# The hydrodynamic evolution of the Maketū Estuary after the re-diversion of the Kaituna River

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# ABSTRACT

The Maketū Estuary and lower Kaituna River located in the Bay of Plenty, Aotearoa, New Zealand have undergone anthropic disturbances since late 1800s, including land reclamation, river diversion and re-diversion, and modifications to the river channels and estuary tidal inlet. This has resulted in estuarine degradation, as is a common issue worldwide. Globally different approaches to estuary restoration have aimed at mitigating the adverse impacts of estuarine degradation. However, there are still gaps in restoration frameworks and how the success of the scheme is evaluated that mean there is no ready-made solution to the issues at Maketū.

This thesis examines the important role of the hydrodynamic processes (including water quality) that govern the overall physical response of Maketū Estuary to two stages of partial re-diversion of the Kaituna River into the estuary. The assessment of this physical response highlighted the necessity of a proper framework in which restoration attempts, such as at Maketū are evaluated.

Field time series data were collected before and after two stages of river re-diversion, Stage 1 in 2020 and Stage 2 in 2021, each over a span of a month, to record the immediate response of the estuary to the added freshwater flows. Freshwater flow into the estuary was constrained to approximately 4 hours during flood tides when the water level In the Kaituna River was at least 40 mm higher than the upper Maketū Estuary. The control gates also operate as a flood control scheme, so they remain shut if there is flood risk causing all the flood volume to discharge directly to the sea through Te Tumu Cut river mouth.

The field data were obtained using Aquadopp ADPs, RBR Maestros, RBR Concertos, and Solinst water level loggers at seven different sites throughout the estuary and the Kaituna River. A hydrographic survey of the estuary using RTK-GNSS was undertaken and combined with LiDAR to produce a bathymetric map of the estuary and Lower Kaituna River. Comparison of this map to previous compilations showed that the tidal inlet and lower estuary have not undergone major changes since the original river diversion in 1958, apart from an expansion in the area occupied by the flood tidal delta. However, the upper estuary has undergone both artificial and natural changes, including construction of artificial channels, causeways and reclamation, which have influenced the flow regime, circulation patterns and the flushing ability of the upper estuary.

Based on field observations, the freshwater inflow to the estuary during Stage 1 was higher than Stage 2 even though Stage 1 was a partial re-diversion restricted to 400,000 $m^3$ per flood tide, compared to the maximum 600,000 $m^3$ for Stage 2. There was great spatial variability in the response of the estuary to the added freshwater flow despite the estuary's small size and lack of inter-tidal vegetation. To better isolate the impact of freshwater flow and eliminate variables such as spring/neap tidal events, rainfall and wind, all of the data were averaged over a semi-diurnal tidal cycle of 12.4 hours. There was an increase in mean water level after both stages. Flow in the mid and upper estuary shifted towards ebb-dominance after Stage 1, but no further shift to ebb-dominance was observed after Stage 2. Mean bottom salinity increased in the upper estuary while it decreased everywhere else after Stage 1. Mean bottom salinity reduced uniformly throughout the estuary after Stage 2, most likely due to higher rainfall rate during the monitoring period, and not the added freshwater flow.

To better understand the mixing patterns within the estuary, Estuarine Richardson number ($R_{iE}$) was calculated at 3 main sites before and after both stages of re-diversion. $R_{iE}$ increased after Stage 1, but not sufficiently to cause a shift in classification; therefore, the estuary remained partially-mixed. Current dynamics within the estuary varied depending on proximity to the tidal inlet, with sites close to the inlet showing a strong tidal signal, and the ones near the control gates showing a decreased tidal influence and an increased response to freshwater inflows during flood tide when the control gates were open. Surface currents were influenced by strong winds during storm events and dictated the mixing (stratification) in the mid and upper shallow estuary. However, it was difficult to assess the significance of these changes in relation to the community aspirations for the re-diversion and estuarine restoration as there were insufficient quantitative or qualitative targets defined.

To complement the field observations and better evaluate the impact of alternative restoration options, a 2D numerical model of the estuary was developed using Delft3D. After successfully being calibrated and validated, Delft3D-FLOW and PART were used to simulate different scenarios to assess the flow regime and flushing ability of the estuary. The scenarios included Stage 1 re-diversion, river inflow flow without control gates; and a pulsed flood flow using control gates that imitated natural flood events. Particle tracking was used determine the residence time across the estuary, and assess within which zones decay rate changed with tidal fluctuations, and which zones were sheltered from the tidal fluctuations. Model results showed that the pulsed flood scenario created the optimal conditions for sediment transport, increased flushing ability, and reduced salinity throughout the estuary. The model results also highlighted differences in how various zones in the estuary responded to the added freshwater flow, further emphasising the need to monitor them separately with an improved monitoring framework.

The results of this study have led to a better understanding of the impact of added freshwater flow on estuarine hydrodynamics and water quality: specifically how the river input moves the boundaries of fluvially or tidally dominated, and mixing zones. The most vulnerable zones in terms of the flushing ability under different scenarios of freshwater restoration were also identified. This study also highlighted the importance of setting tangible targets in the restoration scheme in alignment with the environmental uncertainties such as the average river flow and limitations due to flooding issues in the upper catchment.

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# 1 CHAPTER 1 GENERAL INTRODUCTION

## 1.1 Nature of the problem

Human activities often reduce freshwater flows to estuaries, modifying estuarine mixing processes (Loitzenbauer & Bulhões Mendes, 2012). To remedy anthropic impacts, sustainable restoration of endangered coastal ecosystems has become of great environmental interest and scientific value (Panda et al., 2015). The perception of an environmental problem is usually the first step in the restoration procedure (Livingston, 2006). Regardless of scope, any restoration effort should have a well-defined goal and scientific data are needed to determine the appropriate scale of operations to achieve a realistic goal. This process will determine the expectations from the restoration (Livingston, 2006).

While there are numerous cases of estuarine degradation due to freshwater manipulation, this research is focused on the Maketū Estuary and lower Kaituna River located in the Bay of Plenty, Aotearoa, New Zealand, due to their cultural and historical significance combined with a century long history of man-made alterations. The Maketū Estuary and Kaituna River hydrodynamics have been drastically altered since the late 1880s, predominantly due to anthropic disruptions. One of the most impactful interventions was the diversion of the Kaituna River out of the estuary in 1956-57 to reduce flood risk for the Lower Kaituna River and Maketū Estuary, which contributed to estuarine degradation and general ecological decline of the estuary. Major realignment work was carried out on the lower river during the 1970s and 80s to reduce the effects of flooding, further altering the hydrodynamics in the lower river.

Advocated by iwi (extended kinship group (Greaves et al., 2023)), longtime users of the estuary and the local community, a re-diversion of the river flow back into the estuary was proposed following community consultation and a petition to Parliament in 1984 (Tortell, 1984). In 1998, resource consent was granted to allow ~150,000 $m^3$ per tidal cycle of Kaituna River water to enter the estuary through control gates. This re-diversion was expected to reduce the sediment infilling and restore some of the declining wetland marsh and kaimoana to the estuary (Domijan, 2000). While the 1998 re-diversion assisted in lowering the salinity in the upper estuary, improvements to sedimentation, hydrodynamics and ecology were not observed over the years 1996-2018 (Goodhue, 2007). Subsequently, after 2018 as part of an estuary restoration project, additional freshwater flows of ~400,000 $m^3$ (Stage 1) and then ~600,000 $m^3$ (Stage 2) were allowed back into the estuary in two stages. This new re-diversion scheme was intended to achieve the community aspirations, while minimising the flood risk. Among these community aspirations are scouring out sediment to improve navigation; improving the habitat for food species (including game birds), and traditional plants used by iwi; enhancing water quality; and returning the estuary to the "way it was" (Tortell, 1984).

## 1.2 Study Site

### 1.2.1 Historical and Cultural Significance

Before human habitation, the Maketū Estuary was part of a large ecosystem of sand dunes, swamp lands and tidal flats stretching along the Bay of Plenty coastline (Newnham et al., 1995; Wigley, 1990). Home to various birds, animals and marine life, the Maketū Estuary has supported tens of thousands of Māori in recent centuries (Loomis, 1984). The first Māori settlement in the Bay of Plenty (BOP) was around 1340 CE (Tapsell, 2000) and was associated with destabilisation of coastal dunes due to the loss of vegetation due to the effects of the Kaharoa Eruption and land clearance for growing food (McFadgen, 2007). Te Arawa was one of nine canoes to arrive in the BOP, and is identified as having the most significance for the mana whenua of Maketū as this was the final landing place of the canoe. Te Arawa entered the Maketū Estuary after navigating parts of the BOP coastline, where it may have been anchored to two rocks named Taka-parore and Tuterangiharuru, located inside the estuary mouth, and still present today (Tapsell, 2000).

The Maketū Estuary and the Kaituna River were colonised by Europeans in the 1800s. During this period, deforestation and farming/agriculture activity increased rapidly. This involved the draining of the coastal swamps and tidal wetlands flanking the Maketū Estuary and Lower Kaituna River, and grazing on the coastal dunes which resulted in an increase in wind erosion and transport of sand (Stokes, 1980). The conversion of low-lying land into farms resulting in an increase in reported flooding issues, and the destabilisation of the coastal sand dunes may have contributed to increased movement of the river bed in the lower catchment and an increase in spit breaching events. The drainage of the swamps and wetlands also contributed to major changes to the hydrology and ecology of the estuary (Murray, 1978; Park, 2014)

The first European to settle within Maketū was Captain Phillip Tapsell in 1829 (Richmond & Forbes, 1990; Tapsell, 2000). On Tapsell's arrival in Maketū, 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, most of the swamp areas would have been covered by flax. The arrival of mainstream Europeans took place in the late 1800s following a proclamation by the Governor General of New Zealand, declaring the land known as Te Puke open for settlement on the 27th of January 1880 (BOPCC, 1970). The settlement region included the lower Kaituna River and Maketū 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 the swamps, particularly during the 1890s (Goodhue, 2007; Tortell, 1984).

### 1.2.2 Environmental Features

The Maketū Estuary (Te Awa o Ngātoroirangi) is a small (2.3 $km^2$), shallow (mean depth < 1 m below mean sea level (MSL)) microtidal barrier-enclosed estuarine lagoon (Burton & Healy, 1985) at the mouth of the Kaituna River, in the Bay of Plenty of Aotearoa New Zealand (Figure 1.1). It is approximately 35 km southeast of Tauranga and 50 km northeast of Rotorua. The estuary comprises sand and mud intertidal flats, tidal channels, salt marshes and wetlands and experienced a change in estuarine classification from tidal river mouth to tidal lagoon due to anthropic impacts (Hume et al., 2017).

The main freshwater inflow was from the Kaituna River until the river was diverted away from the estuary at Te Tumu. The river headwaters begin at the Okere arm of Lake Rotoiti, from which it runs 53 km to the sea at Te Tumu (Mawer, 2012). The Kaituna River flow is largely controlled by the Okere control gates (connecting Okere Arm and Kaituna River) and Lake Rotoiti water levels (Figure 1.1).

Tides at the entrance to the estuary are semi-diurnal and mixed, with spring and neap tidal ranges of 1.73 m and 1.16 m, respectively, with a maximum astronomical tidal range of 2.19 m (McKenzie, 2014). The mean spring tidal prism was estimated as 1 $Mm^3$ (Domijan, 2000) and is dominated by marine water entering through the tidal inlet on the estuary's eastern side (Figure 1.2). Three tidal gaugings before 1985, when gates prevented the Kaituna River from entering the estuary, showed a reduction in both flood and ebb tidal range between the tidal inlet and the estuary side of Ford's Cut (Figure 1.2), demonstrating that tidal amplitude decreased up the estuary from the tidal inlet (Burton & Healy, 1985). There was a time lag of up to 1 hour between high water at the tidal inlet to high water at Ford's Cut.

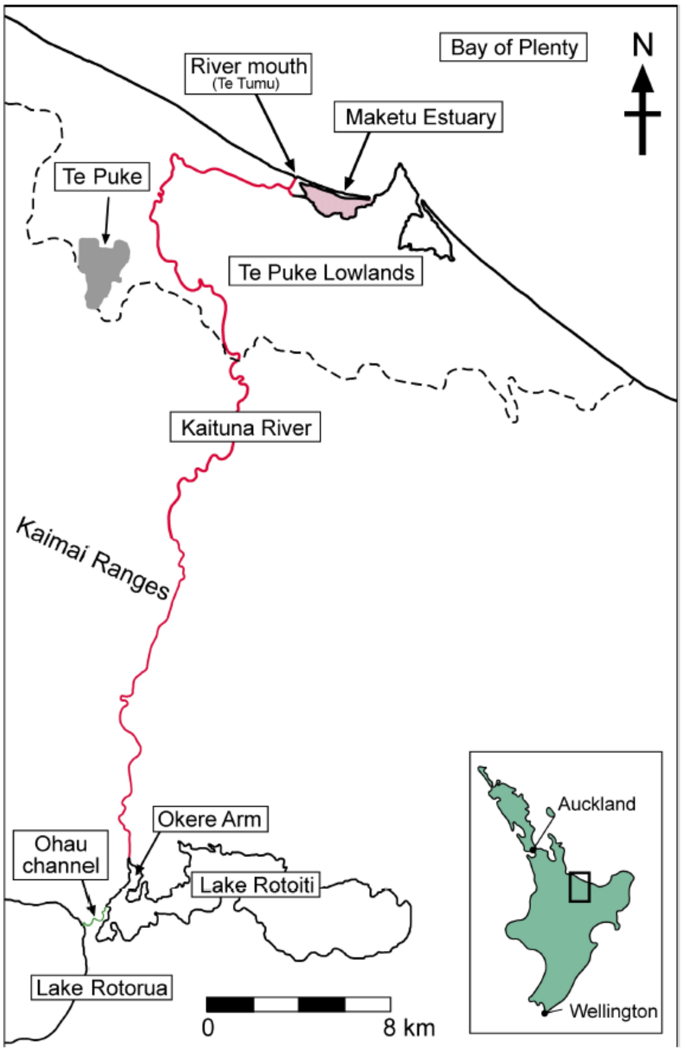


*Figure 1.1 Location map illustrating the Maketū Estuary, Kaituna River, Lake Rotoiti, Lake Rotorua, Te Puke lowlands, Ohau channel, Okere Arm, Te Tumu and the Kaimai Ranges in the Bay of Plenty, North Island, New Zealand. (Source: LINZ, 2006) (Goodhue, 2007)*

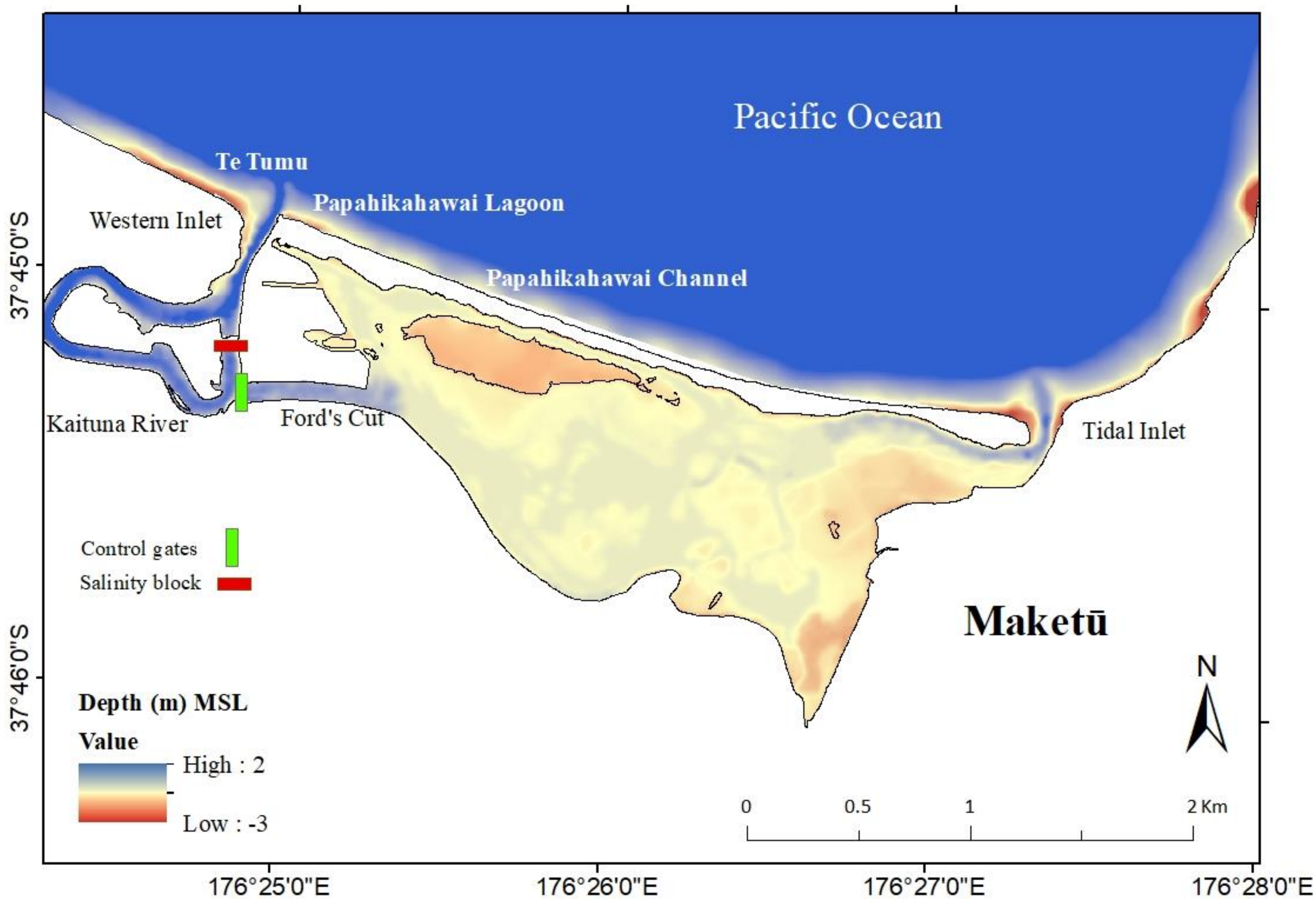


*Figure 1.2 Map of Maketū Estuary and Kaituna River from combined RTK GPS data, single beam echosounder data collected in February 2020, LiDAR data from December 2018–April 2019 provided by BOPRC, as well as offshore data (last updated July 2020) from Land Information New Zealand (LINZ)*

Sketch maps (Figures 1.3 and 1.4) indicate the potential for morphological changes in some areas of the estuary before 1939, due to spit breaching by floods and storm waves resulting in the opening and closing of inlets and migration of inlets between breaching events (Ford & Ford, 2008; Stokes, 1980). Contemporary accounts (Ford & Ford, 2008) refer to shoaling (the deformation of incident waves when water depth decreases) associated with the closure of the tidal inlet (location of the present-day tidal inlet in Figure 1.2) whenever a new river outlet formed by spit breaching.

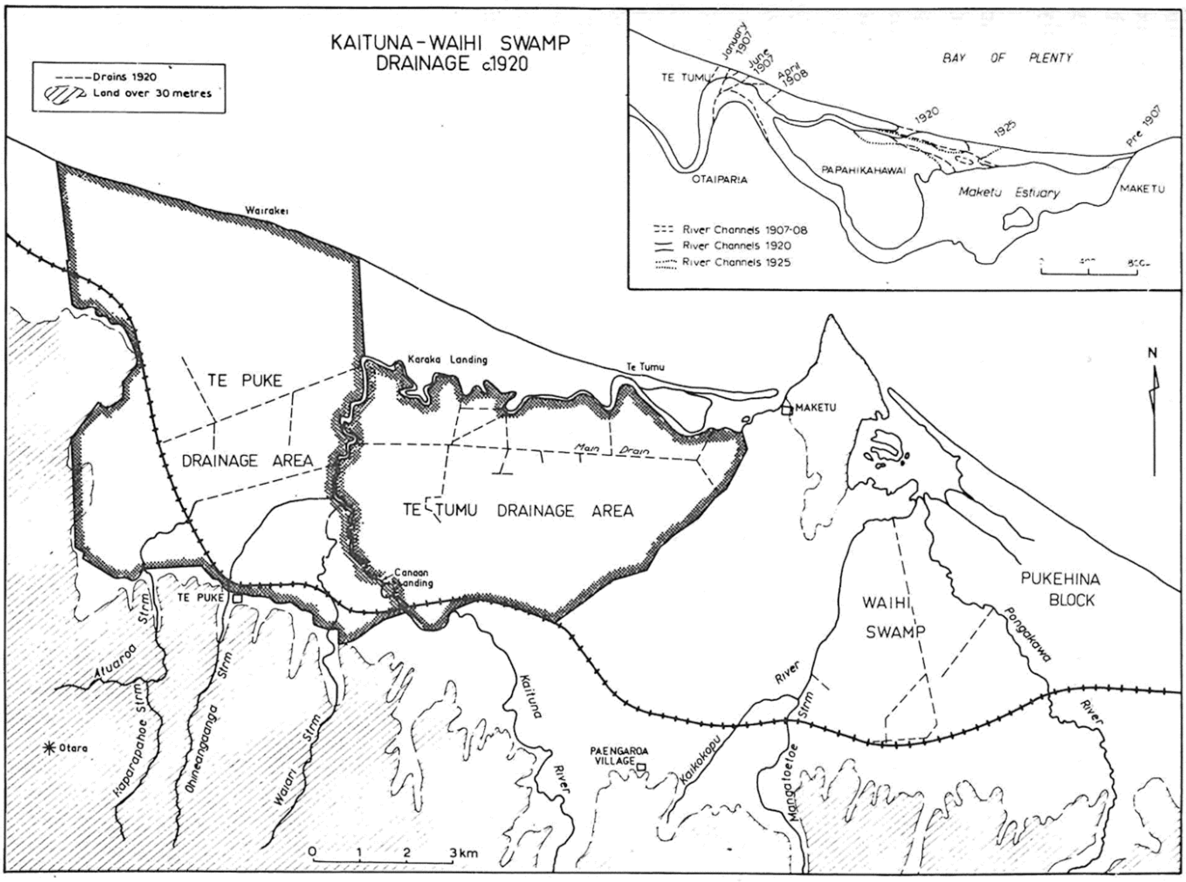


*Figure 1.3 Sketch map of Maketū Estuary and swamp drainage in 1920 (Stokes, 1980)*

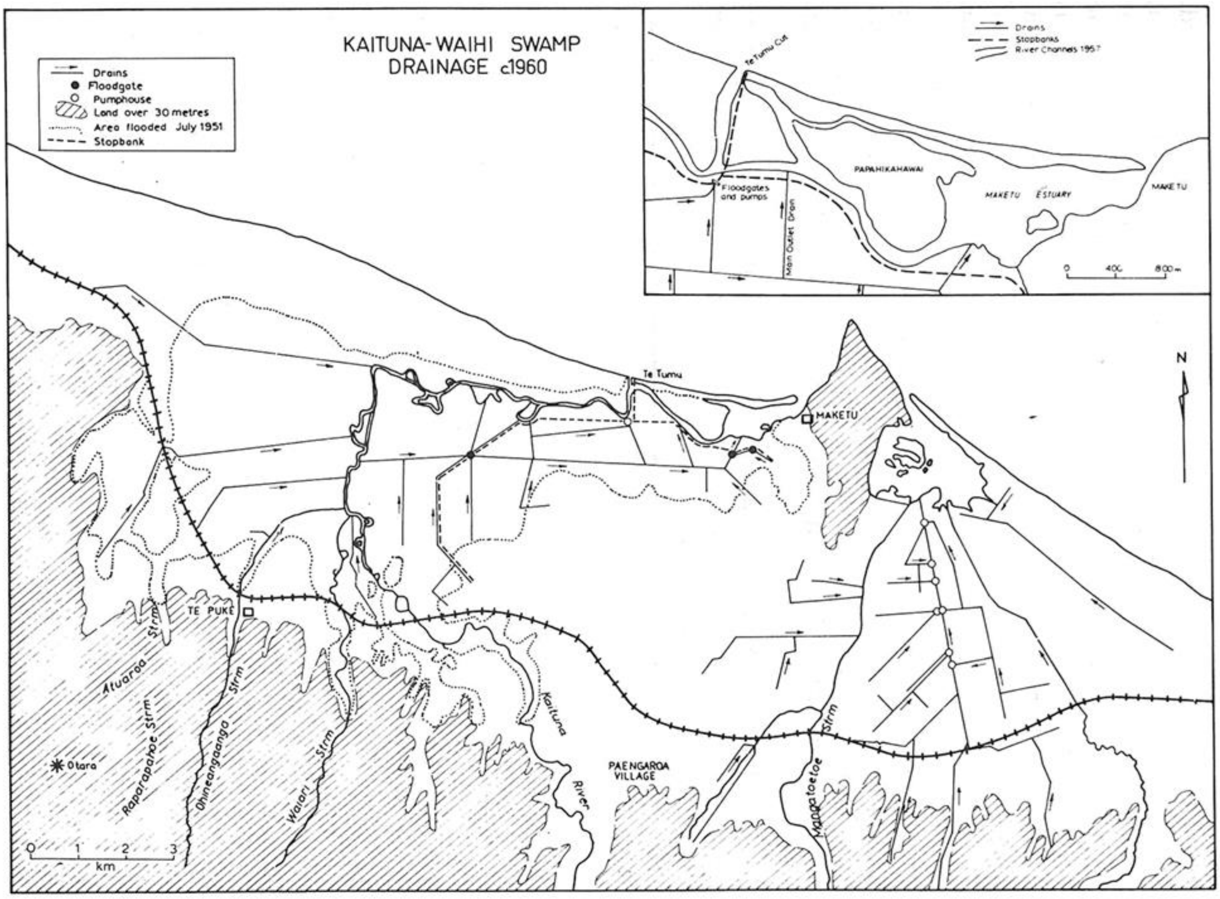


*Figure 1.4 Sketch map of the Maketū Estuary and swamp drainage in 1960 (Stokes, 1980)*

Aerial photos from 1939 (Figure 1.5) clearly show that the estuary was well-covered with sandbanks and with braided river channels meandering between. The main river channel near the estuary mouth seemed to have been wide and relatively deep (Domijan, 2000). By analysing multiple aerial photographs and calculating bathymetric changes from 1975 to 1984, Burton (1987) concluded that the former course of the Kaituna River dominated the channel pattern of Maketū Estuary in 1985. Burton and Healy (1985) also concluded that “The sequence of morphological changes of the Maketū inlet and spit, based on historical aerial photographs, shows clearly the influence of the Kaituna River diversion, with the immediate formation and continued expansion of a large flood delta".

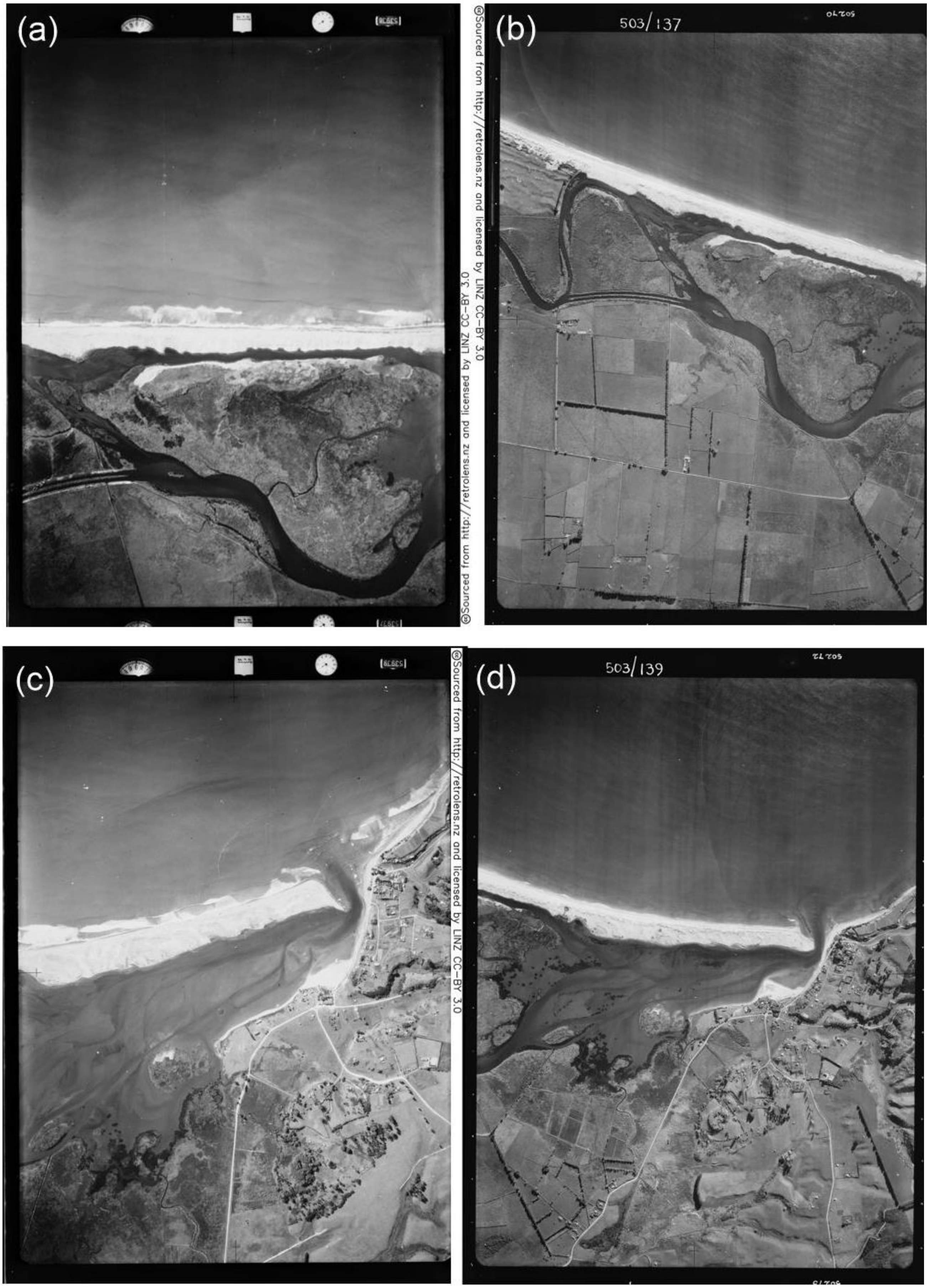


*Figure 1.5 Aerial images of Kaituna River (a and b) and Maketū Estuary (c and d) in 1939 and 1948, respectively (sourced from https://retrolens.nz and licensed by LINZ CC-BY 3.0)*

A comparison of the estuary morphology in 1939 from aerial photographs (Figure 1.5) to the present day shows that the overall morphology of the lower and mid-estuary has mainly remained unchanged despite the diversion and re-diversion of freshwater flows. The largest morphological changes since 1939 have been the growth of flood/ebb tidal deltas and partial infilling of the middle Papahikahawai Channel by transgressive sand dunes and sheets from the coastal barrier. According to Tortell (1984), residents of the area reported that before diversion of the Kaituna River, the estuary tidal inlet shifted occasionally and sand built up during severe storms. However, the scouring action of the river associated with periodic floods would offset these influences.

### 1.2.3 History of Changes

Te Awa o Ngātoroirangi (Maketū Estuary) has undergone multiple anthropic shifts since the early 1900s. The earliest changes were associated with the drainage and reclamation of the tidal coastal wetlands surrounding Te Puke Lowlands, disconnecting them from the Kaituna River and estuary (Stokes, 1980). This disconnection led to the Kaituna River being confined to a meandering channel through the estuary, predominantly along the southern margin of the present estuary. The Papahikahawai Channel on the northern side of the estuary periodically became the main channel when floods breached the barrier spit (Ford & Ford, 2008), mainly at Te Tumu (8 breaches were recorded between 1907 and 1929), where a meander bend in the river had progressively migrated seaward during the 1800s and narrowed the barrier dunes (Stokes, 1980). The tidal inlet at Maketū frequently closed up following spit breaches due to the accumulation of sand carried by longshore wave-driven sediment transport.

Between 1926 and 1929, improvements were made to more quickly drain floodwater from the Kaituna River into the estuary (Stokes, 1980), such as an artificial cut across the a meander bend (Ford’s Cut). At Ford’s Cut, twin channels were excavated across a bend in the Kaituna River after 1925 (Figure 1.2), but the exact timing is not known (Wallace, 2008). The narrow strip of land between the channels was later removed to form a larger single channel. When Ford’s Cut was completed, the main river flow inside the estuary occurred in the original deep channel on the southern side of the estuary before splitting into multiple shallow channels connecting over the central deltaic region to the tidal lower Papahikawawai Channel on the northern side of the estuary. Murray (1951) assessed the effectiveness of Ford’s Cut and concluded it was too small to divert significant quantities of water (the central strip hadn’t been removed before his assessment).

Later, a report by Murray (1956) provided a great deal of factual data on rainfall intensities and distribution within the catchment, flow regime in the river including peaks, the contribution of various tributaries, water levels and outflow rates at Ford's Cut and Maketū Estuary entrance between 7 May to 4 June 1956. According to Murray (1956), the problems experienced would not be eliminated by the proposed cut at Te Tumu and bypassing the estuary, which he considered an essential ponding area to relieve high tidal levels (Domijan, 2000).

However, Te Tumu diversion cut was effected in February 1958 after technical debate established that no satisfactory alternative would give the same immediate flood relief within the same time and cost (Rutherford et al., 1989). In 1978, the Papahikahawai spit breach led to large-scale sediment fluxes and the development of a lunate flood-tidal delta. By the end of 1984, the tidal inlet had migrated eastward back to its former location, resulting in further lateral expansion of the flood-tidal delta and deterioration of the entrance channels (Burton, 1987).

Before 1957 the estuary was a tidal river mouth (dominated by river and tidal flows), and it became a tidal lagoon (restricted to only tidal flows) based on flow characteristics after diversion of the Kaituna River through Te Tumu Cut directly to the ocean (Hume et al., 2017). Before Te Tumu diversion, the Kaituna River generally flowed out to sea through the location of the present tidal inlet (Figure 1.2). However, at times, the river breached naturally through the spit between the estuary and the sea at Te Tumu (Figure 1.2) (Park, 2014) as occurred in 1907, before generally migrating eastward in the direction of littoral drift, maintaining the Papahikawawai Channel as the main tidal channel (Healy & de Lange, 2014).

Since diversion through Te Tumu Cut, the estuary and lower Kaituna River have had a complicated history of anthropic changes. Before diversion, the Kaituna River discharge into the estuary over a tidal cycle was estimated as ~1,165 $m^3$, at an average rate of ~94 $m^3/s$ (calculated using a single-day survey during spring tide), equivalent to 97% of the spring flood tidal prism (Burton & Healy, 1985), and the entrance of the estuary exhibited a typical tidal river mouth configuration with a very small ebb-tide bar, no flood tide delta, a shallow braided transition zone between the river channel and the tidal/river inlet, and river flows dominated over tides within the estuary (Hume et al., 2017).

Once the new channel was artificially created to divert the river directly into the sea at Te Tumu (Figures 1.1 and 1.2) in the west, the river connections to the estuary through the Papahikahawai Channel and Ford's Cut were closed off to prevent flooding of low-lying farmland (reclaimed tidal wetlands) surrounding the estuary. Further, the Papahikahawai Block in the upper estuary was reclaimed, and access was provided by several causeways that restricted tidal exchange between the main estuary and the Papahikahawai Lagoon forming the north-western arm of the estuary.

Removing the dominant freshwater source into the estuary substantially reduced the flushing ability of river-enhanced ebb tide currents, and there was accretion on the sandy intertidal flats close to the entrance, and the development of a substantial flood and larger ebb-tidal delta at the original inlet (Hume et al., 2017). However, the most noticeable change between the earliest aerial photographs in 1939 and the present is the loss of large areas of saltmarsh and tidal wetlands, mainly where several causeways that restricted flows were constructed between large reclamations within the upper estuary (dominated by Papahikahawai Block, or 'island', in the upper estuary in Figure 1.2); with smaller reclamations around the estuary margins, as also noted by Park (2014). The causeways isolated the upper Papahikahawai Channel to effectively produce a lagoon separate from the main estuary (Papahikahawai Lagoon).

The loss of salt marsh and wetland habitats (Bergin, 1994; Donovan & Larcombe, 1976), build-up of sediment in the lower estuary associated with the growth of the flood/ebb tidal delta system, increased salinity, and reduced flushing have had wide-reaching effects including the demise of culturally-important estuarine kaimoana (seafood) including pipi (*Paphies australis*), tuangi (cockle/ *Austrovenus stutchburyi*) (Hamerton, 2014), and also contributed to degrading water quality (McIntosh, 2005) and restricting estuary access and navigation (Goodhue, 2007). From 1957 to 1995, the only freshwater flow from the Kaituna River into the estuary was minor seepage and "pulsed" overflows during floods.

In 1982, the Okere Gates control structure was commissioned to control Lake Rotoiti discharges into the Kaituna River (BOPRC, 2005). Subsequently, restricted flows of 2 $m^3/s$ of fresh water (up to ~100,000 $m^3$ per tidal cycle and 4% of the river flow) were restored to the estuary through the Ford's Cut control structure (Figure 11.) in 1996 (Hume et al., 2017).

Figure 1.6 summarises the main changes made to the Maketū Estuary and Kaituna River from the late 1880s to the present, as discussed above.

