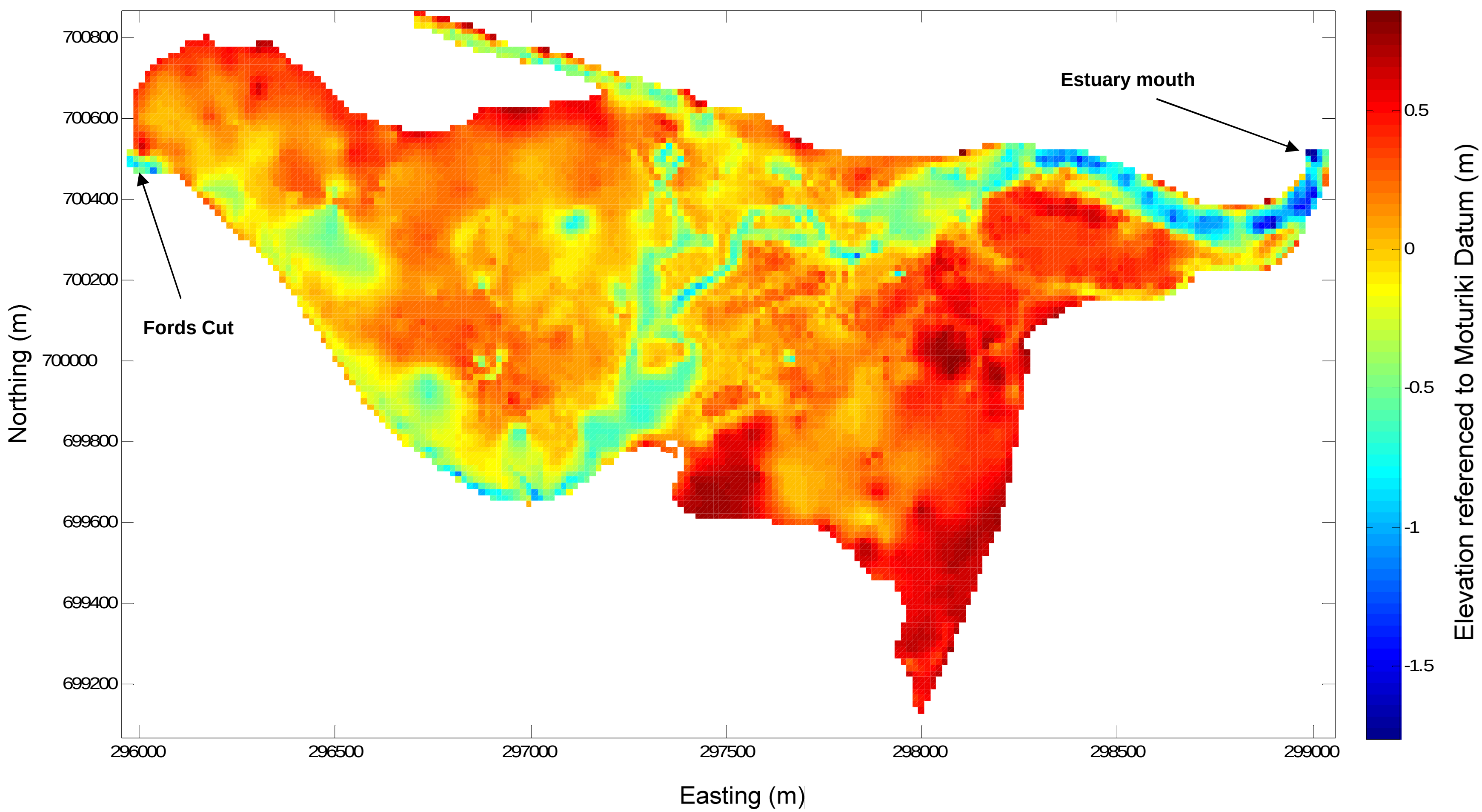

Figure 4.11. Maketu Estuary Bathymetry. 15 × 15 meter grid referenced to Moturiki Datum (mean sea level).

4.4) Conclusion

The bathymetry data presented in this chapter is critical in determining the accuracy and reliability of the numerical modeling undertaken in this study. A range of different techniques were used to collect and create a bathymetric grid of the lower Kaituna River and Maketu Estuary. For the Maketu Estuary, the most accurate technique was RTK. However due to time constraints with the RTK it was limited to the critical areas of the estuary including the estuary mouth and main channels. Imaging techniques were applied to the central region of the estuary and represented the major channels well, although due to the errors and limitations of the technique, the smaller intertidal channels and bed bathymetry below the low water mark were not able to be represented in the final bathymetry grid. The 1995/97 survey data proved invaluable in the regions where data had not been collected during this research, with observations showing little change in elevation and channel morphology over the past decade had occurred in these areas. The bathymetry data collected for the lower Kaituna River was critical for this research, as previous to now no complete bathymetry data set was available.

Chapter Five

Hydrodynamic modelling of the Maketu Estuary and lower Kaituna River

5.1) Introduction

The Maketu Estuary experiences a wide range of tidal currents and residual circulation both within the estuary's defined channels and on the tidal flats, creating complex hydrodynamic flows. To complicate the hydrodynamics further, freshwater inflows and meteorological conditions can also affect the circulation within the estuary (Domijan, 2000). The lower Kaituna River has undergone large engineering developments over the past six decades (refer Chapter Two for details). The modifications have resulted in substantial changes to the lower river's flow regime. The hydrodynamic numerical model ELCOM offers the ability to predict the hydrodynamic flows and scalar (i.e. salinity) transport within an estuary or river.

This chapter explains how the hydrodynamic model ELCOM was initialised and applied to both modelling domains (Maketu Estuary and lower Kaituna River) and validated against field measurements Calibration and validation results are discussed and the current hydrodynamic situation in the lower river and estuary is described. Problems and advantages of applying a 3D model (ELCOM) to the lower river and estuary are also discussed.

5.2) Data collection

Hydrodynamic data for this study were primarily used for (a) setting boundary conditions within the model and (b) model calibration and validation. The type of data needed for each domain (estuary and lower river) is described. Sections 5.3, 5.5 and 5.6 explain how the data were collected and applied to each boundary and used for model calibration and validation.

5.2.1) Lower Kaituna River

For the lower Kaituna River, flow, river stage (height), and water temperature variables were sourced from Environment Bay of Plenty's (EBOP) monitoring data archives. EBOP monitoring provided data for the Kaituna River at Te Matai, the Kaituna tributaries including Waiari Stream, Kopuroa Canal, Ohineangaanga Stream, Raparapahoe Canal, and at the river mouth (Te Tumu) (refer to Figure 5.1 and 5.2 for locations). EBOP's monitoring program does not include measurements of all the variables at each location over the same time period or frequency, therefore averaging and, where appropriate, regression fits were applied to the data set and this is explained in more detail in Section 5.3. Field data collected specifically for this study included CTD (Conductivity, Temperature, Density) measurements to quantify the propagation of the salt wedge over a tidal cycle and a deployment of temperature loggers to measure the spatial and daily variability of temperature.

5.2.2) Maketu Estuary

Following the 1996 partial re-diversion, EBOP commissioned two flow gaugings to determine the actual volume and timing of water passing through the gates over a tidal cycle. The results of these gaugings were used to determine the freshwater inflow into the estuary in the model. Coinciding with the first stage of the re-diversion (1996), EBOP have monitored (approximately quarter-annually) the salinity and temperature at two locations within the estuary. Several full surface salinity surveys have also been carried out in the estuary post-1996.

Hydrodynamic field data collected for this study involved measuring tidal currents and water elevation over spring and neap tides at a number of locations in the estuary (Figure 5.1) using portable FSI (Falmouth Scientific Institute) current meters. During a spring tide current meters were deployed continuously over 2 tidal cycles (24 hours) at locations S1 and S2. During a neap tide, the two current meters were switched positions at low tide and only measured over one tidal cycle (12 hours) at locations N1, N2, N3 and N4. An inconsistency with the FSI's internal timing at location N2 resulted in invalid data at this location.

CTD profiling along the main channel from the estuary mouth to Fords Cut was carried out over a high tide to evaluate the extent of freshwater mixing.

5.2.3) Meteorological variables

For accurate representation of water thermodynamics, ELCOM requires various meteorological variables to be specified. The required parameters include solar radiation, wind speed and direction, relative humidity and air pressure and temperature (Hodges *et al.* 2001b). The meteorological data for this study was sourced from a number of meteorological stations within close proximity of Maketu. Geographically, Te Puke meteorological station was the closest to the lower Kaituna River and Maketu Estuary. However not all the required meteorological variables are collected at Te Puke so several parameters were sourced from the Tauranga and Rotorua meteorological station database.

Solar radiation, air temperature, relative humidity, atmospheric pressure and rain variables were applied as hourly averages, in addition to cloud cover which was applied as a daily average. All meteorological variables were applied evenly across both domains over the period of model simulation. Wind data (speed and direction) were not applied during the model simulations.

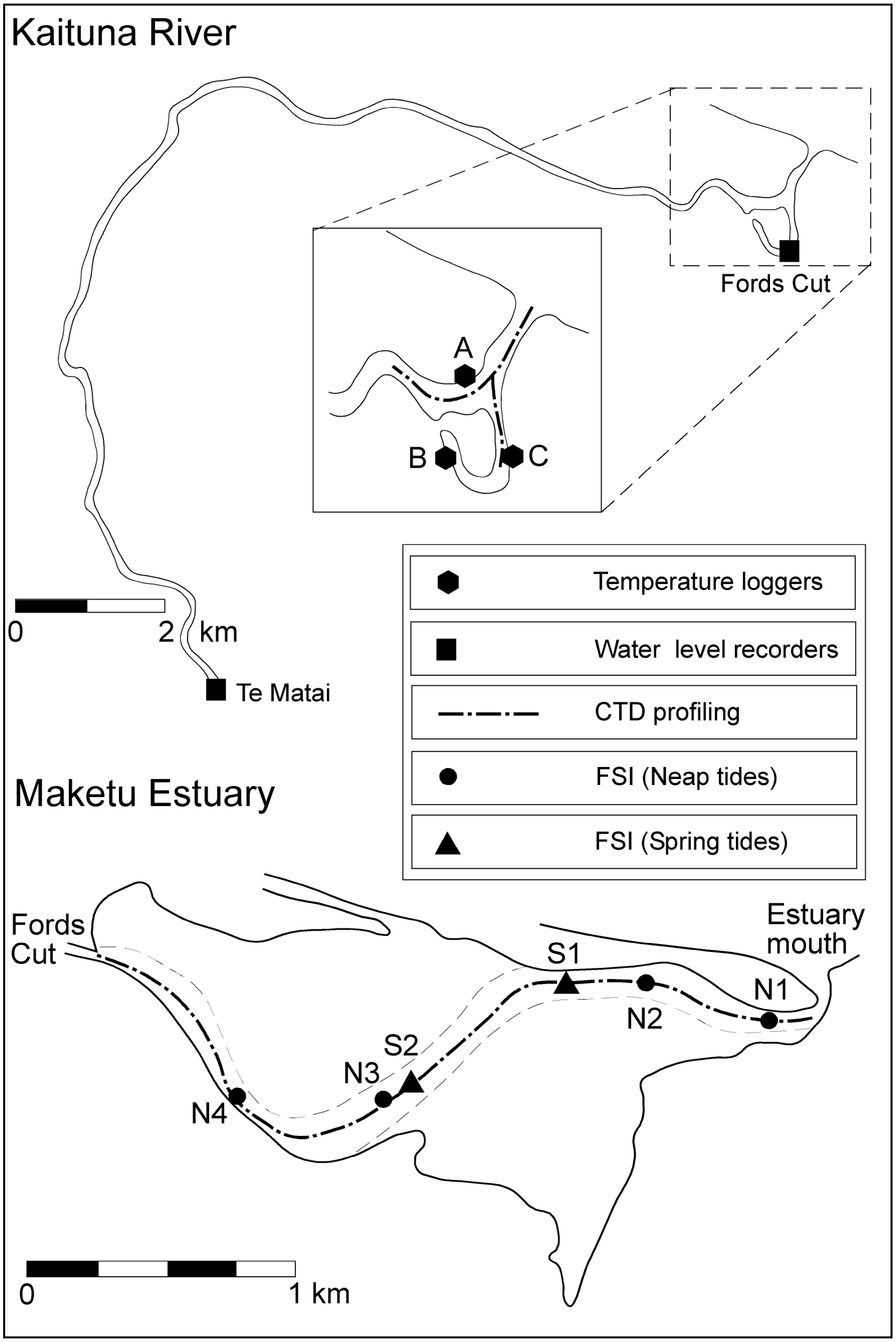

Figure 5.1. Locations of field deployments made specifically for this study. CTD casts were made approximately every 200 m along the shown transects. Dashed lines show the extent of the main tidal channel in the estuary.

5.3) Boundary condition formulation

In total, the lower Kaituna River had four inflow boundaries (Kaituna, Waiari, Raparapahoe, Kopuroa) one outflow (Fords Cut), and one open boundary (river mouth) (Figure 5.2). The Maketu Estuary had two inflows (Fords Cut, southern drain) and an open boundary (estuary mouth). Throughout this chapter the boundaries will be referred to by the names used in Figure 5.2.

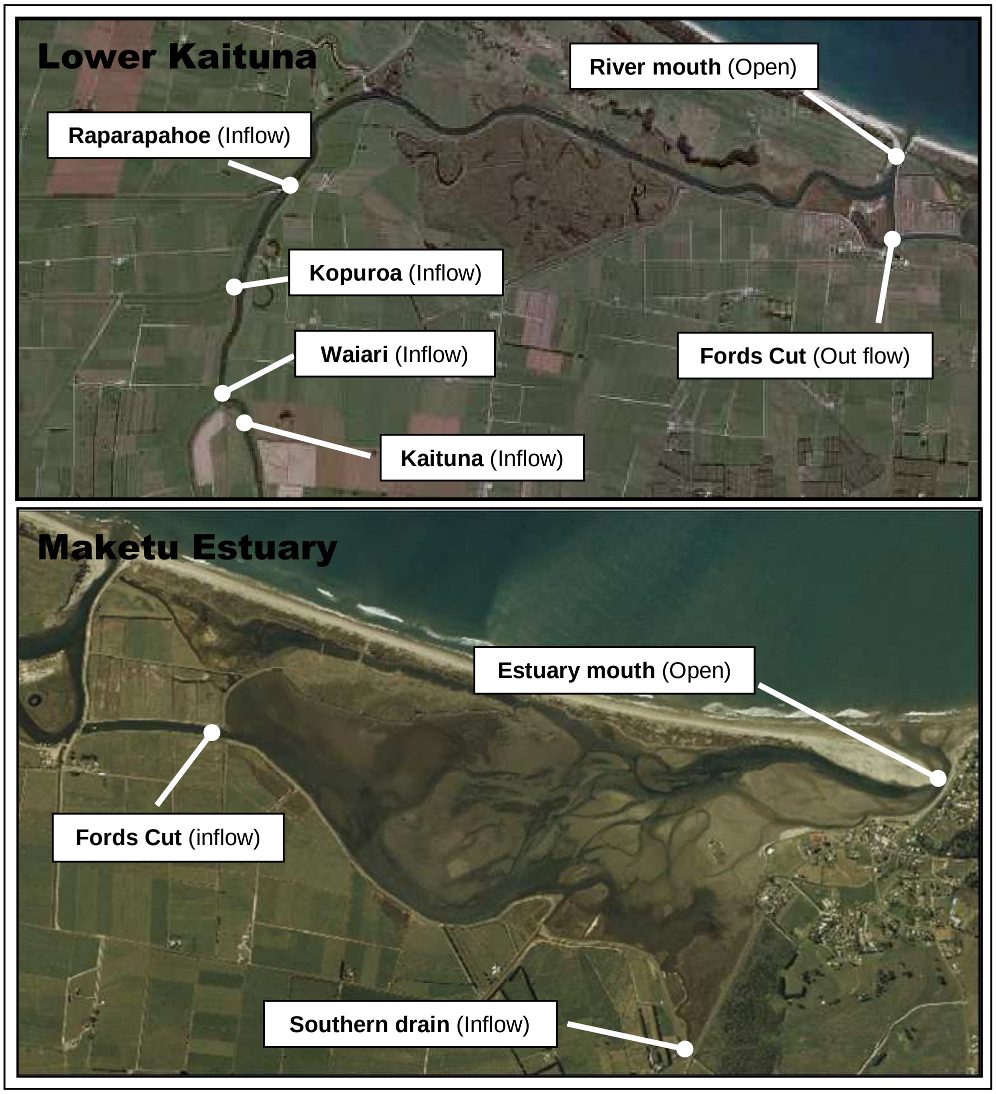

Figure 5.2. Location and type of boundary conditions used at each boundary for the Lower Kaituna River and Maketu Estuary (Source: EBOP RDAM (2004); Google Earth, (2006)).

5.3.1) Open boundary

The open boundaries (estuary and river mouth) were forced with a time series of tidal elevation taken at half hour intervals. The synthetic time series of elevation was created from tidal constituents (M2, S2, N2 and K1). Tidal constituents were extracted using harmonic analysis (Forman 1977, 1978) on the freely available output from the NIWA tidal model at Maketu Estuary entrance. An offset of 0.28 metres was added to the time series of tidal elevation for model simulations. This offset was derived from Domijan's (2000) analysis of the mean sea level relative to the Moturiki datum to which the bathymetry was referenced. Temperature data for the open boundaries were sourced from an EBOP wave buoy located in the Bay of Plenty (13 km offshore of Pukehina Beach). The wave buoy records sea surface temperature every 15 minutes, which was averaged over a day for the model. Salinity was derived from four offshore transects carried out between December 2003 and July 2004 (Park, 2005). For each transect, sea surface salinity (< 20 metres depth) was extracted, averaged and interpolated between the four days of measurements to create the time series over the model simulation period.

5.3.2) Inflow boundaries

Flow rates for the Kaituna River were created from the stage height to flow relationship at Te Matai. After the river's realignment work during the 1980s, the stage record at Te Matai has become influenced by the tide (Stringfellow, 1996). As a result EBOP removed the tidal component from the data and derived a relationship of stage height to flow. This relationship was then used to create a daily average flow rate at Te Matai. An assumption was made that river discharge at Te Matai was equal to the discharge at the beginning of the modelling domain plus the flow rate of Ohineangaanga Stream which confluences with the Kaituna between Te Matai and the beginning of this model domain. A summary and general comparison of the 2004 flow data for Waiari Stream, Kopuroa Canal, Raparapahoe Canal and Kaituna River (at Te Matai) is given in Table 5.1. Flow rates for Waiari Stream and Raparapahoe Canal were supplied by EBOP. Kopuroa Canal and Ohineangaanga Stream flow rates were derived from a number of point measurements assuming their discharge behavior was similar to that of Raparapahoe Canal.

To define daily temperature for the four inflow boundaries in the river domain, a regression fit to the total temperature data set was used. Since EBOP monitoring on the Kaituna and Waiari commenced, temporal resolution of temperature measurements is limited to approximately four times a year and was not sufficient enough to represent the temperature in the model. However the 20 years of data for Kaituna and 3 years for Waiari Stream showed a relationship between temperature and time of year (e.g. Figure 5.3 (A)). Therefore a second order polynomial regression fit to the total data set was used to provide a daily temperature for the Kaituna and Waiari inflows for 2004. Temperature data for the Kopuroa and Raparapahoe Canals are not measured, so the water temperatures for the two canals BC were set to the same daily average temperature as the Kaituna BC.

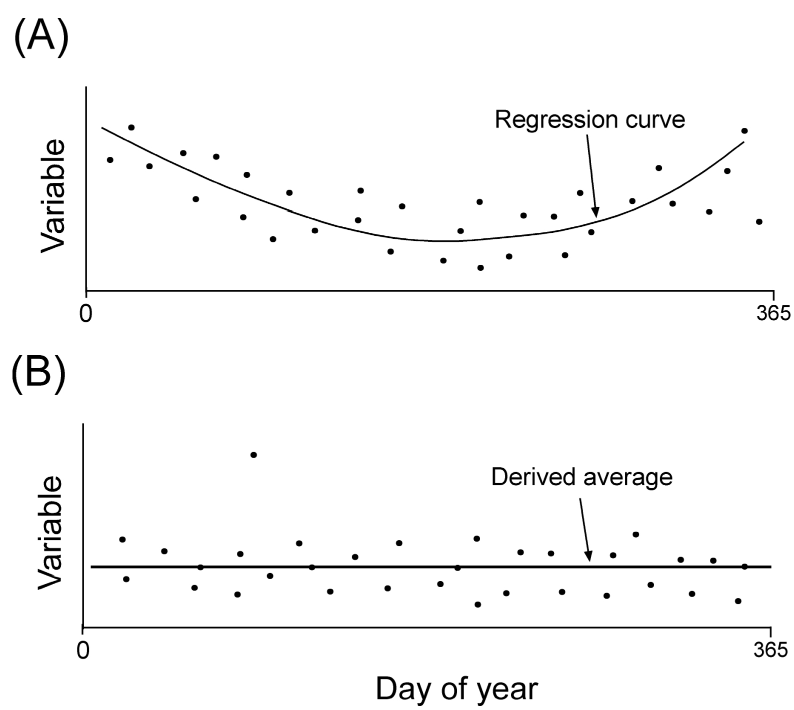

Figure 5.3. Schematic of how the time series of the variables used in the model were derived from the measured data set. (A) If a clear relationship between time of year and the variable was observed then a regression curve was fitted to the total data set (i.e. temperature). (B) If no relationship between time of year and variable was observed, then that variable was set as an average of the total data set. Note that before the average was derived the data set was analyzed for long term trends.

The major freshwater inflow into the estuary (Fords Cut) was created from the river model output (Section 5.3.3). The inflow boundary on the southern side of the estuary (southern drain) represents an amalgamation of four small culverts and drains that flow into the estuary all within close proximity of each other. There was only a point measurement of discharge through these drains taken in November 1994 (McIntosh *et al.* 1995). To create a time series of flow rates, the point measurements were scaled to match the discharge behaviour of the Kopuroa Canal, which appears to drain a similar catchment.

Table 5.1. Flow discharge for the inflow boundaries in the lower Kaituna River and Maketu Estuary for 2004.

Boundary	Mean flow 2004 (m^3s^{-1})	Peak flow 2004 (m^3s^{-1})
Kaituna River	31.97	67.00
Waiari Stream	3.00	14.20
Kopuroa Canal	0.38	2.93
Raparapahoe Canal	1.94	14.65
Fords Cut	100,000 (per tide)	n/a
Southern drain	0.10	0.47

5.3.3) Outflow boundaries

The only outflow boundary in the model occurred in the Kaituna River at Fords Cut, the join between the river and estuary modelling domains. The model's predicted outflow scalars (temperature, salinity and variables needed for CAEDYM) were used as the inflow into the estuary. The outflow is regulated by control gates which allow flow to occur only from the river into the estuary. The outflow in the model occurred over a single horizontal cell, 20 metres in width, and four vertical cells (1.2 metres in height) and did not necessarily match the design or area of the control gates. The discharge rate has been gauged several times (Domijan, 2000; McIntosh *et al.* 1996) and is approximately 100,000 m^3 per tidal cycle.

The results of the CTD measurements indicated that marine water propagated up to the control gates at Fords Cut, suggesting that saline water could be drawn through the control gates into the estuary. McIntosh *et al.* (1996) demonstrated this was occurring by measuring the salinity of the water passing through the control gates. An analysis of the McIntosh *et al.* (1996) results showed that the water drawn through the control gates during that particular tidal cycle had a salinity varying from 0–27 psu (average of ~2–10 psu).

Preliminary model runs indicated that allocating the correct vertical grid cell to the outflow in the model was critical for determining the mix of marine to fresh water drawn through the outflow. The importance of the outflow height can be demonstrated in Figure 5.4. Specifying the outflow vertical grid cell too low caused a large proportion of marine water to be drawn through the outflow. Alternatively specifying the outflow at a vertical cell that was too high resulted in an error. This error was caused by the model trying to draw water through the outflow before water elevation had reached the base of the outflow cell.

To further complicate implementation of the outflow boundary, discharge only occurs through the control gates when the water elevation on the Kaituna River at Fords Cut is higher than in the estuary at Fords Cut. Otherwise, reverse pressure keeps the gate's valve closed. Flow through the gates takes place approximately 2 hours after low tide for a duration of 5–7 hours (Domijan, 2000; McIntosh *et al.* 1996), thus the boundary condition in the model needed to mimic this. For this to occur a synthetic time series of the outflow rate was created using the shape of the tidal elevation curves with the constraint that the average volume flushing through the gate over a flood tide was preserved (100,000 m^3) and the flow occurred with the correct duration.

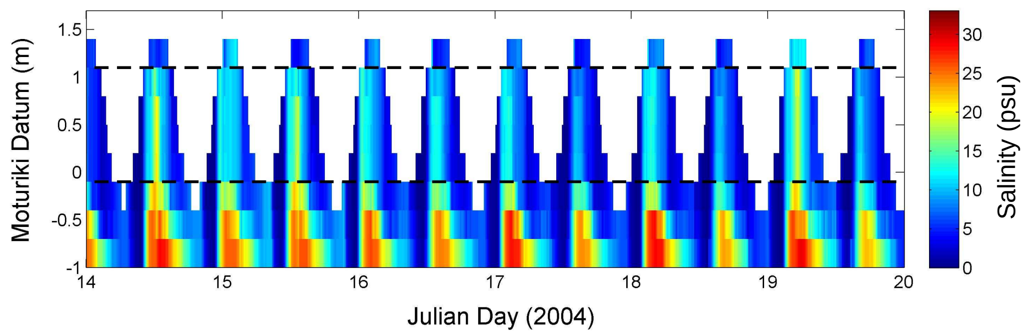

Figure 5.4. Time series illustrating the vertical variation of salinity in the model cells adjacent to the outflow. Dashed lines indicate the range of vertical grid cells covered by the outflow. Note that lowering the outflow height (bottom dashed line) would cause a greater proportion of marine water to be drawn through the outflow.

5.4) Model setup and simulation periods

5.4.1) Grid size and resolution

A number of horizontal and vertical grid sizes were experimented with during this study, with the final resolution being a compromise between accurate model results and acceptable runtime ratios. Typically a large reduction in run time ratios (i.e. the ratio of real time to model simulation time) occurs when using a three-dimensional model over 2D or 1D models (Tee, 1998). One way to increase this ratio (i.e. to speed up the model) is to increase the grid size, however increasing grid size is not always possible. In some cases, such as in the Kaituna River, specifying a large grid cell (>20 metres) can cause the model to become constricted around river bends. Similarly in the Maketu Estuary, specifying a grid cell that is too large (>15 metres) results in the loss of bathymetric detail needed to represent the major intertidal channels and sand and mud flats. Acceptable run time ratios can be achieved by reducing the vertical resolution, however in situations like the lower Kaituna, where vertical resolution is important to resolving the salinity stratification, this may not be desirable. The final grid resolution for the estuary and river are summarized in Table 5.2 along with approximate ELCOM run time ratios.

Table 5.2. Grid resolution, overall size and number of wet cells for Maketu Estuary and lower Kaituna River modelling domains. Approximate run time ratio (real time : simulated time) using the hydrodynamic model ELCOM simulating thermodynamics and density are given.

Domain	Horizontal cell size (m)	Size of girded domain	Vertical cell size (m)	Total wet cells	Run time ratio
Kaituna River	20 x 20	316 x 135	0.3	25,544	1:22
Maketu Estuary	15 x 15	123 x 208	1.0	40,770	1:45

5.4.2) Model simulation period

For calibrating and validating the hydrodynamic model ELCOM, simulations were made over the period when model results could be compared to measured data. Due to all model simulations beginning from a cold start (i.e flat water, no currents and uniform salinity and temperature), a period of 2 days (4 tidal cycles) was allowed to ‘warm up’ the model before any results were extracted.

5.5) ELCOM calibration and validation – Kaituna River

5.5.1) Water levels

EBOP operate two water level recorders in the lower Kaituna River at Te Matai and Fords Cut (Figure 5.1). ELCOM’s predicted water elevations at the corresponding horizontal cells were compared to the recorded elevations. To compare modelled water elevations at Te Matai, the river domain was extended to Te Matai. In Figure 5.5 the measured and modelled water elevation are illustrated for a high river flow event over a 10 day period in 2006. Fords Cut water elevation is dominantly controlled by tidal height where as the Te Matai water levels are dominantly influenced by river flow. ELCOM accurately captured the phase difference in the tide (~1 hour) between the mouth (Fords Cut) and upper river (Te Matai).

However, the modelled water elevations at Te Matai and Fords Cut did not mimic all the fluctuations in measured elevation and shape. One explanation for the discrepancy at Te Matai could be that flow rates specified at the boundaries were daily averages and the flow (and therefore elevation) can vary significantly over a day. ELCOM’s water elevation predictions at Fords Cut also showed some discrepancies in tidal amplitude. The discrepancies occurred at low tide, by where the modelled water elevation closely mimicked the tidal elevations of the open boundary, falling below that of the measured elevation at Fords Cut. The discrepancy in elevation was most pronounced during high river flow events as shown by the circle in Figure 5.5 (A). The discrepancy could be attributed to wave set up and storm surges which could explain the greater difference in elevation observed during a large river flow event (assuming high river flow is correlated with a storm event). However, discrepancies between modelled and measured elevations at Fords Cut during low flow events still show a significant difference at low tide indicating that there is a flow restriction issue at the river mouth. However the bathymetry at the river mouth was not altered in an attempt to correct the elevation discrepancy for two reasons: firstly, the modelled propagation of the marine water in the lower river is in good agreement with our measured salinity data (Figure 5.7); secondly, flow through the control gates does not occur below approximately mid tide, the discrepancy of water elevation at low tide should then not effect the outflow function, which is a principal aspect of the lower Kaituna model domain.

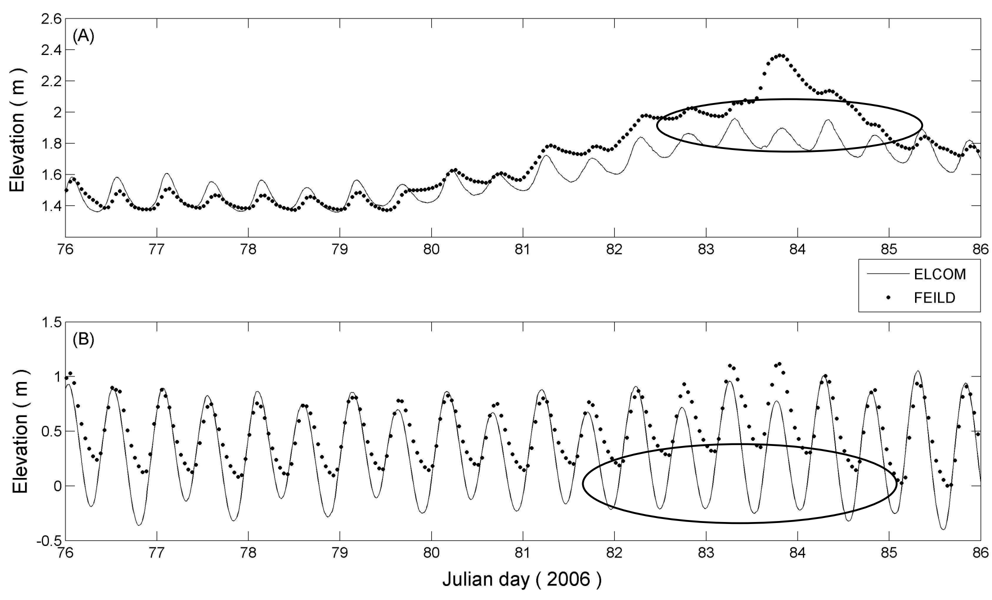

Figure 5.5. Modelled (ELCOM) water elevations in the Kaituna River compared to measured data. (A) Te Matai (circle highlighting the discrepancy during peak flow conditions) (B) Fords Cut (circle highlighting the greatest discrepancy during a possible storm event). (Refer to Figure 5.1 for locations of recorders)

5.5.2) Thermodynamics

To validate ELCOM thermodynamics, model predictions of water temperature were compared to observed values at three locations within the lower river. Three Tidbit temperature loggers were deployed at locations (A), (B) and (C) (Figure 5.1) and compared to the modelled temperature extracted from the corresponding vertical and horizontal cell. ELCOM predicted the inter-daily variations and the eleven day trend in water temperature reasonably well (Figure 5.6). ELCOM modelled a spike in temperature occurring at high tide, evident in data in (A) between day 240–246. The cause of this spike is associated with the warmer (by 2–3 ^{o}C) marine water entering the model cell that the temperature data was extracted from.

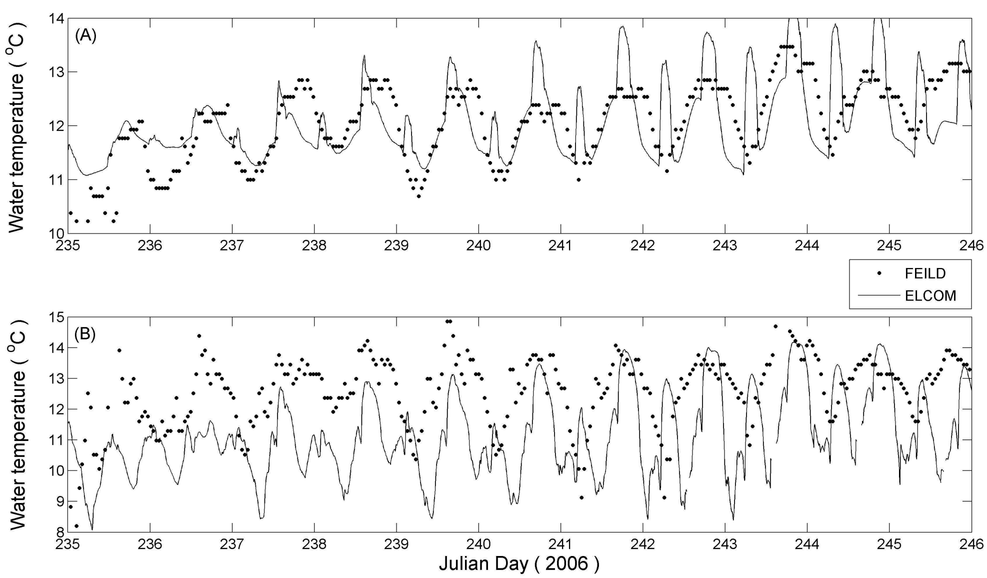

Figure 5.6. Modelled (ELCOM) water temperature in the lower Kaituna River compared to measured temperature. (A) Main river (B) Closed loop (Refer to Figure 5.1 for locations of deployment).

5.5.3) Salinity variations and vertical mixing

The salinity results from our CTD casts in the lower river were compared to ELCOM simulations under the same river flow and tidal conditions (Figure 5.7) illustrating a good correlation between model and measured data. Accurately modelling the degree of fresh and marine water mixing in the lower river was important for a variety of reasons. Vertical height and maximum distance up the river reached by the marine water were important in determining the proportion of marine/freshwater drawn through the control gates (Section 5.3.3). Furthermore the residence time and degree of mixing of the marine water in the lower river is important for ecological / water quality aspects (Chapter Six). The measured CTD data showed strong vertical stratification between the marine and freshwater. Scatter-plotting temperature against salinity of the measured profiles at high, mid ebb and low tide (Figure 5.8) illustrates clearly the two distinctive water bodies present in the lower river (indicated by circles) and the extent of marine – freshwater mixing.

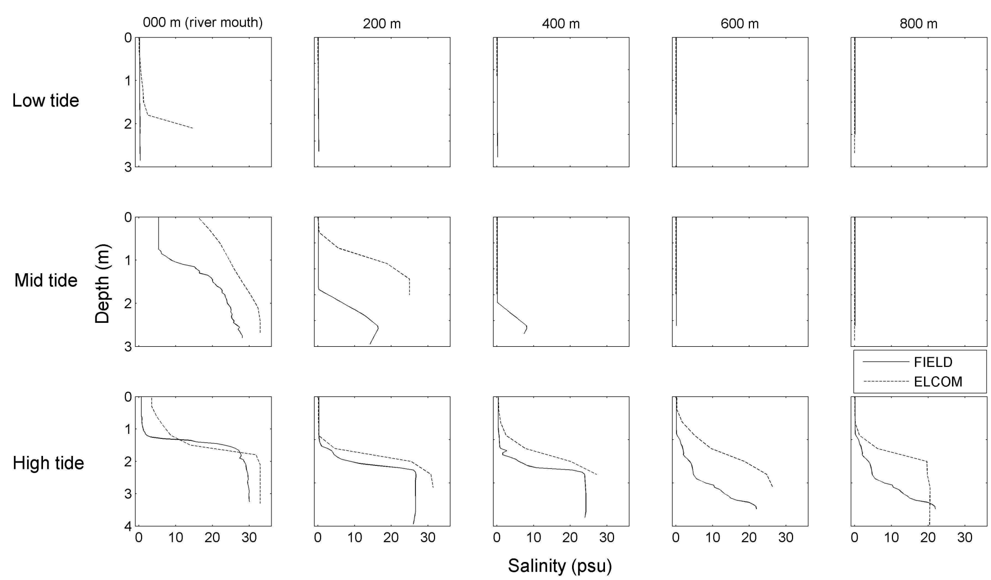

Figure 5.7. Measured (CTD) and modelled (ELCOM) salinity profiles over low, mid and high tide in the Kaituna River from the river mouth (000 m) to 800 m upstream on 21st August 2006.

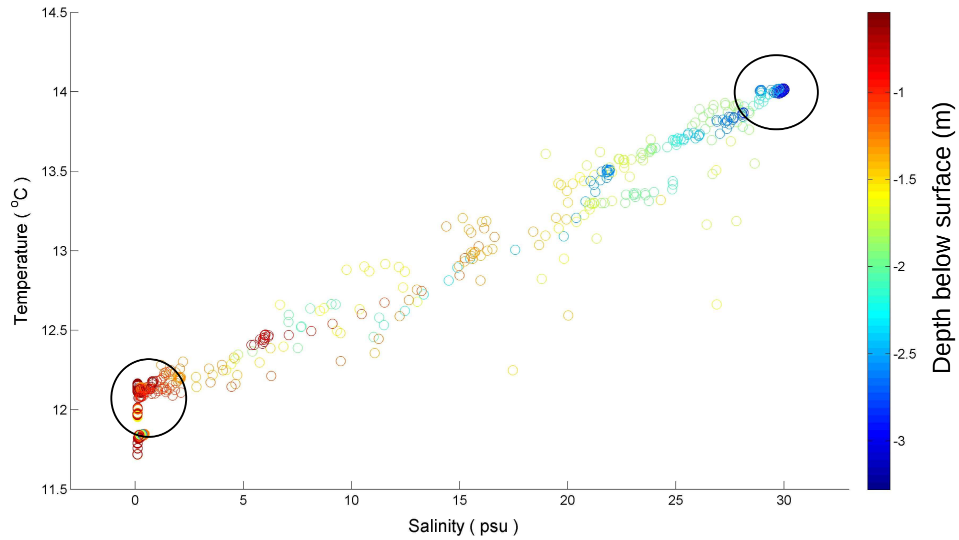

Figure 5.8. Scatter plot of measured temperature verses salinity in the lower Kaituna River (from the mouth to 800 m upstream) during high, mid ebb and low tide. Color indicates the depth the measurements were taken below the water surface. Lower left corner circle represents freshwater, upper right circle represents marine water. Intermediate mixed water lies between the two circles.

5.6) ELCOM calibration and validation – Maketu Estuary

5.6.1) Tidal phase and current velocities

ELCOM's hydrodynamics (current velocity and water elevation) for the estuary domain were calibrated by varying the bottom friction co-efficient in the model and finding the smallest residual (RMS) between modelled and measured data. The measured water velocities and elevations from the spring tide FSI deployment S1 and S2 (for location refer Figure 5.1) were used in the calibration. Water velocity and elevations from the corresponding grid cells in the model were extracted and interpolated at the same time as measured data, then compared using root mean square error (Figure 5.9).

ELCOM allows the user to specify a Bottom Drag Coefficient (BDC) which can be either applied evenly across the domain or varied spatially; for the calibration the BDC was applied evenly across the domain. However the results of the calibration identified that a varying BDC would be needed to best fit the measured spring tide water elevation and current velocity data (Figure 5.9). A higher (more bottom friction) BDC value was set in the main channel near the estuary mouth and at Fords Cut (0.005), and a lower (reduced bottom friction) BDC for the mid estuary and intertidal flats (0.003). The spatially varying BCD derived from our spring tide measurements was in agreement with past hydrodynamic modelling work in the Maketu Estuary (Domijan, 2000). Domijan (2000) carried out a sediment size survey of the entire estuary in 1997. The results of the 1997 survey were used in setting the BDC for his 2D hydrodynamic modelling and revealed a higher BDC was needed in the mouth and main channel of the estuary while a lower value was need for the further reaches of the estuary. Comparing the modelled current velocity and elevation using a varying BDC derived from the calibration gave a good fit to the measured spring tide data (Figure 5.10).

Neap tide measurements of tidal elevation and current velocity (N1, N3 and N4) were then compared to model output and gave a reasonable fit. Using the varying BDC determined from spring tide measurements, model current velocities under neap tide conditions showed a maximum error of ± 0.25 ms^{-1} between modelled and measured data. Modelled water elevation lagged measured data by 21–28 minutes, however this lag was relatively constant (varying by 7 minutes) at each location and may have been caused by a change in the bathymetry between neap tide measurements (February 2006) and the estuary's bathymetry survey (July – September 2006). If the time series of neap tide data was longer (i.e. at least one tidal cycle) then an attempt would have been made to calibrate a BDC from the neap tide data. This may have resulted in a better agreement of measured and modelled data for neap tides as the best BDC in a numerical modelling can be different for neap and spring tides (Li *et al.* 1999).

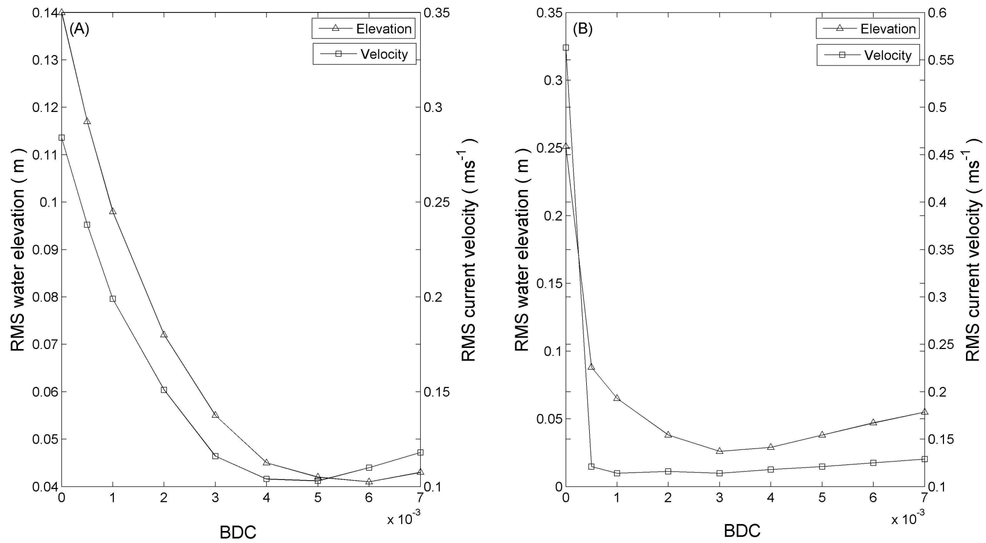

Figure 5.9. RMS differences between measured and modelled water elevation and current velocities using varying bottom drag co-efficient (BDC) in the model at (A) Estuary mouth (S1) and (B) Mid estuary (S2).

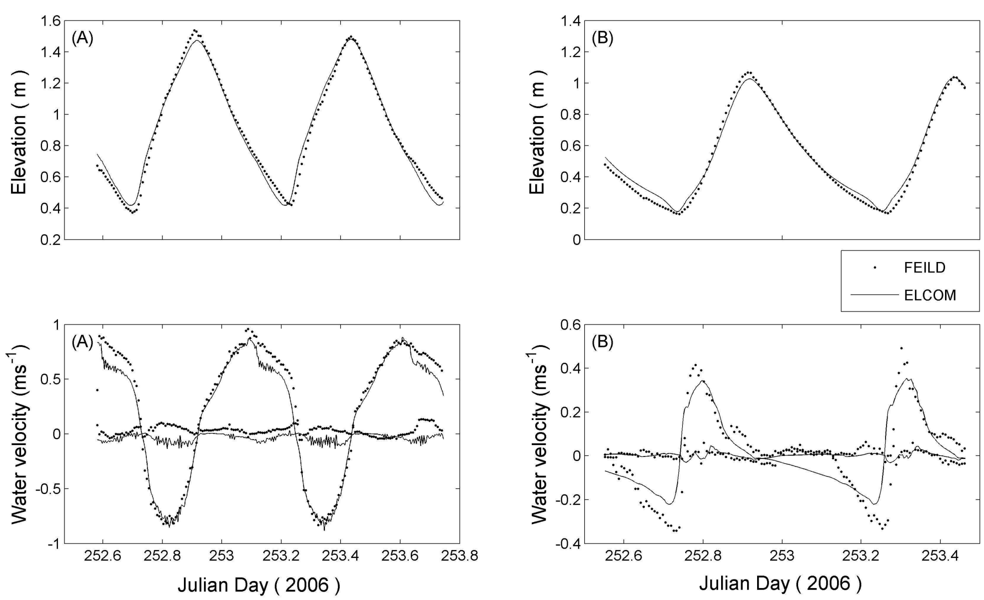

Figure 5.10. Modelled against measured water elevation and velocity (A) Estuary mouth (S1) (B) Mid estuary (S2) using a varying BDC determined from calibration. Multiple lines for the water velocity are the u and v velocity components.

5.6.2) Salinity variations and mixing

A salinity survey of the estuary for this study was carried out over a high tide along the main channel from the estuary mouth to Fords Cut (for location refer to Figure 5.1). The results of the survey suggest that the estuary is generally well mixed in the vertical but demonstrates a longitudinal gradient from Fords Cut to the estuary mouth (Figure 5.11). An analysis of other salinity surveys of the estuary (McIntosh *et al.* 1996; McIntosh *et al.* 1997; Domijan, 2000) reveal different degrees of stratification varying over the tidal cycle, but generally well mixed vertical conditions.

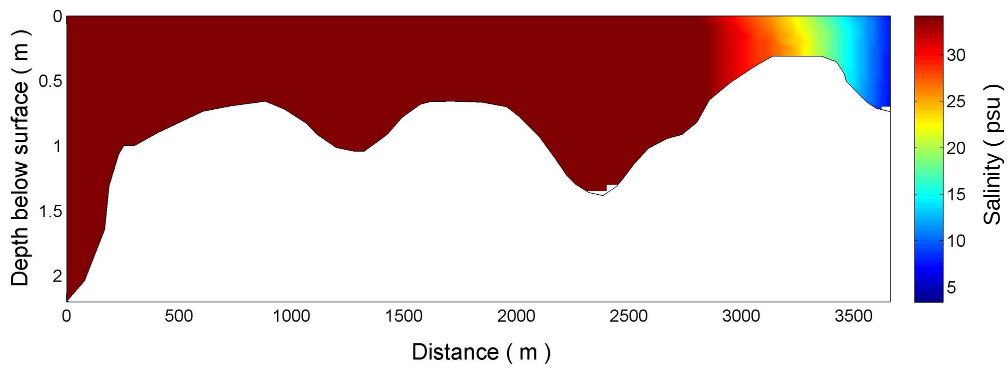

Figure 5.11. Measured salinity in the Maketu Estuary from the estuary mouth (0 metres) to Fords Cut (3650 metres) along the main channel at high tide on the 12 August 2006. Measurements show very little vertical stratification demonstrating the estuary is generally well mixed.

5.7) Results

In order to accurately predict nutrient and phytoplankton dynamics in the lower Kaituna River and Maketu Estuary, the hydrodynamic driver ELCOM, needed to be set up, calibrated and validated against field measurements. The results presented in this chapter are a brief description of the hydrodynamic properties that are relevant to water quality (e.g. residence time, residual currents). Section 5.8 then leads on to discuss the calibration–validation results, as well as the predicted hydrodynamic properties.

5.7.1) Maketu Estuary

Figure 5.12 illustrates the depth-averaged velocities at high, mid-ebb, low and mid-flood tide during spring tidal conditions. The strongest currents can be observed in the main channel near the estuary mouth at mid-ebb and mid-flood tide. Fords Cut inflow also provides a net seaward flow in the far western region of the estuary. Interestingly a number of small eddies are predicted in the estuary, most notably attached to the southern bank in the western region at high tide. Figure 5.13 illustrates the salinity at the same four stages of the tide. Freshwater enters the estuary at Fords Cut from mid-flood to early-ebb tide, creating a distinctly freshwater zone in the western region of the estuary. The area covered by this freshwater is smallest at high tide where the incoming marine water ‘pushes’ it back into the far western reaches of the estuary. On an ebbing tide, the slug of freshwater extends east to where part of the now mixed water exits the estuary near low tide. On a flooding tide this mixed water is pushed back and the process starts again. The inflow that represents four drains along the southern border of the estuary also reduces the salinity in the southern region of the estuary extending northwards on the ebbing tide.