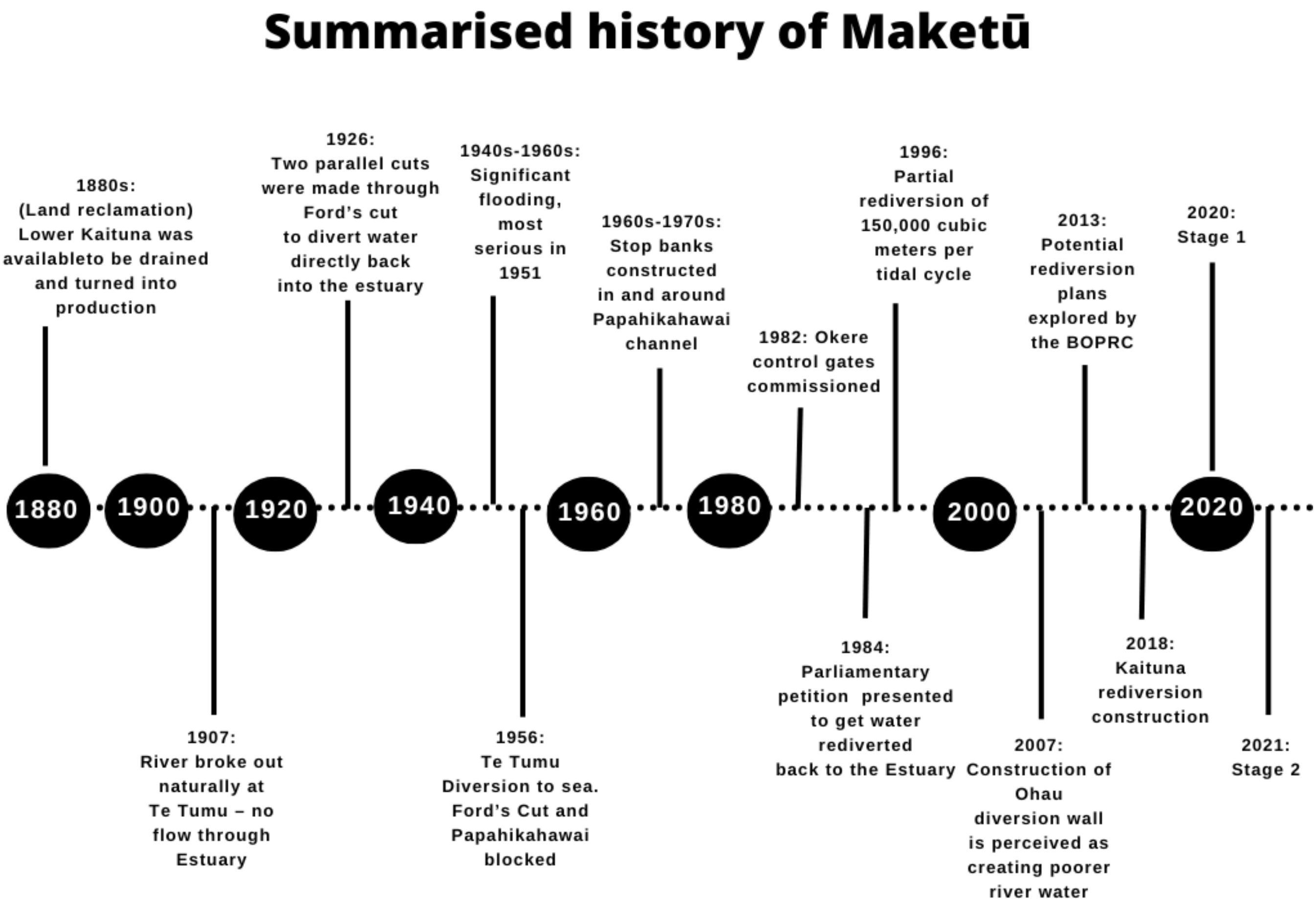


*Figure 1.6 Summarised history of changes made to Maketū Estuary and Kaituna River, based on Stokes (1980), Ford and Ford (2008) and BOPRC*

## 1.3 Thesis Questions and Aims

This thesis investigates the hydrodynamics and evolution of the Maketū Estuary in response to the partial re-diversion of the Kaituna River. This aim will be addressed with four objectives:

1. Quantify the initial response (aimed at two weeks) of estuarine hydrodynamics (currents, salinity, turbidity and temperature) to partial river re-diversion;

2. Establish the inter-annual changes in estuarine hydrodynamics, specifically estuarine circulation and tidal asymmetry, in response to the added freshwater flow;
3. Investigate the response of estuarine flushing and residence time to river re-diversion and
4. Determine the success of the restoration attempt in terms of water quality and management implications.

My research contributes to a more comprehensive understanding of effective estuarine restoration. By focusing on freshwater manipulation, my research extends beyond site-specific evaluation and will help determine what makes a successful estuarine restoration using engineering interventions. As we face mounting environmental challenges such as climate change, it is vital to bridge the gaps in restoration attempts by freshwater to better manage coastal systems and remedy adverse human-induced impacts on them. The insights from my research will serve policymakers, scientists, and practitioners worldwide by creating a more realistic view of restoration targets and schemes; more specifically by highlighting the need to implement spatially variable monitoring programs to cater to each estuary's unique dynamics. By discussing the complexities of river flow manipulation in restoration efforts, my work resonates both nationally and internationally, fostering a more profound comprehension of successful strategies and a more resilient future for estuarine ecosystems worldwide.

## 1.4 Thesis Structure

The subsequent Chapter 2 reviews the literature and previous studies on Maketū Estuary and Kaituna River. This is followed by chapters aligning with the main research questions of this thesis in Chapters 3, 4 and 5, respectively. Chapter 6 presents a summary of findings and general conclusions, including future recommendations. For clarification, Figure 1.7 presents the main themes used in this thesis and Table 1.1 defines the main terms used throughout this thesis.

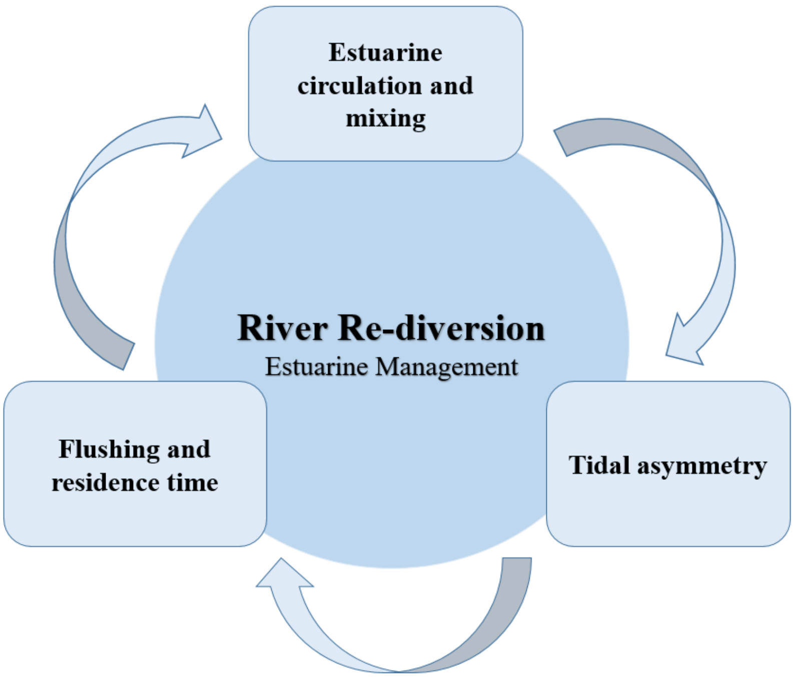

*Figure 1.7 Conceptual diagram connecting the physical parameters explored in the main research articles and their importance in estuarine management*

*Table 1.1 Terms and definitions*

| Term | Definition |
|---|---|
| Flushing time | The time required to replace an initial mass of water contained in an estuary with freshwater and oceanic inflows |
| Residence time | The average time a water parcel or introduced substance remains within a system or area of interest |
| River re-diversion | The intentional redirection of a river's flow to restore or alter its course, typically for ecological or engineering purposes |
| Tidal asymmetry | The unequal characteristics in the value and length of tidal currents or water levels during the rising and falling tides |

The chapters relating to the main research questions are intended to be submitted for publication in journals, so background literature content may be repeated.

Chapter 3 consists of a research article entitled "*Impacts of restored river inflow on tides and salinity in a shallow estuary*" (Razzaghi et al., in prep). It is intended for submission to the "Journal of Physical Oceanography". This chapter aims to answer the following questions: **"How much do water level, depth-averaged current speed and bottom salinity change shortly (in the span of two weeks) after Stage 1 of Kaituna Re-diversion**" and "**How does the added freshwater flow impact the estuarine mixing and tidal asymmetry**". The objectives of this chapter focused on the Stage 1 re-diversion are to (1) determine changes to estuarine water levels and currents, (2) assess whether tidal asymmetry was amplified and whether there were changes to tidal flushing and circulation, and (3) assess how much estuarine circulation and stratification has changed using the estuary Richardson number. This was achieved through comprehensive field data collection and analysis.

The second research article (Chapter 4) is entitled "*Evaluating the immediate and annual impact of partial freshwater restoration on estuarine hydrodynamics and salinity characteristics*" (Razzaghi et al., in prep). This chapter addresses the following questions: "**What is the impact of Stage 2 on water level, depth-averaged current speed and bottom salinity**" "**How do estuarine mixing and tidal asymmetry change**" and "**How Stage 2 changes compare to Stage 1**". The three objectives are directed at assessing the estuarine hydrodynamic response to the added freshwater flow during both Stage 1 and Stage 2, specifically: (1) how much water levels and current velocities changed; (2) whether tidal asymmetry changed and how it influenced the salinity regime; and (3) whether the estuarine circulation and classification changed based on estuary Richardson number. This was achieved through a second round of field data collection and analysis.

The third research article (Chapter 5) is entitled "*Impacts of partial freshwater restoration on residence time in a shallow estuary: the Maketū Estuary*" (Razzaghi et al., in prep). This addresses the questions: "**How**

**much residence time and tidal asymmetry were influenced by Stage 1 re-diversion**" and "**How constant river flow and a pulsed flood flow would impact residence time and tidal asymmetry.**" This chapter aims to investigate the spatial impact of freshwater restoration on residence time, tidal asymmetry and estuarine circulation by comparing three scenarios: (1) Stage 1 of the restoration project, (2) regular freshwater inflow without the control gates and (3) pulsed flood flow for two weeks followed by 2 weeks of zero freshwater discharge.

# 2 CHAPTER 2 LITERATURE REVIEW

## 2.1 Introduction

Estuaries are ecosystems located at the land-sea interface, with strong physical influence, characterized by wide fluctuations in environmental conditions (Falcão et al., 2012). Estuaries are complex landforms, which has resulted in many different definitions and classifications based on characteristics such as geomorphology, sedimentology, hydrodynamics, stratification and salinity, and ecosystems (Healy, 2005). There are approximately 300 estuarine systems in New Zealand, which have a diverse range of characteristics (Hume, 2003). An early classification of these estuaries was based on the residence time (Heath, 1976), but a geomorphic scheme was more commonly used (Healy, 2005).

Due to the need to manage estuaries, which became a legislative requirement under the Coastal Policy Statement created by the Resource Management Act (1991), a geomorphic classification approach that facilitated management was proposed by Hume and Herdendorf (1988). Over time this classification evolved to include other aspects of estuarine characteristics based on schemes developed in South Africa and Australia (Boyd et al., 1992; Dalrymple et al., 1992; Hume et al., 2007), and this became the main approach applied to New Zealand estuaries. Hume et al. (2007) developed 4 different levels of classifications and at Level 1 discussed the main hydrodynamic dominant forces that distinguish between different types of estuaries. These dominant hydrodynamic processes are forced by the interaction of tides and ocean swell with freshwater inflow within the estuary basin, and wind acting on the surface of the estuary basin. Based on this classification the Maketū Estuary changed from C to E after the diversion of the Kaituna River through Te Tumu (Figure 1.1). The diversion led to a reduction in the fluvial dominance while increasing the tidal dominance throughout the estuary; stratification became minimal while wind wave resuspension took over, especially in shallower areas. Later with the added freshwater flow after the re-diversion, these dominant forces were impacted, for example stratification was observed by Domijan (2000) but these changes did not lead to a change in classification.

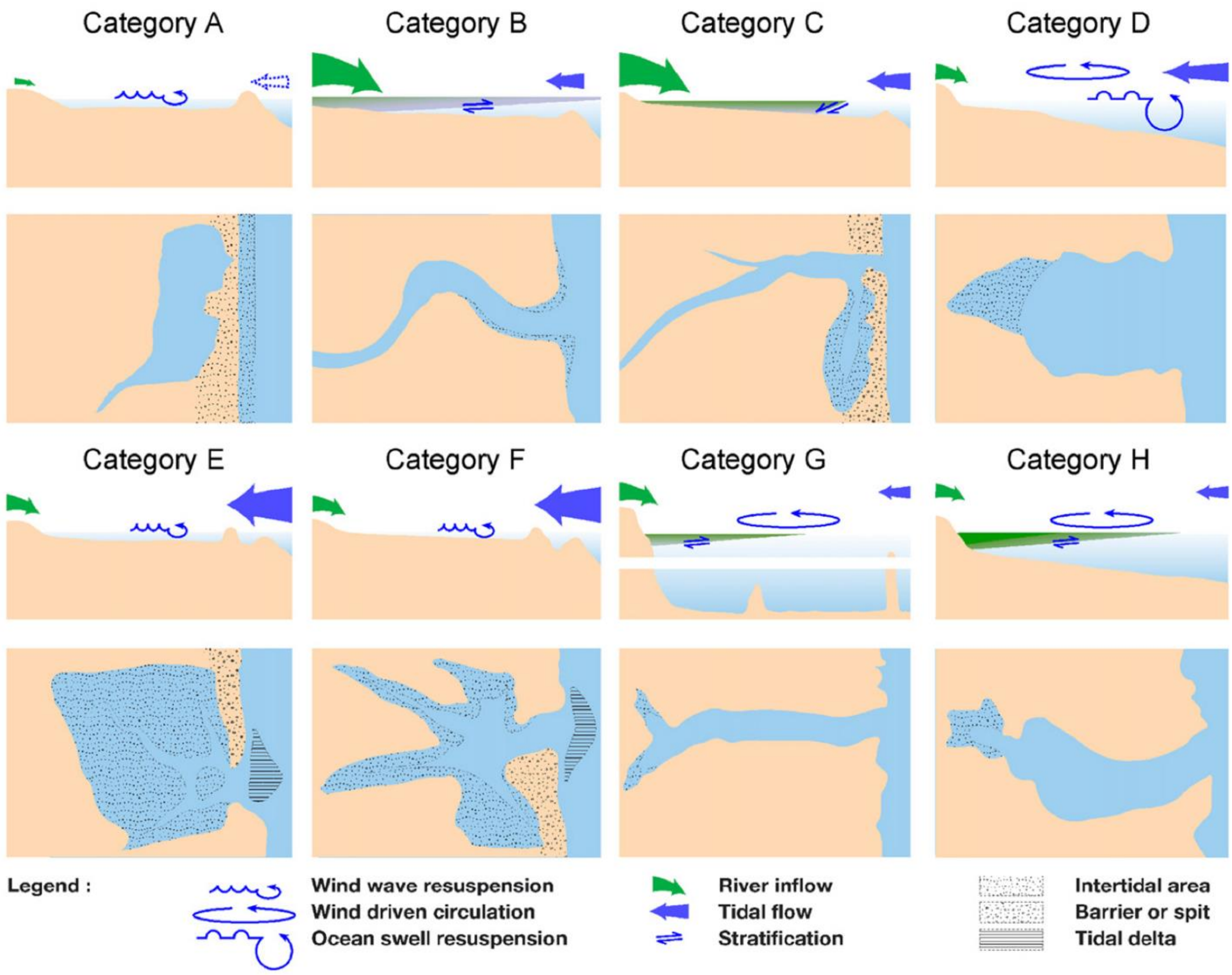


*Figure 2.1 Subdivision of estuaries at Level 1 based on Hume et al. (2007) classification scheme;(A) coastal lakes, (B) tidal river mouths, (C) tidal river mouths, (D) coastal embayments, (E) tidal lagoons or barrier-enclosed lagoons, (F) barrier-enclosed lagoons or drowned valleys, (G) fjords or sounds and (H) sounds, drowned valleys, rias or fjords*

Estuaries are generally highly stressed ecosystems due to a wide range of environmental conditions that may exist within them (Kennish, 2005). These conditions vary spatially and temporally in response to physical factors such as tidal characteristics, variations in fluvial discharge, variable bathymetry, and the effect of weather events, such as storms. Anthropogenic activities can result in additional stresses that may be detrimental to all or some of the ecosystems in the estuary. This makes estuaries among the most heavily impacted by humans on earth (Kennish, 2005).

## 2.2 The value of estuaries and their degradation

Globally, coastal ecosystems and their services have been degraded and even lost in some places, mainly due to human-induced disturbances such as land-use change, alteration of food webs, and climate-related stressors (Green, 2006). The mixing of river water and seawater in estuaries sustains biodiversity and provides essential nursery grounds for diverse marine species; therefore it is vital to maintain river-sea connectivity for restoring ecosystem services (Zamora et al., 2013). For decades, habitat destruction and hydrological alteration, related to the diversion of freshwater flow, diking and the canalization of stream and rivers, as well as the need for assessing their environmental effects have been highlighted in coastal ecosystems (Claudet & Fraschetti, 2010; Crain et al., 2009; Falcão et al., 2012). Physical, chemical, and biological processes within the estuary determine the health of an estuarine ecosystem and estuarine water quality is one fundamental aspect underpinning a healthy ecosystem (Rapport, 1998).

Due to the complexity of estuarine systems, care is required to ensure that the essential parameters are monitored and assessed to determine the environmental state of an estuary Elliot et al. (2007) undertook a review of international restoration projects for estuarine, coastal and marine ecosystems focussing on developing a conceptual framework for restoration and recovery after recognising that there was a confusing mix of terminology and approaches used. They suggested that there were four types of restoration and/or recovery:

- natural recovery from a natural or anthropogenic change (whether adverse or otherwise);
- anthropogenic interventions in response to a degraded or anthropogenically changed environment;
- anthropogenic responses to a single stressor; and
- habitat enhancement or creation

Hallett, Valesini, et al. (2016a), Hallett, Valesini, Scanes, et al. (2016) and Hallett, Valesini, et al. (2016b) undertook a comprehensive review of international and Australian federal and state approaches for monitoring, assessing and reporting estuarine conditions. They identified key features to assess estuarine changes and created a conceptual framework for Dynamic Adaptive Management. They highlighted how an appropriate reference condition and scoring threshold are necessary for evaluating the success of the restoration and monitoring scheme. In our study, no comprehensive data predating the original river diversion exists to be compared to our observed data. Having said that, some of the previous studies and modelling assessments (Tuckey, 2009) used changes to water quality (assuming ecological change as a consequence) as an indicator of the impact of river re-diversion and the added freshwater flow.

## 2.3 Estuarine water quality

In addition to external factors such as the quality of water (e.g. salinity, turbidity, oxygen levels and etc.) entering an estuary through rivers and streams, estuarine water quality strongly depends on the rate at which water is flushed in and out of the estuary relative to the rate of internal biogeochemical processing (Gomez et al., 2012). This flushing rate is commonly parameterised as Residence Time (RT), which is the average time a water parcel spends in the estuary or other water body. This concept is essential to establish the health of a water body when subjected to human-induced stresses, as in general, the longer the residence time, the poorer the water quality (Kenov et al., 2012). Another important consideration for estuarine water quality is the presence and movement of saltwater intrusion and the turbidity maximum. Salinity intrusion is a natural phenomenon occurring in estuaries, and is linked to water level variations such as with the tidal cycle (Dyer, 1973). However, there are many additional factors affecting salinity intrusion, including river flows, topography, morphology, river bed slope, wind velocity and direction, and water temperature (Tran Anh et al., 2018). Estuarine restoration schemes generally aim to address one or more of these water quality issues, such as salt/freshwater balance, or estuarine flushing and residence time.

## 2.4 Estuarine restoration

There is an increasing need to remedy long-standing adverse effects of human activities on estuarine, coastal and marine ecosystems (Elliot et al., 2007), such as via efforts to restore estuarine ecosystems by altering tidal and riverine flows. However, two major gaps impacting estuarine restoration efforts are (1), accurately predicting how estuaries will respond to engineering interventions, including the hydrodynamics and resulting sediment transport, and (2) determining if a scheme has been "successful" (Elliot et al., 2007). Moreover, it is also uncertain how relative sea level changes may affect the longevity of these restorations since the interaction between the morphological development and human activities complicates the prediction of future geomorphological states (Wang et al., 2018).

When an estuary has been degraded, its complete restoration cannot be successful in the long term without addressing the issues that led to its degradation. According to Wolanski and Richmond (2008), if there are several such issues, they must all be addressed, although possibly at a different intensity, because impacts are cumulative. For example, if there are a few ongoing restoration projects, the potential effects of each one of them on the nearby project must not be neglected (Yang, Khangaonkar, et al., 2010). Wolanski and Richmond (2008) also recommend that restoration efforts must focus on the whole ecosystem, principally (1) managing human activities in the whole river catchment and (2) restoring habitats to arrive at an estuarine ecosystem that can absorb human stresses. They also recommended that river flows must be maintained to manage human activities, and the timing of river floods should be controlled. Also, for an estuarine ecosystem to function naturally, fluvial sediment export to the estuary, alongside fluvial pollutants and nutrients, should be limited Wolanski and Richmond (2008).

There is a range of different actions that can be taken towards estuarine restoration (Elliot et al, 2007; NIWA 2017; Liang et al, 2019; Kuang et al, 2020), including:

1. **Managed realignment,** which focuses on removing or relocating coastal protection further inland, and allowing flooding of previously reclaimed land;
2. **Dock restoration**, which involves creating an artificial lagoon to modify the mixing regime and improve water quality and the mixing regime;
3. **Saltmarsh restoration**, by restoring natural morphology, changing drainage patterns, and improving vegetation structure and functioning;
4. **Seagrass restoration,** by improving water quality to reduce stressors inhibiting seagrass growth;
5. **Dredging**, which focusses on modifying hydrodynamics and sediment transport by deepening channels or removing tidal flats for example;
6. **River diversion**, which may affect water quality, hydrodynamics, and sediment transport; and
7. **Combined restoration efforts,** which involve combinations of approaches.

One example of removing tidal flats is the upper estuary in Shuanglong Estuary restoration, Bohai Bay, China, in two phases. Liang et al. (2019) found that this removal in the first phase of restoration induced a switch from flood to ebb asymmetry in unrestored areas, but enhanced flood asymmetry in the restored area, which led to net sediment transport landward in the upper estuary and seaward in the inlet during the first-phase restoration. In contrast, landward net sediment transport occurs for in the whole estuary under their second-phase restoration scenario. An example of type **7** (combined restoration efforts) is documented by Kuang et al. (2020) in which they investigated the spatial distribution of current velocity and tidally-averaged suspended sediment concentration under the restoration scheme in the Fenghe River Estuary, which included the construction of a sluice gate, river channel dredging and shoreline reshaping.

An example of type **6** is The Kaituna River and Ōngātoro/ Maketū Estuary Strategy (Environment Bay of Plenty., 2009) which identified 4 key outcomes from managing and restoring the Kaituna River and Maketū Estuary:

1. Improving water quality, which mostly related to reducing or eliminating sediment and contaminant runoff into the Kaituna River. There were concerns than any material induced into the river could be transported into Maketū Estuary by diverted freshwater;
2. Restoring healthy ecosystem, which involved re-diversion of some river flow into the estuary, and creation of wetlands in the lower Kaituna Catchment;
3. Ensuring sustainable resource use, which mostly involved creating parks and reserves, developing management protocols, and identifying and protecting culturally significant locations; and Supporting Kaitiakitanga and local people's stewardship, which involved including tangata whenua and local people in managing, restoring and enhancing the mauri of the Kaituna River and Ōngātoro/Maketū Estuary.

Considering the historic and cultural significance of Maketū Estuary and Kaituna River combined with previous restoration attempt by river flow manipulation, the estuary is a prime case to study and evaluate the impact of river re-diversion. As river re-diversion is the focus of this thesis, it is discussed in more detail in the next section.

## 2.5 River diversion

Freshwater discharge is a primary factor controlling estuarine salinity (Mofjeld, 1973). Estuaries have often degraded due to reduced river inflows, such as the Barataria Estuary, USA (Das et al., 2012) and the Maketū Estuary in New Zealand (Goodhue, 2007), where rivers were moved. Similarly, the Deschutes Estuary in Washington State, USA (George et al., 2012) was dammed to create a freshwater reflecting pool which usually is a shallow pool of water, undisturbed by fountain jets, for a reflective surface This can lead to adverse salinity regimes, such as the case of Charleston Harbour, South Carolina, USA (Kjerfve & Magill, 1990) and loss of habitat.

River diversion or controlled freshwater flow is one of the many strategies used to revive an estuary's ecosystem by improving its water quality, sedimentation and wetland restoration and adaptation to climate change. River diversion is becoming popular; for example in the Barataria Estuary, USA, the Davis Pond Diversion was the world's largest river diversion project implemented in 2002. This project provided an opportunity to examine salinity variations under different diversion discharge scenarios. A model by Das et al. (2012) for five different discharge values predicted that the difference in salinity changes between different model scenarios can be as high as ten units in some months. Discharge scenarios were selected based on actual freshwater discharges in different years and management alternatives, including a scenario with several new diversions. They indicated that river diversions strongly affected salinities only in the middle section of the Barataria estuary. The upper parts of the estuary are primarily fresh, so the excess freshwater from river diversions has only a minor impact on salinity in this region (Das et al., 2012).

Similarly, Charleston Harbour, South Carolina, USA, has undergone pronounced changes in salinity regimes. Here the riverine input to the estuary was increased by the partial (70%) re-diversion of the Cooper River into the Santee River (which enters the estuary) in 1985. The re-diversion was an attempt to decrease the salinity levels achieved and became less variable under the controlled low-flow conditions.

Another example of restoration efforts with the added freshwater flow is the Breton Sound Estuary, USA. Huang et al. (2011) assessed the Breton Sound estuary restoration with pulsed Mississippi River inputs from the Caernarvon River diversion. The three scenarios considered were: a pulsed scenario of 200 $m^3/s$ corresponding to the actual re-diversion discharge in March 2001, a constant discharge scenario of 40 $m^3/s$ corresponding to the annually averaged discharge of 2001, and a scenario with no discharge. Their results showed enhanced water exchange between wetlands and adjacent water bodies in the second scenario. Also, a noticeable increase in down-estuary residual current with a significant reduction of local estuarine residence times for the whole estuary was observed (Huang et al., 2011).

The Yellow River Estuary, China, is one of the cases in which river diversion was implemented to adapt to climate change; specifically, negative water budget due to increased temperatures, reduced runoff from highlands, decreased rainfall in summer and increased snowfall in winter. In this restoration program, five water diversion projects have been carried out since 2008 and have replenished a total volume of 100,966,700 $m^3$ of water from the Yellow River, which led to restored estuarine wetlands (Yu, 2015).

While interest in, and implementation of estuarine restoration by river re-diversion has increased over the last couple of decades, the long-term impacts of re-diversion and its sustainability are poorly studied, mainly due to the fact that estuaries often have multiple stakeholders with different expectations and issues such as flooding complicate the design of these schemes (Elliott et al., 2016; Hallett, Valesini, et al., 2016a, 2016b; Hallett, Valesini, Scanes, et al., 2016). Moreover, the ecological and hydrodynamic response of estuaries to added freshwater flow are not the same which highlights the need for further research on a variety of case studies. Adding to that, the lack of historic data (from when the estuary was believed to be healthy) makes the restoration schemes more complicated and requires more frequent monitoring to create space for adaptation of the restoration effort according to the observed changes (Verdonschot et al., 2013).

## 2.6 The Maketū Estuary and Kaituna River previous studies

Previous studies on the impact of the Kaituna River diversion on The Maketū Estuary started with Kennedy (1959) and include Murray (1978), Burton and Healy (1985), Domijan (2000), Goodhue (2007), Mawer (2012) and various consultants involved in the design and consenting the re-diversion. The focus of these studies varies from hydrodynamic and geomorphic responses to changes in water quality and inlet stability, some investigating existing re-diversions, and others exploring proposed options.

It was recognised by Andrew Murray's engineering report in 1951 that river diversion would lead to deterioration of the estuary and drainage problems for the surrounding landowners (Murray, 1951). Despite this knowledge and based on priorities at the time, the diversion was still approved. Some of the adverse impacts of the 1956 river diversion were observed shortly after diversion occurred (Kennedy, 1959), but most studies were undertaken at least 20 years after the diversion. This potentially resulted in adverse impacts attributed to the diversion being a consequence of other changes occurring after diversion, such as reclamation and the construction of causeways across arms of the estuary.

Murray (1978) highlighted the impact of removing Kaituna River from the estuary including channels being infilled with sediments even though "… when the Kaituna flowed through the spit considerable volumes of freshwater still entered the lower Maketū Estuary." He reported that the diversion resulted in the change of sediments from sands to muds, with algae being very common in some of the lower channels. Later studies such as KRTA (1986) found that without high flood discharges from the Kaituna River, current velocities within most of the Maketū Estuary were too low to entrain sediment suggesting that only suspended silts and clays transported into the Estuary could be deposited. However, the suspended sediment yield of the Kaituna River is very low (Hicks et al., 2011; Park, 2007), and after diversion the sediment could not enter the estuary. This suggests that the changes reported by Murray (1978) were not due to diversion.

The Murray (1978) study also discussed the potential impact of Rotorua Sewage discharge into the Kaituna River influencing the water quality in Lower Kaituna and Maketū Estuary. This was one of the main arguments against bringing the river back into the estuary with the concern of further damage to the estuarine ecosystem; specifically, Bay of Plenty Catchment Commission (BOPCC) was reluctant to re-divert the river back to the estuary; this was also confirmed by Loomis (1984).

Tortell (1984) mentioned how back in 1983 it was believed that since the Kaituna River flow regime had changed due to changes at the outlet from Lake Rotoiti, it was not possible to re-establish the same relationship that used to exist between the Kaituna River and Maketū Estuary. This led Tortell (1984) to suggest returning the flow gradually and in stages. He also noted that the estuary was deprived of flood events which are part of the natural cycle in estuarine environments. As part of the same investigation, Loomis (1984) conducted a social study on the Kaituna diversion and impact on the local people of Maketū. This raised concerns about impacts on navigation through the tidal inlet, and the loss of traditional kaimoana.

In 1983, the Maketū Estuary tidal inlet closed, which created issues for the estuary. Despite the lack of a thorough sedimentation study, the common perception was that siltation was a huge problem after the diversion of the Kaituna River as discussed by Murray (1978). Siltation was also believed to be the cause of a reduction in fish stocks. The hydraulic stability of the tidal inlet in Maketū Estuary after the 1956 river diversion was assessed by Burton and Healy (1985) to evaluate the management options to preserve the tidal inlet as a navigable waterway. Burton and Healy (1985) showed that the Maketū inlet is sheltered by Maketū headland and concluded that the closure of the tidal inlet was unlikely to be due to the estuary reaching equilibrium.

Instead she suggested that there was an influx of marine sediment due to the loss of the freshwater component of the tidal prism, resulting in the formation of a flood tidal at the tidal inlet. No evidence of siltation further into the estuary was presented. Burton and Healy (1985) suggested dredging the estuary channels, in case of re-diversion, generating additional inflow from the river in order to avoid flooding during a spring tide since it would elevate water levels in the lower estuary and impact low-lying areas of Maketū township adjacent to the estuary.

The Bay of Plenty Catchment Commission established a steering committee in 1985 to oversee a study of the Maketū Estuary to assess the effects of the river diversion and any potential impact of re-diversion. The first phase of this study was undertaken by KRTA Ltd (KRTA, 1986). This study determined that the diversion of the Kaituna River was only one factor contributing to the decline of the estuary reported by the local community (Loomis, 1984). They also attributed the decline to drainage of the surrounding Kaituna swamp land affecting nutrient availability and loss of habitat for spawning fish; reclamation by dikes (stopbanks) and drainage of the saltmarsh within the estuary; land clearance within the Kaituna River Catchment increasing suspended sediment loads; spit breaching causing an influx of sediment (overwash); reclamation and re-nourishment along the shoreline of Maketū township; and potentially overfishing within the estuary.

KRTA (1986) also reported that there was no clear evidence of siltation within the estuary, apart from the flood tidal delta that rapidly formed after the river diversion, and suggested that there had instead been some erosion in the middle and upper estuary. They concluded that the estuary was not in danger of completely infilling, as suggested by Tortell (1984), and also indicated that re-diversion would not result in the removal of sediment from the estuary under normal flow conditions. Their modelling also indicated that a full re-diversion would create a flood hazard as the channels were too small to accommodate flood discharges. However, flood discharges could produce morphological changes resulting in sediment removal and the establishment of deeper channels.

Given the concerns raised by various studies and other concerns involving the unknowns not investigated, the authorities gravitated to the idea of gradually returning the river flow back into the estuary, allowing time to clean up the river and make the necessary improvements.

After the approval of re-diverting up to 150,000 $m^3$ of controlled freshwater per tidal cycle in 1996, Domijan (2000) investigated the hydrodynamics and sedimentation of the Maketū Estuary. His research showed a generation of a significant residual current regime after the partial re-diversion as well as a different vertical velocity structure over the whole water column, indicating a change in flow structure due to the presence of a stratification. He highlighted that the major influences on the salinity stratification were river inflow (-33%) and wind stress (-21%) associated with the prevailing south-westerly wind blowing across the estuary, explaining a large variability in salinity over the course of the tidal cycle at the surface and bottom (24-30). Overall, he concluded that "vertical density gradients caused by the newly-formed salinity-temperature regime had a stabilising effect on the vertical mixing processes within the water column due to the re-diverted river". They also found that, after the 1996 re-diversion, the residence time was approximately a half-tidal cycle shorter.

However, long-term improvement within the estuary were not been achieved and the need for further action in restoring the Maketū Estuary was identified by studies such as Goodhue (2007). Using the nutrients, phytoplankton and hydrodynamics of the Maketū estuary as indicators of the overall estuarine condition, he developed and calibrated a Delft3D model with observational data of the Maketū estuary and lower Kaituna River. His model simulations (focusing on extra freshwater flow) predicted the maximum residence time in the Maketū Estuary occurring in the inner western region to be 1.5 days. He also predicted that the extra freshwater would produce an increase in net flow towards the estuary mouth and a reduction in salinity. However, it was considered that the extra inflow being entirely freshwater was probably not achievable due to the proximity of control gates to the river mouth (a proportion of water drawn through the structure could be seawater; and the 2020/2021 re-diversion includes a salinity block to avoid this issue).

Subsequently in order to make an informed decision regarding the 2020/2021 re-diversion, Environment Bay of Plenty (2009) commissioned DHI NZ, Water and Environment to create a hydrodynamic and advection/dispersion model of the lower Kaituna River and Maketū Estuary for impact assessment. With good calibration, their model highlighted the areas vulnerable to floods (area between Ford's Cut and Te Tumu)(Tuckey, 2009).

Mawer (2012) investigated the geomorphic response at Te Tumu Cut to re-diversion due to community concerns about the loss of all-weather access to the sea for small vessels. He considered proposed options of lowering the Ford's Cut Culverts to RL-1.6 m or reopening the Papahikahawai Channel, by developing a coupled 2-dimensional wave, hydrodynamic and sediment transport model. He found that by partially restoring the river flow into Maketū Estuary, Te Tumu Cut can remain unblocked. However, a consequence of the partial re-diversions modelled was the alteration of the discharge and flood currents through Te Tumu Cut, thus influencing the sedimentation patterns and potentially the Cut navigability. The re-opening of the Papahikahawai Channel (the original channel of the Kaituna River before Ford's Cut) had the largest effect on sediment transport and morphology at Te Tumu, and also resulted in a large increase in the volume of sea-water entering the upper estuary.

Thus, while there have been multiple studies on the impact of Kaituna re-diversion so far and many advances in estuary restoration with freshwater, there are still major gaps in combining the existing knowledge for management purposes. First, the amount of added freshwater flow had not exceeded 150,000 $m^3$ per tidal cycle since 1996, and the upper-estuary bathymetry had not changed in response to diversion and re-diversion to the extent expected for 2020/2021 re-diversion. Second, predictions of the response of the estuary to the added freshwater flow remained limited to the previously proposed options. These options changed over time, partly due to changing priorities expressed by the local community and also due to concerns about potential adverse effects due to re-diversion.

The eventual consented re-diversion involved a staged process, which was intended to allow the identification of adverse impacts before they became severe and/or irreversible. In this study, we have explored the observational data before and after each stage of the 2020/2021 re-diversion, comparing them to the predictions and expectations of previous studies (while assessing the key factors determining the success of the restoration). This will allow assessment of the staged approach for re-diversion as a tool for estuarine restoration management.

# 3 CHAPTER 3

## Impacts of restored river inflow on tides and salinity in a shallow estuary

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## 3.1 Abstract

Estuarine restoration by manipulating river flows is common practice globally, however the immediate impacts of it may vary depending on the estuary's classification and history of anthropic alterations. The variability of the river flow (discharge rate and duration) also remains a crucial factor in the success of the restoration. Te Awa o Ngātoroirangi (the Maketū Estuary) in the Bay of Plenty of Aotearoa, New Zealand, has had multiple major shifts in the salinity regime, with a long history of engineering works on river inflows. Anthropic changes include coastal wetland drainage in the 1900s, followed by the diversion of the Kaituna River out of the estuary in 1956 to prevent flooding, which caused the degradation of the estuary. However, in 2020 and 2021, ~20% of the river flow was restored into the estuary in two stages through 12 control gates, with a key driver being to improve the ecological condition. This study focused on the immediate effects of the Stage 1 re-diversion consisting of the return of 13% of Kaituna River's average flow into the estuary, where 9 of 12 control gates became operational on the estuarine salinity regime and tidal circulation. Immediately before the Stage 1 re-diversion, estuarine bottom salinity and tidal range varied strongly spatially. Despite the lack of vegetation, there was also a high degree of tidal attenuation (~0.2 m) up the estuary. After the Stage 1 re-diversion, the average salinity decreased in the lower and mid estuary. However, in the upper estuary, the opposite occurred at some sites. The estuary was generally ebb-dominant before Stage 1 and shifted to greater ebb-dominance afterwards. Some of the expectations of the restoration attempt, such as higher flow rate and lower salinity, were met at a few sites, such as mid estuary monitored, but not all. Our study highlights that when it comes to designing and managing freshwater restoration, it is essential to consider tidal asymmetry as well as asymmetry in mixing with the added flow.

**Keywords**: salinity regime, tidal asymmetry, estuarine restoration, river discharge, estuarine circulation

## 3.2 Introduction

Te Awa o Ngātoroirangi (the Maketū Estuary) in the Bay of Plenty, Aotearoa, New Zealand, has been adversely impacted by a century of engineering works to manage flood discharge within the lower Kaituna

River. One of the main drivers of the impacts has been the diversion of freshwater inputs from the estuary to discharge directly to the ocean via Te Tumu Cut, resulting in a significant shift in the salinity, tidal and flushing regimes. It is well known that reduced freshwater inflows into estuaries can lead to adverse salinity regimes for some species (Kjerfve & Magill, 1990) and habitat loss (Elliott et al., 2007).

A solution to estuary degradation caused by anthropic loss of freshwater is to restore river inflows, undertaken previously for Te Awa o Ngātoroirangi, resulting in further shifts in the estuary's salinity regime. Between the 1950s and 2010s, less than ~150,000 $m^3$ per tidal cycle or 4% of the annual average discharge from the Kaituna River, entered the estuary via 4 gates. In 2020, the Stage 1 re-diversion scheme allowed ~400,000 $m^3$ (13% of river flow) per tidal cycle to enter the estuary for 4 hours during the ebb tide. In 2021, the Stage 2 re-diversion increased inflow to ~600,000 $m^3$ (20% of the river flow).

Typically, the goals of the estuarine restoration range include: reducing the salinity (e.g., to preclude hypersalinity); manipulating the flushing times and residual currents; modifying estuarine morphology; or changing inundation regimes. For example, in the Barataria Estuary, Louisiana, USA, partial freshwater restoration aimed to reduce high salinities due to saltwater intrusion and reduce tidal inundation (Das et al., 2012). Similarly, in Charleston Harbour, South Carolina, USA, river inflows were partially (70%) restored to decrease estuarine salinity (Kjerfve & Magill, 1990). In the Breton Sound estuary, USA, pulsed freshwater inflows replicating episodic flood events from the Mississippi River were restored into the estuary from the Caernarvon River diversion, increasing the down-estuary residual current, with a significant reduction of residence times (Huang et al., 2011). Wang et al. (2017) also modelled the impacts of river channel diversions and relative seal level rise on wetland restoration within the tidal delta of the Mississippi River. They found that large diversions significantly affect the water quality variables across the entire estuary compared to small ones. In Lake St Lucia in South Africa, restoring freshwater from the uMfolozi River resulted in greater stability in water levels and decreased salinity (Forbes et al., 2020). Overall, while freshwater restoration to a wide variety of estuary types is frequently being undertaken globally, sometimes on large scales with significant engineering works, the relationship between changing freshwater inflow and the estuarine hydrodynamic response is still not easily predictable, which can cause unrealised expectations.

When it comes to added freshwater riverine input, the expectation is that estuaries become more strongly stratified, driving any salt intrusion seaward (Geyer & MacCready, 2014) and generally decreasing seawater contributions to the estuary (Domijan, 2000). Over the past few decades, tidal asymmetry has been identified as a major or even the main contributor to net estuarine circulation. To better understand estuarine circulation, it is helpful to consider the estuary Richardson number, $Ri_E$ (Nash et al., 2009), which is based only on the river flow and tidal strength and describes the balance between horizontal advection and vertical mixing. Notably, the horizontal Richardson number does not distinguish between flood and ebb tides (Stacey et al., 2001), and based on its range, estuaries can be classified as well-mixed, partially-mixed or salt-wedge. Stacey et al. (2001) also explain that a critical value exists for the estuarine Richardson number, above which we would expect asymmetry to develop in the level of mixing. Furthermore, MacCready and Geyer (2010) mention that the critical value for the estuary Richardson number is dependent on estuarine geometry, and since it may vary, more estimates of $Ri_E$ in different environments are needed to better specify the threshold value.

Significant information gaps impacting estuarine restoration efforts include accurately predicting how estuaries respond to engineering interventions, including the hydrodynamics and resulting sediment transport, and a robust methodology is lacking for determining if a scheme has been "successful". According to Elliott et al. (2007), a key challenge in estuarine restoration is determining if the restoration has been successful in ecological and/or societal terms. They emphasise maintaining suitable physical conditions and creating a habitat that will allow biological recovery to follow. While that is the ultimate aim, there is often an inadequate understanding of the physical consequences of restoring freshwater inflow. The physical parameters determining the restoration's success are water level, salinity distribution, estuarine circulation (Yang, Sobocinski, et al., 2010) and tidal asymmetry.

This study aims to quantify the immediate (about 2 weeks) hydrodynamic impact of partial freshwater restoration in a small, shallow, microtidal estuarine lagoon (Te Awa o Ngātoroirangi), focusing on water level, current speed and salinity. With the unique opportunity to study these parameters before, during and after major river flow alterations, the specific objectives following the Stage 1 re-diversion are to (1) determine changes to estuarine water levels and currents; (2) assess whether tidal asymmetry was amplified and whether there were changes to tidal flushing and circulation; and (3) assess how much estuarine circulation and stratification has changed using the estuary Richardson number.

## 3.3 Study area

### 3.3.1 Environmental setting

Te Awa o Ngātoroirangi (The Maketū Estuary) is a small (2.3 $km^2$), shallow (mean depth < 1 m below mean sea level (MSL)) microtidal barrier-enclosed estuarine lagoon (Burton & Healy, 1985) at the mouth of the Kaituna River, in the Bay of Plenty of Aotearoa New Zealand (Figure 3.1). The estuary experienced a change in estuarine classification from the *tidal river mouth (dominated by river and tidal flow)* to *tidal lagoon (dominated by restricted tidal flows)* due to anthropic impacts (Hume t al., 2017). The Kaituna River is the main source of freshwater inflow to the estuary. Tides are semi-diurnal and mixed, with spring and neap tidal ranges of 1.73 m and 1.16 m, respectively, with a maximum astronomical tidal range of 2.19 m (McKenzie, 2014). Three tidal gaugings before 1985, showed a reduction in both flood and ebb tidal range between the tidal inlet and the estuary side of Ford's Cut (Figure 3.1), highlighting the impact of river diversion on decreasing the tidal amplitude up the estuary from the tidal inlet and creating a time lag of 1 hour between high water at the tidal inlet and Ford's Cut (Burton & Healy, 1985).

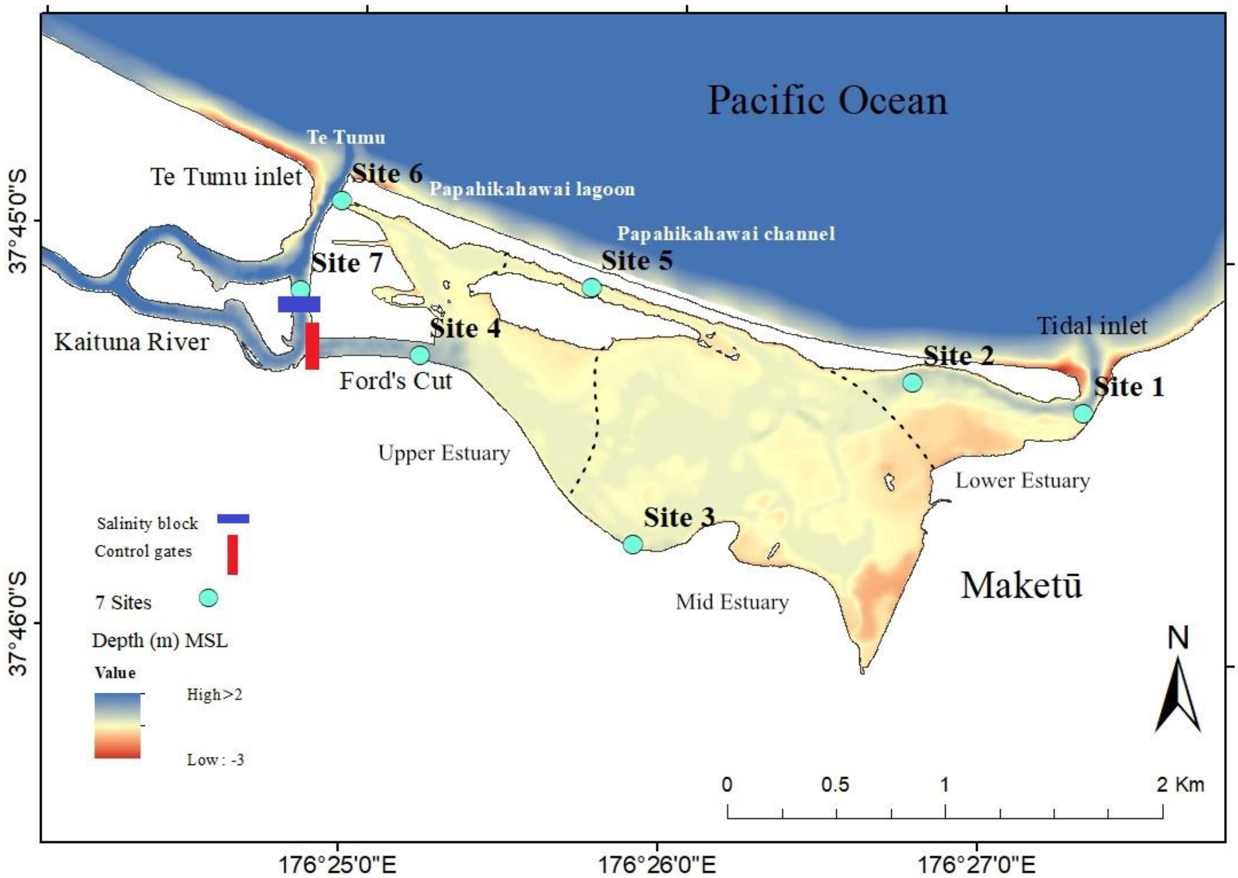



*Figure 3.1 Bathymetry of Te Awa o Ngātoroirangi developed from combined RTK GPS data, a single beam echosounder survey on February 2020, LiDAR data from December 2018–April 2019 provided by BOPRC, as well as offshore data (last updated July 2020) from Land Information New Zealand (LINZ)*

The estuary can be subdivided into three main regions based on morphology and hydrodynamics (Figure 3.1): the upper estuary with a relatively deep fluvial channel bordered by tidal wetlands, most of which have been reclaimed); a central shallow deltaic zone with bifurcating shallow mobile channels (Goodhue, 2007); the lower estuary with the relatively deep tidal lower Papahikahawai Channel (Environment Bay of Plenty, 2009), and a flood/ebb tide system at the tidal inlet.

### 3.3.2 Summary of the history of engineering changes to estuarine freshwater

Te Awa o Ngātoroirangi (The Maketū Estuary) has undergone multiple anthropic shifts associated with drainage and reclamation of the tidal coastal wetlands (Stokes, 1980), building of an artificial channel (Ford's Cut, Figure 3.1), followed by the diversion of the Kaituna River to the sea in 1956-57 to prevent flooding. Before Te Tumu diversion in 1957, the Kaituna River generally flowed out to sea through Te Tumu but at times the river breached naturally through the spit between the estuary and the sea at Te Tumu (Figure 3.1) (Park, 2014). as occurred in 1907, before generally migrating eastward in the direction of littoral drift, maintaining the Papahikawawai Channel as the main tidal channel (Healy & de Lange, 2014).

Since diversion through Te Tumu Cut, the estuary and lower Kaituna River have had a complicated history of anthropic changes. In 1956–7, a new channel was artificially opened to divert the river directly into the sea at Te Tumu (Figure 3.1) in the west, and the river connection estuary through the Papahikahawai Channel and

Ford's Cut was closed off to prevent flooding of low-lying farmland (reclaimed tidal wetlands) surrounding the estuary.

Removing the dominant freshwater source into the estuary substantially reduced the flushing ability of river-enhanced ebb tide currents, and there was accretion on the sandy intertidal flats and the development of a substantial flood and larger ebb-tidal delta developed at the original inlet (Hume et al., 2017). The loss of salt marsh and wetland habitats (Bergin, 1994; Donovan & Larcombe, 1976), build-up of sediment in the lower estuary associated with the growth of the flood/ebb tidal delta system, increased salinity, and reduced flushing have had wide-reaching effects including the demise of culturally-important estuarine kaimoana (seafood) including pipi (*Paphies australis*), tuangi (cockle/ *Austrovenus stutchburyi*) (Hamerton, 2014), and also contributed to degrading water quality (McIntosh, 2005) and restricting estuary access and navigation (Goodhue, 2007). From 1956 to 1995, the only freshwater flow from the Kaituna River into the estuary was minor seepage and "pulsed" overflows during floods. Subsequently, restricted flows of 2 $m^3/s$ of freshwater (up to ~100,000 $m^3$ per tidal cycle and 4% of the river flow) were restored to the estuary through the Ford's Cut control structure (Figure 3.1) in 1996 (Hume et al., 2017).

### 3.3.3 2020–2021 Kaituna river re-diversion project

The main goal of the Kaituna River Re-diversion and Estuary Enhancement Project was to significantly increase the volume of freshwater flowing from the Kaituna River into Te Awa o Ngātoroirangi, to maximise the ecological and cultural benefits, particularly those relating to wetlands and kaimoana, while limiting the economic cost and adverse environmental effects (due to flood events) to acceptable levels and keeping Te Tumu Cut (Figure 3.1) open for flood protection and navigation (Environment Bay of Plenty, 2009). Te Awa o Ngātoroirangi is an area of significant cultural value. One of the main drivers for the project was to restore the mauri (life force) of the river and estuary and enable tangata whenua (local Māori people of this area) to continue the cultural practices of gathering kaimoana (seafood) from the estuary (Environment Bay of Plenty, 2009).

The Kaituna River re-diversion aimed to return at least 400,000 $m^3$ of freshwater per 12.4-hour tidal cycle (~13% of the river flow) (Stage 1, commissioned 12$^{th}$ February 2020) through 9 of 12 control gates between Ford's Cut and the lower Kaituna River becoming operational . This increased to a total of 600,000 $m^3$ per tidal cycle one year later (~20% of the river flow) (Stage 2, commissioned 12$^{th}$ February 2021) through all 12 control gates (Park, 2020). This study focuses on Stage 1 re-diversion. To prevent seawater from Te Tumu inlet from entering the estuary through the control gates, a salinity block cosisting of a 10 m-wide barrier was constructed near Site 7 (Figure 3.1). To maximise river flow into the estuary, the gates open automatically during the flood tide in the estuary when water levels are rising in Ford's Cut, and the water level on the Kaituna Riverside is at least 40 mm higher than the estuary side for at least 10 minutes; and close when the height difference drops below 40 mm for at least 10 minutes. They can also be closed during river flooding conditions to keep low-lying lands surrounding the estuary safe from floods. Notably, the nature of the new gates' operation is different from the control structures in 1996 since they are only open for approximately 4.5 hours (maximum of 5 and minimum of 3 hours) during the flood duration of each tidal cycle.

## 3.4 Methods

Fieldwork was undertaken between 23rd January and 3rd March 2020 to measure water level, velocity, temperature, turbidity and salinity at 7 sites throughout the estuary and the lower Kaituna River (Figure 3.1). The central zone of the estuary was not sampled due to it being too shallow and high probablity of the instruments getting exposed. These sites give comprehensive spatial coverage of the estuary and mainly correspond to the deeper channels on the northern and southern margins of the estuary whilst being safe and discrete places to moor instruments). Two sites were located in the lower estuary (1 & 2), two in the middle estuary (3 & 5), two in the upper estuary (4 & 6), and one site in the lower Kaituna River (7). Within the upper estuary, Site 4 is within the Ford's Cut channel, which connects to the Kaituna River. Site 6 is within the Papahikahawai Lagoon, which is largely disconnected from the rest of the estuary.

Instruments deployed included: 3 Nortek Aquadopp Profilers (upward-facing) measuring water levels, currents and turbidity; and 4 Solinst LTC Level Logger Edge, 1 RBR Maestro and 2 RBR Concertos measuring conductivity, temperature, turbidity and dissolved oxygen (Table 3.1). The sampling interval was 10 minutes for all instruments except the RBR Maestro, which was set to 20 minutes. Solinst loggers were attached to existing navigation poles at Sites 1 and 7 and to temporary stakes at Sites 5 and 6. Aquadopps and Concertos/Maestro were placed together on anchored stainless steel frames at Sites 2, 3 and 4 with sensors located ~0.15–0.27 m above the bed (Table 3.1). At Sites 3 and 4, large plastic lids were attached to the underside of the frames to prevent them from sinking into the mud. Weekly checks were undertaken to clear any sensors' biofouling, particularly at Sites 3 and 4, which had issues with sea lettuce (*Ulva*).

We also completed a baseline bathymetric survey of the estuary using RTK-GPS and a single-beam echosounder before the Stage 1 gates were commissioned in February 2020 with a vertical accuracy of ±3 cm. A bathymetric map of the estuary (Figure 3.1) was developed with the collected data, LiDAR data from December 2018–April 2019 provided by BOPRC, and offshore data (last updated July 2020) from Land Information New Zealand (LINZ). Precipitation and hourly wind data from Tauranga Aerodrome station (4 m above MSL, ~37 km from Maketū Estuary) were provided by the New Zealand MetService. Tidal elevation data from Moturiki Island (~36 km from Maketū) were provided by the National Institute of Water and Atmospheric Research (NIWA).

*Table 3.1 Instrument programming and deployment details (site locations in Figure 3.1), with L, T, C, Tu, DO, and PAR standing for level, temperature, conductivity, turbidity, dissolved oxygen and Photosynthetically Active Radiation, respectively.*

| Site | Date in 2020 | Height above bed (m) | Model & parameters | Mode | Frequency | Sampling interval (min) | Burst length/ averaging interval | Cell size (m) |
|---|---|---|---|---|---|---|---|---|
| 1 (Tidal inlet) | 20 Jan–02 Mar | 0.62–0.64 | Solinst Level Logger Edge (L, T, C) | Continuous | - | 10 | - | - |
| 2 (spit) | 28 Jan–02 Mar | 0.14–0.15 | Nortek Aquadopp (L, T, currents) | Burst | - | 10 | 120 s | 0.25 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 28 Jan–02 Mar | 0.15–0.18 | Concerto | Burst | 6 Hz | 10 | 1024 samples | - |
| 3 (farm) | 23 Jan–02 Mar | 0.235–0.275 | Maestro (L, T, C, Tu, DO, PAR) | Burst | 8 Hz | 20 | 512 samples | - |
| | 28 Jan–02 Mar | 0.14–0.15 | Nortek Aquadopp (L, T, currents) | Burst | - | 10 | 120 s | 0.25 |
| 4 (Ford's Cut) | 28 Jan–02 Mar | 0.14–0.168 | Nortek Aquadopp (L, T, currents) | Burst | - | 10 | 120 s | 0.25 |
| | 28 Jan–02 Mar | 0.15–0.195 | Concerto | Burst | 6 Hz | 10 | 1024 samples | - |
| 5 (Papahikahawai channel) | 22 Jan–02 Mar | 0.42–0.44 | Solinst Levelogger Edge (L, T, C) | Continuous | - | 10 | - | - |
| 6 (upper Papahikahawai lagoon) | 20 Jan–02 Mar | 0.26–0.28 | Solinst Levelogger Edge (L, T, C) | Continuous | - | 10 | - | - |
| 7 (Kaituna River near Te Tumu inlet) | 20 Jan–02 Mar | - | Solinst Levelogger Edge (L, T, C) | Continuous | - | 10 | - | - |

Before data analysis, data were cleaned by removing data during instrument maintenance and sea lettuce fouling, and at Site 2, data after February 25$^{th}$ were removed as the site was disturbed. All the current profile bins above the water surface were also removed. Current profiles were depth-averaged, using the single point method (Maghrebi, 2006) corresponding to 0.7 of the water depth to minimise the error for the shallow channels. The freshwater discharge rate was calculated by multiplying the depth-averaged east-west component of the velocity, water levels, and channel width at Site 4. During the deployments, there were a few gate testing events that were identified in the data as relatively strong easterly current spikes at Sites 3 and 4 and occurred at times inconsistent with the gate opening triggers, such as on February 1$^{st}$–4$^{th}$,5$^{th}$ and 11$^{th}$ where the gates were fully open, and water flowed both towards and out of the estuary. These few events were not removed because their impacts do not go beyond just a few tidal cycles. Atmospheric pressure data were calculated using a weighted average of hourly atmospheric pressure data from two nearby sites (2/3 in Tauranga and 1/3 in Whakatāne) based on the proximity to these surrounding weather stations; the data were then converted to metres of water level response and subtracted from water level data derived from the total pressure measured by the instruments.

One of the data analysis challenges was isolating the effect of restored freshwater from other effects due to tide, wind and wave forcing (i.e., natural variability). To isolate the impact of freshwater re-diversion, an average tidal cycle (canonical tidal cycle) was calculated for the 12 days pre-rediversion and 16 days post-re-diversion for water level, depth-averaged current velocity, and near-bed salinity (0.15–0.6 m above the bed). This canonical semi-diurnal tidal cycle starts at local high tide and ends at subsequent high tide 12.4 hours later.

Tidal asymmetry was assessed by considering the contributions of tidal constituents to the water elevations within the estuary. According to Friedrichs and Aubrey (1988), the distortion of tidal currents within an estuary can be assessed by the relative phases of the $M_2$ and $M_4$ tidal constituents:

- If $0° < 2M_2\text{-}M_4 < 180°$, the estuary is termed 'flood-dominant' and exhibits shorter flood tide durations and necessarily higher velocity flood currents; and
- If $180° < 2M_2\text{-}M_4 < 360°$, the estuary is 'ebb-dominant' with shorter duration and higher velocity ebb tides.

Friedrichs and Aubrey (1988) note that their method was developed for tidally dominated estuaries with negligible freshwater inflow. However, the morphology of Te Awa o Ngātoroirangi predominantly reflects the river-dominated system that existed prior to anthropic modifications started. Since bathymetry significantly influences tidal propagation, it is possible that the measured tidal constituents are not consistent with a tidally dominated estuary for mid and upper-estuary sites. Hence, the Friedrichs and Aubrey method may not be accurate. Therefore, as a check, we also evaluated tidal current asymmetry using the tidal velocity asymmetry (TVA) parameter, which is the ratio of peak flood current speed to peak ebb current speed (de Ruiter et al., 2019).

Tidal asymmetry can contribute to stratification, which may also occur due to the introduction of additional freshwater. To assess if estuary stratification changed after Stage 1, the estuarine Richardson number ($Ri_E$), as defined by Fischer (1976), was calculated as follows:

$$Ri_E = g\frac{\Delta\rho}{\rho}\left(\frac{Q_f}{Wu_{tidal}^3}\right) \qquad (1)$$

Where g is the gravitational acceleration, $\Delta\rho/\rho = 0.025$ is the fractional density difference between river (fresh) and ocean (salt) water, $Q_f$ is the mean river flow (25 $m^3/s$ before and 45 $m^3/s$ after the freshwater re-diversion), $u_{tidal}$ is root-mean-square tidal current speed and, $W = 80\ m$ is the effective channel width at Site 2 (within the lower Papahikahawai Channel close to the tidal inlet).

## 3.5 Results

### 3.5.1 Environmental conditions

Before the Stage 1 re-diversion, measurements include a neap tide and a perigean spring tide (Figure 3.2c). Te Awa o Ngātoroirangi experiences two spring tides per lunar month, with one (apogean spring tide) that is only slightly larger than neap tidal conditions. The Stage 1 re-diversion started 3 days after a perigean spring tide. The sampling period after Stage 1 included a neap tide followed by an apogean spring tide. Tidal ranges during the five weeks of measurements were ~1.1 m during the neap tide, ~2 m during the perigean spring tide and ~1.5 m during the apogean spring tide (Figure 3.2c).

Rainfall during this period was insignificant (8.2 mm total over 10 days of rain). Hourly winds were mainly from the southwest (typical of this region), with an average hourly speed of 13.2 km/h (Figures 3.2a and 3.2b). Before Stage 1, the strongest winds were from the East at ~20 km/h and from the South at ~30 km/h (Figures 3.2a and 3.2b). After Stage 1, the dominant wind directions remained from the East with a maximum speed of

~20 km/h, but occasional southwards winds were stronger with a maximum speed of ~25 km/h (Figure 3.2a and 3.2b).

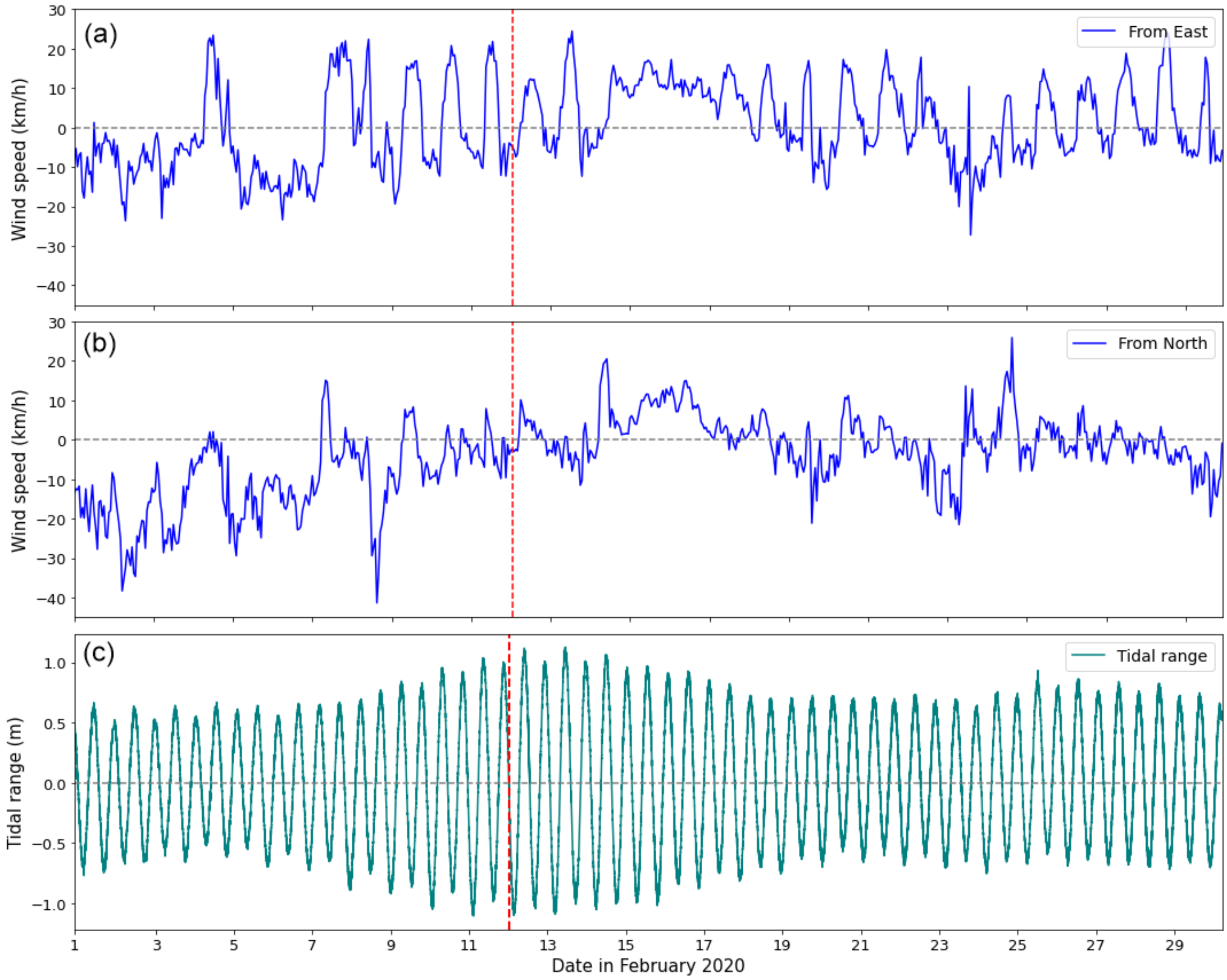



*Figure 3.2 (a) wind speed and direction, and (c) tidal range for Te Awa o Ngātoroirangi during the instrument deployments with the red dashed line showing the date of Stage 1; Tidal elevation data are from Moturiki (~36 km from the estuary) provided by NIWA*

### 3.5.2 Pre-rediversion conditions

During the pre-rediversion period measured in the 12 days before Feb 12th, 3 of the 12 control gates were operating, allowing an average of ~2 $m^3/s$ fresh riverine water into the estuary (~150,000 $m^3$ per 12.4-hour tidal cycle, ~4% of the river flow).

At Sites 1 and 2, both of which are in the main tidal channel (tidally dominated) of the northern margin of the estuary at an average depth of 1.5 m near the tidal inlet (Figure 3.1), maximum seaward bottom and surface currents of ~0.6 m/s and ~0.75 m/s were observed during the ebb tide respectively and a maximum westward bottom and surface current speeds of ~0.6 m/s and ~0.75 m/s during the flood tide (Figure 3.3a). Salinity varied with tidal fluctuations between 20–32 and 15–34 at Sites 1 (Figure 3.5d) and 2 (Figure 3.5j), respectively. In the mid-estuary, Site 3 (Figure 3.1) is located in a channel (average depth of 1.5 m) on the southern margin surrounded by tidal flats. Here, bottom and surface current speeds vary between 0.25–0.4 m/s and 0.5–0.5 m/s, respectively (Figure 3.3b), and salinity varied with tidal fluctuations between 15–32 but with inconsistency

(Figure 3.5e). In the upper estuary near the Ford's Cut control gates, Site 4 is located in the excavated channel closest to the control gates at an average depth of 1.5 m.

The calculated freshwater discharge through the control gates before Stage 1 (at Site 4) varied from 15–25 $m^3/s$ and ranged from 30–55 $m^3/s$ after Stage 1 (Figure 3.4b and 3.4d), reflecting the increased inflow from 150,000 $m^3$ to 400,000 $m^3$ per tidal cycle. Ignoring gate testing events, including on February 1st–4th, 5th and 11th, bottom current speeds at Site 4 were typically < ~0.25 m/s during ebb tide (gates closed) and increased to ~0.7 m/s during flood tides (gates open); similarly, surface current speeds reached ~0.1 m/s during ebb tide and ~0.75 m/s during flood tide (Figure 3.3c). At Site 4, salinity varied between 8–30, mostly fluctuating with the freshwater influence, such as sharp drops in salinity levels when the gates were open (Figure 3.5f). At Sites 5 and 6 in the Papahikahawai Channel within the mid and upper estuary, currents are weak and were not measured. The salinity varied from 12–33 between low and high tide at Site 5 (Figure 3.5k). Site 6 showed slight salinity variation with the tide cycles, although salinity increased gradually from 13–25 in less than 8 days (Figure 3.5l).

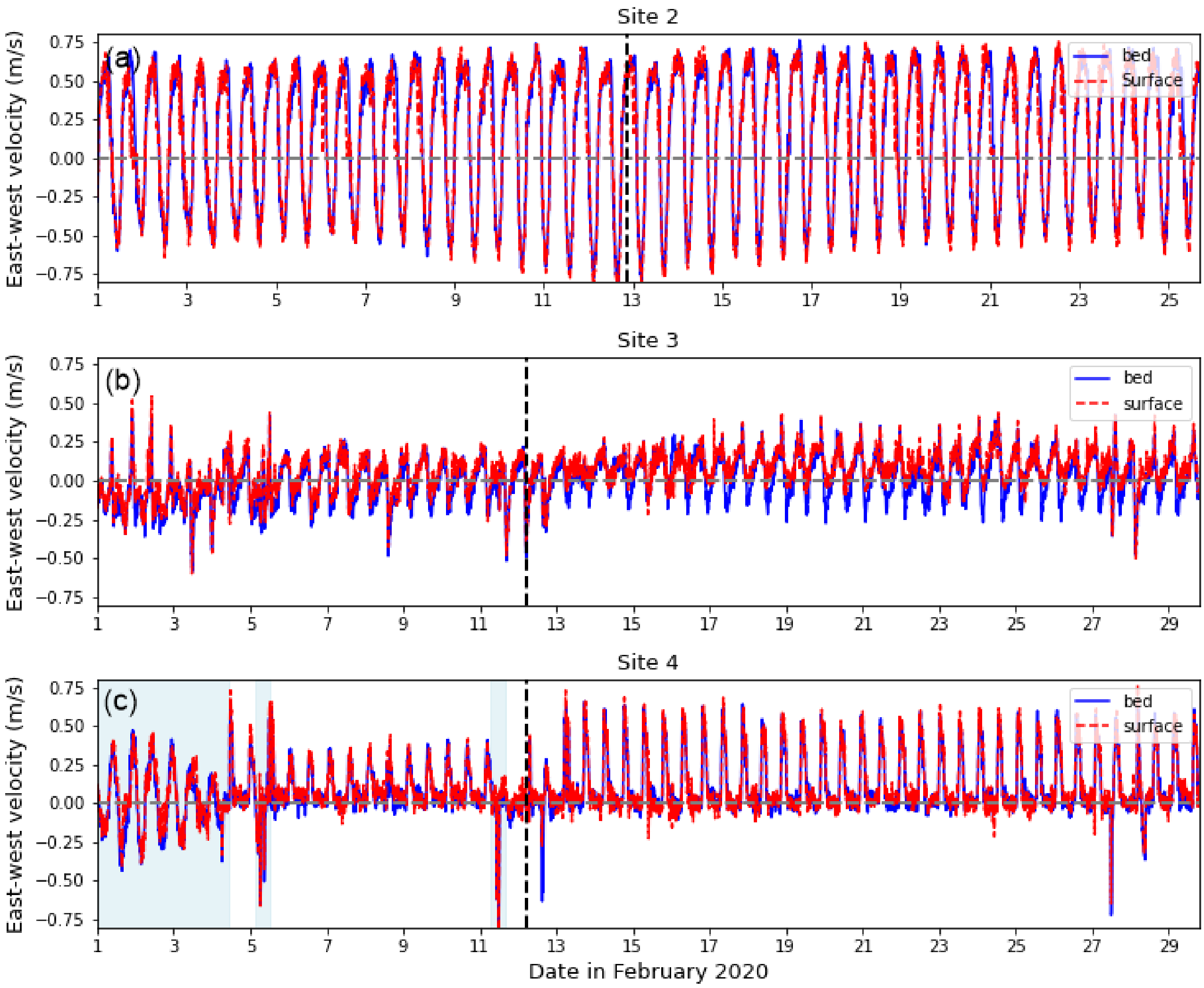



*Figure 3.3 Current speeds (positive towards the tidal inlet at the eastern end of the estuary) at Site 2 (a), Site 3 (b) and Site 4 (c); the black dashed line represents the start of Stage 1 control gate operation (February 12th ). When measurements coincided with gate testing events (shown by lightblue), spikes of high westward currents towards the control gates were evident (mainly at the surface)*

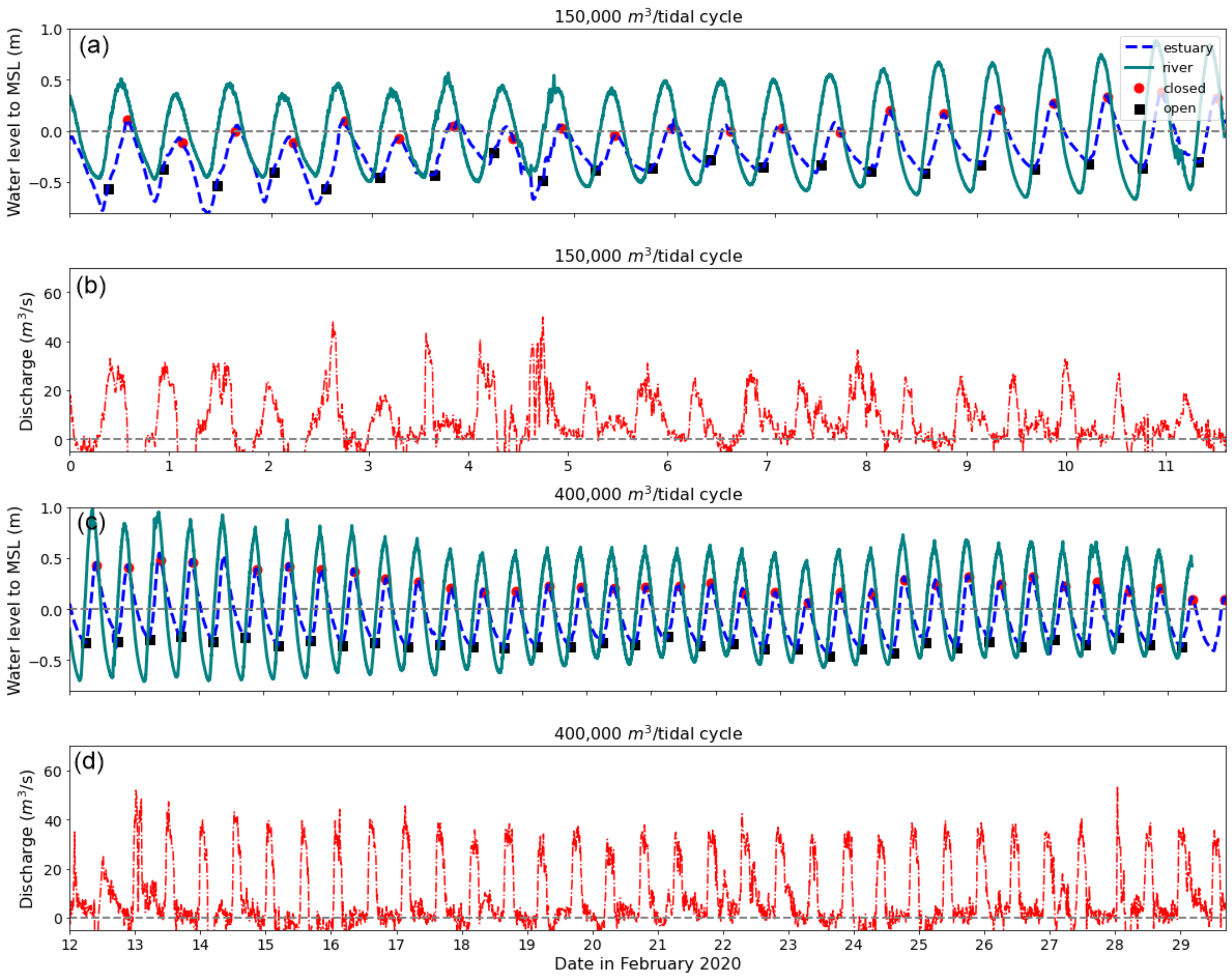



*Figure 3.4 Comparison of water levels at Site 4 (blue) and the lower Kaituna River (green, obtained from BOPRC measured at Ford's Cut, riverside of the control gates) before and after Stage 1 (a and c), as well as freshwater discharge into the estuary (a and c) estimated at Site 4. Approximate gate opening times are shown with black squares, and closing times with red circles*

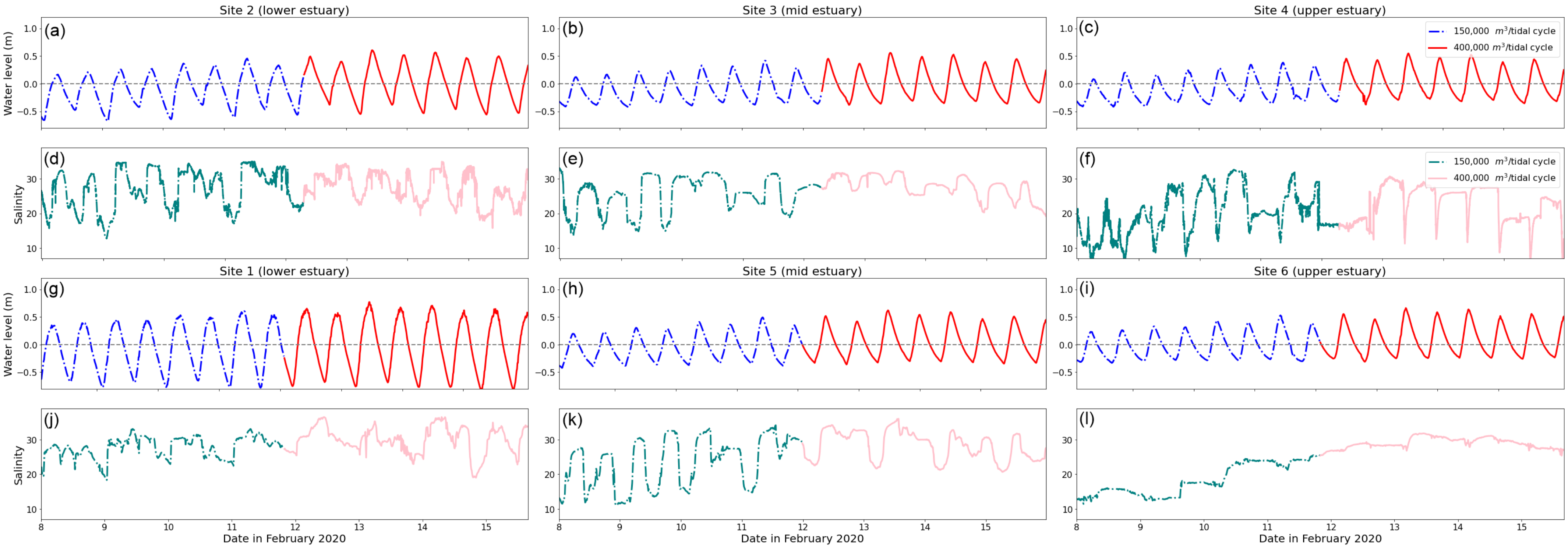



*Figure 3.5 Water level and salinity at Site 2 (a, d), Site 3 (b, e), Site 4 (c, f), Site 1(g, j), Site 5 (h, k) and Site 6 (I, l) from February 8th to 16th showing water level and salinity before (blue/ green) the and after (red/ pink) the Stage 1*

### 3.5.3 Post-rediversion conditions

Overall, the canonical average water level at Sites 2, 3, 4 and 6 (Figure 3.6a, 3.6b, 3.6c and 3.6l) increased substantially after the start of Stage 1 and only slightly at Sites 5 and 1 (Figure 3.6j and 3.6k). During gate opening hours, higher canonical depth-averaged current speeds (Figure 3.6g, 3.6h, 3.6i) for Site 2, 3 and 4 were observed, as well as reduced canonical average salinity for Site 1, 2, 3 and 5 (Figure 3.6m, 3.6d, 3.6e and 3.6n). These observations are discussed in more detail below.