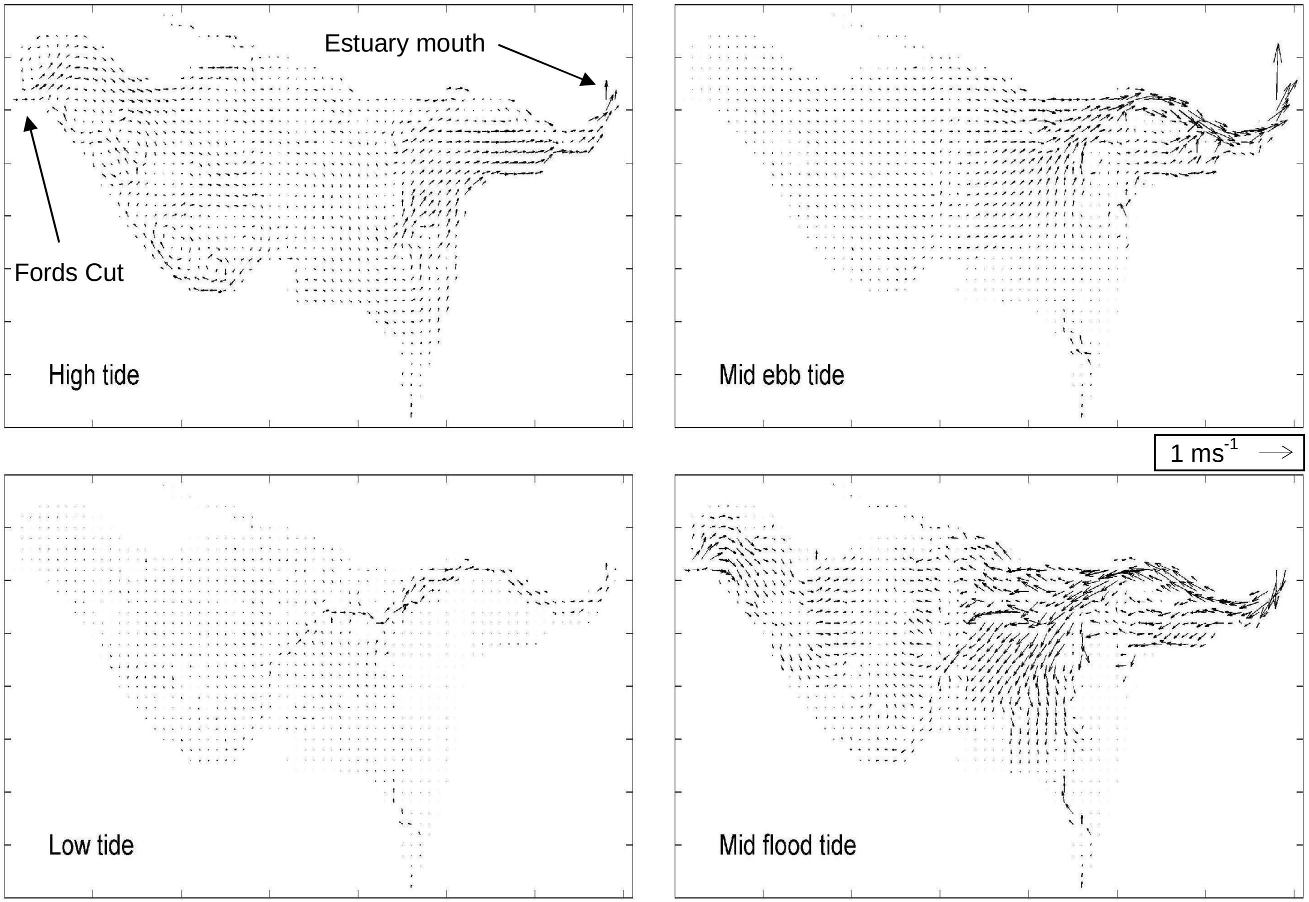

Figure 5.12. Depth-averaged current velocities at four stages of the tide in the Maketu Estuary during spring tidal range. Vectors are plotted at every third model cell (45 m). Stage of tide is determined from the water elevation at the estuary mouth.

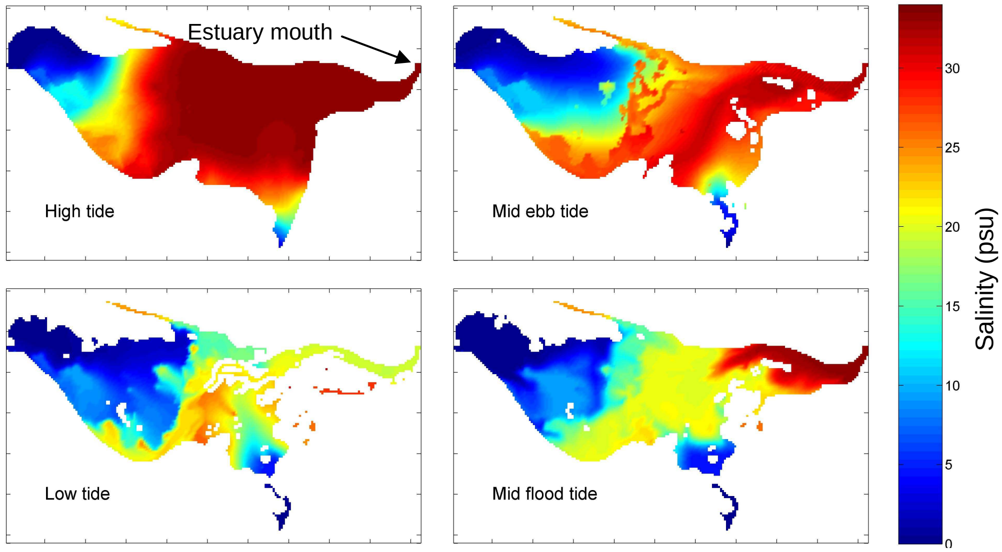

Figure 5.13. Depth-averaged salinity at four stages of the tide in the Maketu Estuary during spring tidal range. Stage of tide is determined from the water elevation at the estuary mouth.

Figure 5.14 (A and B), illustrate the time and depth-averaged residence time and salinity respectively in the Maketu Estuary over a 21 day period in January 2006. The results indicated the highest average residence time is ~1.2 days occurring in the western region of the estuary. Analysis of the time varying results (not presented) showed that a maximum residence time of ~1.5 days occurred in the same region. The average salinity shows a marked decrease in the western region of the estuary due to the freshwater inflow at Fords Cut as well as a reduction in the southern region due to the southern drain inflow. The highest average salinity occurred on the intertidal sand flats in the eastern region of the estuary. Figure 5.14 (C) illustrates the residual currents within the Maketu Estuary evaluated over 10 tidal cycles during spring tide conditions, the residual currents demonstrate a net seaward flow with the strongest currents occurring at the estuary mouth. There is also a net seaward flow occurring at Fords Cut and in the southern estuary both due to freshwater inflows. The eddies that were predicted at high tide in the estuary (Figure 5.12) do not seem to effect the residual circulation in the estuary. It would be likely that the speed and duration of the eddies is not significant enough to contribute to the overall residual circulation.

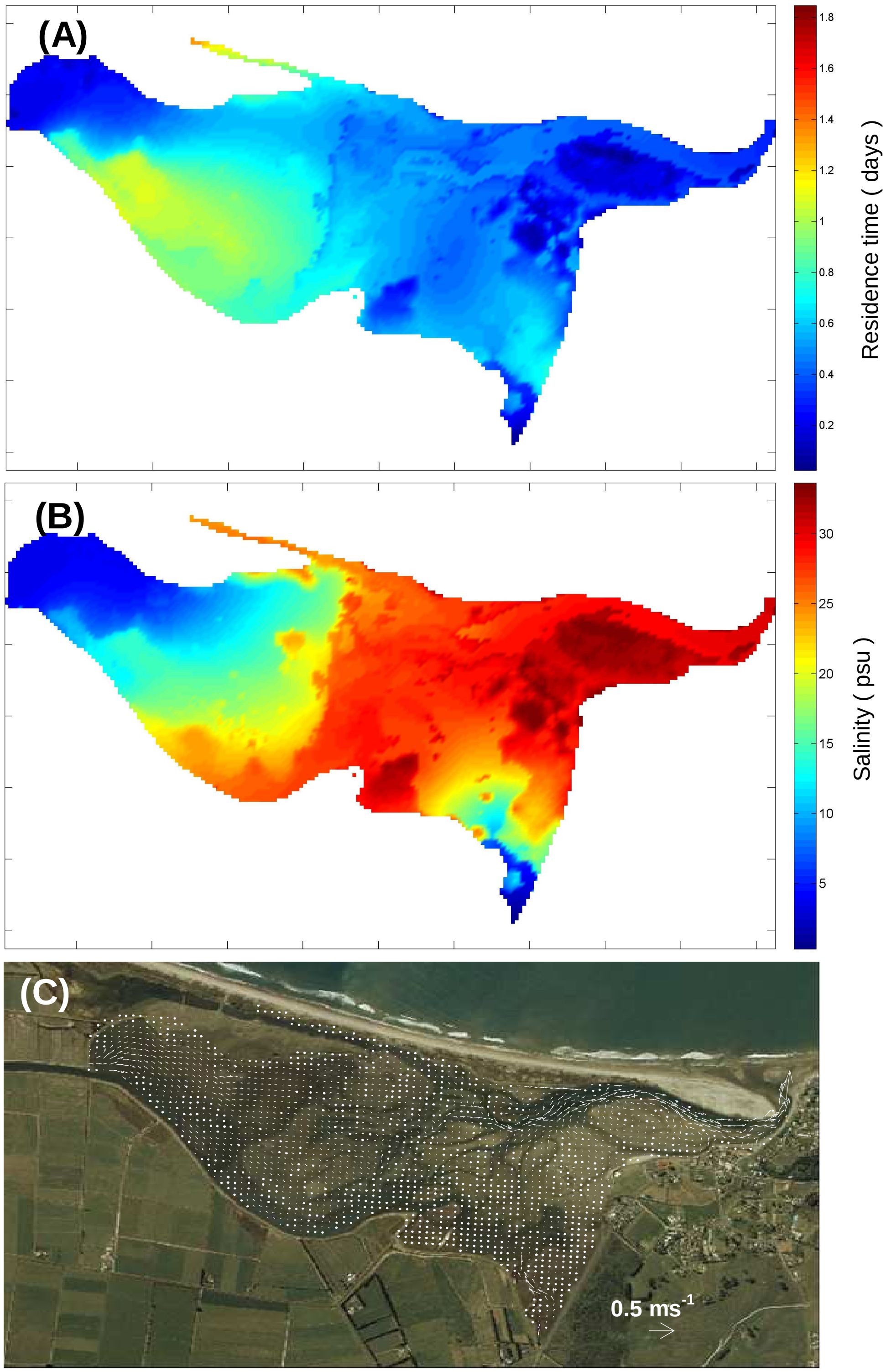

Figure 5.14. Modelling results over a 21 day period in January 2006. (A) Residence time averaged over the 21 day period. (B) Salinity averaged over the 21 day period. (C) Residual currents illustrated as a vectors over ten tidal cycles in January 2006 over-laid on an aerial photo. Note: Aerial photo was taken in 2004 and may not represent the bathymetry used in the model to derive the residual flow. (Photo source: EBOP RDAM, 2004)

5.7.2) Kaituna River

Unsurprisingly, the residence time in the lower Kaituna River increased steadily downstream from the Kaituna boundary to where it exits the river, at the river mouth. The greatest time it takes for a parcel of water to reach the river mouth from the start of our model domain is 10 hours (excluding the loop); this highest residence time occurred over a flood tide when river velocities were reduced and subsequently the lowest residence (7.2 hours) at the river mouth occurred over an ebbing tide. Variations in residence time were predicted near the river mouth and were due to, intrusion of marine water, reduced river flow over an incoming tide and insufficient flushing in the closed loop as shown in Figure 5.15. The closed-off loop near the mouth showed the highest retention time with the maximum ranging from 18–27 hours over the 21 day simulation. This elevated residence time was due to the absence of sufficient flushing. Because marine water is completely exchanged in the lower river over a tidal cycle, a reduction in the depth-averaged retention time was also predicted over a flood tide.

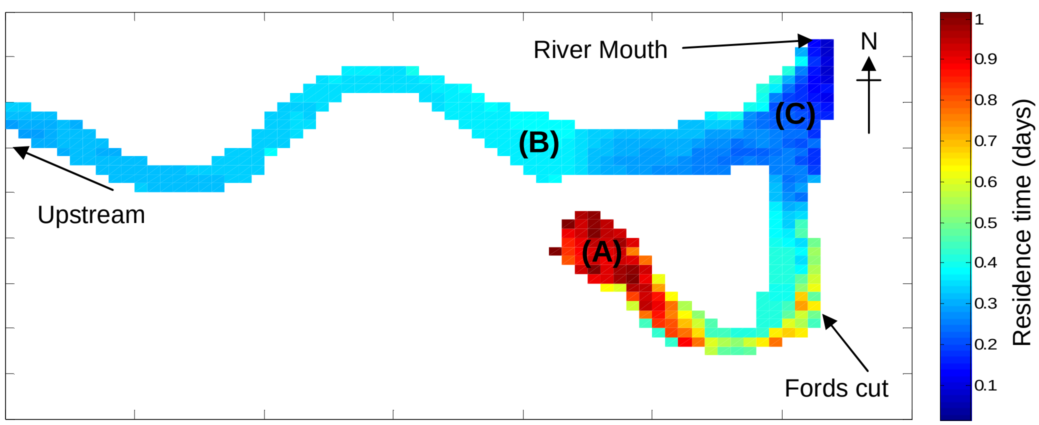

Figure 5.15. Snapshot of the predicted depth-averaged water retention time within the lower Kaituna River (river mouth to 1500 m upstream) during a flood tide. (A) This region illustrates the closed loop where the highest retention times were predicted. (B) In this region an increase in retention time was observed during a flood. (C) In this area there is a reduction in retention time associated with inflow of marine water over a flood tide.

5.8) Discussion

5.8.1) Maketu Estuary

The most recent and comprehensive hydrodynamic modelling application to the Maketu Estuary by Domijan (2000) used a 2D depth-averaged numerical model. At the time of Domijan's (2000) study, the estuary bathymetry was quite different to present, most notably the position and width of the mouth has changed (Figure 4.5). While Domijan's modelling predictions (water elevation and current velocities) match his measured data well, the scope of his study was based on barotropic forcing and could make no allowances for baroclinic terms, vertical variations or solving the salinity distribution in the estuary. Due to practical run time constraints (Section 5.4.1) the vertical resolution of the final grid used in this study was too coarse to allow analysis of the modelled vertical variation. However, the measured salinity profiles carried out for this research, and previously, suggest that vertical variation is minimal in the estuary (Section 5.6.2). According to Prichard's (1955) classification the small ratio of freshwater to marine (~0.1), would result in categorizing the Maketu as a partially stratified estuary, adding to the justification that vertical salinity differences can be generally neglected.

The predicted residual currents in the Maketu Estuary (Figure 5.14 (C)) are a result of freshwater inflows and tidal asymmetry (over tides). The modelling results demonstrated a net seaward flow with the strongest currents occurring at the estuary mouth and near Fords Cut. The magnitude and direction of the residual flow is predicted by the interaction between the estuary bathymetry and tidal and freshwater flows. Because of the well mixed vertical conditions in the estuary it was assumed that baroclinic terms would not be numerically important in determining the residual flows, hence the vertical resolution in the model was set very low. In an estuarine situation over-tides can cause the ebb tide to persist over a greater period of time than that of the flood (Brown *et al.* 1999) effecting residual currents and net sediment transport patterns (e.g. Shetye *et al.* 1992). Spring tide water elevation and current velocity measurements suggested that tidal harmonics or 'over-tides' are present in the Maketu Estuary (Figure 5.10). This asymmetry between ebb and flood current flows would likely contribute to the observed ebb dominance of the residual flow. Domijan (2000) also found net sediment transport in the Maketu estuary would be ebb dominated due to the presence of the freshwater inflows and tidal asymmetry (over-tides). However, analysis of Domijan's 2D modelling revealed a possible error in determining the residual flows. At Fords Cut, where the river water flows into the estuary, Domijan's model had prescribed in it an open boundary which allowed water to flow in both directions. In reality the control gates only allow flow from the river into the estuary. Therefore the magnitude of the ebb–flood asymmetry predicted by Domijan's modelling may not be as weak as his results demonstrated. Never the less, the modelling undertaken in this study concurs with Domijan's (2000) conclusion that the Maketu Estuary is ebb dominated.

The results of hydrodynamic modelling undertaken in this study revealed that the residence time varies spatially within the estuary with a maximum of ~1.5 days occurring in the western region of the estuary. ELCOM calculates the residence time of each cell in the model with new water (i.e. inflows) given an age of zero and then the age increased with each model time step. A general but less accurate method for determining the residence time in an estuary is the tidal prism method (Officer, 1976). By comparing the ratio of incoming water to total estuary volume and multiplying that ratio by the tidal period, Domijan (2000) calculated this to be ~13.3 hours for the Maketu Estuary. However this method assumes that the water in the estuary (marine and fresh) is completely mixed over a tidal cycle. By looking at salinity surveys of the Maketu Estuary (Figure 5.11), we know this is not the case, and therefore Domijan's (2000) estimation would be a lower limit.

Wind data (speed and direction) were set to zero for the period of model simulation. In ELCOM wind variables affect the water thermodynamics, vertical mixing and wind induced circulation. Validation of the thermodynamics in the lower river (Figure 5.6) showed that model and measured data were in good agreement without including the effects of wind. Domijan (2000) identified residual currents in the Maketu Estuary could be partially explained by wind shear. Further a field in the Manukau Harbour, Bell *et al.* (1998) modelled circulation response to wind shear and found the largest response was on the intertidal (shallow) flats, and Geyer's (1997) numerical modelling implied that the influence of wind can also significantly effect the flushing times of shallow estuaries. This would suggest that for more accurately defining the hydrodynamics in the Maketu Estuary, the effects of wind shear stress could be numerically important, particularly on the shallow intertidal flats. Wind speed and direction data were not included as a forcing condition in this study.

The high salinity predicted on the sand flats near the estuary mouth (Figure 5.14 (B)) implies that only fully marine water is in contact with the sand flat; analysis of the estuary salinity over a tidal cycle suggest why this was occurring and the theory is illustrated in Figure 5.16. During the late stages of a flood tide marine water flows over the sand flats. Similarly during the first stages of the ebb tide this fully marine water would pass over the sand flats in the opposite direction. However in the later stages of the ebb tide when mixed (fresh and marine) water reaches the sand flats, the water level has fallen to be confined to the channel. This resulted in only marine water overlying the sand flats on the last of the incoming and first of the outgoing tides. Li *et al.* (1997) modelled tidally driven flows in a shallow estuary and suggested that a residual pressure gradient could cause a net landward flow over the shoals (sand flats) and be balanced by a return flow in the channel. This theory could be used to explain the observed salinity distribution. However, for the Maketu Estuary no net landward flow was observed over the sand flats (Figure 5.14 (C)).

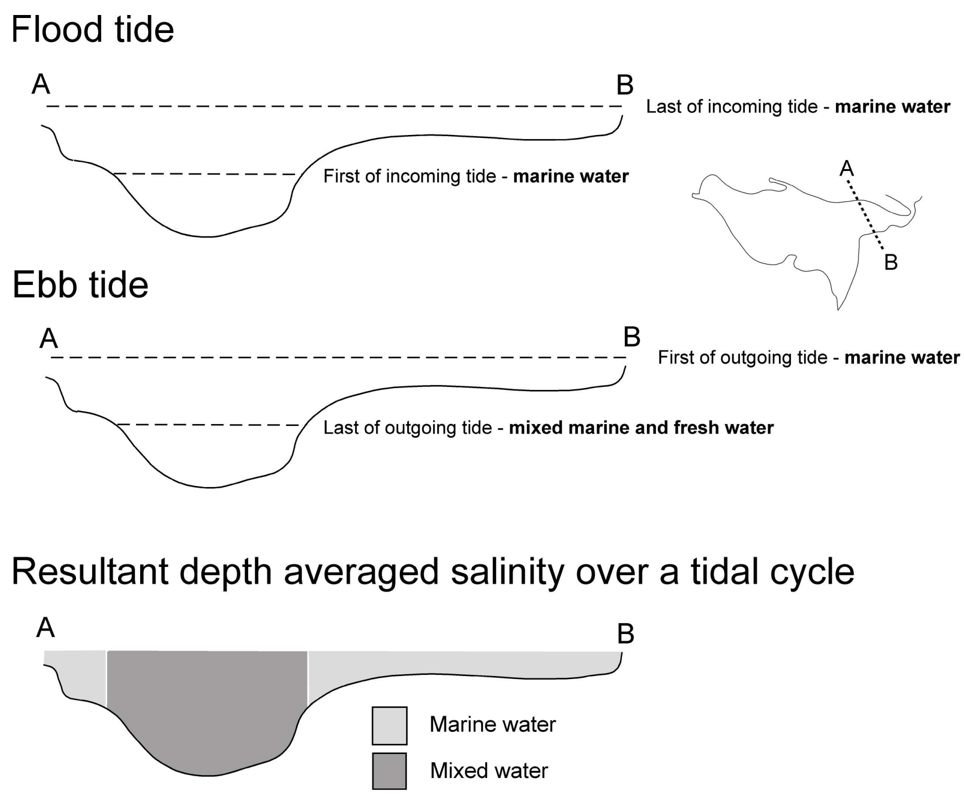

Figure 5.16. Schematic of how the highest average salinities in the Maketu Estuary were predicted by ELCOM on the sand flats near the estuary mouth. A–B represents a cross section across the main channel and sand flat (insert). Dashed lines represent the water level at different stages of the tide.

5.8.2) Kaituna River

To the best of the author's knowledge the only other numerical modelling work to be carried out on the lower Kaituna River was completed while designing the optimal flow rate of the control structure at Fords Cut using a 1D flow model MIKE 11 (EBOP, 2001). However the model was purely a flow model and therefore could make no predictions of salinity, temperature and their associated effects on the hydrodynamics in the lower river. Through measured and modelled data, our study gives a good insight into the lower river's existing hydrodynamic condition and the ability to look at a range of possible scenarios.

CTD measurements in the lower Kaituna revealed high salinity-driven stratification and therefore ELCOM's ability to model the propagation of the marine water was critical for this modelling study. A salt wedge occurs in an estuary or river mouth when the river discharge is large enough to maintain a salinity gradient stronger than that of the tidal and wind driven mixing (Geyer *et al.* 1989). The CTD measurements demonstrated the lower Kaituna River does exhibit a saltwedge of dense marine water propagating as an under flow up the river to a maximum distance of ~1000 m. This observed saltwedge also fits in with Pritchard's (1955) classification due to the high freshwater to marine ratio. ELCOM predictions of the vertical and horizontal salinity were in good agreement with measured data (Figure 5.7), with the largest discrepancies occurring at the river mouth (000 meters) at low- and mid-tide. This discrepancy at the river mouth could have been reduced by extending a 'buffer zone' beyond the mouth (e.g. Robson *et al.* 2004). Creating a buffer zone in the model at the Kaituna River mouth was experimented with, however the timing and distance reached by the marine water up the river was not modelled as precisely with the buffer zone in place so was not included in final model simulations. Figure 5.7 also reveals that ELCOM tended to underestimate the vertical depth of the freshwater layer. This under estimation can also be demonstrated by the warm 'spikes' observed in the time series of modelled temperature in Figure 5.6 (A). Figure 5.17 illustrates how the marine water was causing the warm 'spikes' in the modelled temperature time series. The reason that the measured data did not show the spikes is because the measured data had no tidal variation. Therefore it can be assumed that because the measured and modelled temperature data were extracted from the same vertical height that the spikes demonstrate the depth of the freshwater layer was under predicted by the model.

The distance reached up a river by a salt wedge can be explained by variations in river flow and tidal range (Brockway *et al.* 2005 and Liu *et al.* 2006). Furthermore, variations in tidal ranges can also cause different strengths of stratification (Peters, 1997). Model results illustrated that the distance reached up the Kaituna River by the marine water also varied with tidal height and river flow. The range of this variation was not able to be compared to measurements as the CTD casts were only carried out over one flood tide. Therefore, to allow better validation of the salt wedge it would be useful to have CTD measurements over different tidal ranges and river flows. Predicting the variation in saltwedge inundation would allow more precise modelling of the marine water being drawn through the control gates.

Modelling the salinity regime of the lower Kaituna River was critical in determining the concentration drawn through the control gates and hence inflow into the estuary at Fords Cut. Measurements have shown that marine water is drawn through the control structure, therefore modelling the salt wedge propagation is crucial to accurately representing the salinity, temperature and CAEDYM variables entering the estuary at Fords Cut. This is most easily explained by comparing the relative nutrient concentrations of Bay of Plenty coastal water, which have low concentrations, to the Kaituna River water, which have higher concentrations of dissolved nutrients. This is a typical pattern for estuarine systems (Briggs, 1979). If the model over-predicts the salinity flowing through the outflow, then the nutrients flowing into the estuary will be under-predicted and vice versa. The outflow's vertical height also proved to be critical in determining the ratio of marine to freshwater drawn through the control gates (Section 5.3.3). ELCOM's three-dimensional grid allowed adjustment of the vertical cells the outflow occurred over. In a 2D depth-averaged numerical model it would have been almost impossible to control the proportion of marine to freshwater drawn through the outflow.

Modelling results revealed the retention time of the lower river is very low, with exception of the closed off loop near the river mouth in which the residence time was slightly increased. These residence time results are within the time frame given by White *et al.* (1978) who estimated the retention time of the Kaituna from Okere (where it exits Lake Rotoiti) to the mouth as one day. Model results in the closed off loop (Figure 5.15) near the river mouth revealed the highest residence time in the lower river. Comparing the measured temperature in the loop at location (B) (Figure 5.1) to the main river (A) revealed an increased temperature in the loop as well. If we assume that the water entering the loop was at the same temperature as the main river then the increase in temperature could be caused by solar heating of the water as it spends longer residing in the loop which is also very shallow.