### 3.5.4 Water levels, gradients, and currents

Water levels (Figure 3.6), water level gradients (Figure 3.7), and subsequently the currents were affected by the Stage 1 re-diversion. Within the lower estuary at Site 1 (in the tidal inlet), the mean water level after the Stage 1 re-diversion increased by up to ~0.05 m between hours 0-4 and 8-12 of each tidal cycle (Figure 3.6j), with the largest increase around high tide.

At Site 2 in the lower Papahikahawai Channel (Figure 3.6a), there was a considerable increase of ~0.1m in the mean water level around high tide, with higher levels maintained for longer during the tidal cycle (hours 0-8 and 10-12). This corresponded to increased tidal asymmetry with the ebb tide duration prolonged by ~45 minutes compared to before Stage 1, and the rate of change from ebb (positive, east) currents to flood (negative, west) currents (hours 7-9) was significantly faster after Stage 1 began (Figure 3.6g). However, the flood to ebb transition (hours 10-12, 0-2) is unaffected. The standard deviation in current speeds was also larger after Stage 1 between hours 9–10 of the tidal cycle. The tidal currents at Site 2 remained ebb dominant (as assessed by the TVA ratio) before and after the Stage 1 (Figure 3.8d), with a notable increase in peak ebb velocities of ~0.08 m/s afterwards (Figure 3.8a). The dominant flow direction remained east-west direction and did not show any change after the onset of Stage 1.

Within the mid-estuary, at Site 3 in the former Kaituna River channel, between hours 0–9 and hour 12 of each tidal cycle, the mean relative water level increased by ~0.1 m, but between hours 9–11, only increased by ~0.05 m (Figure 3.6b), and mean current speeds towards the east increased by ~0.2 m/s (Figure 3.6h). During the canonical tidal cycle at hour 9 (flood tide), there was a shift in the mean current speed direction from westwards (-0.18 m/s) to eastwards (0.2 m/s) (Figure 3.6h), reducing the duration of flood-directed flow. This occurs because the tidal flow is in the ebb direction during the flood tide when the gates are open. The tidal currents at Site 3 were flood dominant (westward) before Stage 1 (Figure 3.7e), with a peak flood velocity of ~0.2 m/s (Figure 3.8b). Afterwards, there was a shift to ebb dominance, with the peak flood velocity reduced to ~0.05 m/s and a reduction in the duration of flood flow, as noted above (Figures 3.6h and 3.8b).

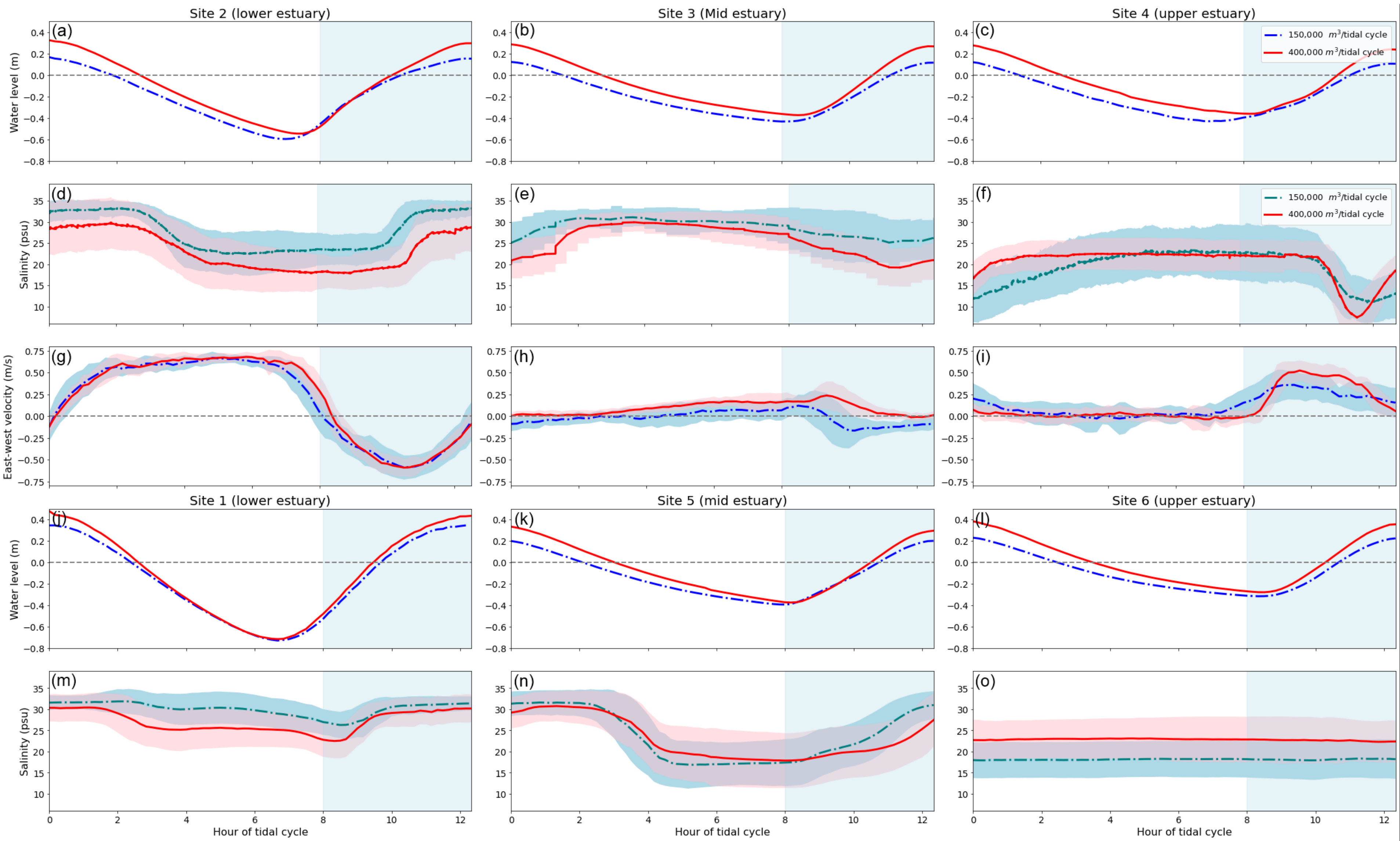
Water levels at Site 4 (Ford’s Cut) in the upper estuary increased by 46% on average over most of the tidal cycle to a maximum of ~66 % (0.2 m) at high tide. However, little change was observed between hours 8–10 of the tidal cycle (Figure 3.6c). Moreover, the timing of low water was delayed by ~1 hour, increasing the ebb tide duration compared to before Stage 1. The automatic operation of the gates maintains a steeper water level gradient between Sites 7 and 4 (Figure 3.7c) than would occur without the gates. The hydraulic head of at least

40 mm at the gates drive increased eastward (ebb-directed) current speeds at Site 4 (Figure 3.6i), which extend to at least Site 3 along the former Kaituna River Channel.

At Site 4, there was barely any current between high and low tide (the ebbing tide), whereas between low and high tide (flooding tide), there was a strong flow, but in the eastward direction. This contrasts strongly with Site 2 in the lower estuary, where the flooding tide was in the westward direction when new water flowed in from the entrance of the estuary). Before Stage 1, mean current speeds at Site 4 were relatively low (up to the maximum value of 0.1 m/s towards the east) at hours 0–8 and increased during flood tide to a maximum of ~0.25 m/s, still towards the east. Flows only briefly occurred towards the west (flood direction) in response to turbulence, as shown by the standard deviations. After Stage 1, the ebb-directed current speeds increased by ~0.2 m/s during the flood tide, between hours 8–12 of each tidal cycle when the gates open to let freshwater in. Current speeds remained close to 0 during ebb tide between hours 0–8 when the gates were closed. There was also a shift to a longer ebb tide duration by ~1.5 hours (Figure 3.6i). The average water level at high tide increased by ~0.2 m at Sites 2,3, and 4, but water levels remained somewhat the same at low tide (Figure 3.6a, 3.6b and 3.6c, respectively). Figure 3.8c shows these changes as a tidal stage versus velocity plot to allow comparison with Sites 2 and 3. Site 4 was ebb dominant before the Stage 1 re-diversion and remained so afterwards (Figure 3.8f). The ebb tide duration increased at most locations within the estuary (Sites 2, 3, 4, and 5) and was unchanged at the tidal inlet (Site 1) and Papahikahawai Lagoon (Site 6). Hence, for most of the estuary, the timing of tidal flow reversals changed, and the transition from ebb to flood became quicker.

In the mid estuary at Site 5 and upper estuary at Site 6 within the Papahikahawai Channel and Lagoon, respectively, there was an average increase of ~0.09 m in relative water level (Figure 3.6k and 3.6l). These two sites show a similar water level pattern throughout the tidal cycle, but the tidal range is reduced at Site 6 relative to Site 5. Current velocities were not recorded at these sites.

Comparing water levels between sites throughout the tidal cycle shows that Site 2, in the lower estuary, was consistently lower than Site 4 in the upper estuary at Ford’s Cut during ebb tide and higher during the flood tide. The ebb tide water level gradient became steeper between Sites 4 and 2 after Stage 1 (Figure 3.7b), resulting in increased current speeds towards the tidal inlet. The flood tide water level gradients between Site 2 and 4 reduced afterwards, consistent with a reduction of the current speeds towards Ford’s Cut (westward) between these two sites. The mean water level gradient between Sites 3 and 4, the former river channel and artificial channel in the upper estuary indicates that after the onset of Stage 1, the gradient reversed after hour 9, which may account for the flow reversal (Figures 3.7b and 3.7e). However, the gradients between Sites 3 and 4 are very small relative to other parts of the estuary (Figures 3.7a-c) and may represent the response to the current produced by the re-diversion inflow.



Site 2 (lower estuary)
Site 3 (Mid estuary)
Site 4 (upper estuary)
(a)
(b)
(c)
150,000 $m^3$/tidal cycle
400,000 $m^3$/tidal cycle
Water level (m)
(d)
(e)
(f)
Salinity (psu)
(g)
(h)
(i)
East-west velocity (m/s)
Site 1 (lower estuary)
Site 5 (mid estuary)
Site 6 (upper estuary)
(j)
(k)
(l)
(m)
(n)
(o)
Hour of tidal cycle

*Figure 3.6 Average tidal variations of mean water level, bottom salinity and depth-averaged east-west component of velocities before (blue/green) and after (red) Stage 1 at each site: Site 1 (j, m), Site 2 (a, d, g), Site 3 (b, e, h), Site 4 (c, f, i), Site 5 (k, n) and Site 6 (l, o) with standard deviation shown by light blue (before) and light green (after). The shaded area starting at hour 8 indicates the period during which the control gates may open if the necessary conditions are met*

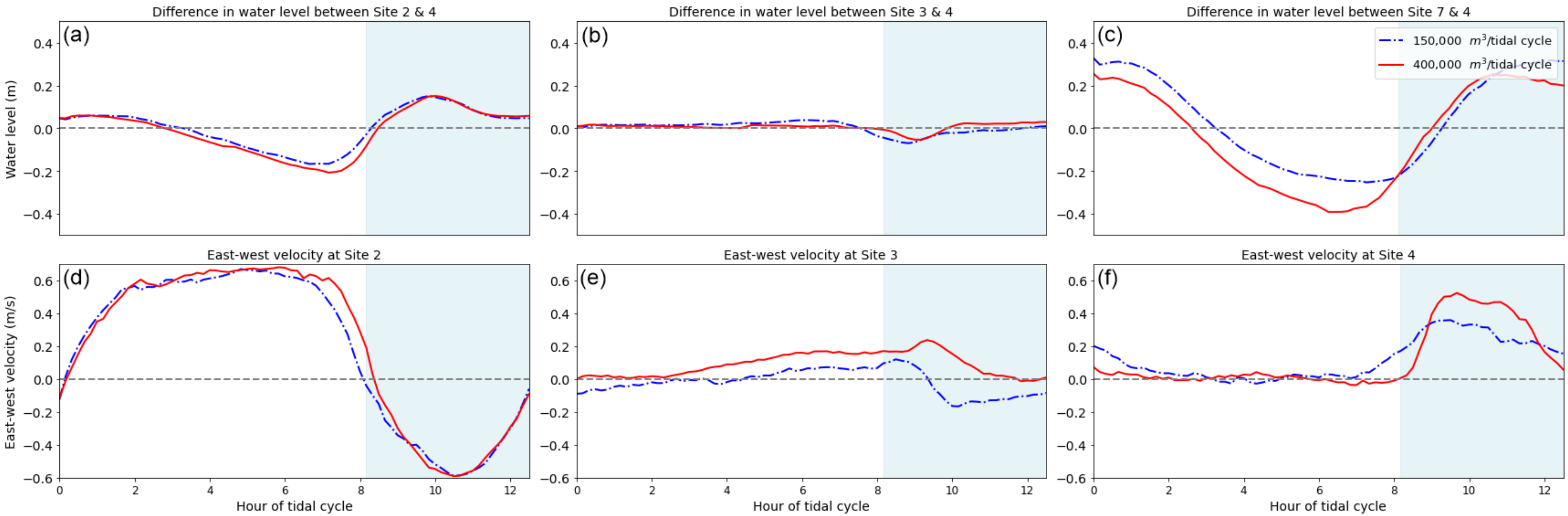



*Figure 3.7 The difference in mean water levels before (red) and after (blue) Stage 1 determined as (a) Site 4 minus Site 2, (b) Site 4 minus Site 3, and (c) Site 7 minus Site 4, and depth-averaged east-west component of velocities at Sites 2 (d), 3 (e) and 4 (f). The shaded area starting at hour 8 indicates the period during which the control gates open if the necessary conditions are met*

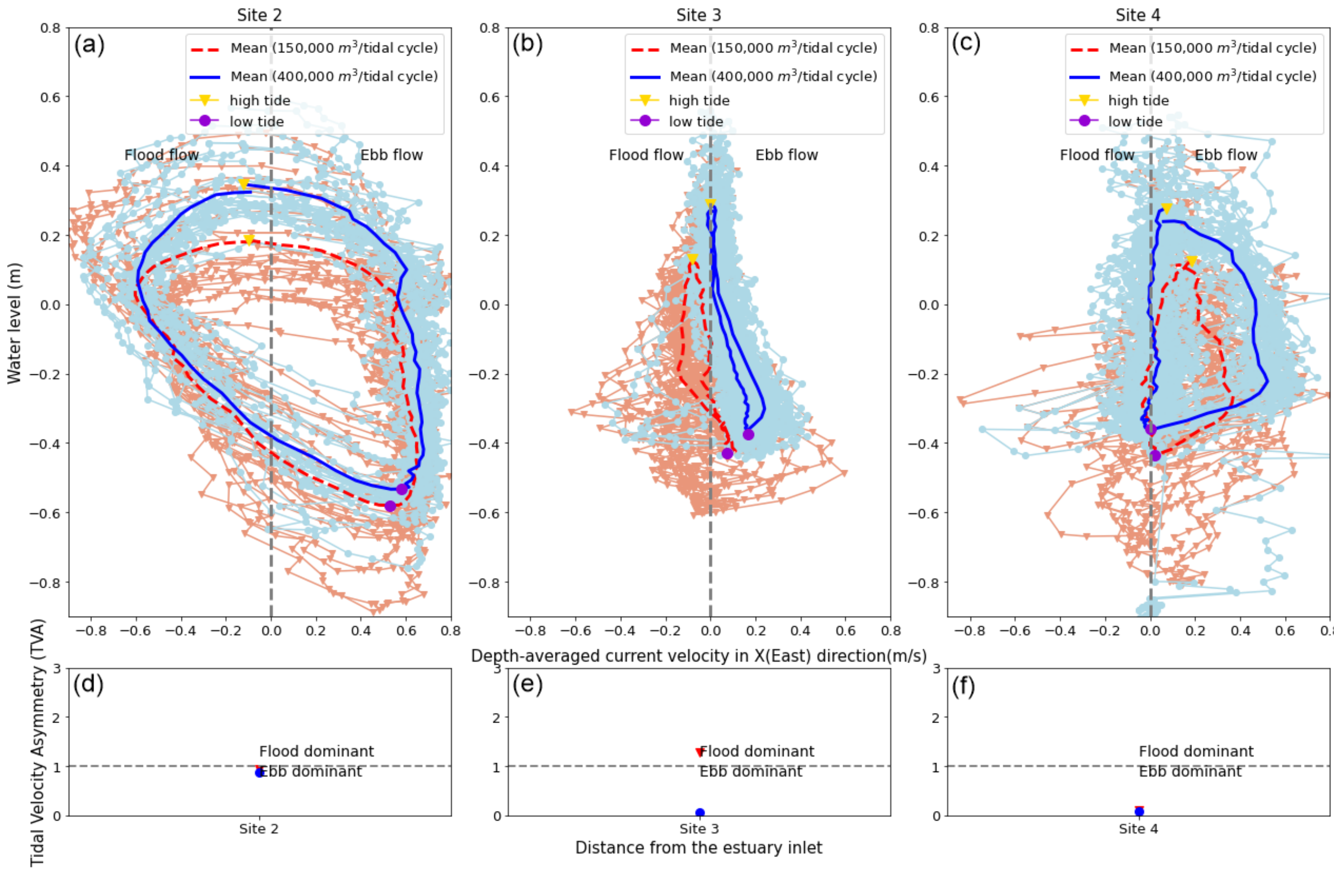



*Figure 3.8 (a) Tidal stage plots of mean and all (dots) depth-averaged east-west component of velocities vs average water level with TVA before and after Stage 1 at (a) Site 2, (b) Site 3 and (c) Site 4; and tidal velocity asymmetry values before (red) and after (blue) the Stage 1 at (d) Site 2, (e) Site 3 and (f) Site 4. Note that because of the channel orientation, the east-west component captures most of the variations (see Figure 3.7)*

Tidal dominance is estimated using two methods before and after Stage 1, where: (1) the phase and amplitude of the $M_2$ and $M_4$ constituents were extracted with U_Tide for 5 sites within the estuary before, and the Friedrichs and Aubrey (1988) method was applied; and (2) the TVA method was applied to compare ratios of peak flood to peak ebb current speeds. The Friedrichs and Aubrey (1988) method showed that the estuary was flood dominant before Stage 1, and after, despite the additional freshwater flow into the estuary affecting the tidal currents (Table 3.2), the phase results indicate no change in tidal dominance. However, based on the TVA method, Site 2 in the lower estuary and Site 4 in the upper estuary were ebb dominant before Stage 1 partial freshwater restoration and remained ebb dominant afterwards. However, Site 3 in the middle estuary switched from flood dominance to ebb dominance. These results differ from those in Table 3.2. Currents were not measured at Sites 1 and 6, so the TVA method could not be applied for comparison.

*Table 3.2 Results forResults for tidal dominance were determined by the method of Friedrichs and Aubrey (1988) for 5 sites within the Maketū Estuary.*

| Sites | $2M_2$-$M_4$ (before) | Dominance | $2M_2$-$M_4$ (after) | Dominance |
|---|---|---|---|---|
| Site 1 | 109 | Flood | 90.74 | Flood |
| Site 2 | 126 | Flood | 90.74 | Flood |
| Site 3 | 58 | Flood | 57.7 | Flood |
| Site 4 | 44.8 | Flood | 52.1 | Flood |
| Site 6 | 54 | Flood | 58 | Flood |

### 3.5.5 Salinity regime

Overall, when freshwater inflow through the gates increased from ~150,000 $m^3$ to ~400,000 $m^3$ per tidal cycle at the onset of Stage 1, there was a substantial reduction in the near-bed salinity in the lower and mid-estuary. However, salinity levels remained the same or increased in the upper estuary. At Site 1 in the lower estuary near the tidal inlet, there was an average decrease in salinity of ~5 during the ebb tide and only ~2 during the flood tide (Figure 3.6m). Similarly, Site 2 in the lower estuary experienced a decrease of ~5 in salinity over the tidal cycle (Figure 6d). Site 1 and 2 salinity had a relatively large range in standard deviation (Figure 3.6m and 3.6d, respectively). The maximum salinity levels for Site 1 occurred between hours 9–11 of each tidal cycle (last half of flood tide), with the maximum salinity reaching ~30 (Figure 3.6m). However, at Site 2, the flood tide salinity increase occurs ~1 hour later, with the maximum salinity level of ~29 occurring at high tide and the minimum of ~18 during hours 4–10, or mid-ebb to mid-flood tide (Figure 3.6d).

At Site 3 in the mid estuary, during the ebb tide, mean salinity was similar to before Stage 1, but the flood tide mean salinity decreased by ~5 with an increased standard deviation. The maximum salinity for Site 3 after Stage 1 was ~30 and occurred between hours 2–4 during the ebb tide, while the minimum of ~20 occurred between hours 10–12 during the flood tide (Figure 3.6e). At Site 5 in Papahikahawai Channel, after Stage 1, mean salinity increased by ~3 between hours 3–7 of the ebb tide, then decreased by ~5 between hours 8–11 during the flood tide (Figure 3.6n).

In the upper estuary at Site 4 (closest to the control gates; Figure 3.1), for most of the tidal cycle between hours 0–10, mean salinity increased after Stage 1 and reached ~23 and remained constant until hour 10 when it decreased to a minimum of ~7. Salinity then increased to ~23 again between hours 10–12 during the flood tide (Figure 3.6f). At Site 6 in Papahikahawai Lagoon (Figure 3.1), there was a uniform increase of ~5 in mean salinity levels after Stage 1 (Figure 3.6o). Sites 4 and 6 in the upper estuary and Site 5 in the mid estuary had a relatively high standard deviation with the maximum salinity occurring at high tide for Sites 4 and 5 (Figure 3.6f and 3.6n). On the other hand, at Site 6 salinity had high values throughout the tidal cycle (Figure 3.6o).

It is also helpful to consider the time series of salinity measurements in Figure 3.5 for the 8th to 16th February, particularly for the upper estuary. Starting with Site 1 at the tidal inlet as an indicator of the salinity of seawater entering the estuary (Figure 3.5j), there is a trend of increasing salinity with a superimposed diurnal cycle. Salinity and tidal elevation have no clear relationship (Figure 3.5g). This suggests that the flood tidal flow consists mainly of water discharged during the preceding ebb tide, with little mixing with offshore seawater. There is also a pattern of increasing range of salinities during the day, with some large salinity declines around the 14th February. These spikes of freshwater may be due to the re-diversion as there was little rainfall during this period, and they may also account for the decrease in salinity noted during the ebb and early flood tide (Figure 3.6m) as they all occur during this part of the tidal cycle.

At Site 2 in the Papahikahawai Channel within the lower estuary, there is a small increasing trend in salinity (Figure 3.5d). However, average daily salinity increases slightly until Stage 1 and then decreases. The variation appears to be linked to the tidal range and timing of low water as the daytime low tide progressive moves from morning to afternoon. The differences between the canonical tidal cycles noted above may reflect this underlying pattern. However, there are both diurnal and semi-diurnal cycles, with salinity decreasing to a minimum at morning low tides and the salinity range varying over 2 tidal cycles (Figures 3.5a and 3.5d).

Site 3 in the eastern end of the former Kaituna River channel within the middle estuary shows a similar pattern of slightly increasing and decreasing mean daily salinity, as noted for Site 2. There are also broad similarities between the semi-diurnal and diurnal salinity variations at Sites 3 and 2, although the 'noise' is reduced at Site 3, particularly after the onset of Stage 1. Salinity tends to decrease before the start of the flood tide and hence before the opening of the gates. Figure 3.6e does show a later change in behaviour following the Stage 1 re-diversion at Site 3 than at other sites, particularly Sites 2, 4 and 5.

Site 5 in the Papahikahawai Channel and included in the mid-estuary shows a temporal salinity variation that falls between those exhibited by Sites 2 and 3 (Figure 3.5k). It shows the same trend of slight increase and then decrease of daily mean salinity and a change in the daily variation after the onset of Stage 1 inflows. One difference that does occur at Site 5 is that before Stage 1, there is a strong semi-diurnal signal and after, it becomes a dominant diurnal signal. This switch in the dominant salinity cycle occurs despite the increased range of semi-diurnal tidal fluctuations (Figure 3.5h).

Site 6 in the Papahikahawai Lagoon within the upper estuary also displays a trend of increasing and decreasing mean daily salinity (Figure 3.5l). However, the salinity peaks 4 days after the start of the Stage 1 re-diversion, whereas the decline coincides with re-diversion at all the other estuary sites. Site 6 also displays an irregular weak diurnal variation and no semi-diurnal variation. The delayed start of the declining salinity and lack of a tidal variation account for the features shown in Figure 3.6o.

Site 4 in Ford's Cut within the upper estuary is closest to the inflow of freshwater and is likely to show the most significant response to the start of the Stage 1 re-diversion. This site also shows a trend of increasing and then decreasing mean daily salinity (Figure 3.5f), as observed at all other sites except Site 1. There is a strong semi-diurnal signal involving a sharp decrease in salinity occurring at ~11 hours as shown in Figure 3.6f. This signal breaks down between midday on the 10th  February and midday 12th February, which may be due to gate testing before the start of Stage 1. The main change evident in the pattern before and after the start of Stage 1 re-diversion is that the salinity drop associated with gate opening has a faster rate of change and a shorter duration than before Stage 1 (Figures 3.5f and 3.6f).

## 3.6 Discussion

### 3.6.1 Water level

Water levels in Ford's Cut (Site 4) were generally lower during ebb tide and higher during flood tide compared to the lower Kaituna River (Site 7),. However, due to the 1-hour delay associated with tidal propagation within the estuary, there is a period during the flood tide within the estuary when Site 4 water levels are still lower than at Site 7 (Figure 3.7c). The increase of ~1 hour in the ebb tide duration after Stage 1, at Sites 2,3 and 4 indicates that the extra inflow from the river during flood tide cannot drain quickly from the estuary during the ebb tidal stage. Compared to before Stage 1, the re-diversion inflows now occur in a shorter time interval, given the settings of the automatic gates.

Following the increased freshwater inflow after Stage 1, all measured sites within the estuary had an increase in average water levels over the tidal cycle (Figure 3.6), with the largest increase at high tide. The increase in average water level, especially at Sites 2, 3, 5 and 6, is likely due to friction backup of water flowing from the upper estuary to the tidal inlet. This occurs because, during the second half of each tidal cycle, when the gates open, the added freshwater modifies the water level gradients between Site 4 in the upper estuary and elsewhere (Figure 3.7a & 3.7b). The resulting barotropic pressure gradients force estuarine currents that may enhance or oppose the currents generated by propagating tidal waves. For example, the opening of the gates results in an eastward pressure gradient force towards Site 3 (Figure 3.7b) that opposes the westward pressure gradient force generated by the flooding tide. This results in eastward (ebb) flow in the southern mid-estuary at Site 3 (Figure 3.7e). At the same time, in Papahikahawai Channel (e.g. Site 2), the flow is westward (flood) as expected during a flood tide.

The most substantial gradients associated with the inflow from the Kaituna River occur from Site 7 to Site 4 to Site 3 and control the inflow rate and initial spread of the freshwater. The gradients in the rest of the estuary are small, and it was impossible to distinguish the influence of the freshwater inflow from the effects of tidal propagation. It is expected that changes in water level gradients in natural systems will trigger a chain reaction, where currents adjust, resulting in a change to the bathymetry. The changing bathymetry will change water level gradients, currents and eventually the bathymetry. This cycle allows the system to try to reach a new equilibrium (Smolders et al., 2015). However, the average restored freshwater flow of 45 $m^3/s$ for approximately 5 hours during each tidal cycle, compared to the mean tidal prism is not significant enough to cause a large effect on the morphodynamics of the estuary.

Further, changes to the bathymetry require that the currents are capable of entraining and transporting sediment to allow erosion and that there is a sufficient supply of sediment to allow accretion. The lack of change in the morphology of the upper and middle estuary (excluding anthropic changes such as causeways and reclamation) suggests past flow changes were insufficient to cause significant bathymetric changes. For the Stage 1 diversion, the slight to negligible water level gradient changes for most of the estuary results in small current velocity changes. The absence of current-induced bedforms for the upper and middle estuary indicates that the re-diversion is not affecting the bathymetry.

### 3.6.2 Tidal asymmetry

In order to classify estuaries accurately in terms of ebb (having shorter, higher velocity ebbs) or flood dominance (having shorter duration, higher velocity floods) we used the method of Friedrichs and Aubrey (1988). According to our results, a major shift in the $2M_2$-$M_4$ phase was not observed, which classified the estuary as flood dominant. However, this approach assumes that there is no freshwater inflow and that the tidal constituents are in equilibrium with the morphology. For Te Awa o Ngātoroirangi, there is a freshwater inflow, which is being increased progressively at Stages 1 and 2 of the re-diversion. Further, we observed more prolonged duration ebb flows with weaker currents during flood flows in the lower estuary and longer ebb flows, and a shift to stronger ebb flows in the mid and upper estuary. We suggest that the role of tidal asymmetry on estuarine circulation and mixing exists even without a noticeable change in $M_2$-$M_4$ phase and $M_2/M_4$ amplitude as previously proposed by Jay and Musiak (1994). In this case, another measure of asymmetry may be more appropriate.

The TVA method using the ratio of peak flood to ebb current velocities better captured the observed pattern of flows before and after Stage 1 re-diversion, confirming a shift from flood to ebb dominance in the mid-estuary. Based on the TVA method, Site 3 showed the biggest shift to ebb dominance, but Site 2 and 4 remained flood dominant with little change after the partial freshwater re-diversion. This behaviour for Site 4 (closest to the gates and the most impacted by the partial restored freshwater) was not expected since, according to Dronkers (1986), river flow is likely to increase flood currents and reduce the ebb currents in the deepest parts of the channels near the sea bed due to the imposed density differences. However, increased currents are observed during both ebb and flood at Sites 2, 3 and 4. Considering no change in $M_2$-$M_4$ phase and $M_2/M_4$ amplitude, therefore, we infer that the added freshwater flow is not significant enough to affect the tidal constituents and create higher ebb currents due to the timing of the opening and closing of the control gates. Moreover, Site 3 showed a strong residual circulation, meaning the flow continues to ebb (flow in the eastward direction) long after the tide has turned; this residual flow shows an average magnitude of ~0.1 m/s after Stage 1.

One of the implications of tidal asymmetry is contribution to the residual circulation as well as mean shear stress in the same sense as the estuarine circulation (Geyer et al., 2000; Stacey et al., 2001). Moreover, an expected consequence of increased freshwater inflow is the flushing of bed-load sediment out of the estuary and the stabilization of the bathymetry in the long term. In the case of Te Awa o Ngātoroirangi, the largest changes in current velocities occur in areas (Sites 3 and 4) with little sediment availability and no possible connection to the tidal inlet to allow the export of sediment. The only area where sediment export could occur is the lower estuary. However, the changes to current velocities are too small to result in sediment export.

### 3.6.3 Estuarine circulation

The increased freshwater inflow following re-diversion could result in stratification or worse hypoxia, which was not considered desirable for the ecological state of the estuary (Conley et al., 2011). The results showed an increase from ~0.23 to ~0.53 in the Estuarine Richardson number at Site 2 after Stage 1, indicating the estuary is still partially mixed with weak density gradients. Although the restored freshwater flow does not reach the general threshold to change the estuarine mixing classification, it impacts the mixing dynamics by affecting tidal asymmetry and the longitudinal salinity gradient. Stacey et al. (2001) explain that a critical value exists for the estuarine Richardson number, above which we would expect an asymmetry to develop in the level of mixing. We have observed this value ($Ri_{crit}$) to be ~0.3. However, in partially-mixed estuaries such as Te Awa o Ngātoroirangi, when $Ri_E$ > $Ri_{crit}$, mixing cannot prevent the development of stratification that intensifies each tidal cycle (Monismith et al., 1996). Moreover, this transition between stratification states changes the upstream salt flux , leading to higher bottom salinity levels (Monismith et al., 2002), observed in the upper estuary. Therefore, for Te Awa o Ngātoroirangi, instead of the general range of 0.1< $Ri_E$<1 this critical value should be 0.3< $Ri_E$<1.

The study sites responded differently to the added freshwater flow from the gates. With the lower estuary being the least affected and the upper estuary (due to proximity to the gates) being impacted the most. Sites 4 and 6 in the upper estuary showed a higher salinity level on average after the Stage 1 re-diversion. The time series salinity data indicates a reduction in variation after the Stage 1. The difference between Sites 1 and 2 suggests an influence from shallow intertidal flat water. Comparing the salinity behaviour at Site 1 with the other sites inside the estuary suggests that Stage 1 has resulted in a trend of reducing salinity that dominated over the increasing trend for the incoming seawater. Moreover, average salinity tends to decrease before the start of the flood tide and hence before the opening of the gates. This suggests that this is caused by a lagged effect of the freshwater inflow during the previous tidal cycle that has mixed with estuarine water while advecting to Site 3 from Ford's Cut.

With decreased freshwater input, one expects an increase in salinity in the upper estuary (Alber, 2002). However, increased freshwater input does not necessarily create the opposite effect; Te Awa o Ngātoroirangi is an example of that. As mentioned before by Ralston et al. (2008), the instantaneous structure of the salinity distribution in an estuary depends on the response to unsteady forcing from river discharge and tides over time scales ranging from days (river discharge after precipitation events) to weeks (spring–neap variability in tidal amplitude) to months (seasonal discharge variability). Considering the complex and unsteady nature of freshwater inflow only during flood tide (the gates are closed for ~7 hours during every tidal cycle), we believe the existing steady increase in salinity at the bottom layer in the upper estuary, specifically Site 6 is due to increased residual salinity which is created by unsteady freshwater input combined with wind forcing and restricted connections to the main body of the estuary.

## 3.7 Conclusions

After the Stage 1 re-diversion, water levels increased at Site 2 in the lower estuary, Site 3 and 5 in the mid estuary and Site 6 in the upper estuary. This is likely due to friction backup of water flowing out of the upper estuary in the lagoon, as there was a decrease in water level difference between Sites 7 and Site 4 (near the control gates). Considering the same tidal range in the ocean, the added freshwater flow has increased the net flow in general, especially in the mid and upper estuary.

The ebb duration increased at some sites and flood current speed increased in the mid and upper estuary. There was a shift from flood dominant to ebb dominant at Site 3 (mid estuary) in terms of the TVA, and current speeds increased for Sites 2, 3 and 4, which indicates better flushing of the estuary. However, it seems to have created residual salinity in the upper estuary and more stratification was inferred.

The bottom salinity response to increased freshwater inflow was highly variable throughout the estuary. There was a general increase in salinty in the upper estuary especially at Site 4 near the gates. Site 4 showed a general increase and only decreased during the hours gates were open during the flood tide and Site 6 showed a significant increase in salinity. There was a significant decrease at Site 1 and 2 in the lower estuary and Site 3 in the mid estuary; there was a slight decrease in salinity for Site 5 in the mid estuary.

The Te Awa o Ngātoroirangi restoration project was expected to optimize freshwater delivery while minimising flood risk. This project was also expected to reduce sediment import to the estuary by affecting the tidal asymmetry; based on our findings, the estuary may be exporting sediment out of the lower estuary in the short term. However, the impact on sedimentation elsewhere appears to be negligible.

One of the challenges in this study was isolating the impact of the added freshwater flow among natural variables such as wind and precipitation. Further research, ideally using hydrodynamic modelling, would better demonstrate the true effect of this freshwater re-diversion attempt.

# 4 CHAPTER 4

## The impact of partial freshwater restoration on estuarine hydrodynamics and mixing

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### 4.1 Abstract

Estuarine freshwater restoration plans are critically needed to remedy adverse human-induced impacts. Te Awa o Ngātoroirangi (the Maketū Estuary) in the Bay of Plenty of Aotearoa, New Zealand has a long history of changes, including drainage of estuarine wetlands for land reclamation in the 1900s and diverting the Kaituna River out of the estuary in 1956 to prevent flooding of farmland. This resulted in the loss of freshwater inflow and degradation of the estuary, including increased sedimentation, loss of tidal channels, decreased flushing, saltwater intrusion and ecological decline that have had significant cultural and social impacts. However, in 2020 and 2021, about 20% of the river flow has been restored back into the estuary in two stages through 12 control gates. This study uses field data to focus on the effects of this partial freshwater restoration of the Kaituna River on the estuarine hydrodynamics, specifically tidal asymmetry and mixing over the two stages. During Stage 1 of the project in 2020, when 9 of the 12 control gates were commissioned and despite the estuary’s small size (230 hectares), field measurements showed great spatial variability in salinity, with average salinity increasing in the upper estuary while it decreased elsewhere. Tidal range decreased with increasing distance from the tidal inlet, while the ebb duration increased. Stage 2 measurements in 2021, when the remaining 3 gates were commissioned, showed a uniform decrease in salinity at all sites monitored, but there was no significant change in tidal asymmetry. The Estuarine Richardson number was calculated to evaluate the level of stratification and it after Stage 2, it did not change significantly from that after Stage 1, but the impact of wind forcing on stratification was present in 2021 and not in 2020. This study shows how the immediate and one year after response of shallow estuaries to partial freshwater restoration with complex topography are different. It also highlights how expected restored freshwater inflow rates may not be achieved due to variable river discharge, impacting the hoped-for estuarine response.

**Keywords**: estuarine restoration, river discharge, hydrodynamics, salinity regime, tidal asymmetry

### 4.2 Introduction

Estuaries are ecologically and socio-economically important environments (Ducrotoy, 2010), which are often a sink of terrestrially-derived nutrients, sediment, and contaminants through the combined action of freshwater inflow, wind, waves and tidal action (Hansen & Rattray, 1966; Tay et al., 2013). Globally, estuaries and their ecosystem services have been degraded and even lost in some places, mainly due to anthropic disturbances such as land-use change, alteration of food webs, and other environmental stressors (Green, 2006). In many cases, estuarine deterioration is a result of reduced river inflows, such as due to the construction of upstream dams (George et al., 2012) or the diversion of freshwater out of estuaries to address issues such as flooding of low-lying land (Das et al., 2012). Reduced freshwater inflows have led to adverse salinity regimes for some estuarine species (Kjerfve & Magill, 1990) and habitat loss (Elliott et al., 2007).

Estuarine restoration attempts to mitigate or even reverse the adverse effects of human-induced loss of freshwater. The specific goals of estuarine restoration range from reducing the salinity (e.g., to preclude hypersalinity) to manipulating the flushing, morphology, residual currents or inundation regimes (Verdonschot et al., 2013). One potential approach to achieve these goals is to restore river inflows to estuaries. For example, in the Barataria (Das et al., 2012) and Breton Sound (Huang et al., 2011) estuaries in Louisiana, USA, Charleston Harbour (Kjerfve & Magill, 1990) in South Carolina, USA, and Lake St Lucia (Forbes et al., 2020) in South Africa. Generally, the relationship between the increased freshwater inflow, the magnitude of hydrodynamic estuarine response, and the consequences in the long term has not been well studied. There is an assumption that achieving and maintaining suitable physical conditions and creating a habitat will allow biological recovery to follow. However, estuaries are inherently nonlinear systems with highly variable responses (Elliott et al., 2007).