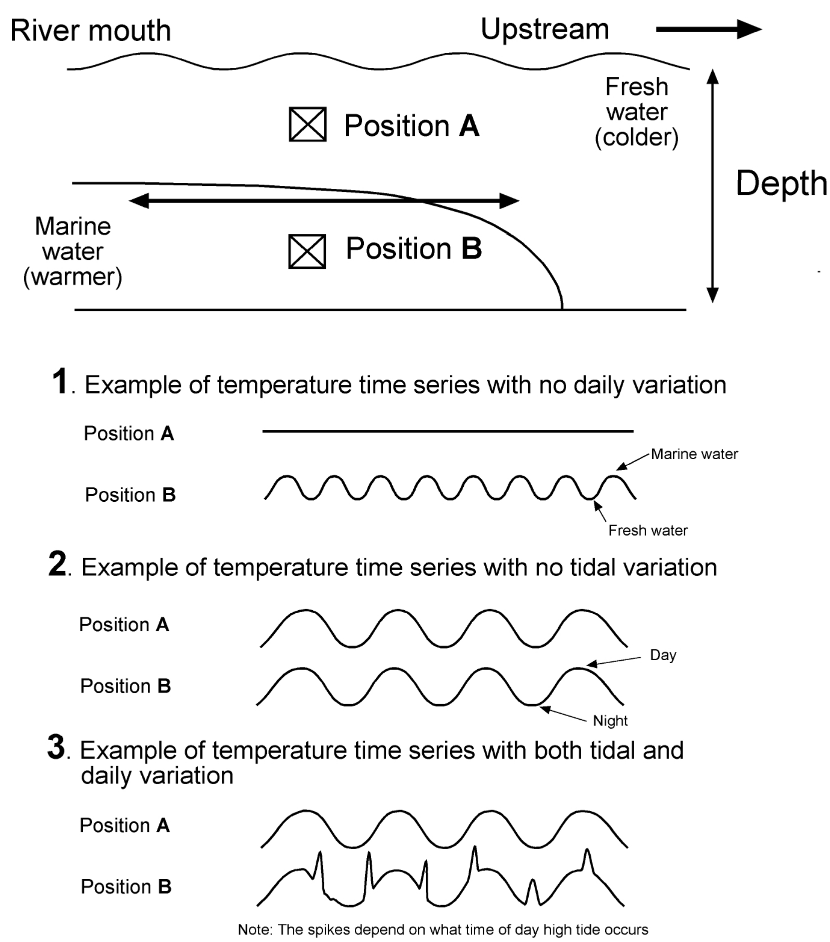

Figure 5.17. A schematic illustrating how the depth of the freshwater layer can effect a time series of temperature data and explain the observed spikes in the modelled temperature time series. The top panel is a cross-section along the river. Lower panels show examples of the time series that might be extracted given different input scenarios.

5.9) Conclusion and future model applications

This Chapter outlined how the hydrodynamic model ELCOM was initialised and applied to both model domains and where possible calibrated and validated against field measurements. Hydrodynamic measurements made during this work included temporal measurements of water velocities, elevation, and temperature as well as a number of salinity profiles in both the river and estuary. The measured salinity allowed the extent of mixing in the estuary and river to be evaluated while the measured water velocity and elevation data enabled calibration and comparison to modelled data. Validating the ELCOM model output against field data gave an overall reasonable fit with the main discrepancy occurring in the water elevation predictions in the river domain.

A small horizontal grid size limited the model simulation periods. The small grid size was needed to accurately represent the intertidal channels in the estuary and to reduce flow restrictions in the river domain. Increasing simulation period in the estuary domain was possible by reducing the vertical resolution as salinity measurements had showed vertical resolution was not important. However, vertical resolution was still vital for the river domain. ELCOM's three-dimensional grid was critical for defining the outflow variables at Fords Cut. This is because the proportion of marine to freshwater drawn through the outflow proved to be very sensitive to vertical height due to the salt wedge configuration, thus the added complexity of ELCOM's 3D grid was needed. Hydrodynamic model results allowed more accurate quantification of the residence time and mixing conditions present in the Maketu Estuary and lower Kaituna River than in previous work.

Some suggestions for future work involving application of ELCOM to the Maketu Estuary and lower Kaituna River include.

- Deploying FSI current metres to measure water elevation and velocities for an extended period of time, incorporating a number of tidal cycles at each location. A longer deployment would allow more complete calibration and validation of the hydrodynamic numerical model.
- Using a CTD to measure salt wedge intrusion during various river flow rates and tidal ranges in the lower river to determine maximum inundation and depth of the marine water. A better understanding of the dominant controls on the extent of marine water intrusion in the river would be useful for (a) devising flow rates and locations for inflows into the estuary and (b) allowing a more rigorous model validation.
- Experimenting with various horizontal and vertical grid resolutions. Model simulation periods were limited by the grid resolution. It would be useful to experiment with increasing the grid size and seeing if the model output still agreed well with the measured hydrodynamic variables.
- Extending the Kaituna River model domain to include the remaining river mouth and a region of the Bay of Plenty for more accurate bathymetry representation.
- Using wind forcing data (wind speed and direction) in the model to determine the effects of wind shear stress on the residual current flows.

Chapter Six

Chemical and biological modelling of the Maketu Estuary and lower Kaituna River

6.1) Introduction

By coupling the water quality model CAEDYM to the hydrodynamic driver ELCOM (Chapter Five), it is possible to model aspects of the chemical and biological dynamics in the lower Kaituna River and Maketu Estuary and the influence of hydrodynamics on these processes. This chapter describes how CAEDYM were applied to the Maketu Estuary and lower Kaituna River. Four phytoplankton groups are included in the CAEDYM simulations and their relative growth and mortality rates are evaluated and related to the major chemical and hydrodynamic processes in the lower river and estuary.

6.2) Model simulation period and simulated chemical and ecological variables

The year 2004 was chosen for CAEDYM simulations in the lower Kaituna River and Maketu Estuary. This year was selected as the full range of CAEDYM water quality variables were available for each model boundary over 2004. It was also close enough in time to the present (2006), that confidence could be attributed to the measured bathymetry (Chapter Four) used for numerical modelling (i.e. the bathymetry was likely to closely resemble the major channel and mouth morphology present in 2004). Initially ELCOM-CAEDYM model simulation periods were planned to cover an entire year, however, after generating (Chapter Four) and calibrating/validating (Chapter Five) the model domains for ELCOM, model run times made simulating an entire year impractical. Running the coupled model (ELCOM-CAEDYM) typically reduced the runtime by 6–10 times compared to running ELCOM only (Table 5.2). Simulated model runs were therefore limited to a maximum of 3–4 weeks. Throughout this chapter and Chapter Seven the simulated period is noted when results are presented.

CAEDYM allows the user to model multiple species of aquatic organisms (for details refer to Hipsey, 2006). For this study four groups of phytoplankton were simulated including two freshwater, one estuarine and one marine group (Table 6.1). The groups were chosen to represent the main pelagic algae that would likely dominate in the Maketu Estuary and Kaituna River, reflecting both the freshwater input from a eutrophic lake (Lake Rotoiti) and the inputs from temperate marine coastal waters. The four groups chosen are common in numerical modelling of phytoplankton for estuary studies (e.g. Robson *et al.* 2004).

For chemical and biological simulations CAEDYM requires the user to specify a number of variables which are prescribed at each boundary in the model (Hipsey, 2006). Table 6.1 summarizes the variables used in CAEDYM simulations of the Maketu Estuary and lower Kaituna River. The variables were chosen to accurately represent the nitrogen (N), phosphorus (P) and carbon (C) cycles.

Table 6.1. Variables simulated in the lower Kaituna River and Maketu Estuary using the coupled model ELCOM-CAEDYM.

CAEDYM variable name	units
Dissolved oxygen (DO)	(mg l^{-1})
Ammonium (NH_4)	(mg l^{-1})
Nitrate (NO_3)	(mg l^{-1})
Labile particulate organic nitrogen (PONL)	(mg l^{-1})
Labile dissolved organic nitrogen (DONL)	(mg l^{-1})
Dissolved reactive phosphorus (PO_4)	(mg l^{-1})
Labile particulate organic phosphorus (POPL)	(mg l^{-1})
Labile dissolved organic phosphorus (DOPL)	(mg l^{-1})
Labile dissolved organic carbon (DOCL)	(mg l^{-1})
Labile particulate organic carbon (POCL)	(mg l^{-1})
Suspended solids (SSOL1)	(gm^3)
Tracers / colours	(–)
Phytoplankton groups	
Dinoflagellates (DINOF) - estuarine	(µg chl *a* l^{-1})
Marine diatoms (MDIAT) - marine	(µg chl *a* l^{-1})
Freshwater diatoms (FDIAT) - freshwater	(µg chl *a* l^{-1})
Cyanobacteria (CYANO) - freshwater	(µg chl *a* l^{-1})

6.3) Boundary condition formation and initial conditions

Each boundary condition (BC) requires the concentrations of the variables (listed in Table 6.1) to be specified over the period of simulation, and can be specified as either a constant value or time-varying at an interval specified by the user. The location of each BC is illustrated in Figure 6.1 and throughout this chapter will be referred to by the names used in Figure 6.1. Concentrations were derived from Environment Bay of Plenty's (EBOP's) monitoring data archives; for more details see: McIntosh *et al.* (1995); Bruere *et al.* (1996); McIntosh *et al.* (1996); McIntosh *et al.* (1997); McIntosh, (2003); Park, (2003); Park (2005).

Figure 6.2 illustrates the average concentration of the major nutrients (NH_4, NO_3 and PO_4) at each boundary for January 2004. Variables at Fords Cut were derived from model output and reflect the mixture of freshwater (which is relatively high) to marine water (relatively low) nutrient concentrations in the lower Kaituna River. A brief explanation is given describing how the boundaries variables were derived.

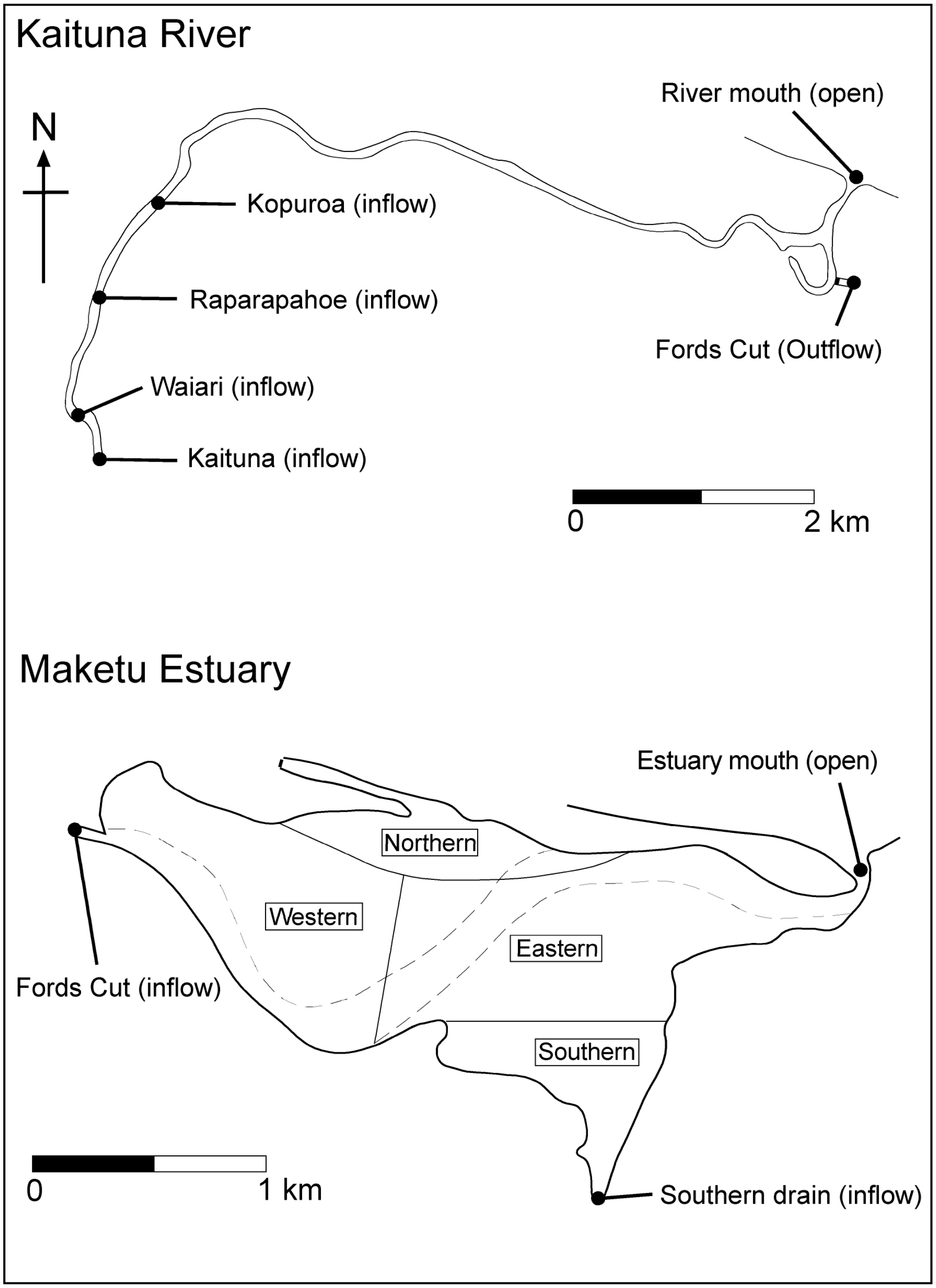

Figure 6.1. Location of the boundary conditions specified in ELCOM-CAEDYM simulation of the Maketu Estuary and lower Kaituna River. Regions of the estuary are also defined for when they are referred to in the Results and Discussion. Dashed line show the extent of the main tidal channel.

6.3.1) Open boundaries (river and estuary mouth)

Over 4 days between December 2003 to July 2004, chemical, physical and biological measurements were collected for three transects over the coastal shelf out to 200 metres water depth within the Bay of Plenty (Park, 2005). Surface (< 20 metres depth) concentrations of the variables of interest from each transect were extracted, averaged for each day and linearly interpolated between the four days to create the open BC data for the period of simulation.

6.3.2) Kaituna River

Water quality variables are measured in the Kaituna River 3–6 times each year by EBOP at Te Matai (Figure 5.1), and extend over a 20 year period (n = 87). The variables of interest were analyzed for any annual or long term trends and specified in the model as either an annual average value or a regression fit to the total data set using the relationship between the water quality variables and the time of year as illustrated in Figure 5.3.

6.3.3) Kopuroa and Raparapahoe Canal

Water quality variables for Kopuroa and Raparapahoe Canal canals were set to the same concentration as the Kaituna BC, as the available data set for the two canals was small. Because (a) there is no indication that nutrient concentrations in the two canals would be vastly different from the Kaituna and (b) their overall flow contributes on average only 3.2 percent total flow in the Kaituna River during the period of model simulation, the errors should not be significant to the overall concentration in the Kaituna River.

6.3.4) Waiari Stream.

The Waiari Stream is elevated in PO_4 and NO_3 which is probably due to seepage from Te Puke wetland which receives treated waste water from Te Puke township (McIntosh, 2005). Seventeen measurements over three years were used to derive the variables for Waiari BC. Again as for the Kaituna BC, the variables were analyzed for any annual or long term trends and specified in the model as either annual average value or a regression fit to the total data set.

6.3.5) Fords Cut inflow into the estuary

Output from ELCOM-CAEDYM in the Kaituna River domain was used to predict the concentrations of variables flowing into the Maketu Estuary through the control gates at Fords Cut. ELCOM allows the user to save output of the average concentration of scalars (i.e. salinity, temp, nutrients, phytoplankton) flowing through an outflow at a time step defined by the user. To define the inflow variables flowing from the Kaituna River into the Maketu Estuary, the outflow variables were saved at a time step of 15 minutes and converted into the correct format for an inflow boundary.

6.3.6) Southern drain

In 1994, Bruere *et al.* (1996) measured a number of water quality parameters for four drains that enter on the southern border of Maketu Estuary. The results of the monitoring at the discharge drains (monitoring sites closest to the estuary) were extracted and an average value derived for the southern drain BC.

6.3.7) Initial conditions

A horizontally and vertically uniform initial condition was applied across the estuary and river domain. Preliminary modelling results indicated that the high flushing rate of both the estuary and river allowed the model to equilibrate within a few tidal cycles. For the Kaituna River model domain, initial concentrations of CAEDYM variables were set to the same values as the Kaituna BC and for the Maketu Estuary model domain initial concentrations were set to match the estuary mouth BC.

6.3.8) Sediment interaction and nutrient flux

The CAEDYM configuration allows the user to specify sediment nutrient fluxes. Sediment release in the model is also affected by the pH and oxygen concentration of the overlying water. Measured data and preliminary modelling showed no evidence of oxygen depletion in the water near the sediment-water interface, therefore the oxygen consumption rate could be neglected along with pH which was not a simulated variable for this study. A constant flux rate for NH_4, NO_3 and PO_4 between the sediment and overlying water was prescribed and is given in Table 6.2.

6.3.9) Phytoplankton concentrations

For model simulations in the Maketu Estuary and lower Kaituna River, phytoplankton concentrations were represented by chlorophyll *a* and derived through a number of methods. CAEDYM allows the user to specify phytoplankton in either chlorophyll *a* (µg Chl-*a* l^{-1}) or carbon (mg C l^{-1}) units. Chlorophyll *a* units were chosen because the parameters and rates (Appendix 1) sourced from the literature and past modelling work using CAEDYM were expressed in terms of chlorophyll *a*, which is common for phytoplankton modelling (e.g. Robson *et al.* 2004; Hu *et al.* 2006). Chlorophyll *a* concentrations for the two marine and estuarine groups (marine diatoms and dinoflagellates) were derived from measurements collected in the Bay of Plenty over 4 days between December 2003 and July 2004 (Park, 2005). For each day of measurements, the surface concentrations of chlorophyll *a* (< 20 metres depth) were averaged, and divided between the two groups determined by cell counts (Park, 2005). To create a time series of chlorophyll *a* for the model boundaries, the four point measurements were linearly interpolated over the simulation period; the interpolated time series is illustrated in Figure 6.3. Outflow chlorophyll *a* concentrations from Lake Rotoiti at the head of Kaituna River were used to define the concentration of the two freshwater species (freshwater diatoms and cyanobacteria). The outflow chlorophyll *a* concentrations were sourced from phytoplankton modelling carried out on Lake Rotoiti using CAEDYM (Hamilton *et al*. 2005). Chlorophyll *a* concentrations for the Kaituna BC were reduced to 75 percent of the predicted concentration at the outlet to account for dilution with tributaries between the outlet and the Kaituna BC. A dilution of 52 percent was calculated using the average flow rates in the Kaituna at the lake outlet and at Te Matai (McIntosh, 2005). However reducing the concentration to 52 percent would likely underestimate the total phytoplankton biomass at the Kaituna BC as tributaries also contribute phytoplankton. EBOP operates a cyanobacteria monitoring program in the Kaituna River, determining species and number of cells. An initial attempt was made to convert the cell counts into chlorophyll *a* concentrations using the techniques given by Hillebran *et al.* (1999) and Montagnes *et al.* (1994) assuming cyanobacteria volumes can be approximated using a spherical shape. The calculated chlorophyll *a* concentrations for 2004 were extremely low compared to predicted model output from Lake Rotoiti. It was judged that the concentrations derived from the modelling are more likely to represent the actual cyanobacteria numbers present in the Kaituna River, consequently the higher values were used in the model simulations.

Chlorophyll *a* for the two marine species was specified at the open boundaries (river and estuary mouth). The two freshwater species were specified at the Kaituna and Waiari boundary at the same daily concentration as no other means for estimating chlorophyll *a* in Waiari Stream were available. Kopuroa, Raparapahoe and Southern drain inflows had no phytoplankton biomass specified for their BCs. In order to evaluate the relative growth rate of each phytoplankton group, a conservative tracer (i.e. no growth or decay) was specified at each boundary to match the concentration of the phytoplankton group considered. The growth rates ($\overline{gr}$) averaged over the 15 day simulation period can be expressed as a percentage for each phytoplankton group as:

$$\overline{gr}(i,j) = \frac{1}{n}\sum_{k=1}^{n}\left(\frac{chla(i,j,k) - tracer(i,j,k)}{tracer(i,j,k)}\right)\times 100 \qquad (6.1)$$

Where i, j are the grid cell numbers in the horizontal dimensions. k is each time step, n is the total number of time steps and Δt is the time between each time step, so that $n\Delta t$ =15 days.

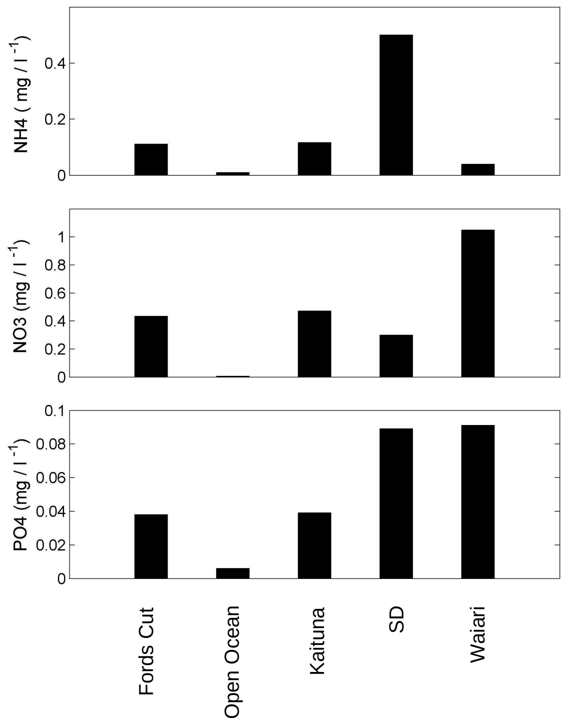

Figure 6.2. Concentrations of major nutrients specified for each boundary condition averaged over January 2004. Raparapahoe and Kopuroa Canal are specified at the same concentration as Kaituna River. Note that Fords Cut is derived from model output and reflects a mixture of both fresh and marine water. SD = Southern Drain.

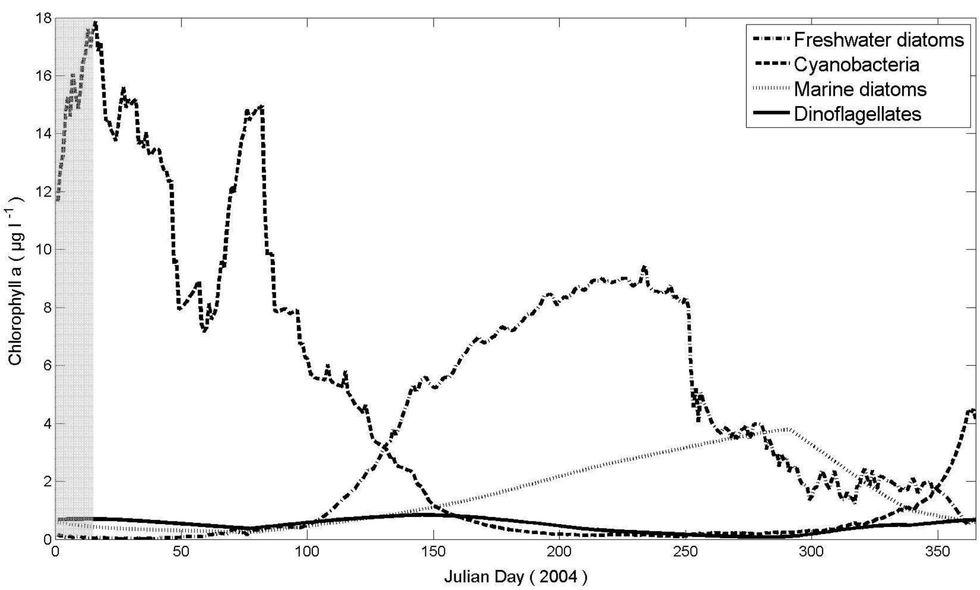

Figure 6.3. Time series of chlorophyll *a* concentrations for 2004 as specified in the model at the river and estuary mouth (dinoflagellates and marine diatoms) and Kaituna and Waiari boundaries (cyanobacteria and freshwater diatoms). Shaded area represents the period of model simulations.

Table 6.2. Sediment nutrient flux parameters used in CAEDYM simulations in the Maketu Estuary and lower Kaituna River.

Parameter	Rate (g m^2 day^{-1})
NO_3 release rate from sediment	-0.200
PO_4 release rate from sediment	0.004
NH_4 release rate from sediment	0.050

6.4) CAEDYM parameters and rates

CAEDYM simulations require specification of a number of parameters and rates for the biological variables. Marine diatoms and dinoflagellate phytoplankton parameters for this study were sourced from literature (Robson *et al.* 2004) while the parameters for the two fresh water groups (freshwater diatoms and cyanobacteria) were sourced from past modelling carried out on Lake Rotorua using CAEDYM (Burger, 2006). Burger’s (2006) initial parameters were sourced from the literature, and then adjusted so model output matched the measured phytoplankton data in Lake Rotoiti. A full list of the parameters used for model simulation in the Maketu Estuary and lower Kaituna River can be found in Appendix 1.