Freshwater inflows into estuaries can increase mean water level (Cai et al., 2016), reduce tidal amplitudes, and delay tidal phases (amplifying tidal asymmetry) (Godin, 1991; Godin & Martínez, 1994; Guo et al., 2019). Normally, tidal asymmetry is reflected by the imbalanced ebb and flood durations and maximum flow velocities, as well as by generating an M4 overtide. However, typically in river mouth estuaries (dominated by river and tidal flow) with significant river discharge, tidal duration asymmetry and peak current asymmetry may become inconsistent, meaning a shorter rising tide coexists with stronger ebb currents (Friedrichs & Aubrey, 1988; Guo et al., 2014). The impact of controlled freshwater input on tidal asymmetry in shallow lagoon estuaries is yet to be investigated. Further, uncontrolled river discharge is highly variable in response to weather events, adding complexity and uncertainty.

Based on simple theoretical models to assess the effects of physical parameters, such as freshwater discharge and tides on salinity distribution in estuaries (Xu et al., 2015), shear flow driven by the estuarine circulation (horizontal density gradient) drives the stratifying influence of freshwater input to an estuary (Simpson & Sharpies, 1992). In that light, tidal asymmetry significantly contributes to the net estuarine circulation. This influence can be characterised by the estuary Richardson number ($Ri_E$)that reflects the balance between horizontal advection and vertical mixing (Monismith et al., 1996; Nash et al., 2009), although it does not distinguish between flood and ebb tides (Stacey et al., 2001). Based on the estuary Richardson number range, estuaries can be classified as well-mixed, partially-mixed or salt-wedge. According to Stacey et al. (2001), when $Ri_E$exceeds a critical value, we would expect an asymmetry to develop in the level of mixing and the shear of the velocity profile. However, it is noteworthy that the critical value may vary between estuaries, and more estimates of $Ri_E$ in different environments are essential to specify better the threshold value and its dependency on the estuarine geometry (MacCready & Geyer, 2010).

The Maketū Estuary has a long history of freshwater flow manipulation, with less than ~150,000 $m^3/s$ per tidal cycle (4%) of river flow entering the estuary between the 1950s and 2010s. In 2020 and 2021, a maximum of ~400,000 $m^3/s$ per tidal cycle (13% of river flow — Stage 1) and ~600,000 $m^3/s$ per tidal cycle (20% of river flow — Stage 2) was allowed to enter the estuary, respectively. In this study, we examined the immediate (post Stage 1) and a year thereafter (post Stage 2) impact of added freshwater flow using control gates in a shallow microtidal estuary (Maketū Estuary in Aotearoa, New Zealand), specifically to assess if the desired ecological and cultural benefits have occurred. These benefits include but are not limited to restoring the mauri (life force) of the river and estuary and enabling tangata whenua (local Māori people of this area) to continue the cultural practices of gathering kaimoana (seafood) from the estuary (Environment Bay of Plenty, 2009).

Expectations were that different zones in the estuary may respond differently to the river re-diversion. Therefore, it was vital to examine them separately. Expectations were that the upper estuary would become more fluvially dominated with added freshwater flow while the lower estuary would remain tidally dominated. A mixing zone was expected to exist in the middle estuary, and the borders of this zone should depend on the interaction of tide and river discharge; the higher the river discharge, the closer to the tidal inlet this zone could be. Wind forcing also plays a vital role in the mixing in this shallow zone; the stronger the wind/storm, the more extended its impact would be throughout the estuary. Suspended sediment was expected to enter the estuary via the gates when they're open (their design blocks bedload trasnport) and suspended and bedload sediment through the tidal inlet; depending on the discharge rate, sediment can also be exported out of the tidal inlet (Figure 4.1).

In this study, we investigate the hydrodynamic response to partial restoration of freshwater discharge immediately after the introduction of increased flows and a year later, focusing on water level, current speed and salinity. The objectives of the study related to the impacts of additional freshwater flow at different zones of the estuary during Stages 1 and 2 and assessed: (1) how much water levels changed; (2) whether tidal asymmetry changed and how it influenced the salinity regime; and (3) whether and how much the estuarine circulation and classification changed.

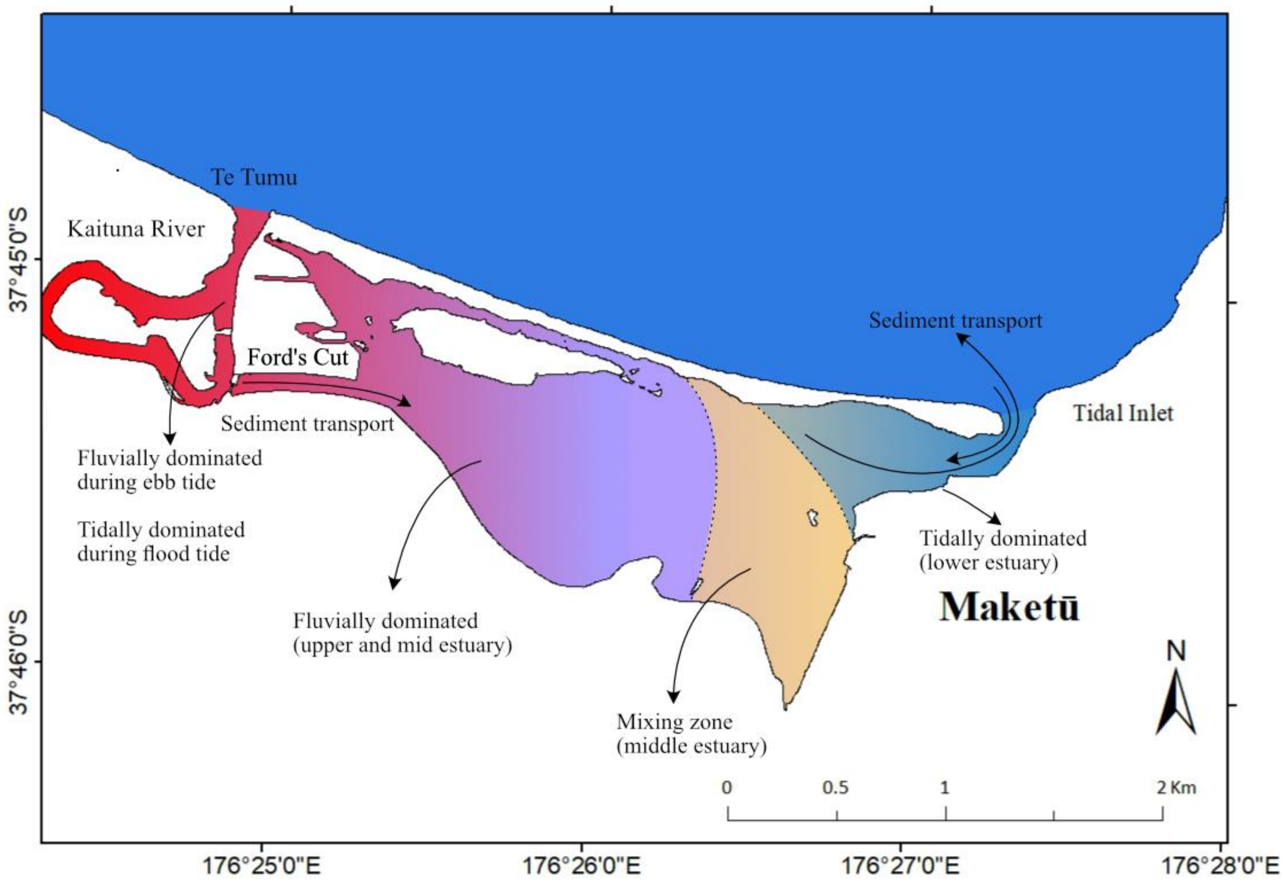



*Figure 4.1 Schematic representation of the expectations after re-diversion of the Kaituna River into the Maketū Estuary*

## 4.3 Study area

The Maketū Estuary is a small (2.3 km$^2$), shallow microtidal barrier-enclosed estuarine lagoon (Burton & Healy, 1985) in the Bay of Plenty of Aotearoa New Zealand (Figure 4.1). According to Hume et al. (2016) and Hume et al. (2007), the Kaituna River diversion changed the estuary's geomorphic classification from a *tidal river mouth* to a *tidal lagoon*. The main body of the estuary includes two main lower estuary tidal channels separated by a flood tidal delta, a shallow deltaic mid-estuary with braided channels, a meandering upper estuary channel, sand and mud intertidal flats, and fringing salt marshes and wetlands; the main freshwater inflow is from the Kaituna River through Ford's Cut (Figure 4.1).

Near-bed salinity levels in the Kaituna River range from 0-20 during flood tide 800 m inland from the river mouth at Te Tumu (Goodhue, 2007). The mean spring tidal prism is estimated at 1,000,000 m$^3$ (Domijan, 2000) and is dominated by marine water entering through the tidal inlet (Figure 3.1). Tides are semi-diurnal, with spring and neap tidal ranges of 1.73 m and 1.16 m, respectively, with a maximum astronomical tidal range of 2.19 m (McKenzie, 2014). The tidal inlet has exhibited relatively dynamic behaviour with reports of increased instability following the Kaituna River diversion (Loomis, 1984; Murray, 1978).

The estuary has undergone multiple modifications such as reclamation of the wetlands, followed by the diversion of the Kaituna River to the sea at Te Tumu (Figure 4.1) in 1956-57 to prevent flooding of the reclaimed land (Murray, 1978). This removal of the dominant freshwater source from the estuary had many consequences, such as a substantial reduction in the flushing ability of previously river-enhanced ebb tide currents and the development of a substantial flood and larger ebb-tidal delta at the original tidal inlet (Hume et al., 2016).

Loomis (1984) summarised the effects of the diversion, focusing mainly on the social consequences resulting from geomorphic, ecological, and water quality changes. They identified four main issues that concerned the local community: siltation of the estuary, including an assessment by the Bay of Plenty Catchment Commission that the estuary would be infilled within 10 years; changes in water quality due to reduced freshwater inflow and tidal flushing that may have reduced the quality and quantity of kaimoana; impacts of "improvements" following diversion, including reclamation, dredging and planting of *Spartina* sp. (now defined as an invasive weed for New Zealand); and contamination of the Kaituna River by agricultural chemicals and effluent. It was also reported that the diversion failed to reduce flood impacts around the Maketū Estuary.

The siltation reported by Murray (1978) and Loomis (1984) primarily occurred close to the inlet, with some occurring within gravity drains entering the estuary from surrounding farmland. Murray (1978) assessed geomorphic changes from historical records and aerial photographs from 1898 to 1977, showing that most changes occurred near the inlet and in response to reclamation and excavation in the upper estuary. Burton & Healy (1985) analysed sediment accumulation and erosion for 0.22 $km^2$ close to the inlet (~15% of the estuary) based on two bathymetric surveys in June 1975 and November 1984. They estimated that allowing for the volume of sediment removed to dredge a channel for vessel access to Maketū, the net accretion rate for this area was 7 $mm.y^{-1}$. This is at the lower end of ranges of 20$^{th}$ Century short-term trends reported for other estuaries around New Zealand, such as 3-15 $mm.y^{-1}$ in Tauranga Harbour (Huirama et al., 2021), 3-33 $mm.y^{-1}$ in Pakuranga Estuary (Swales et al., 2002), 5-25 $mm.y^{-1}$ in Mahurangi Estuary (Oldman et al., 2009) and 18-33 $mm.y^{-1}$ in New River Estuary (Stevens & Robertson, 2011).

Hume et al. (2016) also suggested that there was extensive build-up of sediment on the sandy intertidal flats, although no measurements were available to assess sediment accumulation. Analysis of suspended sediment loads and heavy metals for the Kaituna River and Maketū Estuary (Park, 2010) indicates the main source of fine intertidal sediments within the estuary was the Kaituna River before diversion.

Aubrey and Speer (1985) and Tortell (1985) repeated predictions that the estuary would almost completely infill within a decade, indicating this was contributing to community pressure to restore the estuary. To ameliorate some of the impacts of river diversion, in 1996, restricted flows of 2 $m^3/s$ of freshwater (up to ~100,000 $m^3$ per 12.4-hour tidal cycle and 4% of the river flow) were restored back to the estuary through the Ford's Cut control structure (Figure 4.1) (Hume et al., 2016).

In 2018, the Kaituna re-diversion project was started with its main goal being to significantly increase the volume of freshwater flowing from the Kaituna River into the Maketū Estuary to maximise the ecological and cultural benefits, particularly those relating to wetlands and kaimoana (seafood) (Barrett et al., 2019) while limiting the economic cost and adverse environmental effects to acceptable levels and keeping Te Tumu Cut (Figure 4.1) open for flood protection and navigation (Environment Bay of Plenty, 2009). With increased freshwater flow, restoration targets were likely: (1) reduction in salinity, (2) higher depth-averaged current velocity that can help sediment transport and (3) improved nutrient retention and flushing ability of the estuary. The Kaituna River re-diversion project aimed to return at least 400,000 $m^3$ of freshwater per 12.4-hour tidal cycle (~13% of the river flow) (Stage 1, commissioned 12th February 2020) through 9 control gates, increasing to a total of 600,000 $m^3$ a year later (~20% of the river flow) (Stage 2, commissioned 12th February 2021) through 12 control gates (Park, 2020). To prevent seawater from the western inlet from entering the estuary through the control gates, a salinity block (10 m-wide barrier to prevent seawater from flowing into the river and going through the gates) was constructed near Site 7 (Figure 3.1). To maximise river flow into the estuary, the gates open automatically during flood tide when the water level on the Kaituna Riverside is 40 mm greater than the estuary side (Figure 4.2a and 4.2b), and some or all gates can be closed during river flood conditions at thresholds of ≥1.4 m depending on observed the discharge in the Kaituna River (Hassell et al., 2021).

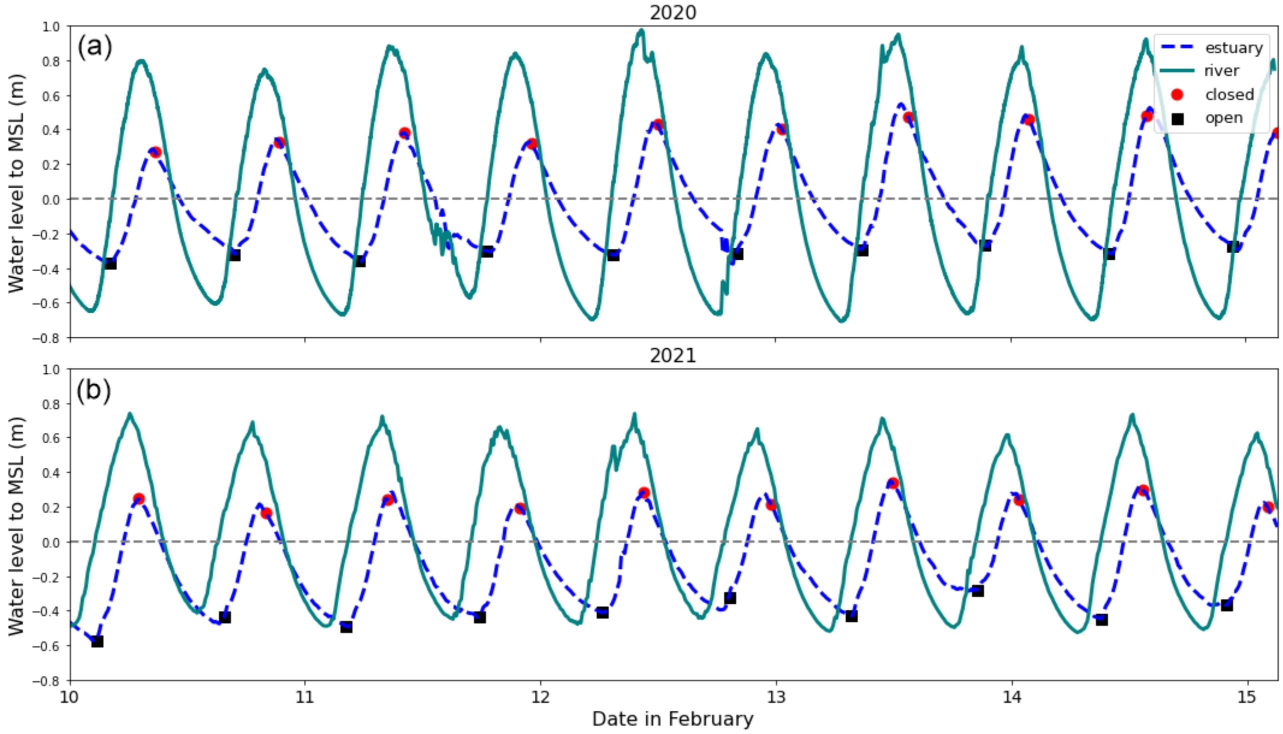



*Figure 4.2 Example of measured water levels on either side of the control gates before (a) and after (b) Stage 1 and 2 commissioning. Kaituna water level data are provided by the Bay of Plenty Regional Council and the estuary data is collected at Site 4. The symbols indicate the gate operation*

## 4.4 Methods

Hydrodynamic data were collected during two periods of fieldwork at 7 sites throughout the estuary (Figure 3.1), undertaken between 23rd January and 3rd March 2020 (Stage 1) and 27th January and 1st March 2021 (Stage 2). Measurements included water level, velocity, temperature, turbidity and salinity. Sites were selected to provide comprehensive spatial coverage, including the major flow pathways and safe locations for deploying instruments. Instrumentation during both field deployments included 3 Nortek Aquadopp Profilers (deployed upward-facing) measuring water levels, currents and turbidity; and 4 Solinst LTC Level Logger Edge, 1 RBR Maestro, and 2 RBR Concertos measuring conductivity, temperature, turbidity and dissolved oxygen.

All the instruments were programmed with similar settings for both sets of fieldwork, with Solinst loggers recording continuously and the other instruments recording in burst mode. The sampling interval was 10 minutes for all instruments except the Maestro, which was 20 minutes. All instruments were running on factory calibration. Solinst loggers were attached to existing navigation poles at Sites 1 and 7 and to temporary stakes at Sites 5 and 6. Aquadopps and Concertos/Maestro were placed together on anchored stainless steel frames at Sites 2, 3 and 4 with sensors located ~0.15–0.27 m above the bed. At Sites 3 and 4, large plastic lids were attached to the underside of the frames to prevent them from sinking into the mud. Weekly checks were undertaken to ensure the sensors were clean and there were issues with sea lettuce (Ulva) fouling at Sites 3 and 4 during the 2020 fieldwork. During the 2021 sampling, the Aquadopp at Site 2 was found displaced on February 5th (most likely due to boat activity).

A bathymetry map of the estuary was developed with the collected data with a vertical accuracy of ±3 cm, LiDAR data from December 2018–April 2019 provided by BOPRC, and offshore data (last updated July 2020) from Land Information New Zealand (LINZ). Precipitation and hourly wind data from Tauranga Aerodrome station (4 m above mean sea level) were provided by the New Zealand MetService. Tidal elevation data from Moturiki (~36 km west of Maketū) were provided by the National Institute of Water and Atmospheric Research (NIWA).

Before data analysis, data during periods of instrument maintenance or sea lettuce fouling, and instrument movement at Site 2, were removed. All the current profile data above the water surface were also removed. Current profiles were depth-averaged to account for temporal variations in depth, using the single-point method (Maghrebi, 2006) at a 0.7 ratio of the water level from the bed. Freshwater discharge rates at Site 4 were calculated by multiplying water levels, channel width (~area), and the depth-averaged east-west velocity component. Atmospheric pressure data were calculated using a weighted average of hourly atmospheric pressure data (33 km and 60 km from Maketū respectively; 2/3 in Tauranga and 1/3 in Whakatane) based on the distance from Maketū to weather stations; the data were then converted to water displacement (metres) due to the inverse barometer effect, and subtracted from collected data to determine the final water level.

One of the data analysis challenges was isolating the effect of restored freshwater inflows from other effects of other processes such as tidal, wind and wave forcing (i.e., natural variability). To isolate the impact of freshwater restoration, average tidal cycles (canonical tidal cycles) were calculated for the 12 days pre-restoration and 16 days post-restoration for water level, depth-averaged current speed and near-bed salinity (0.15–0.6 m above the bed). This canonical semi-diurnal tidal cycle starts at local high tide and ends at subsequent high tide 12.4 hours later. Harmonic analysis was done with U_TIDE (Codiga, 2011)(MATLAB toolbox widely used for tidal analysis) to compare the tidal asymmetry results using water level data collected during Stage 1 and Stage 2.

To evaluate the mixing behaviour, estuarine Richardson number ($Ri_E$) defined by Fischer (1976)was calculated at Site 2, 3 and 4 using the following:

$$Ri_E = g\frac{\Delta\rho}{\rho}\left(\frac{Q_f}{Wu_{tidal}^3}\right) \quad (1)$$

Where g is the gravitational acceleration, $\Delta\rho/\rho$ = 0.025 is the fractional density difference between river (fresh) and ocean (salt) water, $W = 80\ m, 42\ m$ and $40\ m$ is the effective channel width at Site 2 (near the tidal inlet), Site 3 and 4 respectively, $Q_f$ is the mean river discharge, and $u_{tidal}$ is root-mean-square tidal current speed.

## 4.5 Results

### 4.5.1 Environmental conditions

Sampling before partial freshwater restoration during Stage 1 in 2020 included a neap tide and a perigean spring tide (Figure 4.5c), which occurs once a lunar month along the coast of New Zealand. At Maketū, non-perigean spring tides have a smaller amplitude closer to neap tides. The Stage 1 partial freshwater restoration started 3 days after the perigean spring tide. The 16 days of sampling for Stage 2 included a neap tide followed by a non-perigean spring tide. Tidal ranges during the five weeks of measurements were ~1.1 m during the neap tide, ~2 m during the perigean spring tide and 1.5 m during the regular spring tide. Hourly winds were mainly from the southwest (typical of this region), with an average hourly speed of 13.2 km/h (Figures 4.3a, 4.5a and 4.5b). Rainfall during this period was insignificant, with a total of 8.2 mm over 10 days (Figure 4.4a).

Sampling during Stage 2 in 2021 included two spring-neap tidal cycles (Figure 4.5c). Tidal ranges during February 2021 were ~1 m during the neap tides and ~1.9 m and ~1.7 m during the spring tides. Hourly winds were mostly from the northeast, with an average hourly speed of 12.4 km/h (Figure 4.3b, 4.5a and 4.5b). Rainfall during Stage 2 in 2021 was more significant than in 2020 and was ~1.45 mm/hr for 6 days (total of 63.8 mm)(Figure 4.4b).

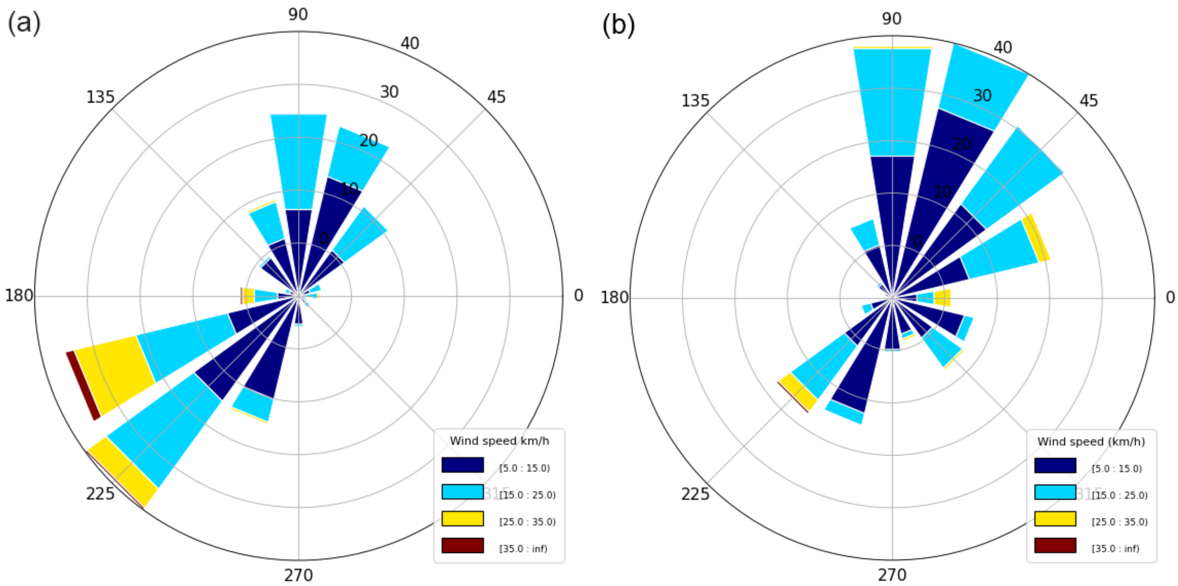



*Figure 4.3 Wind speed and direction in (a) 2020 and (b) 2021 during February provided by NIWA*

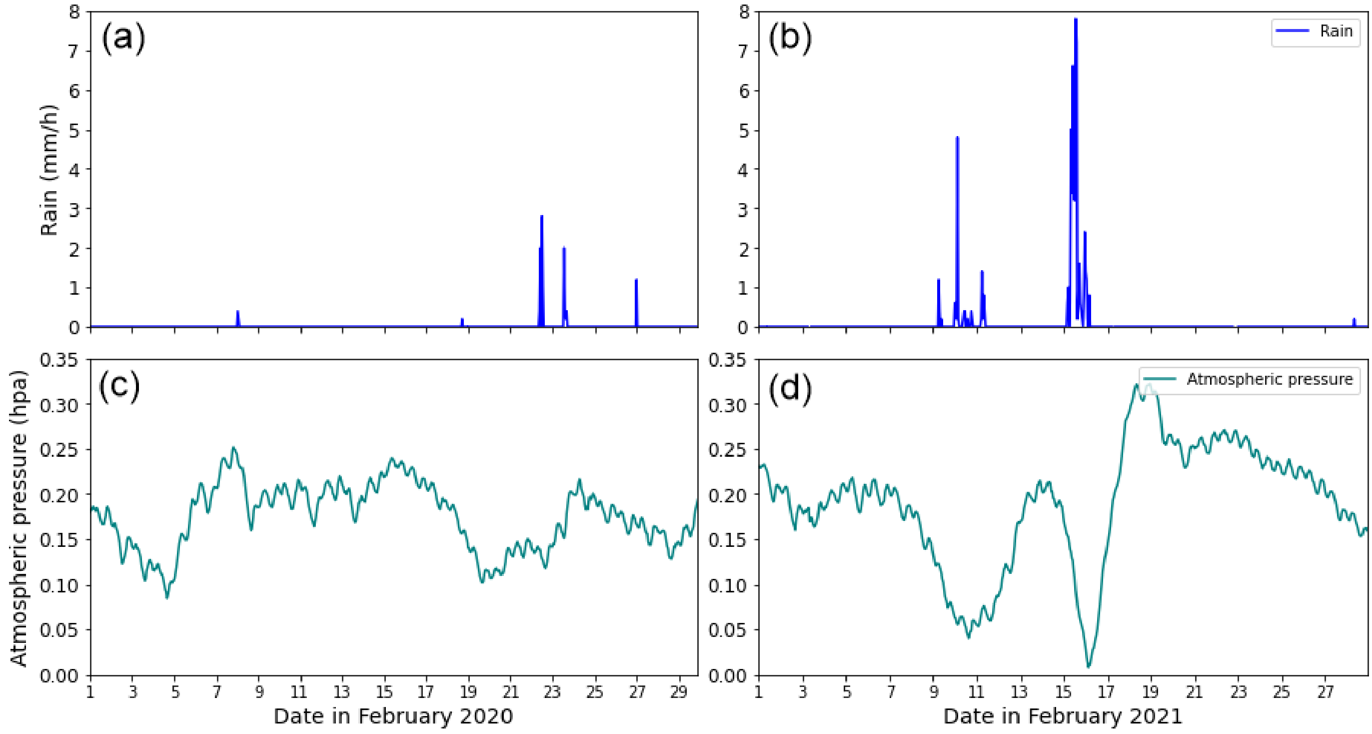



*Figure 4.4 Hourly rainfall and atmospheric pressure for Maketū during the instrument deployments for Stage 1 and 2 monitoring;data provided by NIWA. Note that 2020 was a leap year*

Water levels in the Kaituna River at Ford's Cut showed a smaller range than the tidal elevations measured at the tidal inlet for both the Stage 1 and 2 monitoring periods (Figure 4.5c and 4.5d). The tides during Stage 1 in 2020 had the largest spring tide on 12$^{th}$ February, while for Stage 2 in 2021, the largest spring tides occurred on 1st February and 2$^{nd}$ March either side of the monitoring period (Figure 4.5c). A storm surge of up to ~0.5 m affected water levels recorded in the Kaituna River and the tidal inlet between 15$^{th}$ and 17$^{th}$ February 2021 (Figure 4.5d and 4.6a) associated with the passage of a deep low (Figure 4.4d).

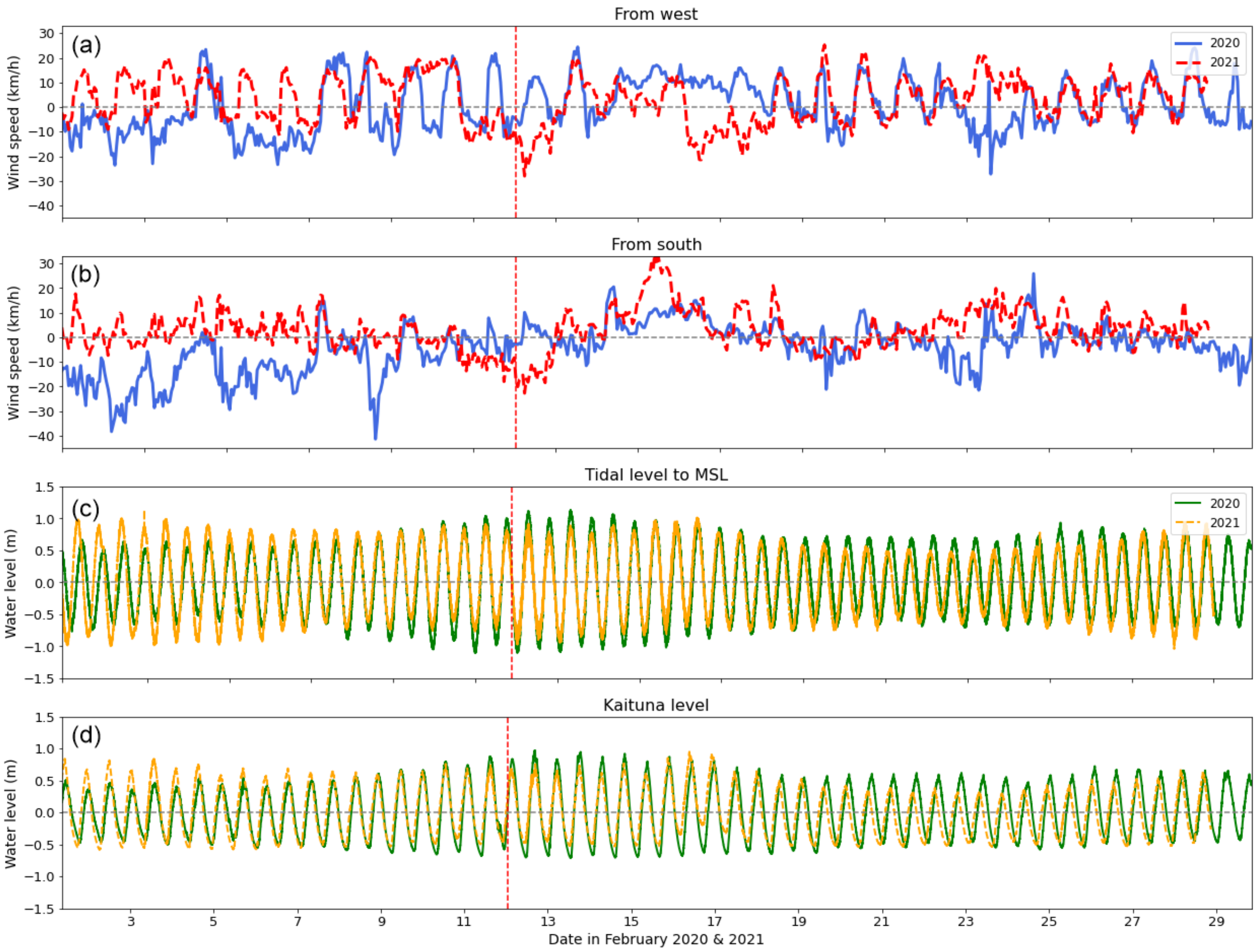



*Figure 4.5 Wind speed and direction from west and south (a and b); tidal elevation (c) and Kaituna water level at Ford's Cut (d) in 2020 and 2021. Wind and tidal elevation data provided by NIWA*

For Stage 2, a maximum of 12 gates were open (under the BOPRC flood control protocols, the number of gates may be less than 12 at times, such as the storm event in February 2021), whereas Stage 1 was restricted to a maximum of 9 gates. The freshwater discharge through 9 gates for the first 12 days of February in 2020 (an average of ~30m$^3$/s) was higher than through 12 gates in 2021 (an average of ~25m$^3$/s) by ~16% (Figure 4.6b) and the remaining 17 days in 2020 show an average of ~45m$^3$/s which is higher than the remaining 16 days in 2021 by ~33% (an average of ~30m$^3$/s) (Figure 4.6c).

On average, the discharge through gates per tidal cycle is calculated at ~540,000 m$^3$ and 396,000 m$^3$ for Stage 1 and 2, respectively, where the design maximum discharges were 400,000 m3 and 600,000 m3 respectively. The lower river discharge during Stage 2 is attributed to the difference in spring tidal range and length, Kaituna river discharge, and gates' operation (some being closed during the flood event on February 17$^{th}$ 2021). Furthermore, BOPRC reported on Kaituna upper catchment flows from 1954 to the present, and their results show a high level of variability in flood occurrences and river flows. More specifically, the discharge is more than 20.687, 25.591 and 35.929 m$^3$/s, 50% of the time, 25% of the time and 10% of the time, respectively (Figure A1; see Appendix A). These data indicate that the actual inflows can deviate significantly from the design inflows.

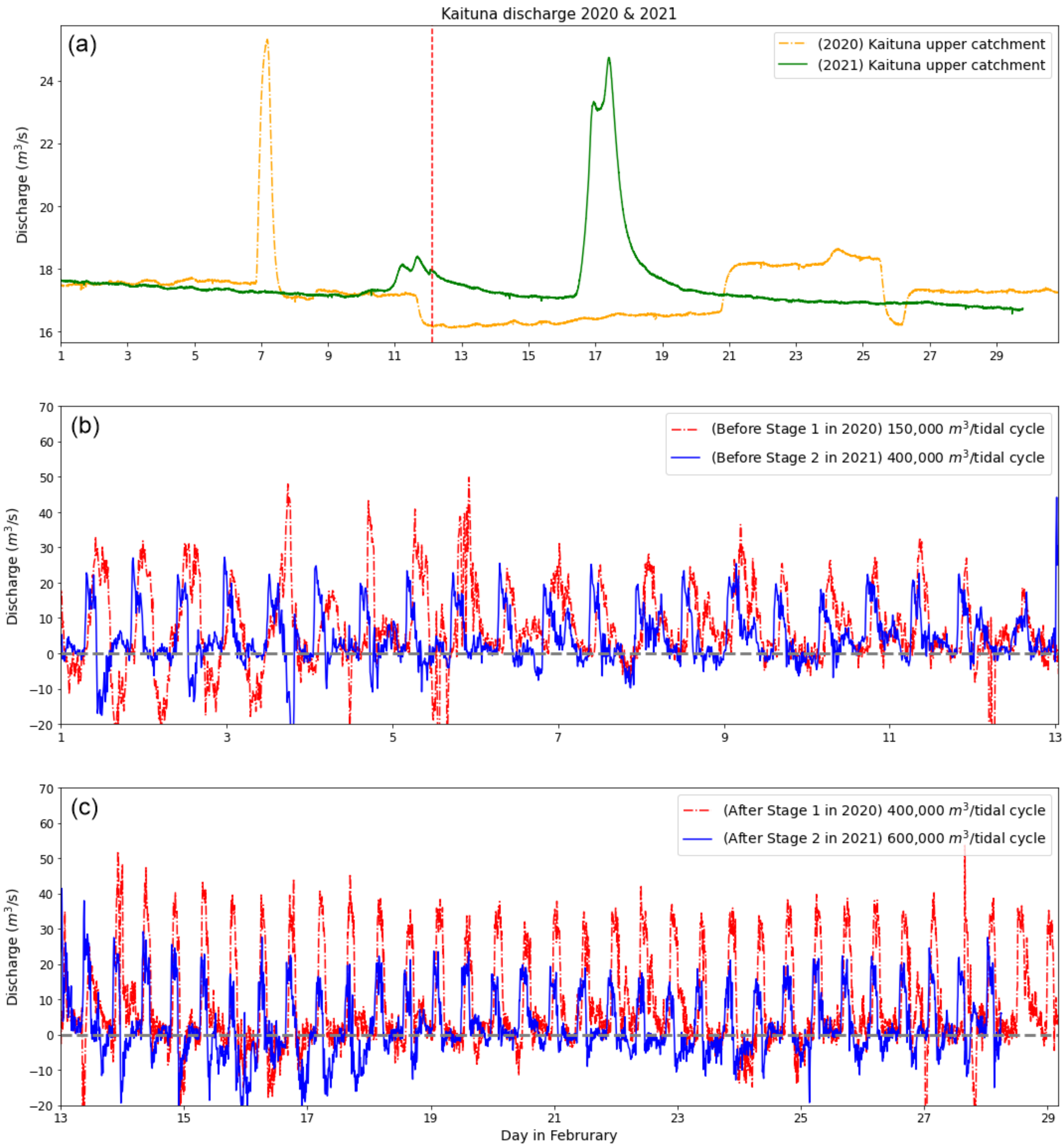



*Figure 4.6 Total Kaituna discharge at (a) Taaheke and Ford's Cut in 2020 and 2021, for the periods (b) before and (c) after Stage 1 and 2 to gate operation to allow increased freshwater discharge into Ford's Cut and the Maketū Estuary*

### 4.5.2 Water level and surface gradients

After Stage 1 in 2020 and before Stage 2 in 2021, with estimated ~400,000 m$^3$ of freshwater per 12.4-hour tidal cycle, average water levels at Sites 1 and 2 do not show any change (Figures 4.7g and 4.7a). At Site 3, in 2021, the average water level decreases by up to ~0.09 m between hours 4–12 of the tidal cycle (Figure 4.7b); Site 4 shows a similar trend throughout the tidal cycle (Figure 4.7c). At Sites 5 and 6, the average water level in 2021 is substantially lower than in 2020, with a general decrease of ~0.1 m and ~0.2 m, respectively (Figure 4.7h and 4.7i). After Stage 2 of partial freshwater restoration, the average water level decreased across the estuary. At all 6 estuary sites, a decline of up to ~0.1 m in average water level was observed, especially at the beginning and end of each tidal cycle. However, no significant ebb or flood flow duration change was observed (Figures 4.7a, 4.7b, 4.7c, 4.7g, 4.7h and 4.7i).