6.5) Results

6.5.1) Kaituna River

Figure 6.4 illustrates NH_4, NO_3 and PO_4 concentrations predicted by CAEDYM averaged over 15 days in January 2004 from the beginning of the model domain (Kaituna boundary) to the river mouth located ~8,500 metres downstream. An increase in NO_3 and PO_4 and decrease of NH_4 can be observed at the Waiari Stream confluence with the Kaituna River. Dilution of nutrients with marine water at the river mouth is also predicted in model simulations. The Raparapahoe and Kopuroa Canals do not alter the nutrient concentrations in the Kaituna River because their concentrations match those of the Kaituna boundary. CAEDYM predicts a minor but steady increase in NH_4 and a decrease for both PO_4 and NO_3 concentrations from the Kaituna boundary to the river mouth. The specified sediment release rate parameters (Table 6.2) can explain part of the increase in NH_4 due to a positive release from the sediment and the decrease in NO_3 caused by the negative release rate. However it would then be expected that PO_4 should increase steadily down river as a positive sediment release rate (0.004 g m^2 day^{-1}) was specified. However it is possible that consumption of PO_4 by the two freshwater phytoplankton groups exceeds the specified release rate causing the observed decrease. The predicted nutrient concentrations are also compared to the ANZECC (2000) trigger values for lowland rivers set by Ministry for the Environment (MfE) (2000) in Figure 6.4. The trigger values are averaged water quality measurements of lowland rivers throughout New Zealand. The values are intended as an assessment tool for water resource managers (e.g. Regional Councils) to compare water quality parameters from their rivers and streams to a national average. Concentrations above these values indicate there may be adverse environmental effects.

Figure 6.5 illustrates the predicted growth rates (Equation 6.1) for the four phytoplankton groups over the 15 day simulation in the Kaituna River. The two freshwater groups, freshwater diatoms and cyanobacteria increase in abundance, by contrast, almost no net change is observed for the marine diatoms and dinoflagellates in the lower Kaituna River. Due to the low amount of mixing and very short residence time of marine water in the river (Chapter Five), salinity limitations imposed on growth rates of the two freshwater species were not observed (as occurred in the estuary). The highest community growth rates of phytoplankton (160% growth) occurred in the closed off-loop (Figure 6.5) and correlate positively with residence time.

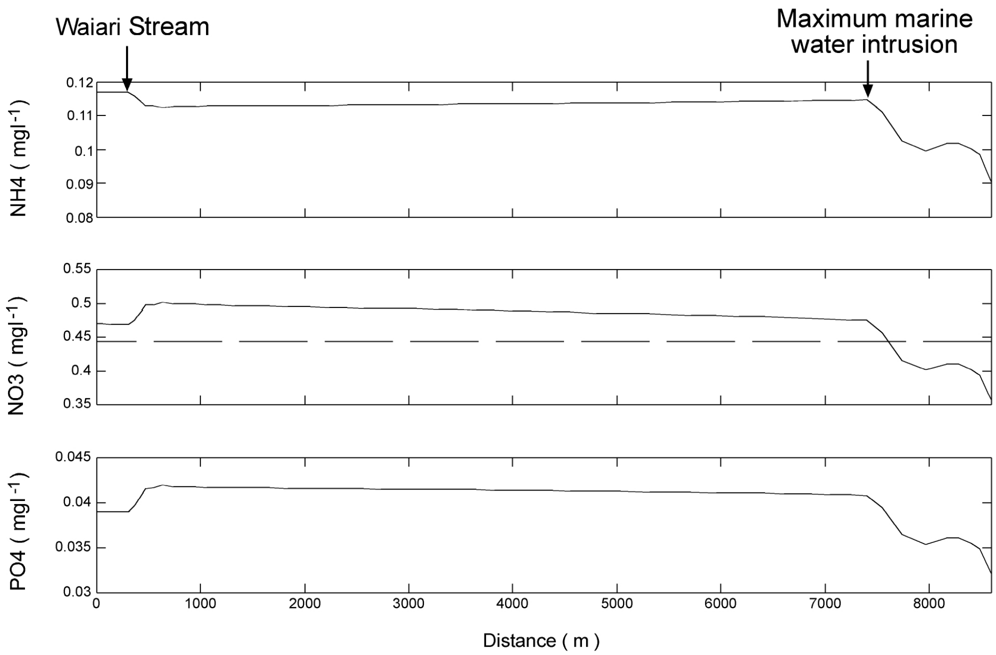

Figure 6.4. Simulated NH_4, NO_3 and PO_4 concentrations in the lower river from the Kaituna boundary (0 m) to the river mouth (8500 m) averaged over a 15 day period in January 2004. Location of Waiari Stream is shown. Dashed line illustrates the trigger values for low-land rivers set by Ministry for the Environment (2000). Trigger values for NH_4 and PO_4 are below the lower axis and are 0.021 and 0.01 mg l^{-1} respectively.

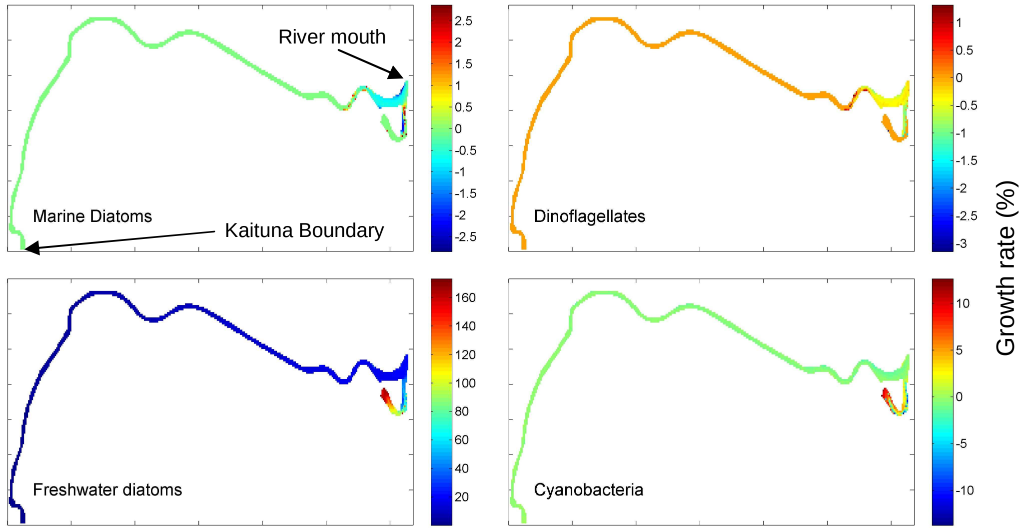

Figure 6.5. Illustrates the distribution of the depth-averaged phytoplankton growth in the lower river averaged over a 15 day period in January 2004 for each phytoplankton group modeled. Note that each phytoplankton group is on a different scale.

6.5.2) Maketu Estuary

Figure 6.6 illustrates ELCOM-CAEDYM's predicted nutrient concentration in the Maketu Estuary averaged over a 15 day period in January 2004 (Julian days 1–15). The plots are time and depth averaged and show the high concentration of NH_4, NO_3 and PO_4 entering the estuary through Fords Cut. The southern drain BC also contributes a relative increase in PO_4 and NH_4 in the vicinity of the drain.

Figure 6.7 shows the time-averaged phytoplankton growth over the same 15 day period in 2004, expressed as percentage increase (Equation 6.1). Model results show that marine diatoms exhibited the highest growth rate of all the phytoplankton groups; however the maximum growth rate over the domain was less than a doubling rate for the period of the simulation. Simulated growth rates for the two freshwater phytoplankton groups were low, with the largest variation in the eastern, southern and northern regions of the estuary, the reduction in these regions is likely to be caused by salinity limitations of the phytoplankton. The estuarine phytoplankton group, dinoflagellates, had the smallest fluctuations in spatial abundance over the 15 day simulation demonstrating only a slight increase in the western region of the estuary. The small fluctuations are likely to be attributed to their broad salinity tolerance. Figure 6.8 is a correlation matrix of the percentage change of the four phytoplankton groups correlated against NH_4, NO_3, PO_4, salinity, temperature and residence time. The data for the correlation was extracted at regular points (every tenth grid cell) from the time and depth averaged variables simulated over the same 15 day period. The phytoplankton groups are correlated positively with NO_3, NH_4 and PO_4 and negatively with salinity. Marine diatoms and dinoflagellates show a positive correlation with residence time. The relationship with temperature does not show an observable trend although the highest growth rates all occurred in the higher range of temperature.

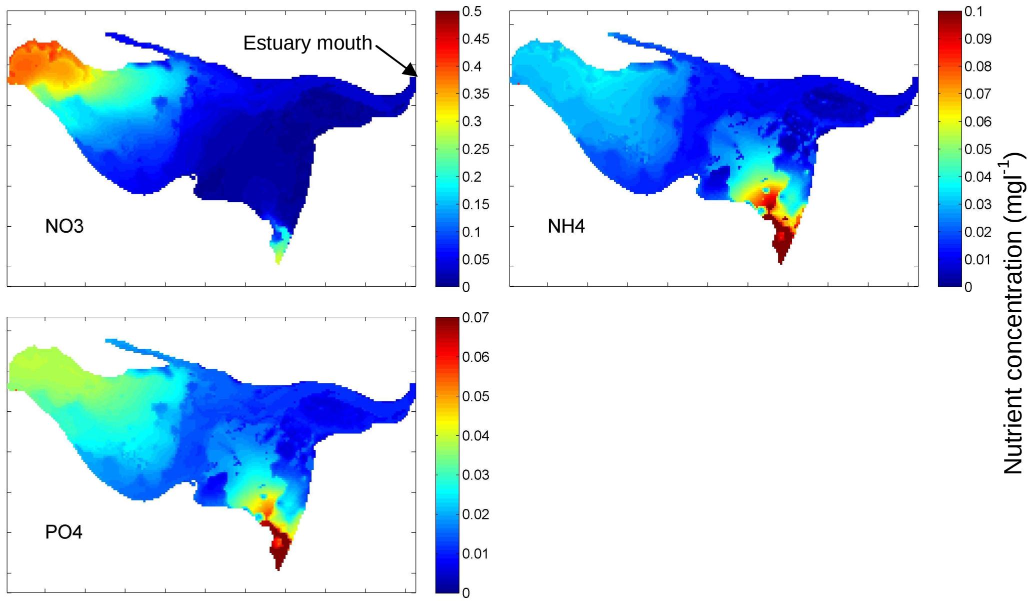

Figure 6.6. Predicted NO_3, NH_4, and PO_4 concentrations in the Maketu Estuary averaged over a 15 day period in January 2004.

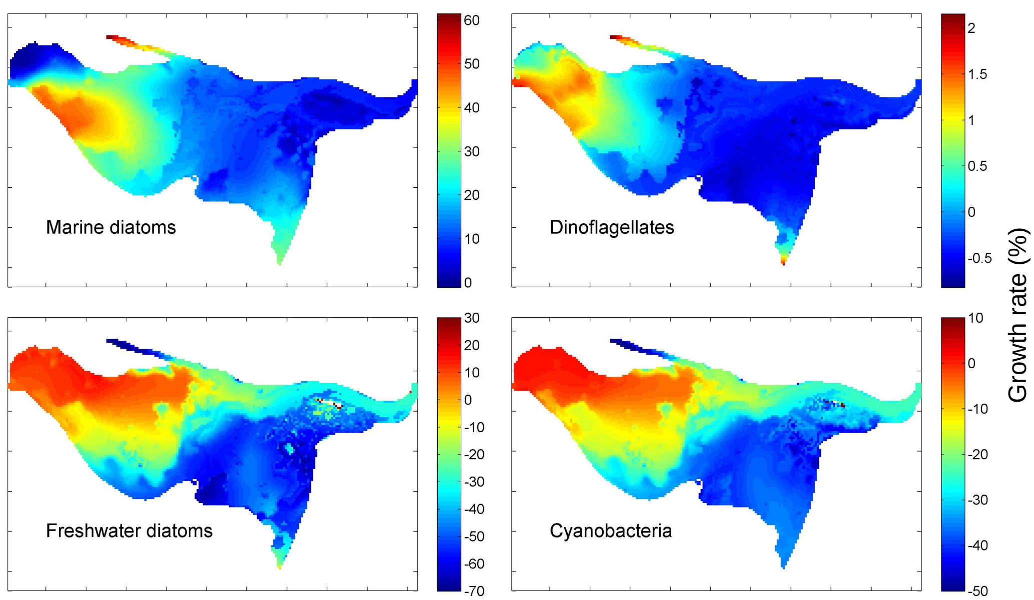

Figure 6.7. Predicted phytoplankton growth averaged over a 15 day period in January 2004. Concentrations are expressed as an average percentage increase over the period of simulations. Note that each phytoplankton group is on a different scale.

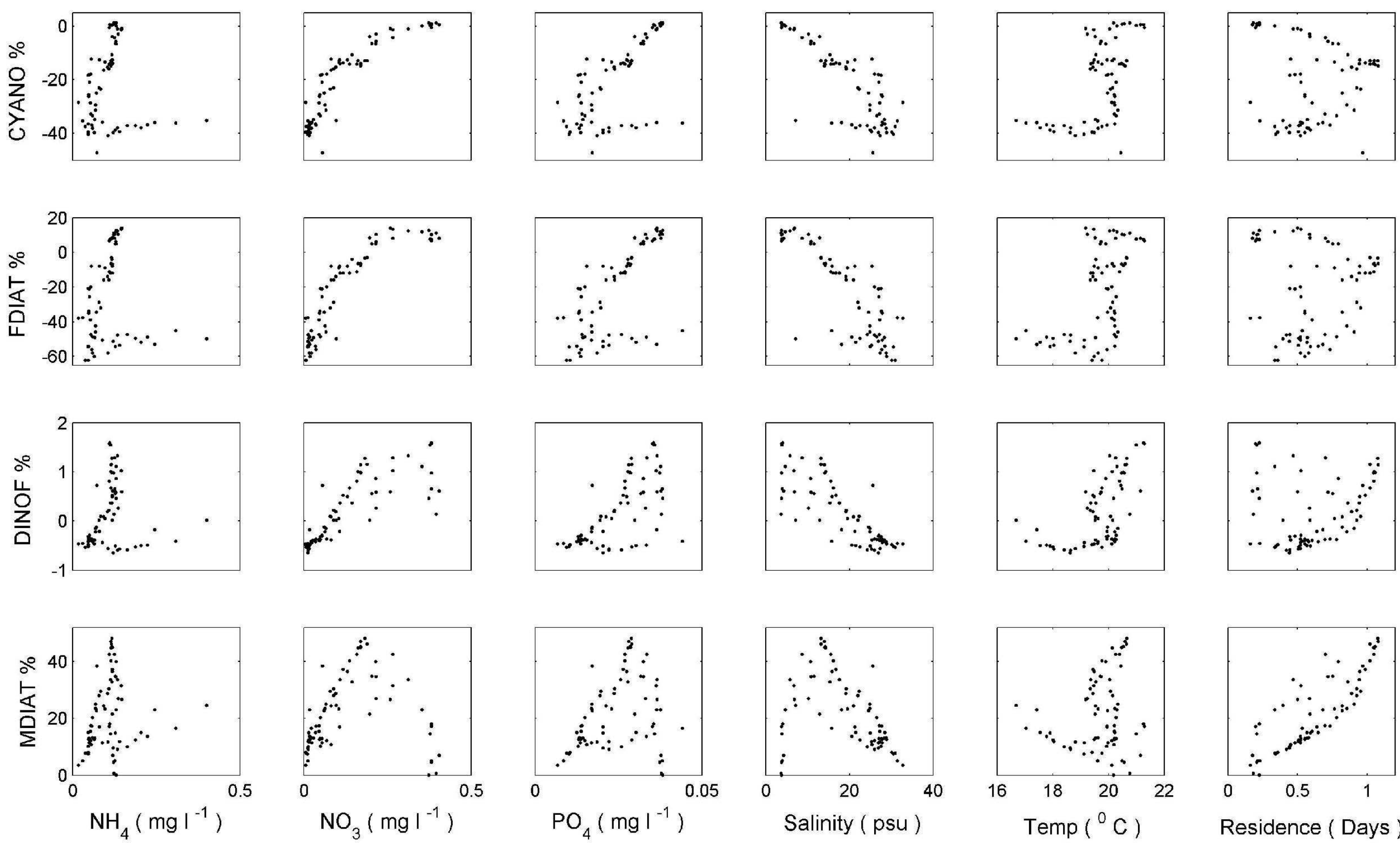

Figure 6.8. Scatter plot of the predicted phytoplankton growth/mortality against six variables from every tenth cell in the Maketu model domain. Results are averaged over a 15 day period. CYANO = cyanobacteria. FDIAT = freshwater diatoms. MDIAT = marine diatoms. DINOF = dinoflagellates.

6.6) Discussion

Water quality (CAEDYM) simulations in the Maketu Estuary and lower Kaituna River were limited to a three week period due to model run time constraints. The data set used to derive the water quality variables at each BC was from measurements collected over several years at a sampling frequency of months (refer Section 6.3 for details). Consequently the short simulation periods were not suitable to allow an accurate model validation with the available data set. In addition, the hydrodynamic model ELCOM was calibrated over a different year (2006) to when water quality simulation occurred (2004). Although calibration of a hydrodynamic and ecological models over separate years has been successfully applied to other estuaries (for example Chau, 2004), for an estuary such as Maketu where the channel and mouth morphology have been shown to change over small time scales (Figure 4.5) it could introduce an error.

Due to the mismatch in interval of the model simulation and field data periods, and different years for the calibration of the hydrodynamic and ecological models, the majority of the water quality variables at the inflow boundary conditions for this study were derived as averages rather than interpolated between field measurements. Therefore the water quality modelling under taken in this study represents the ‘average’ conditions present in the Maketu Estuary and lower Kaituna River over a typical summer month rather than the actual conditions present over the three week simulation.

The controlling factors on phytoplankton growth rates in an estuarine environment are complex and the particular combination of these factors is unique for every estuary (O’Higgens *et al.* 2005) and can vary spatially within an estuary, for example Gibbs, (1993) and Vant, (1993). The predictions of phytoplankton biomass presented and discussed in this chapter have been made by varying the hydrology, residence time, nutrients and salinity and temperature. Because simulations were undertaken in January (summer), it was assumed that light intensity was not limiting to growth. It is also assumed that the euphotic zone or compensation point (Figure 3.3) extends below the maximum depth of the river or estuary. The euphotic zone is the depth down to where light intensity is high enough that photosynthesis exceeds respiration, hence net growth can occur. In the Manukau Harbour it is estimated the euphotic depth ranges from 2.5–7 metres depending on the region of the estuary and water clarity (Vant *et al.* 1993). Therefore, it could be assumed that in the Maketu Estuary (max depth 2.5 metres and Kaituna River (5 metres) light is abundant throughout the water column. The extensive beds of aquatic plants in the river (McIntosh, 2005) and *Ulva* (Park, 1992) that can smother the estuary bed also demonstrate that light is not limiting to plant growths at these depths in the Maketu Estuary and Kaituna River.

It is noted that phytoplankton in an estuary, ocean, lake or river demonstrate species succession, for example a diatom 'spring bloom'. Therefore, the short simulation period does not take into consideration all the variations of the forcing variables. Nevertheless, the water quality simulations have enabled the identification of regions in the river and estuary which may be favorable to high growth rates, and the quantification of limiting factors on phytoplankton.

6.6.1) Kaituna River

CAEDYM simulations in the lower Kaituna River predicted that nutrients are likely to be conserved from the Kaituna boundary to the river mouth. These results concur with measured data that has shown that nutrients are conserved over the entire reach of the Kaituna (McIntosh, 2005; White *et al.* 1978) as would be expected for a river with a low residence time (Hilton *et al.* 2006). Model results indicate that the contribution of Waiari Stream is significant to the nutrient load of the Kaituna River (Figure 6.4). Other nutrient loads arising from a number of farm drain pump stations (Figure 6.9) and diffuse sources were not simulated in the model runs nor to the author's knowledge are there any other direct measurements of these inputs. Larsen (1998) suggest that high dairy cow stocking rates on the Te Puke lowlands could be causing nutrient contamination of the ground water. It is likely that this nutrient rich ground water from dairy farming plus other agricultural practices in the catchment would be contributing to the nutrient load of the estuary and river as diffuse inputs. Diffuse and point discharges of nutrients can be important for controlling water quality in streams and rivers (Pietersa *et al.* 2002) Therefore, it would also be of interest to quantify both diffuse and point source inputs into the lower river for any future water quality modelling or nutrient budget.

Model results predicted that the Kaituna River exceeds the trigger values for NO_3, NH_4 and PO_4 set by MfE (2000). Through 10 years of measured data McIntosh (2005) illustrated that the trigger values were exceeded in the Kaituna River at Te Matai due to the volcanic geology, which has naturally high levels of PO_4, and the high rates of nitrogen leaching from the soil. The trigger values are not an environmental standard and many of the Bay of Plenty's rivers exceed these values.

As predicted by the simulations with the hydrodynamic model ELCOM (Chapter Five), the residence time in the lower river is very low. This low residence time of the river has been predicted as the principal limiting factor to phytoplankton growth (McIntosh, 2005; White *et al.* 1978). Reynold (1984) estimated that a river with a residence time of less than 4–6 days will not incur nuisance algae conditions assuming that the cell doubling rate is two days and that it takes a few cell doubling rates to cause nuisance conditions. Assuming this, we can use a residence time of approximately 1 day (White *et al.* 1978) for the entire river or 10 hours (Section 5.7.2) for the lower river, and apply the assumption of Reynolds (1984) to the Kaituna River. Using a maximum growth rate of 1.44 and 0.7 day^{-1} (Burger, 2006) for freshwater diatoms and cyanobacteria respectively, reveals that phytoplankton cells in the Kaituna River from the headwaters to the river mouth would at most double, even under the most favourable conditions.

Hilton *et al.* (2006) suggest that rivers down stream of eutrophic lakes constitute a special case as algae concentrations at the river head waters are likely to be elevated, but go on to state that in short retention rivers (i.e. similar to Kaituna River) the most significant effect of this algae will be to add to the river's turbidity rather than cause nuisance conditions, as high growth rates could not occur. This can be illustrated by phytoplankton cell counts taken in 2004 showing numbers of cyanobacteria exceeded the bathing guidelines in the Kaituna River, however it was determined that the high concentrations were derived from Lake Rotoiti and not due to growth with in the river (McIntosh, 2005). Model results agree with this prediction, illustrating that the relative growth rates of the two freshwater species (Figure 6.5) are very low and only show a small increase in the closed loop where residence time is amplified (Figure 5.15). Gibbs (1993) identified elevated growth rates of phytoplankton in a side arm of the Pelorus Sound, and Lam (1981) measured an increase in phytoplankton numbers in some of the Waikato Rivers hydro dams; both increases were contributed by an increase in residence time of each system. ELCOM predicted the maximum residence time for the loop as 27 hours, because of this short residence time it would be highly unlikely that nuisance algae blooms would occur in the loop, even if all other conditions were favorable to phytoplankton growth.

For the two marine phytoplankton groups, marine diatoms and dinoflagellates, simulated in the model, residence time in the lower river is in the order of hours as marine water is exchanged completely during a tidal cycle. Therefore growth rates would be expected to be low (as CAEDYM predicted). The greatest growth rates of marine phytoplankton associated with the Kaituna River would likely occur in the immediate coastal region off the river mouth, as demonstrated for river plumes off the east coast of the South Island (Haywood, 2004) and other river discharges (e.g. Spillman, 2007).

Figure 6.9. Picture of water from a pumped drain (just to left of image and shown in insert) entering the Kaituna River near the control structure at Fords Cut.

6.6.2) Maketu Estuary

In general the largest source of nutrient load into an estuary system is derived from the freshwater inflows (Briggs *et al.* 1979; Paerl, 2005). This large nutrient source is typically modified by development in the upstream catchments including inputs from the agricultural, industrial and urban sectors (Quinn *et al.* 2002; Paerl, 2005). A large source of nutrients in the Maketu Estuary is sourced from the Kaituna River which enters the estuary via control gates located at Fords Cut (Figure 6.1). The Kaituna River's elevated nutrient concentrations arise from contributions by the eutrophic lakes as well as the several discharges from industrial sites along its reaches (White *et al.* 1978; McIntosh, 2005). The effects of the Kaituna water on nutrient concentrations in the Maketu Estuary have been illustrated from analysis of measurements taken at several point locations in the estuary (McIntosh *et al.* 1995; Park, 2003). Up until present several salinity surveys have been able to demonstrate how this nutrient rich freshwater is diluted with marine water during a tidal cycle and flushed out of the estuary (e.g. Domijan, 2000; McIntosh *et al.* 1997). However the salinity surveys occurred at limited locations and only over a small (one tide) time scale. By coupling the water quality model CAEDYM to the hydrodynamic driver ELCOM, numerical modelling undertaken in this study has enabled simulation of spatial and temporal variations of nutrients in the Maketu Estuary. Furthermore it has enabled an insight into the interactions of nutrients, salinity, temperature, meterological and hydrodynamic variables on phytoplankton growth.

Model simulations with CAEDYM show that the western region of the Maketu Estuary has the highest average nutrient concentrations due to the freshwater inflow at Fords Cut. This nutrient rich water is partially exchanged with marine water over a tidal cycle with a proportion of the water remaining in the estuary for a maximum of 1.5 days before being flushed out. The location and conditions specified for the open boundary result in fully marine water being brought into the estuary on a flood tide. In reality it is likely a proportion of the marine water flowing into the estuary on a flood tide would have been diluted with brackish water exiting the Kaituna River.

The modelling simulation predicted that the southern drain, which represents an amalgamation of four culverts, delivers a high nutrient load into the Maketu Estuary most notably in the southern region of the estuary (Figure 6.6). McIntosh *et al.* (1997) identified a reduction in salinity in the immediate area associated with these culverts and Bruere *et al.* (1996) measured elevated nutrient concentration in a number of the drains. However it was concluded that, because of the small flow rate of the drains, they were unlikely to contribute significantly to the nutrient load of the estuary (McIntosh *et al.* 1997). The nutrient concentrations and flow rates prescribed for the southern drain boundary are derived from very few point measurements. Because of this uncertainty in deriving the time series used in the model from so few point measurements, it is expected the actual nutrient load contributed by the drains could vary from what is predicted. However what the model results have indicated is that because of the estuary's small intertidal storage of ~1,000,000 m^3 (Domijan, 2000) a small inflow could contribute to the estuary's nutrient load significantly. This would suggest that the drains and culverts surrounding the Maketu Estuary should be considered as an important part of any nutrient budget or future water quality modelling in the estuary.

ELCOM simulations (Figure 5.14) predicted that the western region (refer to Figure 6.1 for location) of the Maketu estuary is where the highest residence time occurs. If it is assumed that in the estuary residence time is the limiting factor to phytoplankton growth as was observed in the river, then the western region of the estuary is most likely to exhibit the greatest phytoplankton growth rates. The three week CAEDYM simulation suggests that this is correct, with marine diatoms and dinoflagellates demonstrating the highest growth rates of 160 and 3 percent respectively, correlated to retention time (Figure 6.8). However in the estuary, unlike the river, marine water dominates over freshwater inflow and induces greater mixing and ranges of salinity. An area that demonstrates high rates of marine and freshwater mixing is also the western region. Variation in salinity can have a profound effect on the phytoplankton growth rates and biomass (Day, *et al.* 1989; Kirst, 1990; Floder, 2004). For the Maketu Estuary, simulation of the two freshwater species showed significant reduction in relative (predicted – conservative tracer) concentration when mixed with the marine water

(Figure 6.7). Because of widespread and rapid (< 1.5 days) dilution of the freshwater with marine water, it would suggest that growth of a freshwater phytoplankton in the Maketu Estuary would be unlikely to occur.

Elevated nutrient levels are often a prerequisite to repeat occurrences of phytoplankton blooms (Pick, 1989), for example Lake Rotorua and Lake Rotoiti (Vincent, 1984) that partially drain into Maketu Estuary. CAEDYM simulations and measurements (White *et al.* 1989) indicated that nutrients in the Kaituna River are not limiting to the growth of phytoplankton. Simulations in the Maketu Estuary showed phytoplankton growth of all four phytoplankton groups could be correlated with nutrient concentrations (Figure 6.8). However, this perceived correlation may be effected by the relationship between nutrients and salinity. Because of the relative contrast between nutrient concentrations of fresh (high) and marine water (low), a strong correlation between phytoplankton growth and NH_4, NO_3 and PO_4 concentrations is observed. This observed trend may be inaccurate and the limiting variable to growth could be salinity. Because of this it is hard to directly determine the effect of nutrient concentrations on phytoplankton growth in the estuary. Although in other New Zealand estuaries or sounds it has been shown that the growth of marine or estuarine species of phytoplankton show a positive relationship with nutrients (Gibbs, 1997; Vant, 1993).

To determine what is controlling phytoplankton growth a sensitivity analysis of the forcing variables could be carried out. For example, set salinity at all the boundary conditions to zero and then observe the predicted relationship between phytoplankton growth and nutrient concentration. A multiple linear regression on the predicted growth rates and forcing conditions may also be able to distinguish what are the dominant controls of phytoplankton growth in the estuary and river.

Sediment interaction

From a modelling perspective, what has become apparent is the importance of the water–sediment interactions or more specifically the nutrient flux parameters in CAEDYM (Table 6.2). Burger (2006) demonstrated through measurements that nutrient release from the sediments can influence phytoplankton biomass in Lake Rotorua. However, in Lake Rotorua the nutrient release rates are highly influenced by anoxic conditions. The oxygen measurements undertaken in this study showed minimal depletion of oxygen in the water column of the estuary or river. The parameters for this study were set to an arbitrary value of one third that used in CAEDYM simulations of Lake Rotorua (Burger, 2006) and applied evenly across both river and estuary domain. The specified sediment – water fluxes fit in the ranges found in eutrophication modelling literature (Schladow, 1996) although measurements of nutrient fluxes have shown the rates can vary remarkably between water bodies, from substrate to substrate and over a single day (Sakamaki, 2006; Sandwell, 2006; Burger 2006). Isolation of the effect of the parameters in the estuary was difficult to distinguish due the highly variable nutrient concentrations already present. However the along river nutrient concentrations showed some effects of the specified parameters (Figure 6.4). This would suggest that future model applications to the river and estuary would need more detailed investigation into the water–sediment fluxes for accurate modelling of nutrient concentrations and biological simulations as these fluxes can have an important effect on phytoplankton concentrations in an estuarine environment (Twomey, 2001).

6.7) Conclusions and future model applications

Model simulations in the lower Kaituna River and Maketu Estuary were limited to a 15 day period, due to restrictions that the grid resolution placed on the model run speed. Because of the short simulation period, accurate model calibration and validation of nutrient dynamics was not possible with the available data set. However by coupling the hydrodynamic driver ELCOM to the water quality model CAEDYM, the model simulations gave a good insight into the nutrient dynamics in the lower river and estuary, as well as predicting the spatial distribution of phytoplankton growth and mortality rates of four diverse phytoplankton groups.

The modelling simulations predicted the largest contribution to plant nutrients (NH_4, NO_3 and PO_4) in the estuary is from the Kaituna River, as water can reside in the estuary for up to one and a half days before being exchanged with marine water. The 15 day simulation also demonstrated that the drains on the southern side of the estuary delivered a high nutrient load into the estuary. Nutrient concentrations in the lower Kaituna River were conserved from the Kaituna boundary to the river mouth, with contribution from Waiari stream and dilution with marine water. No allocation for diffuse or point source (e.g. farm drains) nutrient inputs were made.

Phytoplankton simulations over the three week period illustrated that net growth rates in the lower Kaituna River were very low. In the lower river, growth rates were limited by the residence time, with the greatest predicted growth occurring in the closed-off loop where residence time was increased. In the Maketu Estuary marine diatoms showed the greatest growth rates which was most likely related to concentrations of nutrients and residence time. Freshwater diatoms and cyanobacteria showed the highest mortality when mixed with marine water. However a limiting factor preventing any excessive growth of phytoplankton in the Maketu Estuary or lower Kaituna River is residence time.

Some suggestions for future work involving applications of CAEDYM to the Maketu Estuary and lower Kaituna River include.

- An analysis into the nutrient fluxes from the sediment could be used to better quantify the sediment exchange parameters and effects on water column nutrients and phytoplankton biomass.
- A determination of a nutrient budget for the Maketu Estuary and lower Kaituna River should be carried out. This could involve measurements of nutrients in the drains, culverts and canals entering the estuary and river, as well an allocation for diffuse runoff.
- Reducing the grid size of the model to allow longer periods of simulation. It would then be possible to use EBOP's database to carry out a better calibration and validation of the model to predict water quality in the lower Kaituna River and Maketu Estuary. Because of the complex channel morphology in the estuary and bends in the river, specifying a larger grid size resulted in a poor validation with the hydrodynamic model ELCOM, so was not under taken in this study.
- CAEDYM has built in routines for simulating faecal coliforms, including taking into account the effects of salinity. Faecal coliforms can be present in high numbers in the Kaituna River and can affect bathing (Deely *et al.* 1997) and shellfish for human consumption. A simulation of faecal coliforms in the river and estuary could also be useful when evaluating different freshwater inflow discharges into the estuary.

Chapter Seven

Scenarios

7.1) Introduction

The need to return the river flow back into the Maketu Estuary was advocated by many local people and long time users of the estuary following the decision to divert the Kaituna River out of the estuary in 1956. A perceived decrease in kaimoana, increase in sedimentation rates and loss of the estuary's mauri ('life force') was the main driving force behind efforts to return the river flow back into the estuary (for more details refer to Chapter Two). The return of the river into the estuary was partially fulfilled by resource consent granted in 1998 allowing 100,000 m^3 per tidal cycle of river water to enter the Maketu Estuary though control gates located at Fords Cut. While this partial diversion has decreased the salinity in the upper estuary, up until present the re-diversion has not met its initial aims of reducing the sediment infilling and restoring the maritime-marsh.

Altering the boundary conditions or bathymetry within the numerical model ELCOM-CAEDYM allows a range of hydrodynamic and biogeochemical conditions to be evaluated in the Maketu Estuary and lower Kaituna River. Chapters Five and Six explain how the model was set up, applied and, where possible, calibrated and validated against available field measurements. This chapter examines modifications from the conditions used to validate the model and the effects of these changes on the hydrodynamics and nutrient dynamics in the estuary and river.

Model runs 1–4 were used to simulate increasing the freshwater flow into the estuary from the Kaituna River. The original application for resource consent was for 800,000 m^3 per tidal cycle but was reduced to 100,000 m^3 per tidal cycle (Park, 2003). Scenarios 5–8 examine the effects of returning the freshwater inflow back through the historic channel (Papahikahawai). Pre-1956 the Kaituna River entered the Maketu Estuary through the Papahikahawai Channel. The effects on salinity and residual flows in the estuary are predicted for each inflow volume and location associated with runs 1–8.

Runs 9–12 involved applications of ELCOM-CAEDYM to simulate the effects of the proposed Rotoiti wall diversion on the lower Kaituna River and Maketu Estuary. To reduce the high nutrient load entering Lake Rotoiti from Lake Rotorua, a proposal has been put forward to construct a ~1 km diversion wall in the Okere Arm (Figure 1.1) of Lake Rotoiti. The diversion wall would redirect a greater proportion of the nutrient rich water from Lake Rotorua, down the Kaituna River instead of into the main body of Lake Rotoiti. The proportion of Lake Rotorua water flowing down the Kaituna River would not be constant with the diversion in place and would depend on the time of year and relative water temperatures. McIntosh (2005) estimates the nutrient loads associated with the diversion wall would result in an annual average increase of 20 percent in total phosphorus (TP) and 7 percent in total nitrogen (TN) at Te Matai, which is located near the upstream boundary in the river model domain. The aim of model runs 9–12 is to simulate the increase of nitrogen and phosphorus loads in the lower Kaituna River and Maketu Estuary and evaluate the spatial changes in nutrient concentration and the likely effect on phytoplankton growth.

Simulation of runs 13–18 were used to determine if altering the bathymetry in the lower river could result in a decrease of marine water entering the estuary through Fords Cut. Currently a proportion of water that is drawn through the control gates at Fords Cut is marine, reducing the effectiveness of the re-diversion, which was designed to increase the freshwater inflow into the estuary.

7.2) Methods

For runs 1–4 the flow rate at Fords Cut was increased as described in Table 7.1. These simulations would be equivalent to increasing the number of culverts in the control structure. For simulation of runs 5–8 the location of the freshwater inflow into the estuary from the Kaituna River was altered. The location of the inflow boundary was alternated between the current location (Fords Cut) and the historic Papahikahawai Channel as illustrated in Figure 7.1. A combination of both locations operating simultaneously was also included in addition to doubling the inflow volume through Papahikahawai Channel (Table 7.1). For each model run (1–8) the time period of the inflow remained constant as described in Section 5.3.3, resulting in only a variation of the discharge rate.

To evaluate model runs 9–12, ELCOM-CAEDYM model runs needed to be simulated in both the river and estuary domain. For the river domain this was achieved by increasing the nutrients NH_4, NO_3 and PO_4 at the upstream boundary (Kaituna). NH_4, NO_3 and PO_4 were increased by 7, 7 and 20 percent respectfully. The predicted nutrient and phytoplankton concentrations flowing through Fords Cut outflow were compared between the status quo (run 9) and the elevated nutrients (run 10) over the same time period. In the estuary domain the predicted outflow concentrations at Fords Cut from run 9 and 10 were used to force the inflow into the estuary (run 11 and 12).

Evaluation of runs 13–20 involved changing the bathymetry in the lower river domain to reopen the loop ~750 metres upstream from the river mouth. Figure 7.2 demonstrates the bathymetry used in the model to represent the loop open and the loop closed. Due to preliminary results revealing that the extent of marine water entering the river is effected by tidal range and river flow, both bathymetries were compared over spring and neap tide conditions and at high (60 m^3s^{-1}) and low (25 m^3s^{-1}) river flow (Table 7.1).

Model runs 1–8 were simulated for a total of 15 tidal cycles from high tide to high tide in 2006 starting on Julian day 251. Scenarios 9–12 were run over a total of 15 days starting on Julian day 1. Scenario 13–18 were simulated over a period of 14 days in 2006 (spring tide = Julian days 230–244; neap tide = Julian days 136–150). At least three additional tidal cycles were included for the model to ‘warm up’ in all runs.

For scenarios 1–8 and 11–12 the desired variables (e.g. salinity, velocity, phytoplankton and nutrient concentrations) where extracted as depth-averaged measurements at a time step of half an hour and three hours respectfully. The extracted variables were then time-averaged for each horizontal cell over the simulation period to allow easy visual comparison between the different runs.

Equation 6.1 was used to calculate phytoplankton growth rates in terms of a percentage. For scenarios 13–20 the predicted salinity drawn through the control structure was extracted every 15 minutes and an average salinity over the 15 tidal cycles was derived for comparison.

Table 7.1. Model run number for the various simulations carried out in the estuary and river model domains.

ESTUARY	**Inflow location and volume (m^3 per tidal cycle)**		**Diversion wall?**
	Fords Cut	**Papahikahawai Channel**	
Run 1	100,000	-	-
Run 2	200,000	-	-
Run 3	400,000	-	-
Run 4	800,000	-	-
Run 5	100,000	-	-
Run 6	-	100,000	-
Run 7	100,000	100,000	-
Run 8	-	200,000	-
Run 11 (CAEDYM)	100,000	-	No
Run 12 (CAEDYM)	100,000	-	Yes

RIVER	**Loop open**		**Loop closed**		
	River flow	**Tidal range**	**River flow**	**Tidal range**	
***Run 9 (CAEDYM)**	-	-	-	-	No
***Run 10 (CAEDYM)**	-	-	-	-	Yes
Run 13	-	-	high	spring	-
Run 14	-	-	low	spring	-
Run 15	-	-	high	neap	-
Run 16	-	-	low	neap	-
Run 17	high	spring	-	-	-
Run 18	low	spring	-	-	-
Run 19	high	neap	-	-	-
Run 20	low	neap	-	-	-

* Simulated under the flow and tidal conditions present over the 15 day period in January 2004.

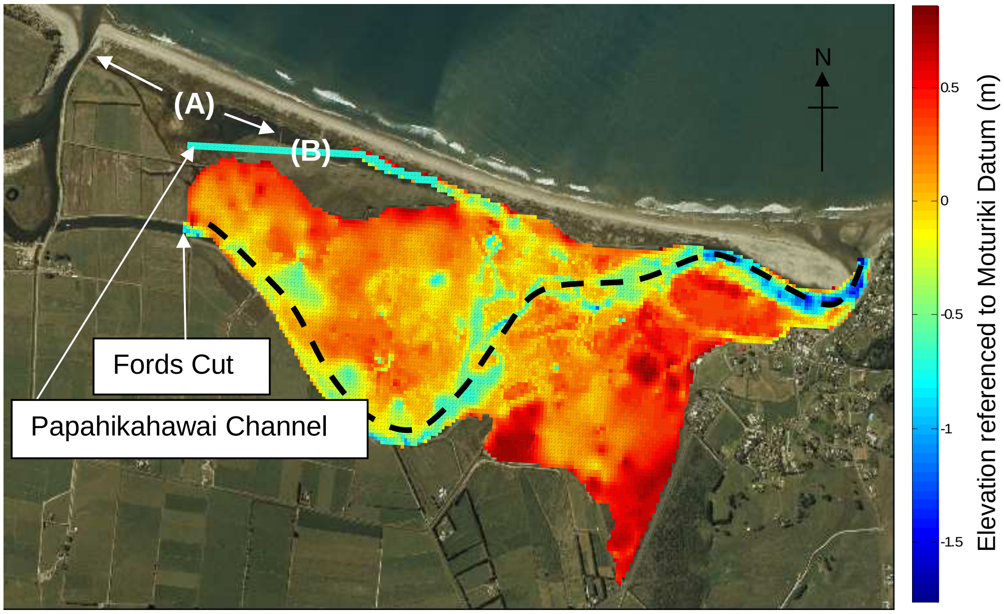

Figure 7.1. Bathymetry of the Maketu Estuary domain illustrating the locations of Fords Cut and Papahikahawai Channel inflow boundaries used in model simulations. (A) The location of the historic channel (Papahikahawai). (B) The simulated Papahikahawai Channel in the model runs. (Photo source: EBOP RDAM, 2004).

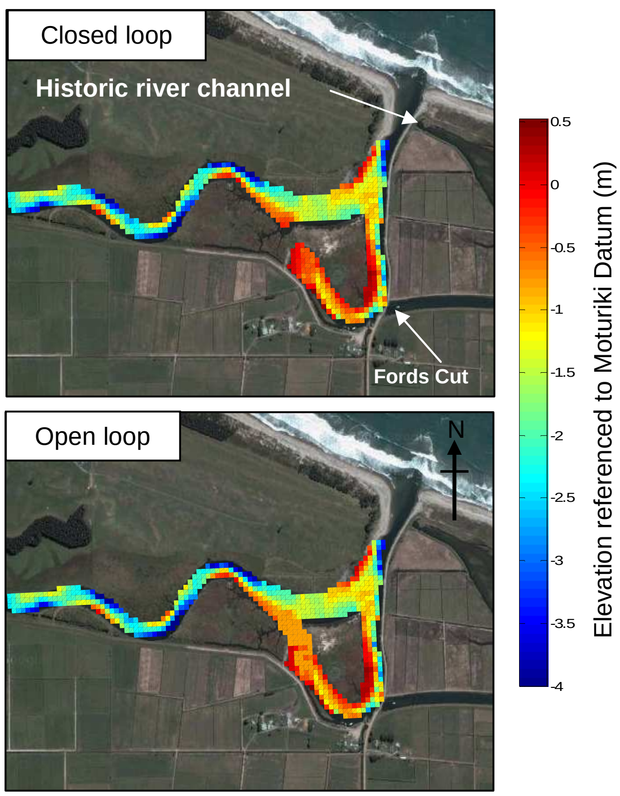

Figure 7.2. Lower Kaituna River model bathymetry (river mouth to 1.5 km upstream) overlaid on an aerial photograph depicting the current bathymetry (closed loop) and the modelling scenario (open loop). (Photo source: Google Earth, 2006).

7.3) Results

7.3.1) Runs 1–8. Freshwater inflow volume and location

Figure 7.3 illustrates the time (15 tidal cycles) and depth-averaged salinity in the Maketu Estuary for four different inflow rates. Model results demonstrate that the region of freshwater influence in the estuary is extended towards the mouth as the freshwater inflow volume increases. The strong front at the marine and freshwater boundary is also maintained for each different case (Figure 7.3). The mean, minimum and maximum salinity at ~100 m spacing along the main tidal channel (Dashed line in Figure 7.1) in the estuary is shown in Figure 7.4 for the simulation period of 15 tides. This simulation reveals that increasing the freshwater inflow not only reduces the mean salinity in the Maketu Estuary but also increases the range of salinity experienced over a tidal cycle, most notably in the eastern region of the estuary. In addition, areas of the western region of the estuary become completely devoid of marine water for run 3 and 4. Residual currents over the 15 tidal cycle simulation (Figure 7.5) show a greater net seaward direction as the freshwater inflow rate increases.

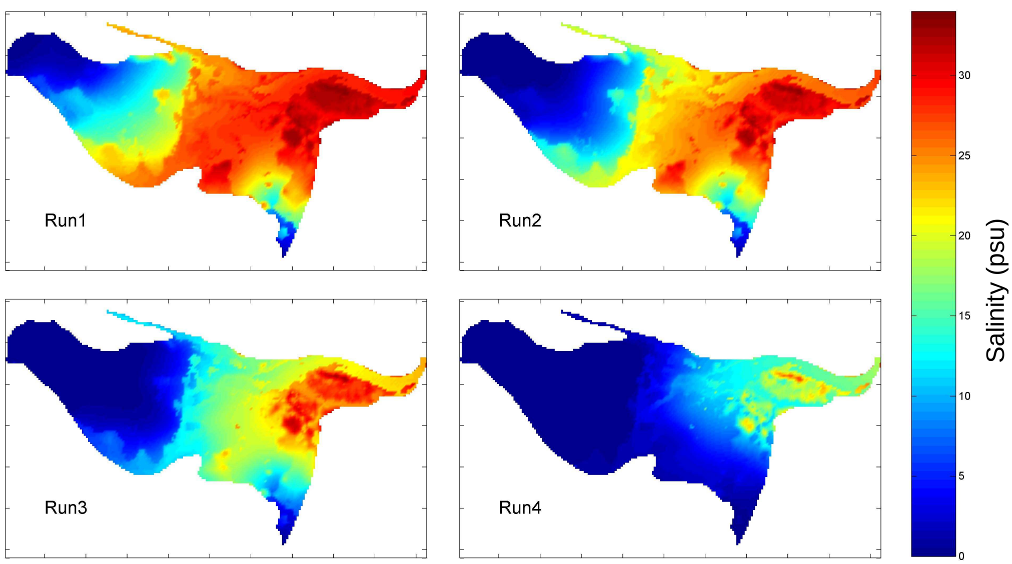

Figure 7.3. Salinity averaged over 15 tidal cycles in the Maketu Estuary for varying volumes of freshwater entering through Fords Cut (runs 1–4).

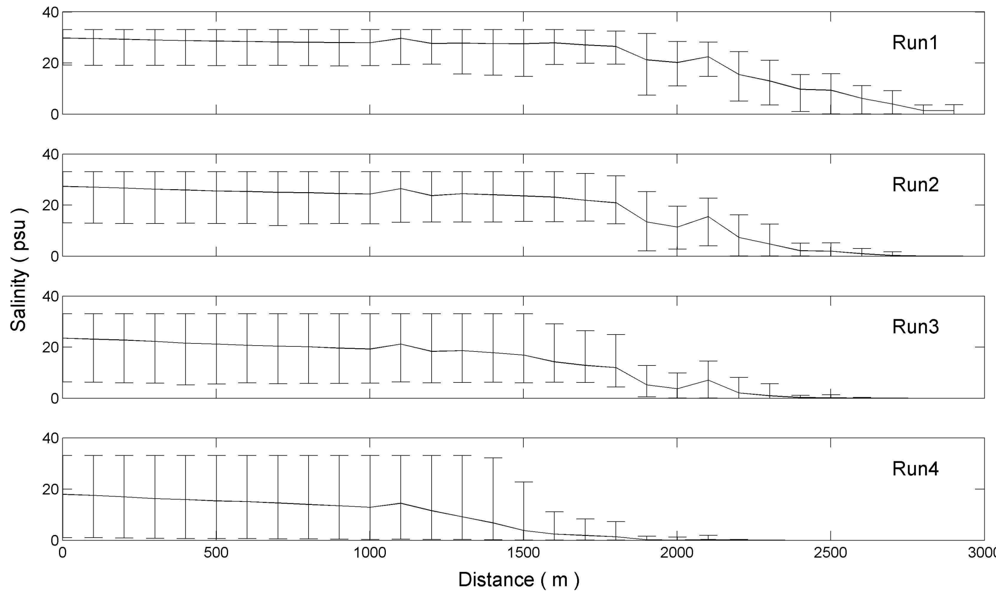

Figure 7.4. Along-channel salinity variations, averaged over 15 tidal cycles for model runs 1–4. The channel runs from the estuary mouth (0 m) to Fords Cut (3000 m). Results are extracted at 100 m intervals along the main channel. The solid line corresponds to the mean salinity and the bars represent the minimum and maximum values over the 15 tidal cycles.