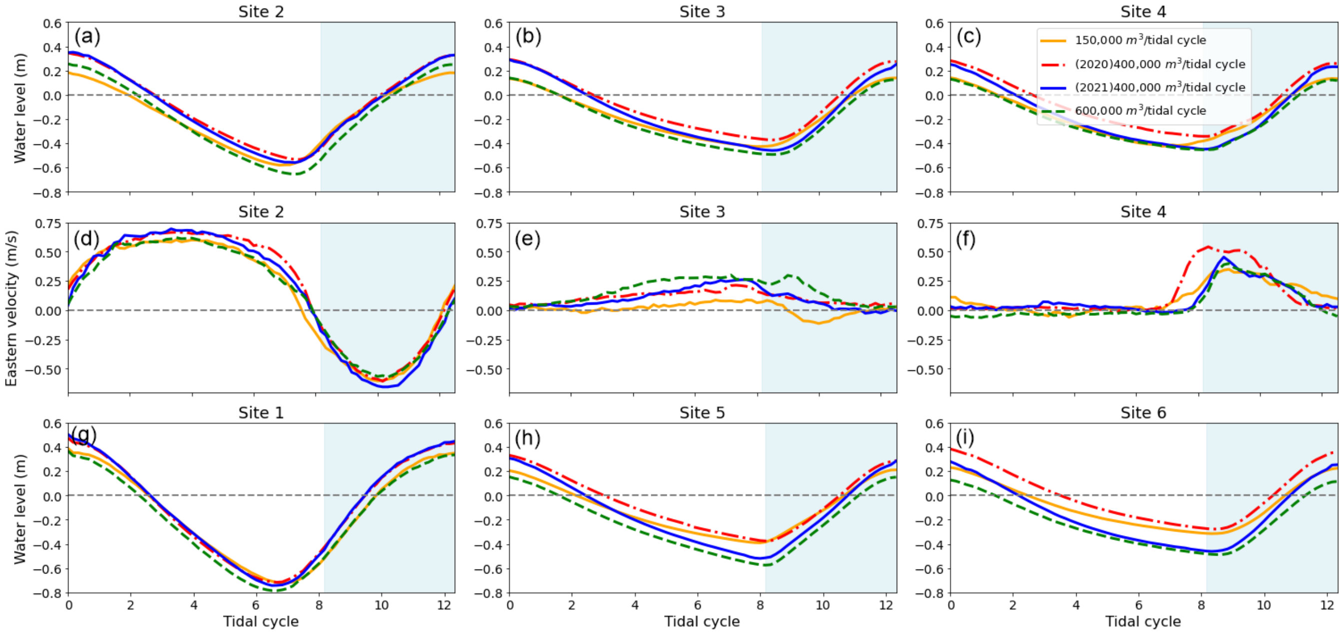



*Figure 4.7 Average tidal cycle variations of mean water level and depth-averaged east-west component of velocities were measured (Sites 2, 3 & 4), before (orange) and after (red, dash-dotted) the Stage 1 and before (blue) and after (green, dashed) Stage 2 gate commissioning at each site. The shaded areas correspond to the period during flood tide when the control gates may be open based on water level difference on either side of the gates*

Water level gradients provide some insight into the direction and intensity of the flows between monitoring sites at different locations in Maketū Estuary (Figures 4.8 and 4.9). After Stage 2, water level gradients between Sites 2 and 4 (Figures 4.8d) decreased by up to ~0.06 m between hours 4–10 of the tidal cycle and then quickly increased by up to ~0.08 until the end of the tidal cycle (Figure 4.7d). Although this pattern of behaviour is similar to that observed after Stage 1, the timing and magnitude of the peak gradients differ, which leads to a uniform reduction of up to ~0.1 m/s in the peak flood and ebb depth-averaged velocities along the channel (west-east) at Site 2 (Figure 4.8g).

Water level gradients between Sites 3 and 4 in the upper to mid-estuary show no change following Stage 2 commission (Figure 4.9a, 4.9b). However, a substantial increase of up to ~0.2 m/s in depth-averaged eastern velocity is observed at Site 3, specifically between hours 4–7 and 9–11 of the tidal cycle (Figure 4.8h).

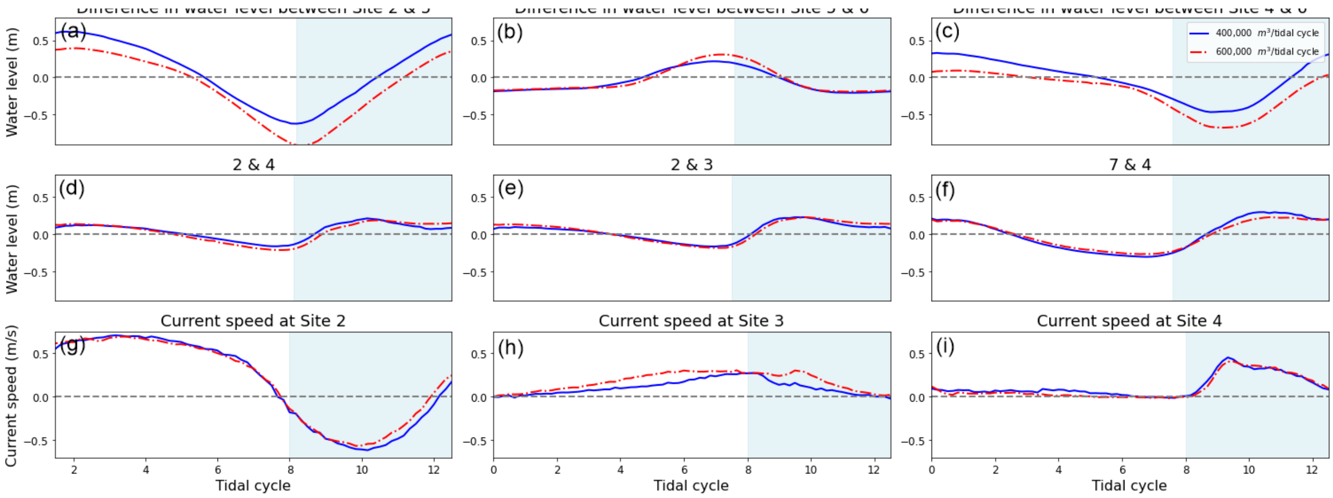
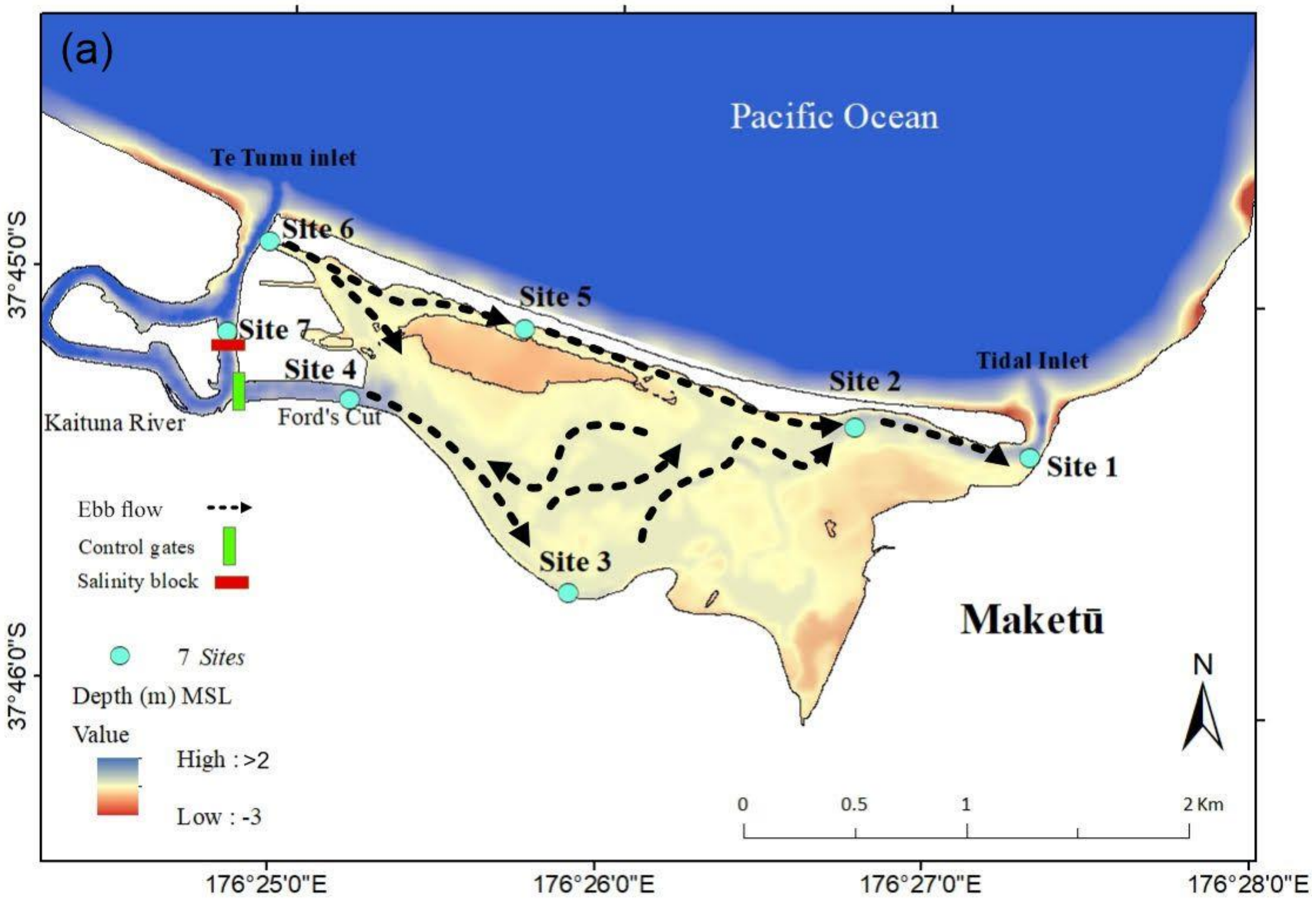


*Figure 4.8 The difference in mean water levels before (blue) and after (red, dash-dotted) the Stage 2 gate commission between (a) Sites 2 and 5, (b) Sitse 5 and 6, (c) Sites 4 and 6, (d) Sites 2 and 4, (e) Sites 2 and 4, (f) Sites 7 and 4 and depth-averaged east-west component of velocity at Site 2 (g), Site 3 (h) and Site 4 (i). The shaded areas correspond to the period during flood tide when the control gates may be open*

The difference in water level between Sites 7 and 4 (Figure 4.8f) is a consequence of the gates opening since the gates are designed to open during flood tide when the water level on the riverside (Site 7) is at least ~0.04 m higher than water level on the estuary side (Site 4). There is a substantial decrease of ~0.1 m in average water level gradient between Sites 7 and 4, specifically between hours 9–12 of the tidal cycle when the gates may be open (Figure 4.8f). However, this decrease does not impact the average depth-averaged eastern velocity at Site 4 (Figure 4.8i), as the gradient predominantly occurs as a step change at the gates (Figure 4.2), which may create a hydraulic jump at the western end of Ford's Cut; and not as a continuous slope from Site 7 at the western end to Site 4 at the eastern end of Ford's Cut. The velocities created by this inflow are apparently dissipated before Site 4. Still, the hydraulic jump may contribute to the increased water level at Site 4.


(a)
Pacific Ocean
Te Tumu inlet
Site 6
Site 5
Site 7
Site 4
Kaituna River
Ford's Cut
Site 2
Tidal Inlet
Site 1
Site 3
Maketū
Ebb flow
Control gates
Salinity block
7 Sites
Depth (m) MSL
Value
High : >2
Low : -3
N
0
0.5
1
2 Km
37°45'0"S
37°46'0"S
176°25'0"E
176°26'0"E
176°27'0"E
176°28'0"E

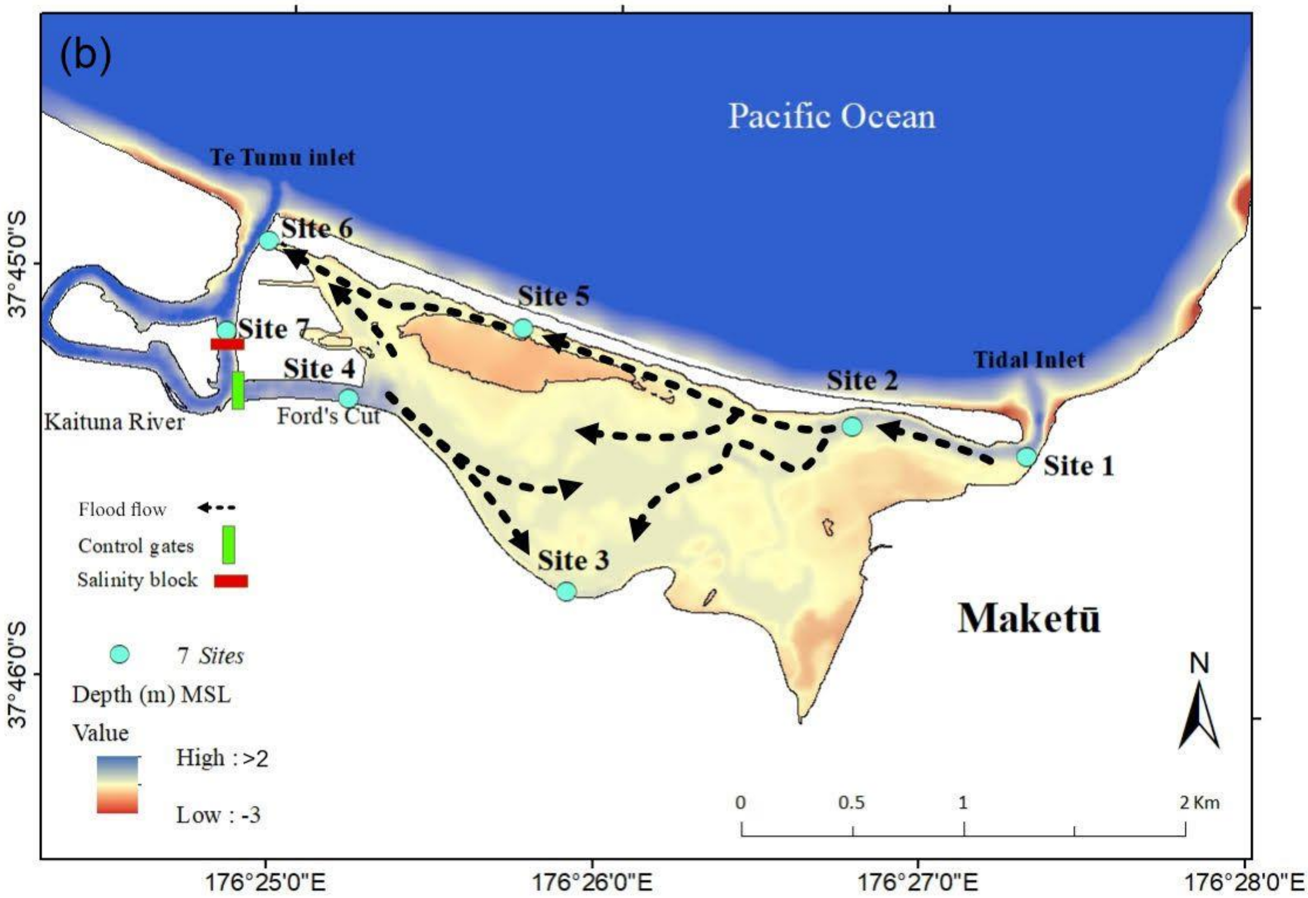

(b)
Pacific Ocean
Te Tumu inlet
Site 6
Site 5
Site 7
Site 4
Kaituna River
Ford's Cut
Site 2
Tidal Inlet
Site 1
Site 3
Maketū
Flood flow
Control gates
Salinity block
7 Sites
Depth (m) MSL
Value
High : >2
Low : -3
N
0
0.5
1
2 Km
37°45'0"S
37°46'0"S
176°25'0"E
176°26'0"E
176°27'0"E
176°28'0"E

*Figure 4.9 Schematic map displays dominant flow directions during (a) ebb and (b) flood tide*

The phase and amplitude of the $M_2$ and $M_4$ constituents were extracted from the water level data with Utide for 5 sites. A comparison of the constituents before and after Stages 1 and 2 (Table 4.1) showed no significant change in the sea surface phase of $M_4$ relative to $M_2$, as defined by $2M_2$-$M_4$ (Freidrichs & Aubrey, 1988). Generally, if 0° < $2M_2$-$M_4$< 180°, the estuary is classified as 'flood-dominant' and exhibits shorter floods and necessarily higher velocity flood currents. If 180° < $2M_2$-$M_4$< 360°, the estuary is 'ebb-dominant' with shorter, higher velocity ebb tides, where $2M_2$ and $M_4$ are the fundamental and first harmonic phases (Friedrichs & Aubrey, 1988).

*Table 4.1 Flood/ebb dominant results in terms of $M_4$ overtide for 5 sites during Stage 1 and Stage 2*

| Sites | 2 $M_2$ - $M_4$ (before Stage 1) | Asym | 2 $M_2$ - $M_4$ (after Stage 1) | Asym | 2 $M_2$ - $M_4$ (before Stage 2) | Asym | 2 $M_2$ - $M_4$ (after Stage 2) | Asym |
|---|---|---|---|---|---|---|---|---|
| Site 1 | 109 | flood dominant | 91 | flood dominant | 122 | flood dominant | 128 | flood dominant |
| Site 2 | 126 | flood dominant | 91 | flood dominant | 99 | flood dominant | 94 | flood dominant |
| Site 3 | 58 | flood dominant | 58 | flood dominant | 59 | flood dominant | 57 | flood dominant |
| Site 4 | 44.8 | flood dominant | 52 | flood dominant | 49 | flood dominant | 47 | flood dominant |
| Site 6 | 54 | flood dominant | 58 | flood dominant | 54 | flood dominant | 55 | flood dominant |

### 4.5.3 Currents

Current measurements were collected at three sites (2, 3 and 4) during Stage 1 and Stage 2 monitoring deployments, with each deployment covering several tidal cycles before and after gates were commissioned in Stages 1 and 2. After Stage 1 in 2020, and before Stage 2 in 2021, at Site 2 in the lower estuary, the mean depth-averaged eastward (ebb) velocity increased from ~0.1 m/s to a maximum of ~0.7 m/s between hours 0–4 of the tidal cycle during ebb tide and then dropped to zero at hour 8 when the gates opened. After hour 8, the mean depth-averaged eastward velocity rose to a maximum of ~0.6 m/s in the westward (flood) direction during flood tide at hour 10 of the tidal cycle (Figure 4.8g). After Stage 2 started, the mean depth-averaged eastward velocity decreased by ~0.05 m/s during ebb tide, and the westward velocity decreased by ~0.1 m/s during flood tide (Figure 4.8g).

At Site 3 in the mid-estuary, before Stage 2, the mean depth-averaged eastward (ebb) velocity steadily increased from 0 m/s at the start of the tidal cycle to a maximum of ~0.22 m/s at hour 10 of the tidal cycle (Figure 4.8h), before returning to 0 m/s. This corresponds to ebb-directed flow throughout the tidal cycle. After

Stage 2 started, a similar trend was observed, but with a double peak involving an earlier main peak at mid-tide (~6 hours) and a second increase of ~0.1 m/s in the maximum depth-averaged eastward velocity between hours 9–10 of the tidal cycle during flood tide (Figure 4.8h).

At Site 4 in the upper estuary at the eastern end of Ford's Cut, after Stage 1, the mean depth-averaged eastward velocities were relatively low (up to the maximum value of ~0.1 m/s) between hours 0–8 of the tidal cycle (up to ~0.05 m/s) before the gates open. Once the gates opened, they rose to a maximum of 0.50-0.55 m/s between hours 8–12, dropping to 0.05 m/s when the gates closed. After Stage 2 was commissioned, the only major difference was that maximum velocities while the gates were open were maintained longer (Figure 4.8i).

To illustrate the pattern of changing tidal velocities throughout the tidal cycle (Defra, 2008; Weisscher et al., 2020), tidal stage velocity (Figure 4.10) and polar velocity-stage (Figure 4.11) were used. Site 2 in the lower estuary (near the tidal inlet) shows a minor ebb dominance with similar peak ebb and flood velocities for all the freshwater inflow conditions (Figures 4.10a, 4.11a and 4.11d). While high tide is associated with slack water (no current velocity), low tide is associated with ebb-directed flows, with the reversal to flood flow occurring while the water level is still falling. The maximum and minimum water levels at high and low tide changed following Stages 1 and 2. After Stage 1 commissioning, the high tide water level was 0.15-0.20 m higher, while the low tide water level was relatively unchanged. After Stage 2 started, both high tide and low tide water levels dropped by ~0.10 m.

At Site 3, east-west currents (coincident with the channel orientation) were ebb dominant before Stage 2 and became more ebb dominant after commissioning, with an increase in peak ebb velocities of ~0.08 m/s. No flow direction changes were observed at this site (Figure 4.10b, 4.11b and 4.11e).

At Site 4 in the upper estuary (near the control gates), east-west currents were ebb dominant through all monitoring periods. Immediately after Stage 1 started the peak ebb velocity was ~0.2 m/s higher, and the minimum low tide elevation was ~0.1 m higher than before the gates were opened. A year later, before the start of Stage 2, the velocities and elevations were similar to before Stage 1 started (Figures 12c, 13c and 13f) both before and after the Stage 2 gate commission with no substantial change in flow velocities. After the commissioning of Stage 2, there was no significant change in tidal velocities and elevations (Figures 4.11c, 4.12c and 4.12f).

Overall, the velocity measures indicate that the lower (Site 2), middle (Site 3) and upper (Site 4) estuary regions are ebb-dominated, which is consistent with a higher ebb tidal prism due to the inflow of freshwater.

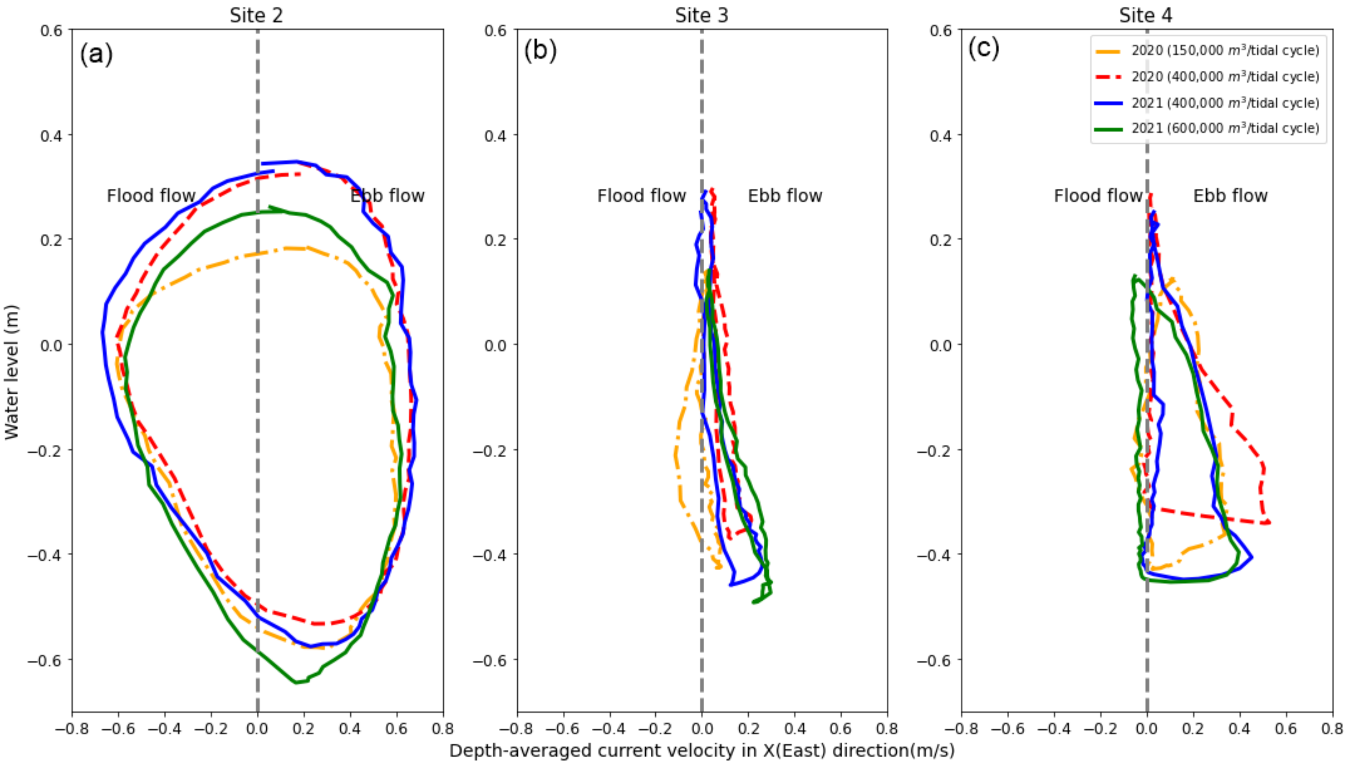



*Figure 4.10 Tidal stage-velocity plot for (a) Site 2, (b) Site 3 and (c) Site 4 before and after Stage 1 (orange and red), and before and after Stage 2 (blue and green), gate commissions*

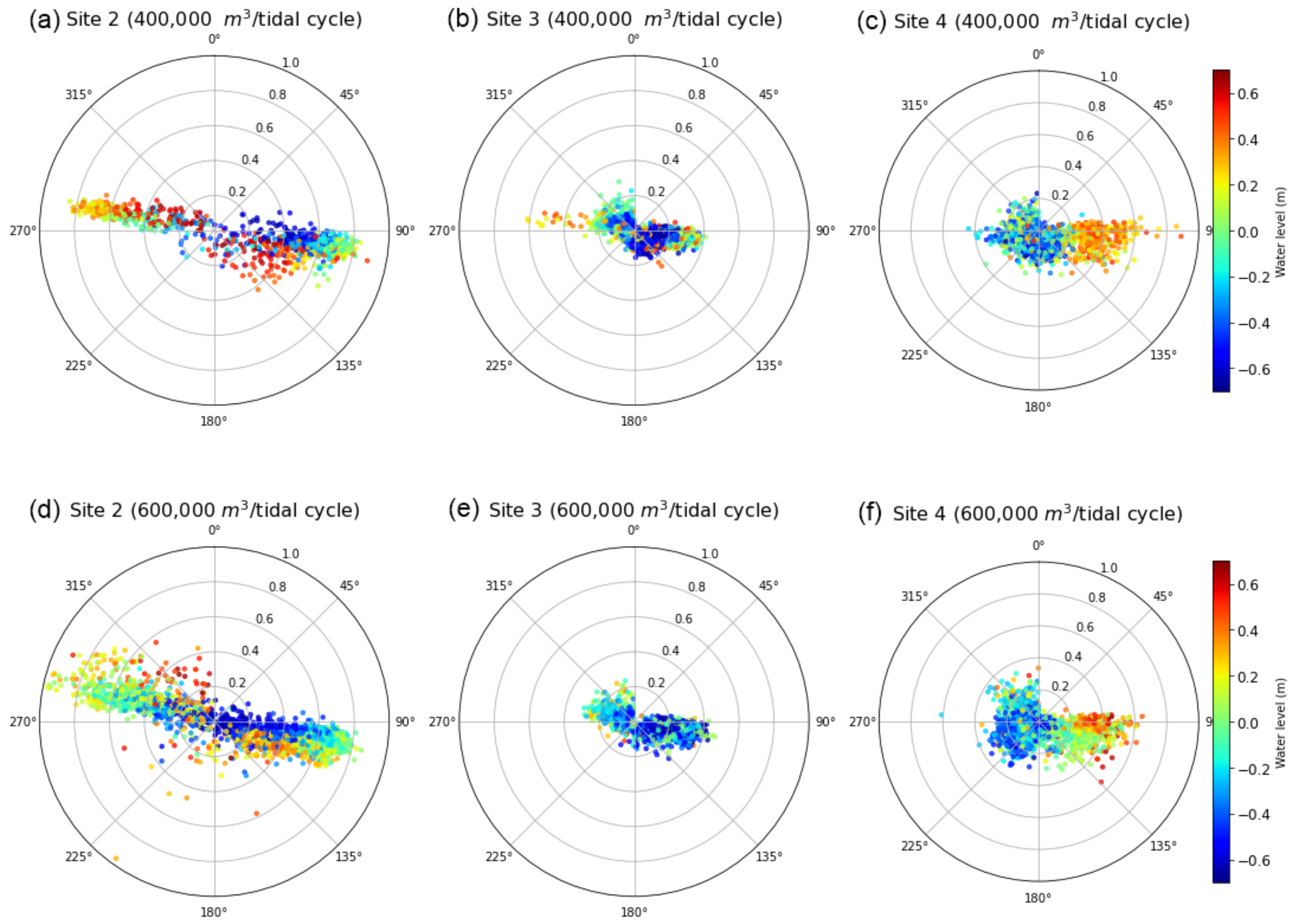



*Figure 4.11 Polar velocity-stage plots for Site 2, Site 3 and Site 4 before (a, b and c) and after (d, e and f) Stage 2 gate commissioning*

## 4.5.4 Salinity

After commissioning Stage 2, there was a substantial reduction in the near-bed salinity at all sites (Figure 4.12). There was a similar reduction in the near-bed salinity for all sites except Site 6 after the Stage 1 commissioning. Between February 2020 and February 2021, the mean near-bed salinities increased at all sites, with the largest increases occurring at Sites 2, 3 and 4. The patterns of salinity changes during a tidal cycle are inconsistent between all the sites (Figure 4.12) and are discussed in more detail below.

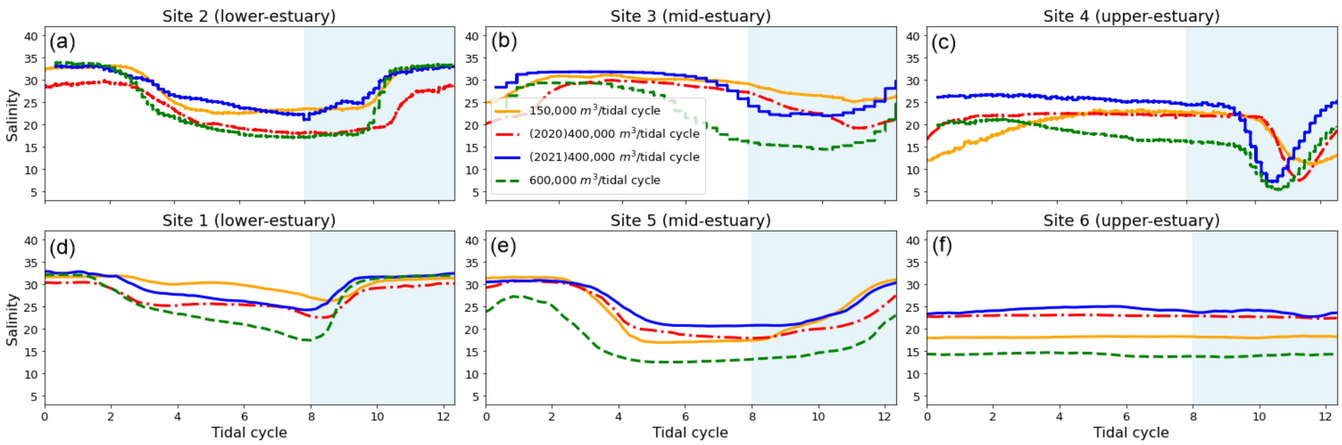


*Figure 4.12 Figure shows the average near-bed salinity levels before (orange) and after (red, dash-dotted) the start of Stage 1 as well as before (blue) and after (green, dashed) Stage 2 commissioning for each site monitored: Site 1 (c), Site 2 (a), Site 3 (b), Site 4 (c), Site 5 (d) and Site 6 (e).*

At Site 1, closest to the tidal inlet, after Stage 1 started in 2020, mean near-bed salinity decreased from ~30 to ~25 during hours 2–8 of the tidal cycle (ebb tide) before increasing sharply to ~30 between hours 8–10. Immediately before Stage 2, a year later, the mean near-bed salinity was ~3–5 higher throughout most of the tidal cycle with a slightly reduced duration of lowered salinity (Figure 4.12d). The mean near-bed salinity dropped from ~33 to ~26 between hours 2–9 of the tidal cycle during the ebb flow before returning to ~33 again (Figure 4.12d). After Stage 2 started, this drop was sharper and reached a minimum of ~19 between hours 7–8 of the tidal cycle (Figure 4.12d).

At Site 2, a uniform increase of ~5 relative to the start of Stage 1 was observed through the tidal cycle before Stage 2 in 2021 (Figure 4.12a), but with a more prolonged decline extending later into the flood tide. Before Stage 2 started, the mean near-bed salinity decreased from ~33 at hours 0–3 to ~24 between hours 5–9 before increasing quickly back to ~33, remaining for the rest of the tidal cycle (Figure 4.12a). After Stage 2, mean bottom salinity at Site 2 decreased from ~33 to ~19 between hours 2–10 of the tidal cycle before increasing to ~33 again for the rest of the tidal cycle (Figure 4.12a).

At Site 3 in the southern mid-estuary, after Stage 1, mean near-bed salinity increased from ~20 to ~28 during hours 0–2 and remained at ~28 until hour 8 before decreasing to ~20 by the end of the tidal cycle. A year later, before Stage 2, the mean near-bed salinity decreased from ~29 at hour 0 to ~25 at hour 8 of the tidal cycle and then increased back to ~29 (Figure 4.12b). At Site 3 before Stage 2, mean near-bed salinity remained at ~31 between hours 0–7 of the tidal cycle and then dropped to a minimum of ~25 between hours 7–12 when the gates were open (Figure 4.12b). After Stage 2 started, this drop happened sooner (at hour 4) and reached a minimum of ~16 between hours 7–11 (Figure 4.12b).

At Site 5 in the northern mid-estuary, mean bottom salinity slowly decreased from ~30 at hour 3 and reached a minimum of ~22 at hour 10 of the tidal cycle before Stage 2. After Stage 2 commenced, it dropped from ~25 at hours 0–2 to ~12 between hours 4–10 of the tidal cycle before returning to ~25 (Figure 4.12e). At Site 4 in the upper estuary near Ford's Cut, after Stage 1, the mean bottom salinity remained at ~20 until hour 11, declining sharply to ~5 at hour 12 before increasing again to ~20. Immediately before Stage 2, mean near-bed salinity remained at ~25 between hours 0–8 of the tidal cycle and then declined sharply to a minimum of ~7 at hour 10 before returning to ~25 at the end of the tidal cycle (Figure 4.12c). After Stage 2 gate commission, the mean bottom salinity level started at ~20 at hour 0 and slowly dropped to a minimum of ~5 at hour 10 before rising to ~20 again (Figure 4.12c).

Before Stage 2 at Site 6, located in the upper estuary with poor connectivity with the rest of the estuary, the mean near-bed salinity remained at ~25 throughout the tidal cycle. After Stage 2 started, the salinity levels were lower and remained at ~15 through the tidal cycle (Figure 4.12f). The salinity range during a tidal cycle consistently increased in the lower estuary (Sites 1 & 2) over time as the freshwater inflow increased, although the mean salinity was variable (Figure 4.13). Site 3 appears to experience an increased range in the middle estuary immediately after the increased freshwater inflow for both Stages 1 and 2. This seems to reduce to a similar range to that observed before Stage 1 after sufficient time. The changes to the range at Site 5 are variable, with no clear trend with increasing freshwater inflow. Site 4 shows the largest ranges in salinity for the upper estuary, and Site 6 has the lowest ranges for both the upper and entire estuary. There is no consistent trend evident for either site.

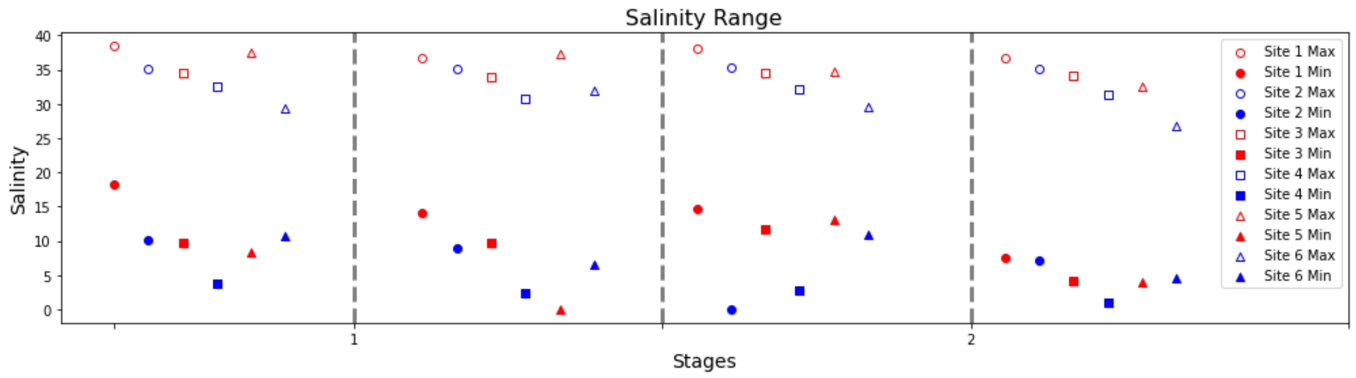



*Figure 4.13 Minimum (solid markers) and maximum (open markers) salinity at each site (1-6) for before and after the two Stages of the re-diversion monitored: before Stage 1 with ~150,000 m$^3$ per tidal cycle; immediately after Stage 1 commenced with ~400,000 m$^3$ per tidal cycle; before Stage 2 with 400,000 m$^3$ per tidal cycle; and immediately after Stage 2 started with 600,000 m$^3$ per tidal cycle. Circles, squares and triangles correspond to the lower, middle and upper estuary*

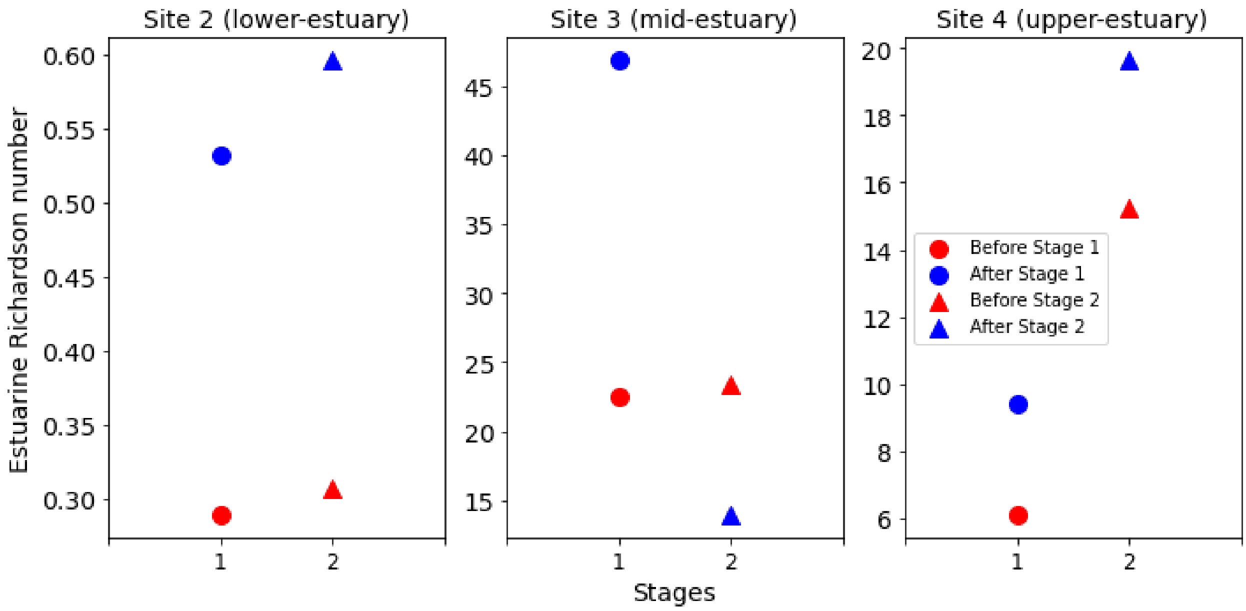



*Figure 4.14 Estuarine Richardson number calculated based on current velocity measurements at (a) Site 2, (b) Site 3 and (c) Site 4 for before and after the two Stages of the re-diversion*

Adding freshwater inflow to an estuary is generally expected to increase stratification, and tidally induced salt intrusion will be weakened and displaced seaward (Domijan, 2000; Geyer & MacCready, 2014). This behaviour can be characterised by the estuarine Richardson number and it increased after Stage 1 for sites 2, 3 and 4, with Site 2 exceeding a critical value of 0.3, which induced asymmetry in mixing. After Stage 2, Sites 2 and 4 showed an increase in Estuarine Richardson number, but Site 3 showed a decrease (Figure 4.14). With increasing freshwater discharge, Maketū Estuary would be expected to move from partially mixed towards stratified conditions. The estuarine Richardson numbers indicate this is the case but do not reach the threshold of 0.8 required for stratified conditions as determined for a similar, but unmodified estuary, at the mouth of the nearby Tairua River (Liu et al., 2019).