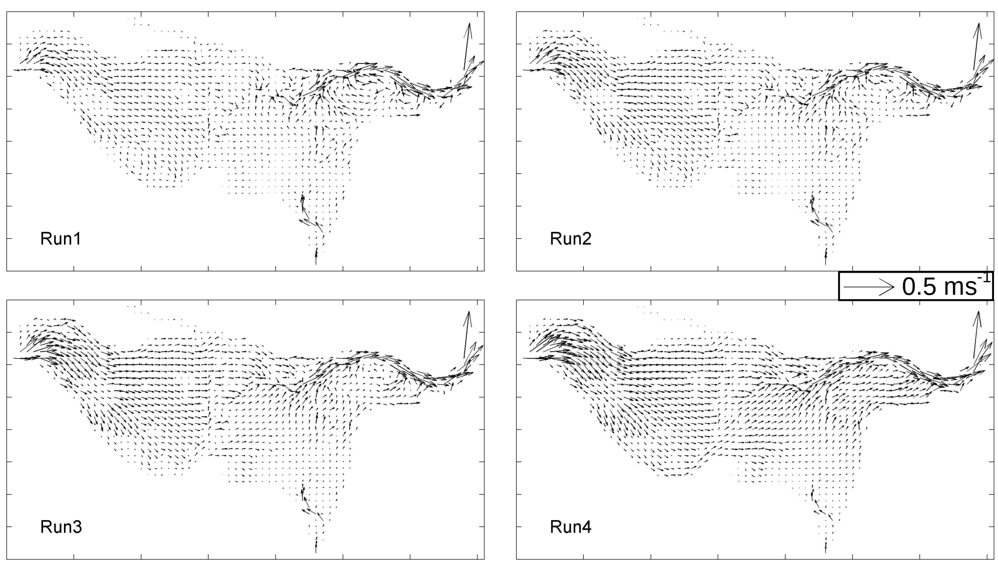

Figure 7.5. Residual currents over 15 tidal cycles in the Maketu Estuary plotted as vectors at every third model cell (45 m) for the different inflow rates (runs 1–4).

Figure 7.6 illustrates the average salinity over the 15 tidal cycle simulation for runs 5–8. Changing the inflow location between Fords Cut and Papahikahawai Channel changes the salinity regime most noticeably in the western and northern regions of the estuary. One of the most marked changes is the degree that the two water bodies mix. With the inflow location at Fords Cut, model predictions show a sharp horizontal marine–freshwater gradient where the two water bodies meet; an inflow through Papahikahawai Channel suggests more mixing, hence a less sharp salinity gradient would occur (Figure 7.6). Doubling the inflow volume at Papahikahawai Channel (run 7) extends the mixing further south and eastwards into the estuary, while having inflows at locations 1 and 2 simultaneously (run 8) results in a combination of a region of very freshwater near Fords Cut extending to a mixed zone further south and east. The range and mean values of salinity along the transect sampled also vary depending on the inflow location (Figure 7.7). An inflow through Papahikahawai Channel is likely to increase the salinity in the far western reaches of the estuary. Residual currents in the Maketu are altered by forcing the inflow through Papahikahawai Channel, most notably the residual flow is reduced in the western region of the estuary and increased in the central northern region of the Maketu Estuary (Figure 7.8). When the inflow volume was doubled for run 7, the residual currents in the western estuary are still minimal.

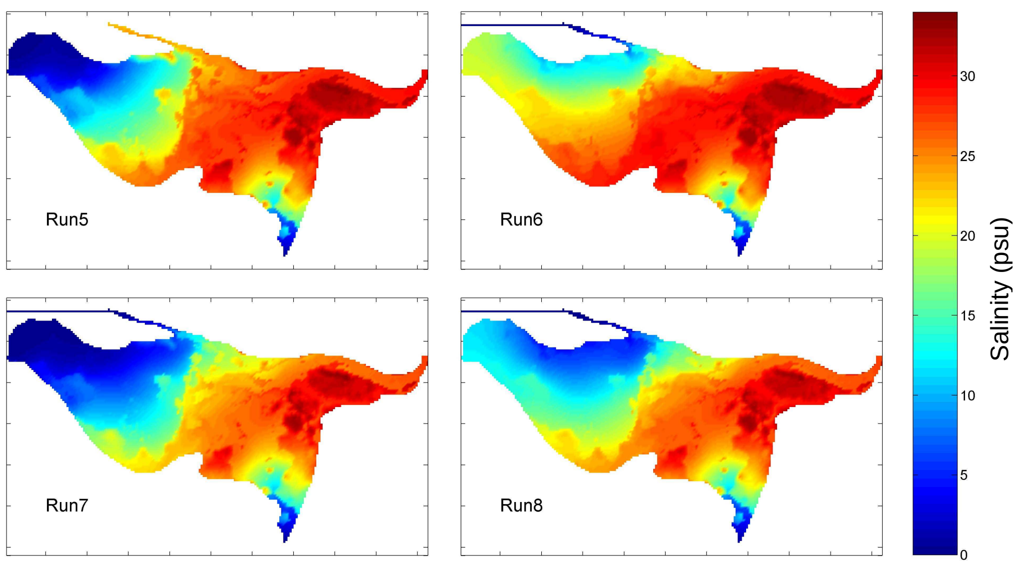

Figure 7.6. Salinity averaged over 15 tidal cycles in the Maketu Estuary for varying inflow locations and volumes of freshwater entering the estuary (runs 5–8).

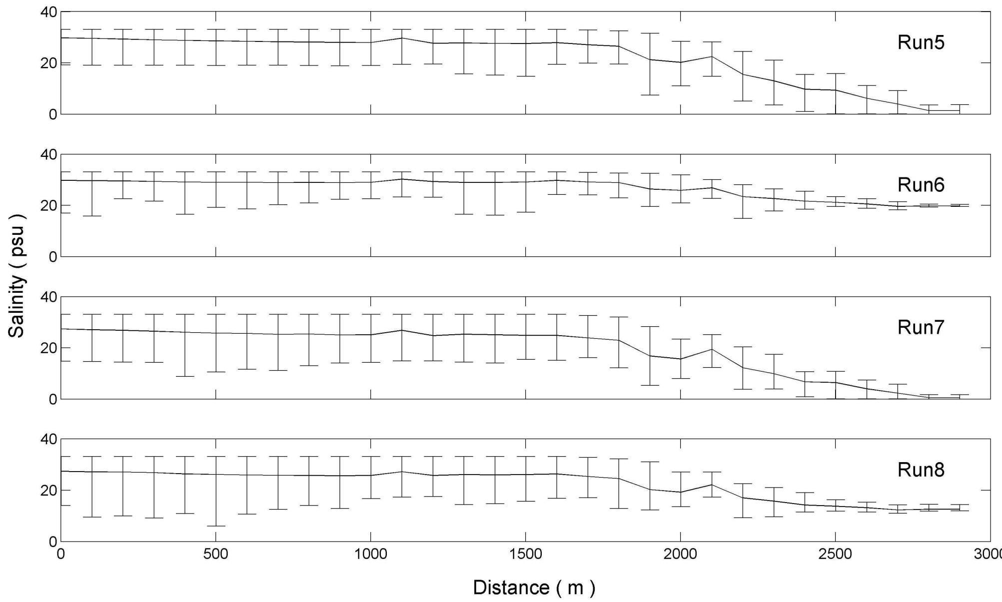

Figure 7.7. Along-channel salinity variations, averaged over 15 tidal cycles for model runs 5–8. The channel runs from the estuary mouth (0 m) to Fords Cut (3000 m). Results are extracted at 100 m intervals along the main channel (Figure 7.1). Solid line corresponds to the mean salinity and the bars represent the minimum and maximum values over the 15 tidal cycles.

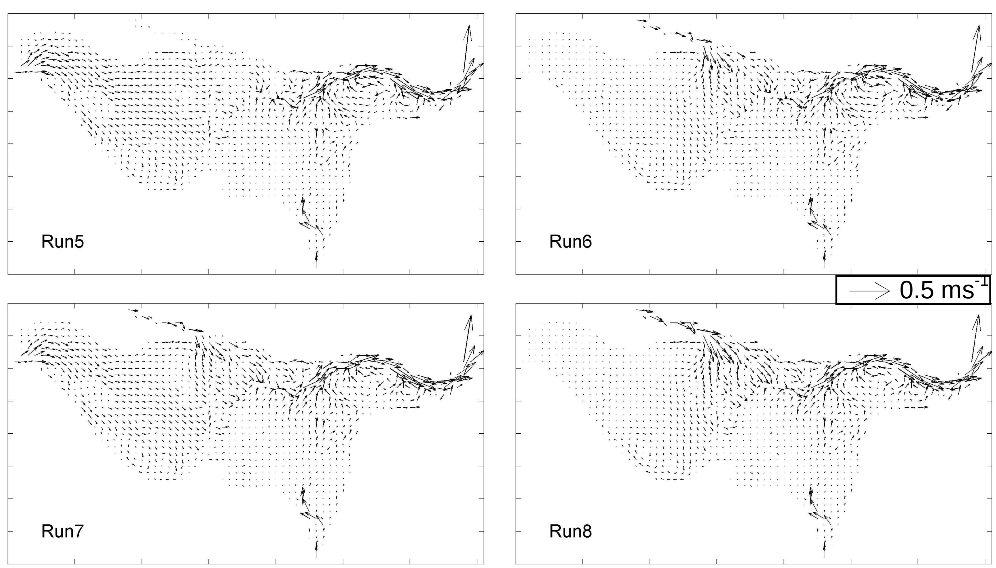

Figure 7.8. Residual currents over 15 tidal cycles in the Maketu Estuary plotted as vector diagrams at every third model cell (45 m) for the different inflow locations and volumes (runs 5–8).

7.3.2) Runs 9–12. Lake Rotoiti diversion wall

Results of the ELCOM-CAEDYM simulations in the lower Kaituna River reveal that no significant changes in the phytoplankton biomass occur when nutrient concentrations increase as a result of the Rotoiti diversion wall. Table 7.2 illustrates the predicted concentrations of the simulated outflow variables at Fords Cut. By comparing the concentrations of run 9 (pre-diversion) to run 10 (post-diversion) over the same 15 day time period it is possible to evaluate the fate of the increased nutrients from the start of the model domain (Kaituna Boundary) to where they exit (river mouth and Fords Cut outflow).

Table 7.2. Model-derived nutrient (NH_4, NO_3 and PO_4) and phytoplankton at Fords Cut outflow averaged over 15 days in January 2004, comparing run 9 (pre-Rotoiti diversion) and run 10 (post-Rotoiti diversion). The predicted change at Fords Cut is given along with the forcing condition at the upstream boundary.

Variable	% change at Kaituna*	Predicted outflow concentrations at Fords Cut averaged per tidal cycle		
		Pre-diversion	Post-diversion	% change
NH4 (mg l^{-1})	+7	0.111	0.118	+6.5
NO3 (mg l^{-1})	+7	0.433	0.459	+6.1
PO4 (mg l^{-1})	+20	0.038	0.045	+18
Cyanobacteria (μgChl-*a* l^{-1})	0	14.64	14.65	+0.1
Dinoflagellates (μgChl-*a* l^{-1})	0	0.05	0.05	0
Marine diatoms (μgChl-*a* l^{-1})	0	0.03	0.03	0
Freshwater diatoms (μgChl-*a* l^{-1})	0	0.092	0.093	+1

*These are the percentage changes in the forcing conditions prescribed at the upstream boundary.

By subtracting the 15 day time-averaged nutrient concentrations of run 12 (post-Rotoiti diversion) from run 11 (pre-Rotoiti diversion) it is possible to compare the spatial differences of nutrient and phytoplankton biomass in the Maketu Estuary. Figure 7.9 illustrates the residual concentrations and reveals that the most significant increase in nutrients will occur in the western region of the estuary. In terms of percentage, the increase represents a maximum of +5–7 % for NO_3, NH_4

and PO_4. Phytoplankton concentrations show very little difference between pre- and post-diversion in the Maketu Estuary (Figure 7.10). If expressed in terms of percentage, freshwater diatoms exhibit the highest change in biomass averaged over the 15 day period with a maximum of ~3 %. The remaining phytoplankton groups, marine diatoms, dinoflagellates and cyanobacteria had an average increase of <1%.

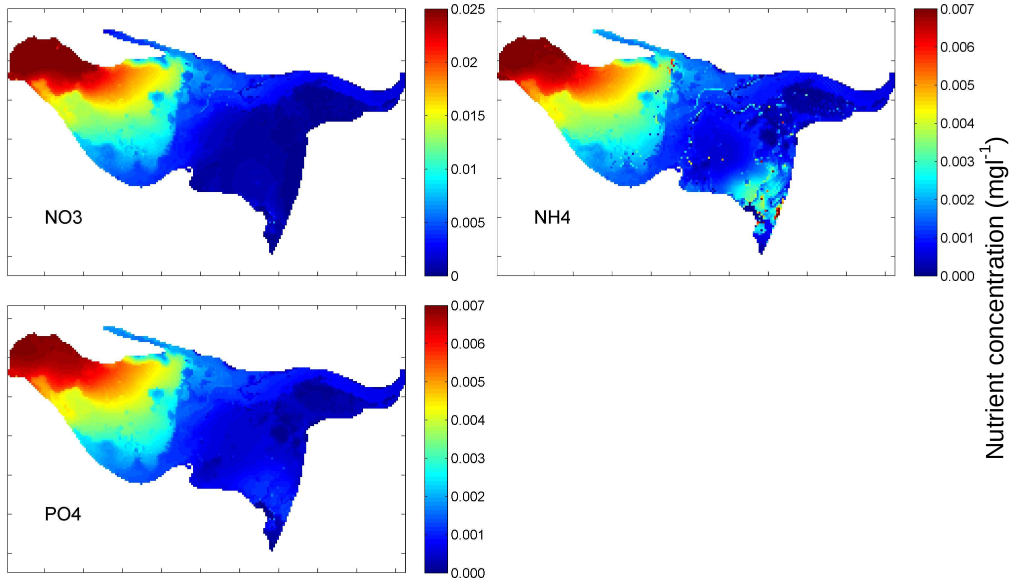

Figure 7.9. Residual NH_4, NO_3 and PO_4 concentrations in the Maketu Estuary derived by subtracting the time-averaged concentrations of pre-diversion (run 10) from post-diversion (run 9).

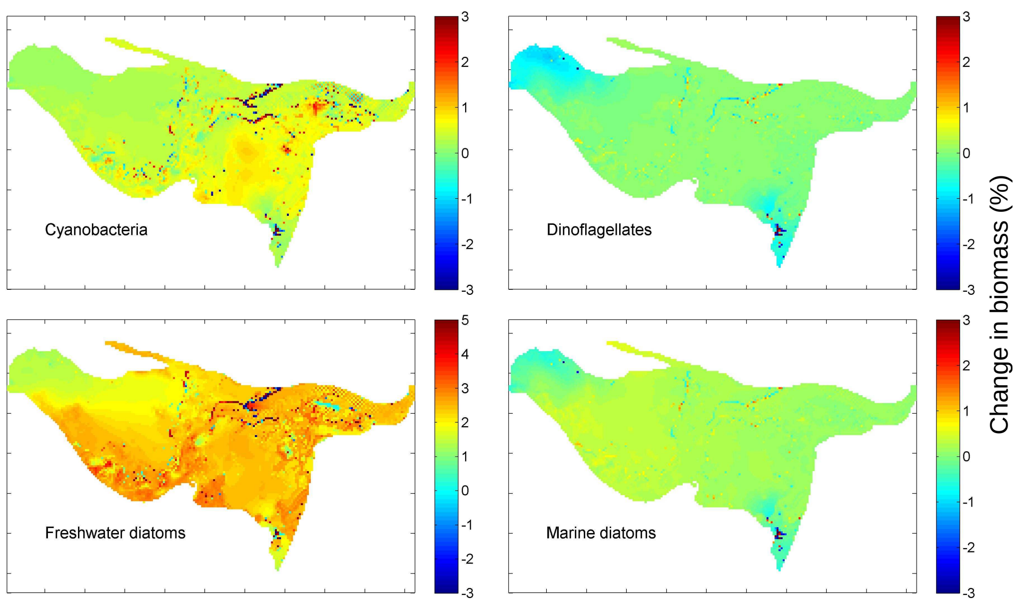

Figure 7.10. Residual phytoplankton concentrations expressed as a percentage in the Maketu Estuary derived by subtracting the time-averaged concentrations of pre-diversion (run 11) from post-diversion (run 12).

7.3.3) Runs 13–20. Decrease the proportion of marine water flowing through the control gates

The model results (Table 7.3) reveal that the salinity drawn through the control gates varies markedly with tidal range and river flow. Additionally, a reduction in salinity is achieved by opening up the closed loop. Table 7.3 summarises the average salinity per tidal cycle drawn through the outflow for the various modelling simulations. The average salinity drawn through the control gates varies depending on the tidal range and river flow where highest salinities occurred during spring tide and low river flow conditions and the lowest salinities occurred during neap tide and high river flow conditions. This agrees with the results from the model validation which suggest that the distance the salt wedge propagates up the river can be determined by the tidal range and river flow. A reduction in salinity was achieved for all flow and tidal conditions by opening up the loop. Assuming that spring and neap tide, high river flow conditions can be ignored (run 13, 15, 17 and 19) due to very low predicted salinity (<0.01), the most significant reduction occurred under neap tides and low river flow (32.6 %) with spring tides and low river flow reduced by 8.4 %.

Table 7.3. Comparison of the averaged predicted salinity drawn through Fords Cut (outflow) over 15 tidal cycles with the loop closed and loop open over spring–neap tidal ranges and high–low river flows.

Tidal range	River flow	Average salinity per tidal cycle (psu)		Reduction	
		Closed loop	Open loop	(psu)	(%)
Neap	**Highflow**	<0.01	0	<0.01	n/a
Neap	**Lowflow**	5.2	3.5	1.7	**32.6**
Spring	**Highflow**	<0.01	0	<0.01	n/a
Spring	**Lowflow**	11.45	10.48	0.97	**8.4**

7.4) Discussion

7.4.1) Runs 1–8. Freshwater inflow volume and location

Increasing the freshwater inflow volume not only resulted in a mean reduction in salinity in the western region of the estuary but also increased the range of salinity in the eastern region. Determining the likely range of salinity in the estuary is important for any attempt to restore the historic ecology in the Maketu Estuary. Both the benthic and pelagic organisms and the vegetation that historically or currently inhabit the estuary have defined salinity tolerances, and exposure outside their tolerance level can be detrimental. A good example of this is the salt-marsh that has disappeared from the Maketu Estuary (see Figure 2.3). Salt-marsh abundance is sensitive to changes in salinity (Partridge, 1987) and it is likely that some of the decline of salt-marsh in Maketu Estuary can be attributed to the increased salinity after the 1956 diversion (KRTA, 1986).

In terms of returning the estuary to its pre-diversion state, it would be an advantage to have knowledge of the salinity regime when the entire river previously flowed into the estuary. To the author's knowledge there are no known salinity measurements before 1956 and Domijan (2000) stated there are no tidal and flow gaugings pre-diversion. By simply altering the models inflow volume input as was done for runs 1–4, would not allow an accurate prediction of pre-1956 salinity regime in the estuary. This is because in the model simulations the inflow only occurs over a set time period (~6 hours) where historically the river would have flowed continually into the estuary. It would be possible to replicate a time series of the entire river flow at the historic Papahikahawai Channel boundary (Figure 7.1). However this would not allow the water to 'back up' in the river over a flood tide, most likely resulting in an underestimation of the volume of marine water entering the estuary. A practical way to estimate the pre-1956 salinity regimes would be to couple both model domains together (river and estuary) to simulate connection of the historic Papahikahawai Channel. It would then be possible to determine the likely historic salinity and current velocities in the estuary and river during all river flow and tidal conditions.

Increasing the freshwater flow at Fords Cut increases the residual currents in the seaward direction, most significantly around Fords Cut and the western region of the estuary (Figure 7.5). In terms of flushing out the fine sediment this outcome would be favourable. However, because no sediment analysis or sediment stability threshold measurements were undertaken as part of this study it would be difficult to conclude which flow rate would result in areas of sediment scour and net removal. A concern that arises with an inflow rate of 800,000 m^3 per tidal cycle (run 4) is that to maintain this volume over a 6 hour time period, the discharge rate (~37 m^3s^{-1}) would be similar to the average flow of the Kaituna River (~39 m^3s^{-1} as reported by McIntosh (2005)). If an inflow of this magnitude was to occur then it is probable that flow at the river mouth will be reduced and additional marine water will be drawn up the river. This would likely result in a high proportion of marine water drawn through the control gates. A reduced river flow would also cause sedimentation at the river mouth (KRTA, 1986) creating problems for boat navigation. Increasing the inflow into the estuary from the Kaituna River also raises concern of an increased risk of flooding; it has been determined that with the estuary's current flood protection measures, the maximum inflow volume is 200,000 m^3 per tidal cycle (EBOP, 1990). It would then be expected that any volume above this threshold would necessitate further flood protection methods to be put in place around the estuary.

Shifting the inflow to Papahikahawai Channel altered the salinity in the western region of the estuary by inducing more mixing of the marine and fresh waters, resulting in a gentle gradient of salinity rather than the sharp gradient between marine and freshwater that was observed with the inflow at Fords Cut (Figure 7.6). An explanation for this observed difference is that current shear induces high rates of mixing. When the inflow occurs at Papahikahawai Channel, the marine water entering the estuary on a flood tide intersects the freshwater at near right angles in a location where current velocities are considerable (Figure 7.11). With the inflow at Fords Cut the confluence of the two water currents is ~180 degrees in a region with considerably less current velocity, resulting in less shear and therefore reduced mixing and a stronger salinity front.

Specifying the freshwater inflow through Papahikahawai Channel resulted in a major shift of the residual currents. A current concern for the estuary is the high rates of sedimentation. Model results suggest that if an inflow was to occur solely through Papahikahawai Channel the residual currents in the western region would be reduced. Consequently this reduction would not help reduce the sedimentation rates that are currently occurring. An inflow through the Papahikahawai Channel would also likely result in an alteration of the main tidal channel. It is predicted that a new main channel would form between Papahikahawai and the estuary mouth, and over time the remaining old channel to the west would silt up.

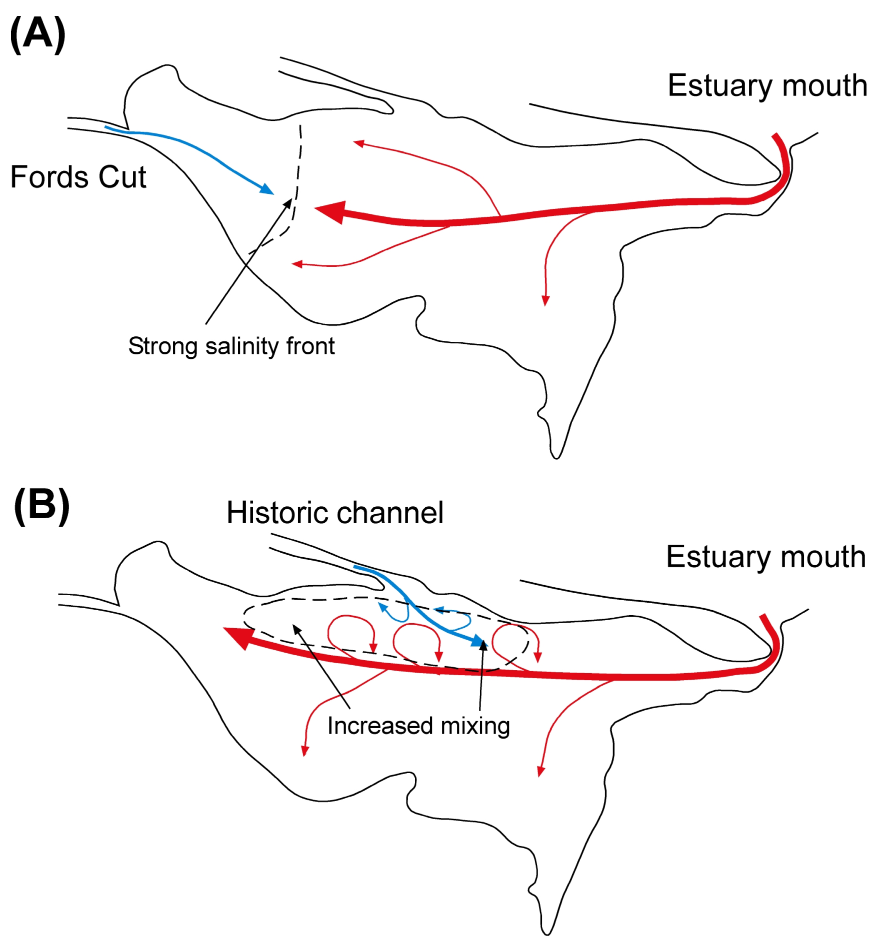

Figure 7.11. A schematic showing a possible explanation of why increased mixing is observed when freshwater inflow is returned to the historic channel. (A) Inflow at Fords Cut (B) Inflow through Papahikahawai Channel. Red line indicates idealized flow of marine water. Blue line indicates idealized flow of freshwater.

CAEDYM simulations were not applied in the estuary and river domain for runs 1–8. However it is likely that as the freshwater inflow increases, the nutrient loads into the estuary would also increase. In terms of phytoplankton growth, increasing the freshwater volume would allow a larger region of the estuary to be freshwater possibly stimulating greater growth rates of the freshwater phytoplankton species. As described in Chapter Six, a key limiting factor on phytoplankton growth in the Maketu Estuary is the residence time. While residence time was not determined for model runs 1–8, it is possible that an inflow through Papahikahawai Channel would increase the residence time in the western region as the residual currents were predicted to be much lower (Figure 7.8). The increased residence time could promote higher phytoplankton biomass, greater than described in Chapter Six.

7.4.2) Runs 9–12. Lake Rotoiti diversion wall

Modelling results indicate that increasing the nutrient load in the Kaituna River is unlikely to promote any further phytoplankton growth. This is in agreement with White *et al*. (1978) who through analytical measurements in the Kaituna River concluded that the elevated nutrient levels already present in the river were unlikely to promote phytoplankton growth as residence time and turbulence are mainly limiting to growth. In 2000 The Ministry for the Environment set nutrient trigger levels for New Zealand rivers (MfE, 2000). McIntosh (2005) compared the nutrient levels in the Kaituna to the MfE trigger levels and found that the river exceeded the trigger values for total phosphorus and total nitrogen with the highest exceedence occurring at Te Matai. As our model results suggest that for the lower river (mouth to 8.5 km upstream), the increased nutrients associated with the Rotoiti diversion will be conserved. Assuming this, the MfE trigger levels will likely be further exceeded if the diversion wall goes ahead, as was also predicted by McIntosh (2005). However, other factors such as the extensive beds of aquatic macrophytes and benthic algae are likely to interact with the available nutrients and neither of these variables are simulated in this study.

Analysis of the modelling results show the Rotoiti diversion wall will increase the nutrient load in the Maketu Estuary (Figure 7.9), with the most affected area being the western region of the estuary where river water is diluted by marine water. In

Chapters Five and Six, the modelling results demonstrated this region of the estuary was the most likely to promote algae growth due to the favourable residence time, temperature and elevated nutrient concentrations. However, the model results suggest that, for the 15 day simulation period undertaken in this scenario, the increased nutrients associated with the Rotoiti diversion are unlikely to cause excessive algae growth (Figure 7.10), as residence time and salinity restrictions will still limit the phytoplankton growth.

7.4.3) Runs 13–20. Decrease the proportion of marine water flowing through the control gates

Model results for these scenarios show that opening the loop (Figure 7.2) could reduce the proportion of marine water being drawn through the control gates at Fords Cut. Though the magnitude of the reduction is likely to be negligible and would vary depending on river flow and tidal range. River discharge and tidal range have been shown to determine the extent of salt wedge intrusion in river systems, for example Liu *et al.* (2006) and Brockway *et al.* (2005), with river discharge described as the dominant control (Liu *et al.* 2006). Therefore as our results have suggested the salinity flowing through the control gates varies from tide to tide, and by reopening the loop the desired outcome of 100 % freshwater is unlikely to be achievable.

7.5) Conclusion and future model applications

By altering the conditions within the numerical model ELCOM-CAEDYM it has been possible to predict the effect of a range of inflow, nutrient and bathymetry changes in the Maketu Estuary and lower Kaituna River. Hydrodynamic model predictions have shown that the average range and mixing regime of Kaituna River water entering the Maketu Estuary can be altered by changing the inflow volume and location of discharge. Furthermore, varying the inflow volumes and locations can significantly affect current velocities in the estuary. Analysis of the modelling results suggest that an inflow through the Papahikahawai Channel alone would be detrimental to the sedimentation in the western region of the estuary due to the reduction in current velocities and loss of net seaward flow. Increasing the inflow volume at the Fords Cut location would increase the net seaward flow in the estuary, helping to reduce sedimentation. However, by increasing the inflow volume the range of salinity increases in some regions, which is an important consideration if attempts are made to restore the ecology of the Maketu Estuary.

Over a 15-day simulation in January 2004, ELCOM–CAEDYM predicted the increase in nutrients associated with the proposed Rotoiti diversion wall will likely not promote any significant algae growth in either the river or estuary. Model runs were restricted to 15 days due to run time constraints, however because the increased nutrient load is not expected to be constant throughout a year, simulation over an extended period of time would be preferable.

By opening the loop in the lower Kaituna River, the model simulations predicted that a reduction in salinity flowing through the control gates is possible. Results show that the salinity can be highly variable and completely eliminating marine water flowing through the control gates under all river flow and tidal conditions may not achievable.

Some suggestions for future work involving the application of ELCOM-CAEDYM to the Maketu Estuary to further investigate the modelling scenarios undertaken in the chapter include:

- Determine the historic salinity and flow regime by coupling the two model domains together (river and estuary).
- Couple the water quality model CAEDYM to the hydrodynamic driver ELCOM to determine water quality issues for a range of inflow volumes and locations. CAEDYM simulations of interest could include nutrient, phytoplankton and faecal coliform dynamics.
- Undertake a sediment survey and analysis in the estuary to derive sediment current thresholds that could be used for determining sediment suspension and transport.
- Use CAEDYM to simulate other biological variables, such as macro algae (aquatic weed) in the river or sea lettuce (*Ulva*) in the estuary that could be potentially effected by the Rotoiti diversion wall.

Chapter Eight

Summary and future recommendations

8.1) General summary

The Maketu Estuary and lower Kaituna River present a complex and challenging region for hydrodynamics and water quality modelling. Over the past six decades large changes have occurred to the flow dynamics in the river and estuary, the most significant change was the diverting the river out of the estuary in 1956. Subsequently, the diversion has been partially blamed for the observed ecological decline and high rates of sedimentation occurring in the Maketu Estuary. Over the six decades following the diversion, locals, Iwi and long time users have advocated that the river be re-diverted back into the estuary. However at the time a full diversion was, and currently still is not, feasible due to water quality, flooding and boat navigation issues. In 1998 resource consent was granted to allow 100,000 m^3 of Kaituna River water to enter the estuary per tidal cycle, this volume represents only a fraction of the total river flow. While the re-diversion did reduce the salinity in the upper region of the estuary, it currently has not met all the aims intended. Moreover the already high nutrient load of the Kaituna River water may be further increased by the construction of a diversion wall in Lake Rotoiti.

Through the use of the numerical model ELCOM-CAEDYM, this study aimed to model the hydrodynamics and water quality in the Maketu Estuary and lower Kaituna River to evaluate the present hydrodynamics and nutrient / phytoplankton dynamics. Model simulations where then carried out to predict the hydrodynamics and water quality for a range of flow and water quality issues. Simulations included quantifying the effects on nutrient dynamics and phytoplankton growth from the proposed Rotoiti diversion wall.

The 1996 partial re-diversion occurred through control gates that only allow water to flow from the river into the estuary. The Maketu Estuary and Kaituna River model domains needed to be run independently as it was not possible to simulate this type of one way flow boundary within a combined estuary and river modelling domain. For both the domains, model simulation periods were hampered by slow run time ratios. The slow run times were due to the high resolution grid that was needed to represent the intertidal channels in the estuary, and prevent flow restrictions in bends in the river. In the river domain, the vertical resolution of the three-dimensional grid was critical for setting the outflow height. This was because marine water penetrated up to Fords Cut outflow as a salt wedge. If the outflow in the model was set too low it would cause a large proportion of marine water to be drawn through this outflow. In the estuary, vertical resolution was not as important since measurements had shown that vertically well mixed conditions dominated. Therefore in the estuary domain the vertical resolution was coarse to allow faster model run speeds.

An important aspect of numerical modelling is to accurately define the bathymetry of the study area. Using a variety of techniques depth measurements of the lower Kaituna River and Maketu Estuary were collected and interpolated onto a grid to represent the bathymetry in the model simulations. The bathymetry data in the estuary were comprised of historic survey data (1995–97), an RTK-GPS survey and data collected using an imaging technique which generated proxy depth points in areas where using the other two methods was not feasible. The historic survey data could only be used for parts of the estuary, as major geomorphological changes had occurred between present and when the historic survey was completed. Prior to this study there existed very little bathymetry data for the lower Kaituna River. To measure the bathymetry, echo soundings were taken from the river mouth to Te Matai which spans approximately 11 kilometres in length. The depth measurements were corrected to a common datum (Moturiki) using two water level recorders based at the river mouth and Te Matai. The Maketu and Kaituna bathymetry data were converted into a 15 × 15 and 20 × 20 metre horizontal grids respectively.

Measured data for this study made use of both field data collected during 2006 and data extracted from Environment Bay of Plenty’s monitoring archives. The archives were used to set the hydrodynamic and chemical boundary conditions in the model, while the 2006 field data was employed to calibrate and validate the hydrodynamic model ELCOM. In the estuary domain calibration of ELCOM involved comparing model output to measured current velocity and elevation data to set a bottom drag co-efficient. The measured salinity and remaining water velocity data were used to validate ELCOM in the estuary domain. For the river domain, the model's predicted salinity, water temperature and stage height were compared to measured data. The agreement between measured and modeled data was pleasing although a longer time series of some data would have been helpful to support a more rigorous calibration and validation. The largest discrepancy between modeled and measured data occurred in the river domain with water elevation at the river mouth (Fords Cut). The discrepancy was probably due to a flow restriction in the river that the model's bathymetry did not replicate.

For status quo, ELCOM-CAEDYM simulations revealed that the highest concentration of nutrients in the Maketu Estuary was from the Kaituna River entering through Fords Cut. Once this nutrient rich plume of freshwater entered the estuary it resided in the western region until mixed with marine water at the front of the marine-freshwater interface. The southern drain inflow also contributed to the nutrient load, although some uncertainty in the prescribed flow and nutrient concentrations for this boundary could have introduced an error. In the Kaituna River, nutrient concentrations were conserved between the Kaituna (up stream) boundary to the exit at the river mouth. An increase in NH_4 and decrease of NO_3 and PO_4 at the confluence with the Waiari Stream was also evident.

The four phytoplankton groups (marine diatoms, dinoflagellates, freshwater diatoms and cyanobacteria) showed very little change in growth in the river apart from in the closed of loop where elevated levels of the two freshwater phytoplankton groups could be correlated with an increase in residence time. Phytoplankton growth in the Maketu Estuary demonstrated spatial variability. Marine diatoms showed a positive correlation with residence time and with the increased nutrients in the western region, and experienced the greatest relative growth rate over the 15 day simulation. Dinoflagellates showed the smallest spatially variability most likely reflecting the broader salinity tolerance of an estuarine species. The salinity limitation on the two freshwater groups (freshwater diatoms and cyanobacteria) dominated their predicted growth rates showing large reductions in all regions of the estuary where marine and freshwater mixed. Once again, due to the slow model run times, simulations of phytoplankton were limited to a 15 day period in January 2004. To completely evaluate the relative growth rates of the four groups it would have been advantageous to simulate an entire year. Simulation of an entire year would have allowed phytoplankton growth rates to be predicted by annual and inter-annual variations in the forcing conditions (i.e. water temperature, light, phytoplankton concentration, neap-spring tides). The 15 day period in January was chosen as light and water temperature were at the maximum and cyanobacteria was at it highest concentration in the Kaituna River, allowing the likely maximum growth rates to be predicted.

Hydrodynamic simulations in the estuary predicted the maximum residence time is 1.5 days over the 15 day simulation and occurred in the western region of the estuary. The Kaituna River showed that, unsurprisingly, the residence time increases progressively down the river, with variations at the river mouth due to, reduced seaward flow in the lower river over a flood tide, intrusion by marine water and insufficient flushing in the closed loop. Analysis of the residual currents in the estuary showed that that the estuary is ebb dominated, which is likely caused by the freshwater inflows and tidal asymmetry (over tides). The strongest residual currents occurred in the main channel near the mouth of the estuary and at Fords Cut where freshwater inflow occurs.

The model conditions were altered from the status quo, to simulate and evaluate several scenarios in the river and estuary domains. Scenarios 9–12 predicted the effects of the Rotoiti diversion wall on nutrient concentrations and phytoplankton growth in the lower Kaituna River and Maketu Estuary. The results indicated that increasing NH_4, NO_3 and PO_4 by 20, 20 and 7 percent respectively at the up stream boundary of the Kaituna River model domain, would not promote any significant further phytoplankton growth in the lower Kaituna River or Maketu Estuary. The nutrient concentrations would increase in the Maketu Estuary with the most effected areas being the western region, as this is where the greatest dilution of freshwater with marine water occurs. The simulation also predicted that in the ~8.5 km stretch of the Kaituna River modelling domain the prescribed nutrient increase (20 and 7 percent) will be conserved between the upper boundary (Kaituna BC) and exit at the control gates or river mouth. Scenarios 13–20 predicted the proportion of marine water flowing through the control structure with the old river channel (closed loop) re-opened. This revealed that the salinity would be reduced by opening up the loop, however, the extent of the reduction would vary with tidal range and river flow, consequently the outcome of zero salinity is likely unachievable for the bathymetry modification used in the study. The first eight scenarios investigated the effects of increasing the freshwater inflow into the estuary and changing the inflow location back to the historic (Papahikahawai) channel. The results illustrated that increasing the freshwater inflow would increase the residual flow towards the river mouth while reducing the salinity in the estuary. An inflow of 4–8 time the status quo would likely cause areas of the upper (western region) to become completely devoid of marine water. An other effect of increasing the freshwater flow is an increase in the salinity range in the estuary with some regions of estuary experiencing complete marine and freshwater within one tidal cycle. Inflow at the historic channel would cause greater mixing of the marine and freshwater, but also reduce the residual salinity in the central and western regions of the estuary. The reduction in net velocity would likely result in negative consequences for the high rates of sedimentation that have been occurring in the estuary.

8.2) Point summary

- Phytoplankton growth in river and estuary are principally limited by the short residence time and variations of salinity. It is predicted that that maximum growth rates would be less than a doubling rate apart from freshwater diatoms in the lower river which demonstrated growth rates of slightly above this in the closed-loop.
- Calibration and validation of the water velocity, tidal elevation, temperature and salinity in the river and estuary were pleasing. Calibration and validation could be improved by longer temporal measurements of the water elevation, velocity and salinity.
- ELCOM's 3D grid was critical for determining the salinity and concentrations of variables drawn through the control gates at Fords Cut. This is because marine water propagates up the river and under the control gates as a salt wedge, and at times can be drawn through the control gates. Therefore being able to replicate the vertical structure and the height the outflow occurred over was important.
- The highest residence time in the estuary is 1.5 days and occurs in the western region of the estuary. In the river, variations to the residence time occurred due to insufficient flushing in the closed loop, backing up of the river over a flood tide and intrusion up the river by marine water.
- The residual flows in the estuary are ebb dominated and due to combination of freshwater inflows and tidal asymmetry (over tides).
- Increasing the freshwater inflow at the current Fords Cut location will increase the ebb flow dominance; this increase in flow will also decreases the average salinity, but increase the range of salinity in parts of the estuary.
- Specifying the inflow through the historic (Papahikahawai) channel would cause greater mixing of the marine and freshwater, however residual flows in the central and western region would be reduced, which would unlikely help reduce the sedimentation rate.
- Model simulation periods were hampered by the slow runtimes. The slow runtimes were caused by the high resolution grid needed to represent the intertidal channels in the estuary and reduce flow restriction in the river domain.

8.3) Recommendations for future work

Some suggestions for future work involving application of ELCOM-CAEDYM to the Maketu Estuary and lower Kaituna River include.

- Experimenting with larger grid sizes and comparing the model output to the measured data for accuracy. Larger grid sizes would allow faster runtimes hence longer period of simulations to occur. In turn this could allow better calibration of water quality parameters with EBOP's data base and evaluation of phytoplankton growth over an entire year.
- Defining the flow rates and water quality variables for the pumped drains and diffuse run off. Modelling from this study has shown these could be numerically important to the Maketu Estuary's and lower Kaituna's nutrient load.
- Extending the river domain further towards the river mouth, including out into the ocean. This would enable better calibration of the salt wedge intrusion and mixing. An extended bathymetry would also allowing more precise modelling of various outflow locations (i.e. historic Papahikahawai Channel).
- Collecting chlorophyll *a* data to supplement EBOP's archives in the river and estuary. This data could then be used for comparing to model output allowing some calibration of the phytoplankton parameters and rates.
- Defining some sediment-velocity thresholds within the estuary. These thresholds could be used for determining geomorphology changes in the estuaries hydrodynamics due to different inflow rates and locations.
- Determining the optimum ranges of variables (i.e. salinity) for species that historically thrived in the estuary, for example the pipi and salt-marsh. Based on these ranges, use the model output to create 'zonation' maps of areas in the estuary that may be favorable for re-establishment.

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Appendix One

Table of parameters and rates of each phytoplankton group used for CAEDYM simulations in the Maketu Estuary and Kaituna River.

Maximum Growth rate (*/ day*)		
	Marine Diatoms	1.6
	Dinoflagellates	0.7
	Freshwater Diatoms	1.44
	Cyanobacteria	0.7
Average C:Chl-*a* ratio		
	Marine Diatoms	42
	Dinoflagellates	52
	Freshwater Diatoms	40
	Cyanobacteria	40
Parameter for slope of PI curve (µE m^2 s^{-1})		
	Marine Diatoms	120
	Dinoflagellates	140
	Freshwater Diatoms	20
	Cyanobacteria	120
Light saturation for max production (µEm^2 s^{-1})		
	Marine Diatoms	380
	Dinoflagellates	180
	Freshwater Diatoms	10
	Cyanobacteria	200
Specific attenuation co – efficient (µg chl-*a* l^{-1} m^{-1})		
	Marine Diatoms	0.02
	Dinoflagellates	0.02
	Freshwater Diatoms	0.02
	Cyanobacteria	0.04
Half saturation constant for phosphorus (mgl^{-1})		
	Marine Diatoms	0.003
	Dinoflagellates	0.005
	Freshwater Diatoms	0.010
	Cyanobacteria	0.006
Low concentration of PO4 that uptake ceases (mgl^{-1})		
	Marine Diatoms	0
	Dinoflagellates	0
	Freshwater Diatoms	0
	Cyanobacteria	0
Half saturation constant for nitrogen (mgl^{-1})		
	Marine Diatoms	0.015
	Dinoflagellates	0.052
	Freshwater Diatoms	0.060
	Cyanobacteria	0.030
Low concentration of N at which uptake ceases (mgl^{-1})		
	Marine Diatoms	0
	Dinoflagellates	0.01
	Freshwater Diatoms	0
	Cyanobacteria	0

Constant internal silica concentration (mg Si / mg Chl *a*)		
	Marine Diatoms	20
	Freshwater Diatoms	20
Half saturation constant of silica (mgl^{-1})		
	Marine Diatoms	0.22
	Freshwater Diatoms	0.44
Low concentration of Si at which uptake ceases (mgl^{-1})		
	Marine Diatoms	0.3
	Freshwater Diatoms	0
Max. internal N (mgN / mgChl *a*)		
	Marine Diatoms	12
	Dinoflagellates	4
	Freshwater Diatoms	4.5
	Cyanobacteria	9
Min. internal N (mgN / mgChl *a*)		
	Marine Diatoms	5.0
	Dinoflagellates	4.5
	Freshwater Diatoms	2
	Cyanobacteria	2.5
Max. internal P (mgP / mgChl *a*)		
	Marine Diatoms	0.60
	Dinoflagellates	0.60
	Freshwater Diatoms	2
	Cyanobacteria	2.20
Min. internal P (mgP / mgChl *a*)		
	Marine Diatoms	0.20
	Dinoflagellates	0.27
	Freshwater Diatoms	0.25
	Cyanobacteria	0.5
Max rate of N uptake (mgN / mgChl *a* / day)		
	Marine Diatoms	12
	Dinoflagellates	1.5
	Freshwater Diatoms	3
	Cyanobacteria	1.5
Max rate of P uptake (mgP / mgChl *a* / day)		
	Marine Diatoms	0.30
	Dinoflagellates	0.06
	Freshwater Diatoms	1
	Cyanobacteria	0.30
Min. internal C conc. (mgC / mg Chl *a*)		
	Marine Diatoms	15
	Dinoflagellates	15
	Freshwater Diatoms	15
	Cyanobacteria	15
Max. internal C conc. (mgC / mg Chl *a*)		
	Marine Diatoms	60
	Dinoflagellates	60
	Freshwater Diatoms	80
	Cyanobacteria	80
Max. rate of C uptake (mgC / mg Chl *a* / day)		
	Marine Diatoms	50
	Dinoflagellates	50
	Freshwater Diatoms	50
	Cyanobacteria	50

Half saturation constant for carbon (mgl^{-1})		
	Marine Diatoms	0.3
	Dinoflagellates	0.3
	Freshwater Diatoms	0.3
	Cyanobacteria	0.3
TEMPERATURE		
Temperature multiplier		
	Marine Diatoms	1.07
	Dinoflagellates	1.10
	Freshwater Diatoms	1.05
	Cyanobacteria	1.08
Standard temp (Deg. C)		
	Marine Diatoms	19
	Dinoflagellates	22
	Freshwater Diatoms	12
	Cyanobacteria	20
Optimum temp (Deg. C)		
	Marine Diatoms	26
	Dinoflagellates	29
	Freshwater Diatoms	20
	Cyanobacteria	28
Max temp (Deg. C)		
	Marine Diatoms	32
	Dinoflagellates	34
	Freshwater Diatoms	30
	Cyanobacteria	35
SALINITY		
Maximum potential salinity (psu)		
	Marine Diatoms	36
	Dinoflagellates	29
	Freshwater Diatoms	12
	Cyanobacteria	12
Optimum salinity (psu)		
	Marine Diatoms	20
	Dinoflagellates	25
	Freshwater Diatoms	3
	Cyanobacteria	1
Salinity limitation at S = 0, S = max SP		
	Marine Diatoms	5
	Dinoflagellates	3
	Freshwater Diatoms	5
	Cyanobacteria	5
Salinity limitations at S=Sop		
	Marine Diatoms	1
	Dinoflagellates	1
	Freshwater Diatoms	1
	Cyanobacteria	1
RESPIRATION, MORTALITY AND EXCRETION		
Respiration rate coefficient (/ day)		
	Marine Diatoms	0.15
	Dinoflagellates	0.05
	Freshwater Diatoms	0.12
	Cyanobacteria	0.05
Temperature multiplier		
	Marine Diatoms	1.07
	Dinoflagellates	1.06
	Freshwater Diatoms	1.05
	Cyanobacteria	1.09

Fraction of respiration relative to total metabolic loss rate		
	Marine Diatoms	0.7
	Dinoflagellates	0.7
	Freshwater Diatoms	0.7
	Cyanobacteria	0.79
Fraction of metabolic loss rate that goes to DOM (remaining goes to POM)		
	Marine Diatoms	0.2
	Dinoflagellates	0.2
	Freshwater Diatoms	0.2
	Cyanobacteria	0.2
VERTICAL MIGRATION AND SETTLING		
Type of vertical migration algorithm		
	Marine Diatoms	constant (1)
	Dinoflagellates	constant (1)
	Freshwater Diatoms	constant (1)
	Cyanobacteria	constant (1)
Rate coefficient for density increase (kgm^{-3} min^{-1})		
	Marine Diatoms	0.9
	Dinoflagellates	0.9
	Freshwater Diatoms	0.9
	Cyanobacteria	0.124
Minimum rate of density decrease with time (kgm^{-3} min^{-1})		
	Marine Diatoms	0.0415
	Dinoflagellates	0.0415
	Freshwater Diatoms	0.0415
	Cyanobacteria	0.023
Rate for light dependent migration velocity (mhr^{-1})		
	Marine Diatoms	0.85
	Dinoflagellates	0.6
	Freshwater Diatoms	0.85
	Cyanobacteria	0.3
Rate for nutrient dependent migration velocity (mhr^{-1})		
	Marine Diatoms	0.65
	Dinoflagellates	0.6
	Freshwater Diatoms	0.65
	Cyanobacteria	0.3
Half saturation constant for density increase (μEm^{-2} s^{-1})		
	Marine Diatoms	25
	Dinoflagellates	26
	Freshwater Diatoms	25
	Cyanobacteria	278
Minimum phytoplankton density (kg m^3)		
	Marine Diatoms	980
	Dinoflagellates	980
	Freshwater Diatoms	980
	Cyanobacteria	990
Maximum phytoplankton density (kg m^3)		
	Marine Diatoms	1050
	Dinoflagellates	1050
	Freshwater Diatoms	1050
	Cyanobacteria	1002

Diameter of phytoplankton (m)		
	Marine Diatoms	0.00001
	Dinoflagellates	0.00005
	Freshwater Diatoms	0.00001
	Cyanobacteria	0.00002
Constant settling velocity (ms^{-1})		
	Marine Diatoms	-0.6×10^{-6}
	Dinoflagellates	0
	Freshwater Diatoms	-0.6×10^{-6}
	Cyanobacteria	0.5×10^{-5}
RESUSPENTION		
Critical shear stress (N / m^2)		
	Marine Diatoms	0.001
	Dinoflagellates	0.001
	Freshwater Diatoms	0.05
	Cyanobacteria	0.05
Rate of re-suspension (mg Chl-*a* m^2)		
	Marine Diatoms	2
	Dinoflagellates	2
	Freshwater Diatoms	2
	Cyanobacteria	2
Phytoplankton Sediment survival time (days)		
	Marine Diatoms	2
	Dinoflagellates	2
	Freshwater Diatoms	2
	Cyanobacteria	2