## 4.6 Discussion

The general purpose of the Kaituna re-diversion project has been to improve water quality, including changes to salinity regime, tidal asymmetry and net transport while minimising the probability of flood occurrence in the lower catchment and the estuary. Among these optimal changes are reduction in salinity, shift to ebb dominance, which then leads to sediment transport out of the estuary with the right conditions. Reduction in salinity combined with less suspended sediment can lead to less harmful macroalgae, which is an indication of improvement in the estuarine ecosystem. Some of these changes can take place immediately while others become effective long term. Therefore, two sets of field data collection were conducted (immediately after each stage) to observe these changes to the hydrodynamics of the estuary; the parameters included water level, current velocity and salinity, with salinity and current velocity being indicators of the mixing and stratification within the estuary.

The Maketū estuary can be divided into three zones based on the tidal impact and hydrodynamics (Figure 4.1): lower estuary (lagoon) dominated by tidal exchange with the sea; upper estuary (lagoon) with relatively confined areas that freshwater inflows may influence; and the middle transitional estuary (lagoon) characterised by shallow braided channels and shoals.

### 4.6.1 Upper-estuary (lagoon)

The upper estuary includes two main channels: the former river channel connecting to the artificially created Ford's Cut (Site 4), Papahikahawai Channel and the lagoon (Site 6) (Figure 3.1). Ford's Cut has a controlled freshwater inflow from the Kaituna River and some inflow from the drainage of adjacent farmland. Papahikahawai Channel is very restricted in terms of connection to the rest of the estuary due in part to reclamations and no longer has a significant direct freshwater inflow. We observed lower water levels in the upper-estuary at Sites 4 and 6 during Stage 2. The lower freshwater input during Stage 2 is due to lower water levels in the Kaituna River in 2021 compared to 2020, despite the higher rainfall during February. Tidal asymmetry is observed at Site 4 due to the added freshwater flow during both stages, although it was more amplified after Stage 1. Therefore, after Stage 1 in 2020, with a relatively high freshwater inflow, a shift towards more ebb dominance was observed in the upper estuary.

Due to the operation of the gates (open during flood tide), freshwater is primarily trapped in the upper estuary (especially in the Ford's Cut) until the ebb tide. Environmental factors such as rainfall, wind and evaporation rate also play an important role in changing the hydrodynamics, especially in the Papahikahawai Channel and lagoon, as they are only connected to the upper Ford's Cut branch around high tide (when the gates are closed). Different drivers like bathymetry, wind stress, tides and freshwater inflow from the rivers govern circulation in the lagoon. Due to the large open surface (lack of high dunes or hills), wind is a significant forcing factor in driving circulation (Panda et al., 2015). According to (Dyer, 1977), the expected circulation pattern in the presence of strong wind is the movement of surface water across the basin which then causes a sizeable horizontal gradient opposing the wind direction that drives the flow.

The storm conditions observed between 15th and 19th February 2021 (wind forcing from the east) intensified the surface freshwater flow and led to stratification in the mid and upper-estuary. This behaviour is consistent with international studies (Gallardo, 1978; Hong & Chao, 2024; Marin Jarrin & Sutherland, 2022; Schoen et al., 2014). An overall decrease in salinity was observed after Stage 2 in this area, especially during the gate opening hours. On the other hand, post-Stage 1 results showed an increase in mean salinity. Richardson number increased after both stages and was generally higher post Stage 2; Estuarine Richardson number remained above the value of 0.8, representing a stratified condition. During Stage 2, between the 15th and 18th of February, the impact of strong storm winds was observed at Site 4; specifically, surface water flowing at the speed of 0.4 $m^2/s$ while the bottom layer remained near stationary. Although current velocity data was unavailable at Site 6 in the lagoon, similar behaviour is expected.

Site 4 became effectively more channelised after Stage 2 due to lower water levels. Post Stage 1 and before Stage 2, over the span of a year with the same amount of estimated freshwater input, we observed a shift towards flood dominance at Site 4 in the upper estuary. Harmonic analysis (HA) did not detect any change from flood dominance before and after either stages. We believe this is because tidal harmonic constants may vary over the analysis period, and conventional HA will leak energy from major constituents to their neighbouring frequencies (Foreman et al., 2009). HA is capable of resolving major tidal constituents during a short period data period (e.g., HA on a data length of 30 days), provided that the nontidal forcing varies little during the data window period. However, when river discharge variability is high, HA will provide inaccurate results because of nearby tidal spectral bands' nonlinear and mutually dependent behaviours (Godin, 1999; Jay & Flinchem, 1997; Jay & Flinchem, 1999). Moreover, nontidal forcing and/or hypsometric effects of intertidal flats may cause modification of tidal currents such that tidal duration asymmetry and peak current asymmetry may become inconsistent; that is, shorter rising tide coexist with stronger ebb currents in tidal estuaries with significant river discharge (Friedrichs & Aubrey, 1988; Guo et al., 2014). We believe this to be the case at Maketū before and after Stage 1, with river discharge being higher than anticipated.

Moreover, Townend (2005) reviewed methods for assessing the stability of estuaries, including different methods for identifying flood and ebb dominance, and found that the Friedrichs and Aubrey (1988) method tended to predict flood dominance while other approaches indicated ebb-dominance. It has been suggested that the thresholds for flood and ebb dominance vary with the ratio of tidal amplitude to the mean channel depth (Defra, 2008). Friedrichs and Aubrey (1988) derived their thresholds for a tidal amplitude of ~0.38 m and a mean channel depth of 2.8 m. They noted that for small ratios of amplitude to depth (<0.2) associated with shallow, short estuaries (similar to Maketū), the estuaries are ebb-dominant.

In the case of Maketū, the data period is short, river discharge is too variable for HA to produce accurate analysis, and tidal asymmetry is more easily determined by visually observing the tidal stage plot. One could argue that HA of current speed data might be more accurate in such case, but since tidal currents are more sensitive than water levels to nonstationary variations, the inaccuracy remains and HA for currents is even less successful than water level records (Godin, 1983; Guo et al., 2015). The TVA (tidal velocity asymmetry) (de Ruiter et al., 2021) was not used for the 2021 data set because the peak flood velocity was almost 0 at Sites 3 and 4.

Expectations were that the upper estuary, especially Site 4, would show the most impact due to its proximity to the freshwater input. Improvement in overall water quality was observed with a reduction in salinity levels at Sites 4 and 6. However, the change in current velocities and tidal asymmetry was not significant enough to lead to major hydrodynamic change, especially at Site 6, due to its somewhat isolated position. The most noteworthy influence was seen in Ford's Cut channel (Site 4 towards Site 3), leading to a proportionate reduction in salinity for Site 3 and a more ebb-dominant flow. A key parameter in determining the added freshwater flow's true impact is the estuary's flushing ability, which is the focus of the following chapter/paper.

### 4.6.2 Middle-estuary

The geomorphology in this area formed when it was a river mouth estuary (Hume et al., 2016; Kirk & Lauder, 2000) and represented the transition from fluvially dominated to tidally dominated processes (Cooper, 2001; Hart, 2009). This area restricts flow between the upper and lower estuary for most tidal cycles due to narrow, shallow braided channels and extensive shoals (intertidal flats).

Similar to the upper estuary, we observed lower water levels in the mid-estuary at Sites 3 and 5 after Stage 2 due to lower freshwater discharge from the gates (opposite to Stage 1). Based on the mean depth-averaged east-west component of velocity results, residual flows exist at Site 3 (mid-estuary) and 4 (upper-estuary), especially after Stage 1 and are amplified during Stage 2. There was a slight shift towards ebb dominance at Site 3 in the mid-estuary, mostly due to lower eastern depth-averaged velocity. The shift towards ebb dominance was more substantial after Stage 1 due to a higher discharge rate. The flow direction remains unchanged after Stage 2, suggesting no real impact on the morphology in this region.

Mean salinity decreased after Stage 2, along with minimum salinity for the data collection period, mostly due to the effect of added freshwater flow and higher rainfall rate. At Site 5, the lowest levels of mean salinity are observed during ebb tide, which shows a degree of mixing in the upper-estuary and reaching mid-estuary during early ebb tide. Mean salinity levels before Stage 2 are generally higher than post-Stage 1 for two reasons: (1) lower freshwater inflow before Stage 2, which prevented the development of stratification and (2) salinity levels stabilising over a span of a year of added freshwater flow since Stage 1.

After Stage 1, the Richardson number had increased at Site 3. Still, we observed a decrease after Stage 2, highlighting a slight change to mixing in this area mostly due to lower current velocity during Stage 2. Overall, currents induced by the added freshwater flow during Stage 2 were not strong enough to influence mixing or tidal asymmetry in a major way in this region.

### 4.6.3 Lower-estuary

Being tidally dominated, the lower-estuary was expected to show the least impact by the re-diversion. The original diversion of the river out of the estuary was associated with the development of a larger flood tidal delta since the 1960s, creating problems for boat access. Although not visible in the satellite images, there is a possibility that it may also have reduced the size of the ebb-tidal delta. Similar to the two other zones, a lower water level after Stage 2 was observed. This decrease in mean water level can also be attributed to changes in the estuary inlet, which has proven to be very dynamic. The orientation and position of the flood tidal delta relate to the change in the tidal inlet, and the dominant flow will change with the change in the estuary inlet. With the entrance narrowing, the ebb-tidal delta (along the coastline) gets shallower, impacting the tidal flow into the estuary. Further discussion of this impact and changes to tidal prism is mentioned in the following chapter/paper.

Mean salinity was lower due to the added freshwater flow and a higher rainfall rate, specifically during ebb tide. This is because freshwater mixes in the upper estuary and reaches the lower estuary during ebb tide, leading to lower salinity levels between hours 4–8 of the tidal cycle. Minimum salinity decreased at Site 1 but unexpectedly increased at Site 2, indicating improved mixing in this region with the influence of the added freshwater flow. As discussed in the previous chapter, the Richardson number exceeded 0.3 after Stage 1, indicating asymmetry in mixing. The value of $Ri_E$ was 0.3 (at Site 2) before Stage 2, so the added freshwater flow from Stage 1 had already had its impact on mixing, and Stage 2 did not impact that greatly. The Richardson number was calculated to be in a similar range after Stage 2 with a slight increase compared to Stage 1, representing a trend towards a more stable circulation pattern. After Stage 2, tidal asymmetry showed no major change and remained ebb-dominant, aligning with our expectations for this zone.

For the freshwater discharge to impact sediment transport, the flow rate needs to be higher. Therefore, higher freshwater discharge imitating an actual flood event may be required. Considering morphology, Cooper (1993), Cooper (2002) and Karunarathna (2011) observed that river discharge and associated river floods are responsible for critical short- to medium-term (i.e., year to decade) estuarine morphological changes (Guo et al., 2014). We believe this would be the case for Maketū if river discharge rates were higher and more persistent, or if the restoration scheme included major pulsed flooding events. This idea has been tested in the following chapter/paper, which also brings insight into the exchange pattern between the upper and lower estuary. Moreover, for long-term decreases in salinity, higher precipitation rates due to changing global weather patterns are the drivers which increase the discharge rates of streams into estuaries (Stocker et al., 2013).

## 4.7 Conclusions

After Stage 1, the shift from flood to ebb dominance at Site 3 (mid-estuary) was observed, as well as increased current speeds for Site 2, 3 and 4, which was expected to improve flushing and transport of sediment out of the estuary according to one of the objectives of the Kaituna re-diversion project. After Stage 2, a similar shift towards ebb dominance was observed at Site 3 but to a lesser extent.

A change in average water level was not expected for any of the sites during either stages. The river discharge through gates exceeded the estimated value during Stage 1 and fell short of it during Stage 2. However, an increase in mean water level after Stage 1 and a minor decrease after Stage 2 were observed. The implications of these changes in terms of mean tidal prism or residence time are included in the following chapter/paper.

The Kaituna River level has a higher range compared to the estuary, and in the past constant, freshwater flow from the Kaituna River would impact the hydrodynamics of the estuary more significantly, but this partial freshwater restoration and the gates are too limiting in terms of freshwater inflow when it comes to considerably impacting the hydrodynamics. A comparison of the upper catchment discharge of Kaituna River as well as at Ford's Cut in 2020 and 2021 shows that that the discharge in Kaituna River can exceed the freshwater discharge upstream. Moreover, commissioning more gates during Stage 2 did not increase the discharge at Ford's Cut. There also exists a tidal signal in the Ford's Cut discharge due to the timing of gate opening and closing, but the extent of this signal appears to vary with the tidal range in the Kaituna River.

This study shows how salinity levels in partial freshwater restoration schemes such as Maketū's case rely on the amount of river discharge (and accordingly rainfall) into the estuary because expected freshwater inflow rates are not achieved with variable river flows.

We acknowledge that coastal water bodies such as estuaries are difficult to classify due to the unique combination of climate regime, river discharge, tidal range, and each estuary's coastal geomorphology. However, proper classification of estuaries enables us to solve complex regulatory management problems, such as determining the river discharge needed to maintain healthy and productive coastal ecosystems (Palmer et al., 2011). For the Maketū Estuary, it is possibly more reasonable to consider it as a coastal lagoon since its hydrodynamics match this classification the best. Further research, using hydrodynamic modelling to isolate the impact of the added freshwater flow among natural variables such as wind and precipitation, would better demonstrate the actual effect of this freshwater restoration attempt.

# 5 CHAPTER 5

## Impacts of partial freshwater restoration on residence time in a shallow estuary: the Maketū Estuary

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### 5.1 Abstract

A key factor in the success of estuarine restoration is ensuring that physical hydrodynamic parameters, such as salinity distribution, tidal propagation and residence time, are in the optimal range for maintaining an ecosystem, while creating a morphological equilibrium. Te Awa o Ngātoroirangi (the Maketū Estuary) in New Zealand has a long history of engineering works modifying river inflows, including the Kaituna River being diverted out of the estuary in 1956 to reduce flooding, resulting in degradation of the estuary, decreased flushing, saltwater intrusion and ecological decline. In 2020 and 2021, 20% of the river flow was progressively restored into the estuary in two stages through a set of 12 control gates. This study investigated the effects of the partial freshwater restoration of the Kaituna River on the estuarine hydrodynamics, including tidal asymmetry, salinity and residence time, by implementing a 2D Delft3D model. After successfully validating and calibrating the model with field observations at multiple sites for water level, current velocities and salinity, three model scenarios were run to assess the response of residence time to re-diversion as a proxy for water quality. The first scenario simulated the gates commissioned during Stage 1 in 2020, the second simulated the freshwater discharge without control gates, and the third scenario simulated a pulsed river discharge (two weeks of high river discharge and then zero discharge for the next two). Our model highlighted the vulnerable areas within the estuary in terms of flushing ability, salinity levels, and sediment transport; we also looked at the ecological impacts and management implications of these scenarios. The model results showed that the best flushing of the estuary is a result of the pulsed flood scenario, followed by constant river flow, and finally the Stage 1 controlled inflows. The pulsed scenario also creates the best conditions for sediment export out of the estuary. Our findings contribute to the design and management of freshwater restoration in estuaries (with complex bathymetries and a history of engineering changes) with a key focus on the physical processes.

**Keywords**: residence time, estuarine restoration, river discharge, hydrodynamics, Delft3D

### 5.2 Introduction

Globally, estuaries and their ecosystem services have been degraded and even lost in some places, primarily due to human-induced disturbances such as land-use change, alteration of food webs and climate-related stressors (Green, 2006). In many cases, estuaries are degraded as a result of reduced river inflows, such as the construction of upstream dams (George et al., 2012) or the diversion of freshwater out of estuaries to address issues such as flooding of low-lying land (Das et al., 2012). There is an increasing need to remedy long-standing adverse effects of human activities on estuarine, coastal and marine ecosystems (Elliott et al., 2007) such as via efforts to restore estuarine ecosystems by altering tidal and riverine flows. Fate and transport of pollutants in a coastal water body and their effects on the ecosystem involve complex physical, chemical, and biological processes that occur at varying spatial and temporal scales (Kimmerer, 2002).

The time-scale for the transport of dissolved and suspended sediment through and estuary is considered an important determinant of the state of the estuary (Nguyen et al., 2014; Takeoka, 1984; Umgiesser et al., 2014; Wan et al., 2013) . There are several different methods used to characterise the transport time-scale at different spatial scales (Bravo et al., 2020; Nguyen et al., 2014):

- Flushing time, which is ratio of the estuary volume to the rate of addition or removal of water (assuming a constant estuary volume and steady state). This assumes that only advection occurs and provides an integrated estimate for the entire estuary. This method is also referred to as turnover time, renewal time, water exchange rate, and confusingly "residence time";
- Residence time, which is the time taken for a parcel of water starting at a specific location in the estuary, to move beyond the boundaries of the estuary. This is a local measure and can be determined separately for all areas within an estuary. The residence times can be integrated across the estuary to estimate the flushing time: for example, the e-folding flushing time which is the time taken for 63.22% of the original water parcels to leave the estuary. Residence time considers both advection and dispersion;
- Hydrodynamic diffusivity is related to small-scale turbulence, and involves the transfer of material from regions of high concentration to regions of lower concentration. Generally at macro scales this is considered dispersion and micro scales it is considered diffusion.

In this study, we have defined residence time as the time initially existing water parcels take to leave the estuary to capture the effects of advection and dispersion (Wang et al., 2004).

Tides, riverine flow, meteorological processes, and the resultant interactions with bathymetry and morphology drive estuarine flushing and hydrodynamics. Tidal forcing results in bidirectional flows that can renew or mix water masses on tidal and spring-neap timescales. Periodic high river inflows (e.g. floods) can thoroughly flush an estuary and replace "old" water, while steady river inflows can encourage a two-layer circulation that produces stratification (Jassby & Nieuwenhuyse, 2005). The combined effects of these forcings influence estuarine hydrodynamics and residence time on timescales ranging from hours to months (Defne & Ganju, 2014). Estuaries with low flushing rates and long residence times are most likely to retain nutrients within the system resulting in high primary productivity rates (Lancelot & Billen, 1984). Conversely, well-flushed estuaries are more resilient to nutrient loading because of lower residence time and better exchange with less impacted coastal waters (Defne & Ganju, 2014).

Natural reoccurring events such as floods, tides, and storms are some of the physical events that control the flux dynamics of sediments, nutrients, organic materials, and water in coastal systems (Day et al., 2009; Gobler et al., 2019; Jiang et al., 2019; Yang & Chui, 2018). Perez et al. (2011) and Ranjbar et al. (2019)suggest that in some cases, diversions of river water into shallow estuarine systems can result in significant reductions in nutrients before reaching offshore waters due to reduced residence time. Previous studies such as the Breton Sound watershed (Day et al., 2009), suggested that pulsed freshwater events, which mimic the natural river flood events (Odum et al., 1995), were most beneficial for the development of deltaic estuarine ecosystems. Therefore, pulsed events are a major focus of this study. One expectation with added freshwater flow is an increase in the tidal prism and flushing ability of the estuary (reduced residence time).

One method for quantifying residence time is particle tracking, which releases and tracks multiple particles until they transit out of the estuary. The change in the total number of remaining particles in an estuary is often used as a measure of the renewal rate (e.g. efolding flushing time) of the estuarine water as well (Abdelrhman, 2002; Brooks et al., 1999; Liu et al., 2004; Monsen et al., 2002; Nguyen et al., 2014). However, since the residence time in an estuary is usually spatially and temporally variable (Zhang et al., 2010) when defining an average residence time for the entire estuary, it is necessary to include the analysis of differential transport of particles within the domain as well. It is known that the water displacement does not necessarily follow a linear process since there is always some degree of mixing within an estuary. The new water coming into the estuary, be it by river discharge, tide or non-tidal circulation, will at least partially mix with water already in the system before displacing some of it. It will take infinitely long time to replace all of the existing water in the system (Wang et al., 2004).

In this study, we applied the Delft3D model to examine the spatial and temporal changes in residence time and circulation in response to partial freshwater restoration in a small and shallow estuary (Maketū Estuary in Aotearoa, New Zealand). The Maketū Estuary has a long history of freshwater flow manipulation, with less than ~150,000 $m^3/s$ per tidal cycle (4%) of river flow entering the estuary between the 1950s and 2010s. In 2020 and 2021, a maximum of ~400,000 $m^3/s$ per tidal cycle (13% of river flow) and ~600,000 $m^3/s$ per tidal cycle (20% of river flow) were allowed to enter the estuary, respectively. This study aims to investigate the temporal and spatial impact of freshwater restoration on residence time, tidal asymmetry and estuarine circulation by comparing three scenarios: (1) Stage 1 of the restoration project, (2) regular freshwater inflow without the control gates and (3) pulsed flood flow for 2 weeks followed by 2 weeks of zero freshwater discharge. We also highlight the vulnerable areas within the estuary and discuss the potential implications for managing nutrients, vegetation and overall ecosystem health.

## 5.3 Study area

The Maketū Estuary is a small (2.3 $km^2$), shallow (mean depth < 1 m below mean sea level (MSL)) microtidal barrier-enclosed estuarine lagoon (Burton & Healy, 1985) at the mouth of the Kaituna River, in the Bay of Plenty of Aotearoa New Zealand (Figure 3.1). The estuary comprises sand and mud intertidal flats, tidal channels, salt marshes and wetlands and experienced a change in estuarine classification from the *tidal river mouth* to *tidal lagoon* due to anthropic impacts (Hume et al., 2017). The main freshwater inflow is from the

Kaituna River. Tides are semi-diurnal, with spring and neap tidal ranges of 1.73 m and 1.16 m, respectively, with a maximum astronomical tidal range of 2.19 m (McKenzie, 2014). The medium suspended grain size varies from 12 µm in the mid-estuary to 2500 µm in the lower estuary.

The Maketū Estuary has undergone multiple anthropic shifts associated with drainage and reclamation of the tidal coastal wetlands since the early 1900s (Stokes, 1980). The Papahikahawai Channel on the northern side of the estuary (Figure 3.1) periodically became the main channel when floods breached the barrier spit (Ford & Ford, 2008), mainly at Te Tumu. The tidal inlet at Maketū frequently closed up, and between 1926 and 1929, an artificial cut was constructed to drain floodwater entering the estuary. When Ford's Cut was completed, the main river flow inside the estuary occurred in the original deep channel on the southern side of the estuary before splitting into multiple shallow channels connecting over the central deltaic region to the tidal lower Papahikahawai Channel on the northern side of the estuary.

This was followed by the diversion of the Kaituna River to the sea in 1956-57 to prevent flooding of reclaimed farmland surrounding the lower Kaituna River. After the diversion, the estuary changed from a tidal river mouth to a tidal lagoon in terms of flow characteristics (Hume et al., 2017). Before 1957, the Kaituna River discharge into the estuary over a tidal cycle was estimated as ~1,165 $m^3$, at an average rate of ~94 $m^3/s$ (calculated using a single-day survey during spring tide), equivalent to 97% of the spring flood tidal prism (Burton & Healy, 1985). As part of the diversion, Ford's Cut was closed off to prevent flooding of low-lying farmland (reclaimed tidal wetlands) surrounding the estuary. Further, the Papahikahawai Block in the upper estuary was reclaimed, and access was provided by several causeways that restricted tidal exchange with the Papahikahawai Lagoon in the northwest of the estuary. Removing the dominant freshwater source into the estuary substantially reduced the flushing ability of river-enhanced ebb tide currents, and there was accretion on the sandy intertidal flats and the development of a substantial flood and larger ebb-tidal delta developed at the original inlet (Hume et al., 2017). From 1956 to 1995, the only freshwater flow from the Kaituna River into the estuary was minor seepage and "pulsed" overflows during floods. Subsequently, restricted flows of 2 $m^3/s$ of freshwater (up to ~100,000 $m^3$ per tidal cycle and 4% of the river flow) were restored to the estuary through the Ford's Cut control structure (Figure 3.1) in 1996 (Hume et al., 2017).

In an attempt to restore the estuary, the Kaituna River re-diversion aimed to return up to 400,000 $m^3$ of freshwater per 12.4 hour tidal cycle (~13% of the river flow) (Stage 1, commissioned 12th February 2020) through 9 control gates between Ford's Cut and the lower Kaituna River (Figure 3.1) in the first year. This increased to a maximum of 600,000 $m^3$ per tidal cycle one year later (~20% of the river flow) (Stage 2, commissioned 12th February 2021) through 12 control gates (Park, 2020). The project had to main goals: First, to significantly increase the volume of freshwater flowing from the Kaituna River into the estuary to maximise the ecological and cultural benefits, particularly those relating to wetlands and kaimoana. Second, it aimed to keep the economic cost and adverse environmental effects (due to flood events) at acceptable levels and to maintain navigability through Te Tumu Cut (Figure 3.1) and for flood protection (Environment Bay of Plenty, 2009). To maximise river flow into the estuary, the gates open automatically during flood tide in the estuary when water levels are rising in Ford's Cut, and the water level on the Kaituna River side is at least 40 mm higher than the estuary side for at least 10 minutes; and close when the height difference drops below 40 mm for at least 10 minutes. They can also be closed during river flooding to keep low-lying lands surrounding the estuary safe from floods.

## 5.4 Methods

### 5.4.1 Numerical model description and set-up

The Delft3D modelling system (Wang et al., 2017) has been used worldwide in many riverine, estuarine, and coastal applications. An idealised 2-D hydrodynamic model was developed using the Delft3D-FLOW module. The system of equations includes the horizontal momentum equations, the continuity equation, the transport equation and a turbulence closure model (Dan et al., 2011). This module accounts for the majority of the processes controlling shallow and complex environments: wind shear, wave forces, tidal forces, density-driven flows and stratification due to salinity and/or temperature gradients, atmospheric pressure changes, drying and flooding of intertidal flats (Lesser et al., 2004; van Rijn et al., 2007; Wegen et al., 2008). The length and width of the entire model domain used in this study are ~3.64 and ~1.1 km, respectively, with a 10 m grid resolution (Figure 5.1). The 10 m grid allowed detailed hydrodynamics to be resolved by the model such as branched channel network and shallower intertidal areas. A bathymetric map of the estuary was developed with the collected RTK data (February 2020) with a vertical accuracy of ±3 cm, LiDAR data from December 2018–April 2019 provided by BOPRC as well as offshore data (last updated July 2020) from Land Information New Zealand (LINZ). Corrections were made to the local mean sea level datums with an offset of 0.197 m (NZVD2016 to NZGD2000/New Zealand Transverse Mercator) as well as vertical datum conversions to MVD53 (Moturiki datum 1953) using the Online Conversions platform on LINZ website; for Maketū the calculated offset was 0.259 m and it was uniformly applied to LiDAR data in QUICKIN in Delft3D. All the samples were combined, corrected to MVD53 and interpolated in QUICKIN within Delft3D using grid cell averaging and the triangular interpolation option. The resulting datum in the model grid is MVD53, and deeper channels were manually corrected using the collected water level data as a reference.

Tidal elevation data were from Moturiki (~36 km from Maketū) provided by the National Institute of Water and Atmospheric Research (NIWA). Tidal constituents were extracted by running the Utide (Codiga, 2011) function from NIWA water level data (Table 5.1) and imposed at the seaward model boundary, situated ~0.7 km away from the eastern estuary inlet. A time-series of freshwater discharge rates was calculated by multiplying the depth-averaged east-west component of the velocity and water levels with the channel width at Site 4. Wind conditions were input uniformly over the estuary domain as a time series. Precipitation and hourly wind data from Tauranga Aerodrome station (4 m above MSL) were provided by the New Zealand MetService. A 7-day warm-up period (standard length of time for the simulation period) was set including a constant freshwater discharge of 20 $m^3/s$ with an average salinity of 20 for transport conditions and actual wind conditions; offshore salinity forcing and offshore tidal forcing remained the same as the simulation period. Due to low levels of rainfall during the simulation period, precipitation was not included in the model.

Initially, the model was set up with no rain and wind conditions and the rest of parameters were set based on an average value. Initial water level and salinity conditions were set to 0.5 m and 35. A constant value of bottom roughness was set at 40 $m^{-1/2}$.s, and the transport conditions at the offshore borders were set at 35 for salinity. The initial freshwater discharge at the control gates was calculated based on the width of the channel, water level and depth-averaged velocity and the salinity was set to 0.5. Water density, gravity and eddy viscosity were set to 1025 $kg.m^3$, 9.81 $m.s^{-2}$ and 5 $m^2.s^{-1}$, respectively (Table 5.2). Particle tracking scenarios were run on Delft3D-FLOW.

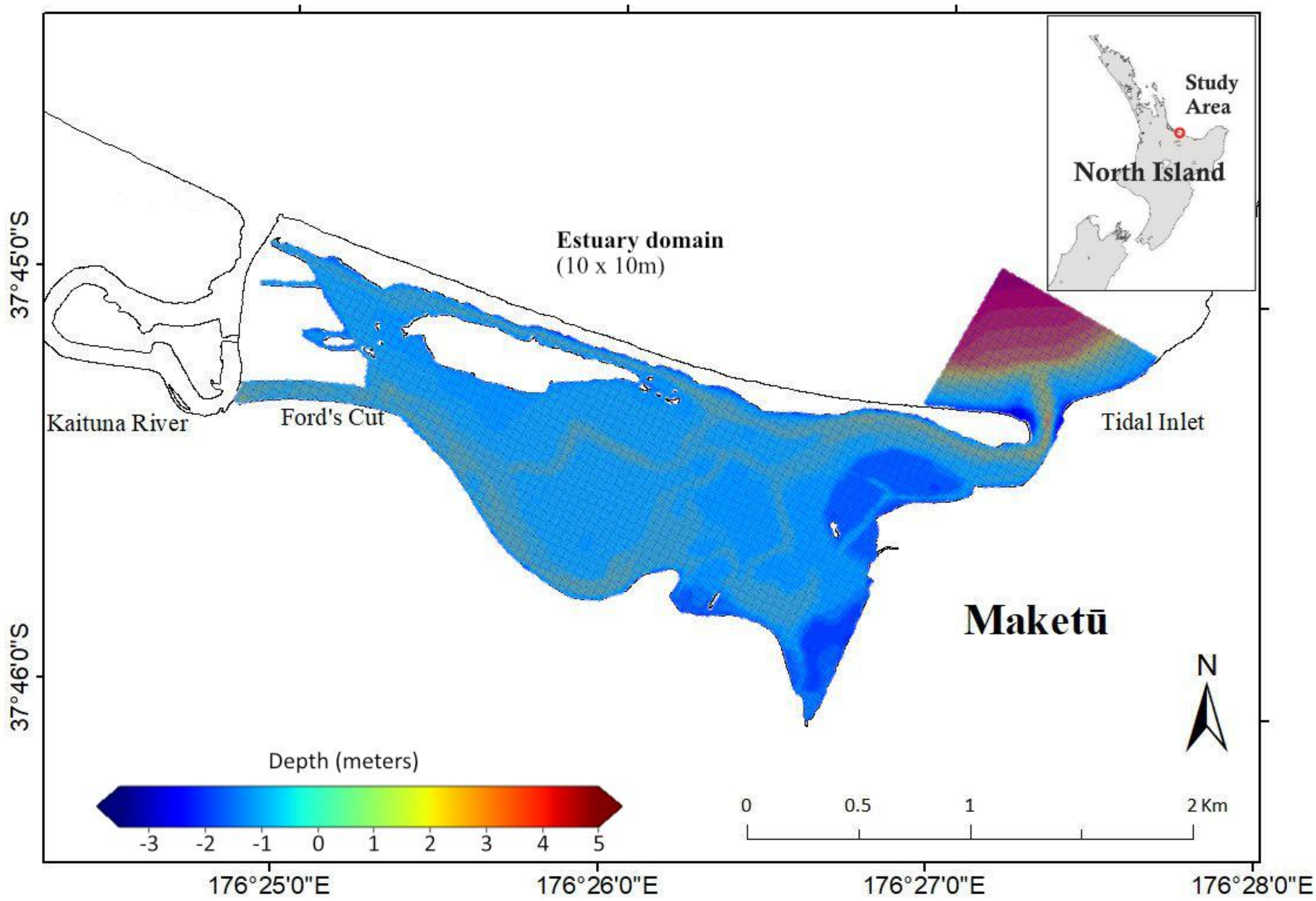



*Figure 5.1 10m structured model grid and depth for Maketū Estuary*

*Table 5.1 Tidal constituents extracted by Utide from NIWA tide data from January until March 2020*

| **Tidal constituent** | **Amplitude (m)** | **Phase (degree)** |
|---|---|---|
| K1 | 0.0863 | 1.56 |
| O1 | 0.0222 | 309.31 |
| M2 | 0.7183 | 199.56 |
| N2 | 0.1525 | 169.97 |
| S2 | 0.0768 | 269.24 |

*Table 5.2 Initial model parameters used in the Delft3D FLOW model*

| **Parameter** | **Value** |
|---|---|
| Time step interval | 0.25 min |
| Warm-up period | 7 days |
| Simulation period | 29 days |
| Gravity | 9.81 $m.s^{-2}$ |
| Water density | 1025 $kg.m^{-3}$ |
| Eddy Viscosity | 5 $m^2.s^{-1}$ |
| Bottom roughness | 40 $m^{-1/2}.s$ |
| Wind conditions | uniform |

### 5.4.2 Particle tracking

The model warm-up period was set to 7 days and then tracers were released into the estuary domain. To obtain a decay map of residence in the estuary, all cells within the domain were uniformly set to an initial concentration value of 1 $kg/m^3$ under the "Pollutants and Tracers" process input section of the Delft3D. Tracers were then released at the start of the simulation period, which was February 1st 2020 and the simulation ran for 1 month. Areas outside the estuary such as freshwater inflow and ocean boundaries ('new' water) were all set with a tracer concentration of 0 $kg/m^3$. In this study, tracer decay rates represent changes in residence time in the estuary. This means that increases in decay rate value affect the pace at which contaminants and sediments are flushed out of different regions (Tay et al., 2013). The decay rate of the tracer was found by fitting an exponential line to the concentrations for each site from the first high tide when the tracers were released until the next low tide. In other words, the tracer decay rate was calculated by:

$$C = C_0 \times e^{-kt} \tag{1}$$

C is the tracer concentration at time (t), C0 is the initial concentration, and k is the decay rate (Moffatt, 2021).

### 5.4.3 Observational data

Fieldwork was undertaken between 23rd January and 3rd March 2020 to measure water level, velocity, temperature, turbidity and salinity at 7 sites throughout the estuary and the lower Kaituna River (Figure 3.1). Two sites were located in the lower estuary (1 & 2), two in the middle estuary (3 & 5), two in the upper estuary

(4 & 6), and one site in the lower Kaituna River (7). These sites were chosen to give comprehensive spatial coverage of the estuary, targeted to the main flow pathways, whilst being safe and discrete places to moor instruments. Within the upper estuary Site 4 is in the Ford's Cut channel, which connects to the Kaituna River. Site 6 is within the Papahikahawai Lagoon, which is largely isolated from the rest of the estuary.

Instruments deployed included: 3 Nortek Aquadopp Profilers (deployed upward-facing) measuring water levels, currents and turbidity; and 4 Solinst LTC Level Logger Edge, 1 RBR Maestro and 2 RBR Concertos measuring conductivity, temperature, turbidity and dissolved oxygen. The sampling interval was 10 minutes for all instruments except the RBR Maestro, which was set to 20 minutes. Solinst loggers were attached to existing navigation poles at Sites 1 and 7 and to temporary stakes at Sites 5 and 6. Aquadopps and Concertos/Maestro were placed together on anchored stainless steel frames at Sites 2, 3 and 4 with sensors located ~0.15–0.27 m above the bed. At Sites 3 and 4, large plastic lids were attached to the underside of the frames to prevent them from sinking into the mud. Weekly checks were undertaken to clear any sensors' biofouling, particularly at Sites 3 and 4, which had issues with sea lettuce (*Ulva*). Some data had to be removed due to sea lettuce fouling and relocation of the instrument at Site 2 (the instrument was dragged by a boat, and data after February 25th were removed). Data analysis included removing current profile bins above the water surface. They were also depth-averaged, using the single point method (Maghrebi, 2006) corresponding to 0.7 of the water level to minimise the error for the shallow channels.

The freshwater discharge rate was calculated by multiplying the depth-averaged east-west component of the velocity, water levels, and channel width at Site 4. There were a few gate testing events such as the one observed on February 1st–4th, 5th and 11th, where the gates were fully open, and water flowed both in and out of the estuary. Atmospheric pressure data were calculated using a weighted average of hourly atmospheric pressure data from two nearby sites (2/3 in Tauranga and 1/3 in Whakatāne) based on the proximity to these surrounding weather stations; the data were then converted to metres of water level response and subtracted from water level data determined from the total pressure measured by the instruments.

In order to get the median grain size for calculating the critical bed shear stress, water samples from each site were collected at low to mid-tide during the deployment, maintenance and retrieval stages of field data collection. These samples were then processed through a Mastersizer 3000. To determine the suspended sediment concentrations the samples were also passed through a water filter, which was later dried at 60 °C and 105 °C to burn off the organic matter in an oven, and weighed before and after. Critical shear stress for non-cohesive sediment was calculated using the following:

$$\tau_c = (0.046 * \rho_w * g * d * (\rho_s - \rho_w)) / (\varphi * \varphi) \qquad (1)$$

Where: $\tau_c$ is the critical bed shear stress (in N/m$^2$), $\rho_w$ is the density of water (in kg/m$^3$), g is the acceleration due to gravity (in m/s$^2$), d is the median sediment particle diameter (in m), $\rho_s$ is the density of sediment particles (in kg/m$^3$), and φ is the porosity of the sediment bed (dimensionless) (Shields, 1936).

To isolate the impact of freshwater restoration, an average tidal cycle (canonical tidal cycle) was calculated for each scenario for water level, depth-averaged current velocity, shear stress, Froude number and near-bed salinity. This canonical semi-diurnal tidal cycle starts at local high tide and ends at subsequent high tide 12.4 hours later. Tidal prism for neap and spring tide was also calculated to evaluate the impact of added freshwater flow on net flow. The number of grids below low and high tide were counted, averaged and then multiplied by the grid area to get the intertidal area which was then multiplied by the tidal range resulting in neap and spring tidal prism of ~676,549 $m^3$ and ~1,032,070 $m^3$, respectively (mean tidal prism of ~853170 $m^3$). Suggested by Gerritsen (1985), the ratio between tidal prism and freshwater discharge during the tidal cycle provides a simple claassification scheme as follows:

$$r = Q_f/_\Omega \quad (2)$$

where $Q_f$ is the freshwater discharge, and Ω is the mean tidal prism. Based on this criteria if $r \leq 0.1$, the estuary is well-mixed, for $r \geq 1$, it is highly stratified and $0.1 < r < 1$, it is partially mixed.

### 5.4.4 Model calibration and verification

Time series data collected in February 2020 for water level, current speed profiles and salinity levels in the study area were compared with model simulations over the same periods. The model was calibrated by adjusting physical parameters such as the eddy viscosity and Chézy friction coefficient values ($m^{1/2}.s^{-1}$). The results showed that due to the complex bathymetry of the estuary, the Chézy friction coefficient value had to be spatially variable. Calibration resulted in a Chézy of 65 $m^{1/2}.s^{-1}$ assigned for deep channels and 35 $m^{1/2}.s^{-1}$ for shallow intertidal areas.  We used the following statistical measures to evaluate model performance during both calibration and validation:

$$MAE = \frac{1}{j}\sum_{j=1}^{J}(y_j - x_j) = \langle|y_{-X}|\rangle \quad (2)$$

$$RMSE(Y,X) = \sqrt{\frac{1}{J}\sum_{j-1}^{y}(y_j - X_j)^2} = \sqrt{\langle(Y-X)^2\rangle} \quad (3)$$

Y is a set of $y_j$ model predictions and X is a set of $x_j$ observations (measured field data). The total number of values in the datasets is J. MAE (Mean Absolute Error) takes the absolute value of the errors before averaging, defined by the straight brackets. The main difference between the accuracy measures is that the RMSE squares the differences, increasing the influence of any outliers in the model datasets, making the RMSE the more conservative measure (Sutherland et al., 2004). Skill is the final method for evaluating a model's performance and compares a measure of the accuracy of the model predictions against the accuracy of a baseline prediction (Sutherland et al., 2004). The baseline predictions (B) used in this study for water level were the average values of the measured field datasets. The Brier Skill Score (BSS) is commonly used to evaluate the performance of hydrodynamic models (Sutherland et al., 2004).

$$BSS = 1 - \frac{MSE(Y,X)}{MSE(b,X)} = 1 - \frac{\langle(Y-X)^2\rangle}{\langle(B-X)^2\rangle} \quad (4)$$

Sutherland et al. (2004) proposed a classification scheme to interpret the BSS and assess the confidence of the model outcomes, where a BSS of 1.0 – 0.5 is excellent and below 0 is bad.

*Table 5.3 Calibration results for water level at 6 sites*

| Sites | BSS (water level) | Classification | RMSE (m) | MAE (m) |
|---|---|---|---|---|
| Site 1 | 0.51 | Good | 0.3 | 0.0 |
| Site 2 | 0.81 | Excellent | 0.13 | 0.0 |
| Site 3 | 0.81 | Excellent | 0.11 | -0.05 |
| Site 4 | 0.44 | Good | 0.22 | 0.01 |
| Site 5 | 0.49 | Good | 0.20 | 0.0 |
| Site 6 | 0.49 | Good | 0.21 | 0.03 |

*Table 5.4 Calibration results for current speed at 3 sites*

| Sites | BSS (speed) | Classification | RMSE (m/s) | MAE (m/s) |
|---|---|---|---|---|
| Site 2 | 0.66 | Excellent | 0.27 | 0.07 |
| Site 3 | -0.07 | Bad | 0.12 | 0.06 |
| Site 4 | 0.85 | Excellent | 0.086 | -0.04 |

The model skillfully reproduced the measured water levels at 6 of the 7 sites as well as current velocities at 2 of the 3 sites with current measurements (Tables 5.3 and 5.4, Figures 5.2 and 5.3). However, modelled current velocities in the mid-estuary at Site 3 lagged and were consistently lower than the observations (Figure 5.3c). Modelled spring tidal range varied from ~1.5 m at Site 1 to ~0.8 m at Site 3 (Figures 5.2a and 5.2c). The model produced a slightly bigger tidal range (up to ~0.1 m) in shallower areas, such as Sites 3 and 6 (Figures 5.2c and 5.2f). The model's salinity results inaccurately represented the fluctuations caused by tidal changes at Sites 3 and 5, exhibiting a more mixed flow (Figures 5.4b and 5.4e). At Site 4, the model only shows the peak salinity levels with small fluctuations with tides (Figure 5.4c).

### 5.4.5 Scenario specifications

To evaluate the impact of freshwater restoration on the hydrodynamics of the estuary, especially residence time, a 2-D model run was conducted using three discharge scenarios: (1) 400,000 $m^3$ of freshwater per 12.4-hour tidal cycle (~13% of the river flow) (Stage 1), (2) a natural discharge freshwater flow without control gates (average of 30 $m^3/s$ entering and exiting the estuary depending on the state of the tidal cycle and water level gradient) and (3) pulsed flood event of 60 $m^3/s$ for 2 weeks (without fluctuations) and no discharge for 2 weeks. These scenarios were selected to represent the restoration impacts and its absence and an alternative (pulsed scenario mimicking natural flood events) not originally discussed in the Kaituna rediversion project.

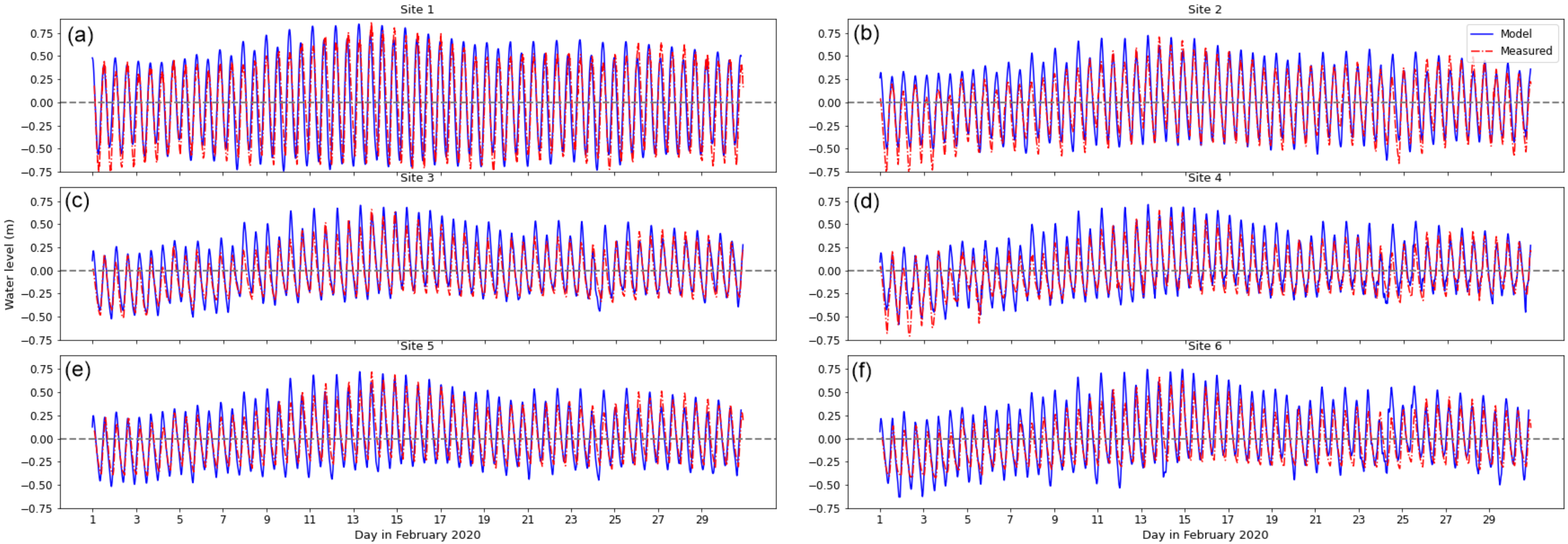


*Figure 5.2 Water level results obtained from the model (blue) and field data (red) at 6 sites*

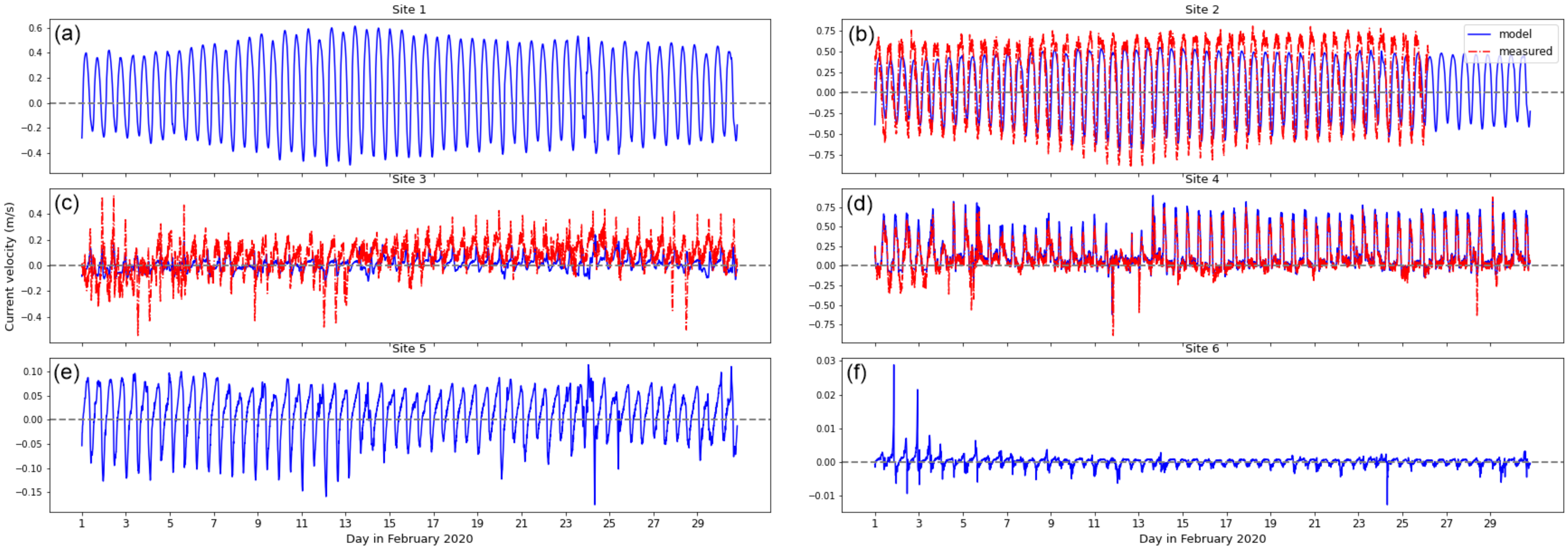



*Figure 5.3 Current velocity results obtained from the model (blue) and field data (red) from the 3 sites where field measurements were made. Note different y-axis scales*

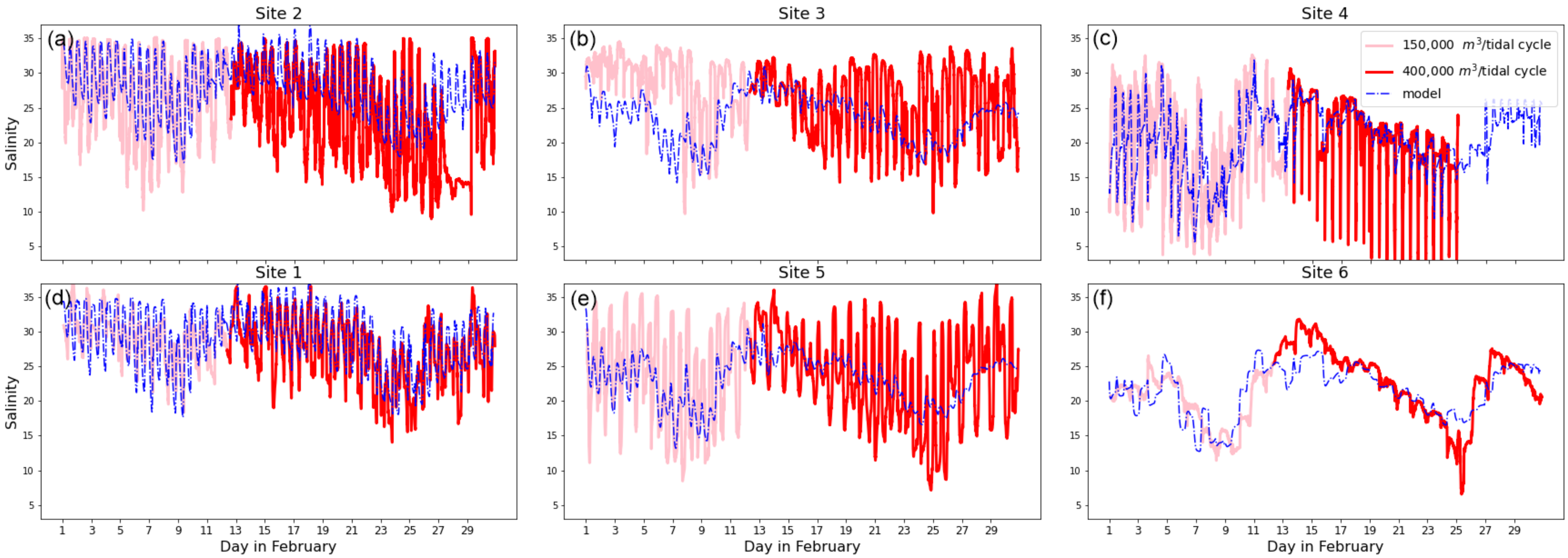



*Figure 5.4 Salinity results from the model (blue) and field data (red)*

## 5.5 Results

### 5.5.1 Tracer decay rate

During Scenario 1 (Stage 1), the modelled tracer concentration in the lower and upper estuary fluctuated with the tide and then exponentially decreased over the first few tidal cycles (Figure 5.5a). Tracer concentration at Sites 1, 2 and 4 fluctuated with the tide and had a sharp decrease during the first tidal cycle, with Site 1 fluctuating the most with the tide (a maximum reduction of ~0.95 kg/m$^3$ followed by an increase of ~0.9 kg/m$^3$ during one tidal cycle) (Figure 5.5a). In the upper and mid estuary (Sites 3, 5 and 6), an initial lag of one tidal cycle in tracer decay was observed because new water (ocean water and freshwater flow) does not reach these two sites immediately (Figure 5.5a). At these sites, a more rapidly declining behaviour in tracer decay rate (k) was observed, reflecting that "new" and "old" water are mixed before reaching these sites. Tracer concentration reached ~0 kg/m$^3$ at all sites within 3.5 days (Figure 5.5a). From high to low tide, the tracer decay rate varied from 0.02 at Site 3 to 0.07 at Site 4 (Figure 5.5d). The average tidal Froude number at Site 1 dropped from ~0.1 to ~0 until hour 1 of the tidal cycle, then increased from ~0 to ~0.18 between hour 0–5 of the tidal cycle and reached ~0 again by hour 8, before increasing again to ~0.15 at hour 11. Site 2 shows a similar trend but with a lower first peak of ~0.15 (Figure 5.5g). Sites 3 and 4 show a value of ~0.01 until hour 6 of the tidal cycle before increasing to ~0.04 and ~0.2, respectively, at hour 8. The average tidal Froude number drops to ~0.01 until the end of the tidal cycle (Figure 5.5g). The average tidal Froude number remains almost ~0.01 and ~0 with minimal fluctuation at Site 5 and 6, respectively (Figure 5.5g).

During Scenario 2 (constant discharge), a similar pattern to Scenario 1 was observed at Site 6 in the upper estuary, where tracer concentration decreased exponentially and reached ~0 kg/m$^3$ within 3 days (Figure 5.5b). Tracer concentration at the other sites decreased overall but fluctuated with the tide; Site 1 had the maximum decrease of ~0.95 kg/m$^{3,}$ followed by an increase of ~0.9 kg/m$^3$ (Figure 5.5b). In the mid and upper estuary (Sites 3, 4, 5 and 6), the tracer concentration takes one tidal cycle to decrease due to seawater and freshwater not reaching the upper estuary immediately (Figure 5.5b). For this scenario, the decay rate at Sites 1, 2 and 6 are low (0.02, 0.02 and 0.04, respectively) (Figure 5.5e). The decay rate varies from 0.05 to 0.1 at the rest of the sites (Figure 5.5e). The average tidal Froude number at Site 1 shows a similar pattern to Scenario 1, dropping from ~0.1 to ~0 until hour 1 of the tidal cycle before reaching a peak of ~0.17 at hour 6, then decreasing again to ~0 at hour 8 of the tidal cycle before reaching the second peak of ~0.13 at hour 11 (Figure 5.5h). Site 2 shows a similar trend in average tidal Froude number with two peaks of ~0.14 at hours 4 and 11 of the tidal cycle and low values of ~0.03 at hours 0, 8 and 12 of the tidal cycle (Figure 5.5h). Sites 3 and 5 reach ~0.02 with minimal fluctuation through the tidal cycle; similarly, Site 6 remains ~0 but Site 4 reaches ~0.01 at hours 4 and 8 of the tidal cycle and fluctuates most with the tide (Figure 5.5h).

During Scenario 3 (pulsed discharge), only Sites 1 and 2 in the lower estuary exhibited tidal fluctuation of tracer concentration with the tidal instant, and the rest showed an exponential decrease in tracer concentration (Figure 5.5c). Sites 3 and 4 showed the sharpest drop in tracer concentration with decay rates of 0.22 and 0.09, respectively (Figure 5.5f). Generally, the decay rate was higher for this scenario and tracer concentration reached ~0 kg/m$^3$ within 2 days, with decay rate (k) varying from 0.04 at Sites 5 and 6 and 0.06 at Site 1

(Figure 5.5c and 5.5f). There was no lag in tracer decay, and Sites 1 and 4 reached ~0.0 kg/m$^3$ within one hour after high tide and tracer release (Figure 5.5c). During this half tidal cycle, tracer concentration at Site 2 dropped quickly and recovered just as quickly, resulting in a high value of 0.05 in the decay rate results (Figure 5.5f). In this scenario, the average tidal Froude number is the highest, with Site 4 increasing from ~0.15 to ~0.23 between hours 0–9 of the tidal cycle and then decreasing until hour 12 (Figure 5.5i). Sites 1 and 2 show the next highest values with peaks of ~0.2 and ~0.14 at hour 5 of the tidal cycle and then decreasing to ~0.03 at hour 9 before reaching ~0.05 around hour 11 (Figure 5.5i). Average tidal Froude number at Sites 3 and 5 increases from ~0.0 at hour 0 to ~0.03 until hour 8 of the tidal cycle before dropping to ~0.0 until the end of the cycle (Figure 5.5i). Similar to the rest of the scenarios, values at Site 6 remain ~0.0 throughout the tidal cycle (Figure 5.5i).

In all scenarios, Ford's Cut, the tidal inlet and channel are well-flushed approaching high tide towards the end of the tidal cycle due to the inflow of "new" water from the lower Kaituna River (Figure 5.6). However, the mid-estuary and upper estuary only get properly flushed in one tidal cycle for the pulsed scenario. In all scenarios, "new" water enters the estuary from the tidal inlet on the eastern side of the estuary and through the gates at Ford's Cut. During Stage 1, this new water then mixes with the existing water in the mid-estuary, and the mixed water flows through the mid and upper-estuary. The new water from the river and the sea converge at Site 5 in the Papahikahawai Channel, leading to the highest tracer concentration at this site (Figure 5.6c).

During the constant discharge scenario, new water enters the estuary from the tidal inlet at the beginning of the tidal cycle and mixes with the existing water until low tide, when freshwater from the gates starts flowing in (Figures 5.6d and 5.6e). Similar to Stage 1, the mixed water flows through the mid and upper estuary, and Site 5 is the most poorly flushed well-flushed site at the end of the tidal cycle; freshwater and seawater have an equal impact on tracer decay (Figure 5.5f). During the pulsed scenario, freshwater from the gates seems to be the dominant force in mixing, and it only takes half a tidal cycle for the mid and upper estuary to be flushed. The mixed water pushes the old water towards the tidal inlet, so Sites 1, 5 and 6 are less flushed than the rest of the sites and show higher tracer concentration (Figure 5.6h). Until the end of the tidal cycle, all the estuary gets flushed out, and tracer concentration is the lowest compared to the other scenarios (Figure 5.6c, 5.6f and 5.6i).

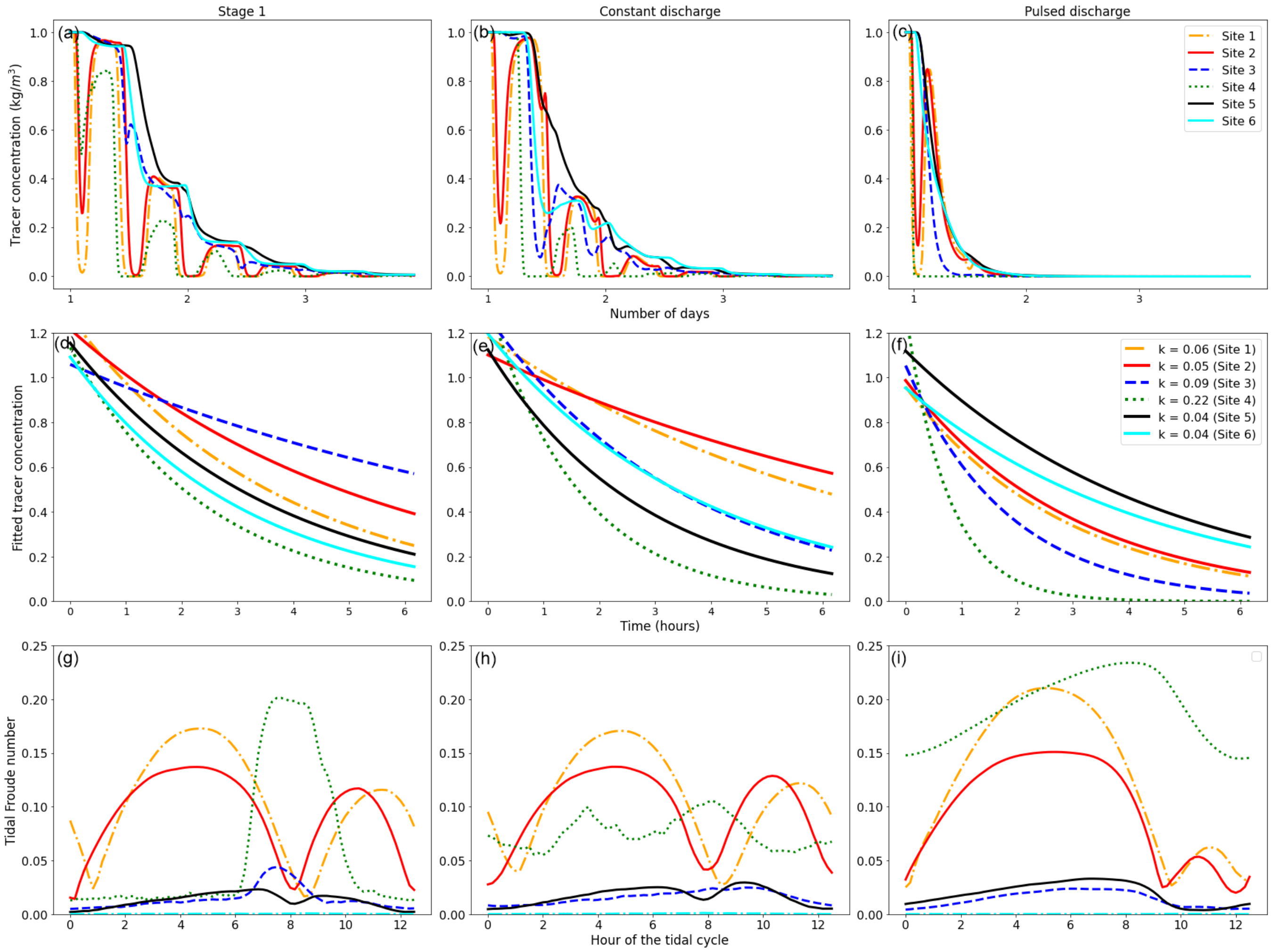



*Figure 5.5 Tracer concentration and decay rate (k) obtained from the model at: (a,d) Scenario 1 (Stage 1), (b,e) Scenario 2 (constant freshwater discharge) and (c,f) Scenario 3 (pulsed freshwater discharge)*

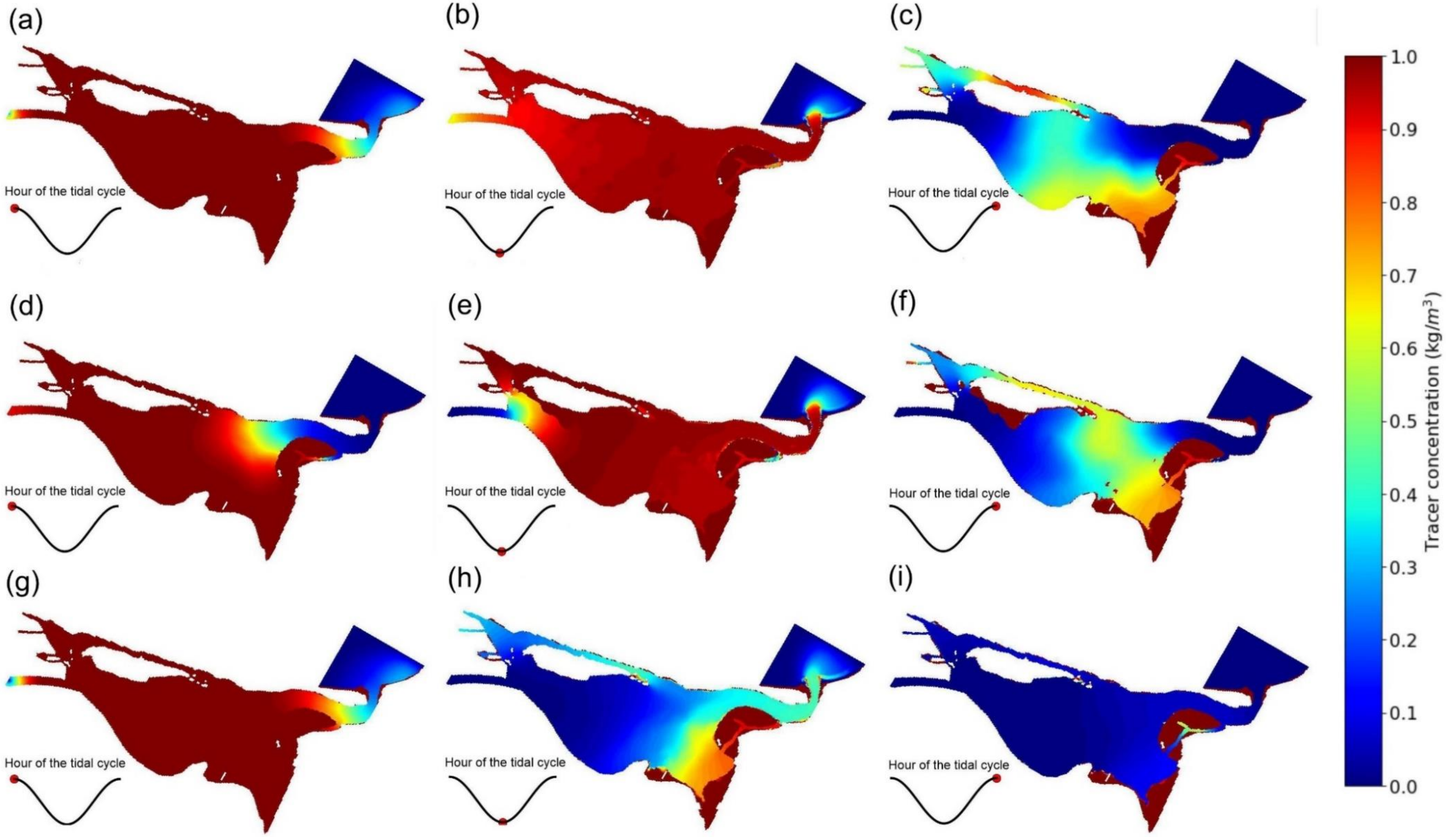



*Figure 5.6 Decay map results obtained from the model at different stages of the tidal cycle for (a) Stage 1, (b) constant freshwater discharge and (c) pulsed freshwater discharge*

### 5.5.2 Average tidal asymmetry, bottom salinity and shear stress

Tidal stage, bed shear stress in the x direction and salinity were averaged over a 12.4 tidal cycle for 3 key sites during all scenarios. At Site 2, the pulsed scenario showed an ebb-dominant behaviour compared to zero and constant freshwater discharge. However, the net transport was smaller than the rest of the scenarios. Stage 1 showed ebb-dominant behaviour with the highest net transport (Figure 5.7a). At this site, for the pulsed scenario, average bed shear stress was the highest (ranging from 0–2 $N/m^3$); critical shear stress was calculated based on the Shields criterion ranging from 8–500 $N/m^3$ which was reached only twice during the tidal cycle (Figure 5.7g). For the other scenarios, average shear stress ranged from 0–400 $N/m^3$ and reached the critical value three times at hours 0, 8 and 12 of the tidal cycle (Figure 5.7d). The average bottom salinity at Site 2 was lowest for the pulsed scenario ranging from 7–24, with the minimum occurring at hour 6 of the tidal cycle; the rest of the sites showed salinity levels of 20–33 (Figure 5.7j).

At Site 3, Stage 1 showed the most ebb-dominant result, and the pulsed scenario was the next most ebb dominant; the remaining scenarios showed a flood-dominant state with somewhat similar net transport (Figure 5.7b). Average bed shear stress was near zero for all scenarios. Bed shear stress reached the critical threshold at 3 instances for the pulsed scenario (hours 0, 9 and 12); and for the rest of the scenarios between hours 1–4 of the tidal cycle and then at hour 8 (Figure 5.7e and 5.7h). Average bottom salinity was lowest for the pulsed scenario at this site (ranging from 7–13) with constant discharge and Stage 1 following after that (ranging from 15–25) (Figure 5.7k).

At Site 4, all scenarios showed an ebb-dominant behaviour, with the pulsed scenario having the most ebb-dominant flow and Stage 1 showing the biggest net transport (Figure 5.7c). Average bed shear stress was the highest for the pulsed scenario, followed by Stage 1 (Figures 5.7f and 5.7i). Critical bed shear ranged from 50–90 $N/m^3$ for the pulsed scenario at Site 4 and was never reached; however for the rest of the scenarios it ranged from 0.2–9 $N/m^3$ and only was barely reached for the last two hours of the tidal cycle (Figure 5.7f). At this site, average bottom salinity was the lowest for the pulsed scenario ranging from 4–11 with constant discharge, Stage 1 and zero discharge following it, ranging from 10–25 (Figure 5.7k).

The tidal prism after Stage 1 was calculated at ~853,170 $m^3$ which is higher than 732,018 $m^3$ measured and calculated by Domijan (2000) following the 1996 re-diversion. Back then with an average discharge of 30 $m^3/s$, r (based on mixing classification criteria) was estimated at 0.77, meaning the estuary was partially-mixed. Our value of r with the same average discharge but higher mean tidal prism is 0.9. This slightly higher value is is still in the partially-mixed range.

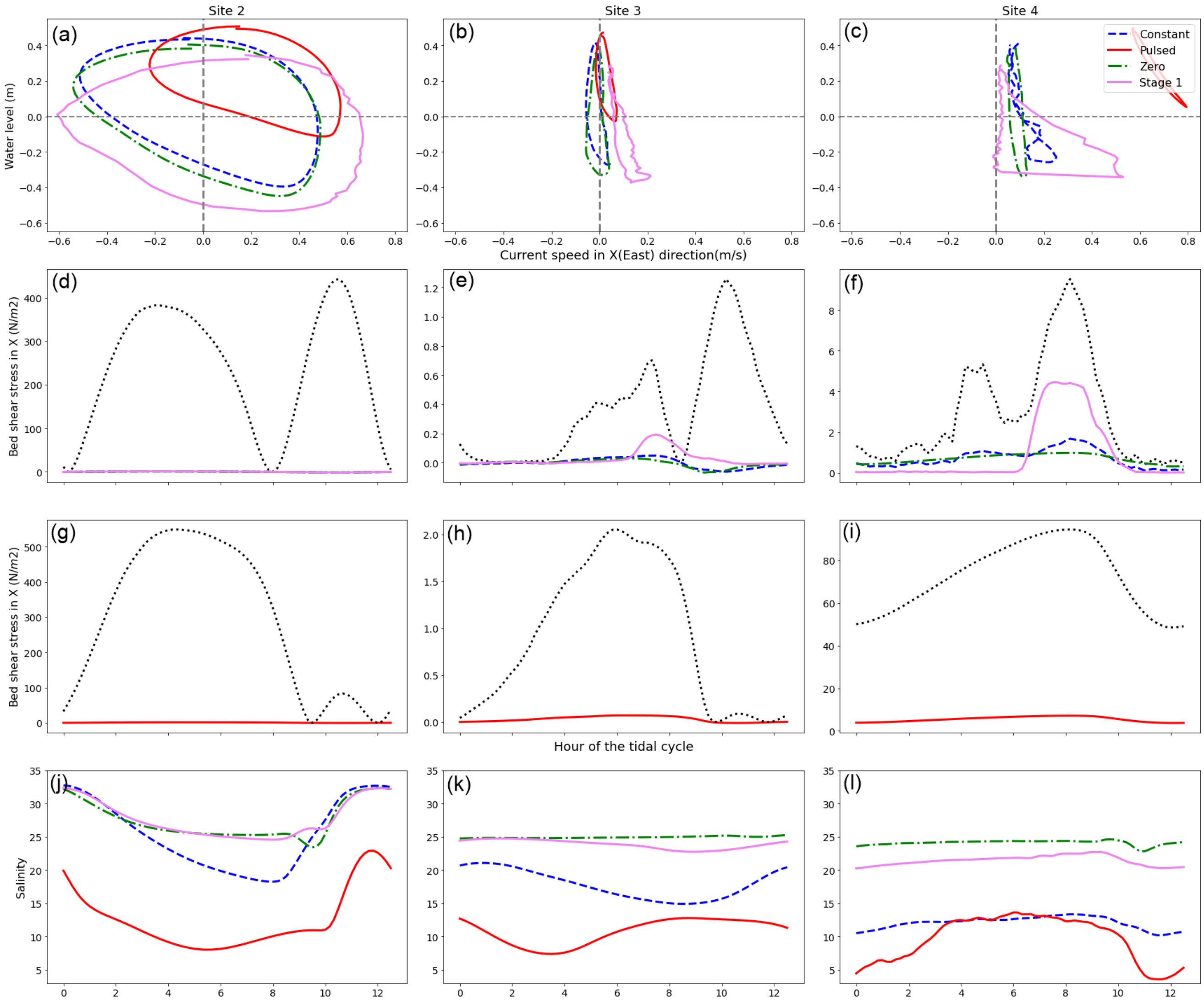



*Figure 5.7 Average tidal stage plot, bed shear stress in the x direction and bottom salinity for 3 scenarios at (a,d,g) Site 2, (b,e,h) Site 3 and (c,f,i) Site 4. Note the different scales for critical and bed shear stress*

## 5.6 Discussion

### 5.6.1 Estuarine hydrodynamics and flushing ability

In microtidal, shallow and partially-mixed estuaries such as Maketū, tidal prism (estuary-ocean exchange) contributes to the majority of the estuary's mean water volume, so it is typical for them to have varying hydrodynamics and flushing abilities depending on their geometry, inflow input (tide, river discharge and rain) and wind (Taherkhani et al., 2023). It is important to note that our model was set and calibrated for summer river discharges, which can differ from other seasons, and they impact the estuarine hydrodynamics the most. Generally, freshwater discharge affects the flow transport in two main ways in estuaries, short-term on their flushing ability and long-term on average salinity levels and salinity intrusion zone.

Our model was not as well calibrated for the current velocity at Site 3 in the mid-estuary compared to the rest of the modelled estuary. Therefore the flushing ability may not be as accurate in this region. We believe this is not due to the bathymetry or roughness level of the estuarine bed but perhaps the lack of wave-forcing conditions and model uncertainties that often fail to model real natural systems.

Our model results showed an increase in tracer decay rate as the river discharge increased in each scenario, with the pulsed scenario having the shortest residence time and Stage 1 having the longest. Sites 3 and 5 in the mid-estuary and Site 6 in the upper estuary showed an exponential decrease in tracer concentration while the rest of the sites fluctuated with the tides. As reported by Wan et al. (2013) this is an indication of a “bottleneck” effect of the upper estuary, particularly at lower flow conditions. In contrast, materials close to the estuary mouth can be quickly flushed out through tidal exchange for short-term. However, the implications may be different for long-term flushing due the dynamic nature of the estuary mouth.

Wan et al. (2013) further add that due to this synergistic interaction between freshwater and tidal flushing, conservative tracers may reside longer in specific zones within the estuary compared to the estuary mouth or tidal channels. They call this zone a “residence time maximum”. A reversal trend in tracer decay is also an indication of this zone, i.e., tracer decay decreases at sites in the upper estuary while increasing in the lower estuary. In our study, this zone travels from the west to the east side of the estuary with increasing river discharge. This is where the geometry of the estuary combined with river discharge plays a major role, specifically having long narrow shallow channels inhibits “new” water flowing in compared to deeper tidal channels elsewhere in the estuary. What is usually observed is a slow-paced inflow of mixed new and old water.

This is also observed with salinity levels at Site 6 in the upper estuary, where there is no sign of fluctuation with tidal forces or river discharge except for the pulsed scenario. According to previous studies such as de Pablo et al. (2022), expectations with pulsed scenarios are that they form a high hydraulic head at the upstream end of the estuary that sets up a large pressure gradient force down the estuary. This increase in river discharge will force tracers out of the estuary. Still, if it reaches exceptionally high values, local eddies could form, retaining tracers in inner bays and less dynamic areas of the estuary.

Model salinity results matched the observed salinity levels for the lower and upper estuary. However, the model overestimates the mixing in the mid-estuary, which resulted in mid-range salinity levels for Sites 3 and 5, which did not capture the salinity fluctuations with the tidal range. Our results showed reduced average salinity levels for the pulsed scenario compared to the rest of the scenarios. To better understand the dominant mixing processes in the estuary, the tidal Froude number was extracted from the model, and all sites and scenarios remained below 1. According to multiple sources such as Dijkstra and Schuttelaars (2021) and Hetland and Geyer (2004), this corresponds to “subcritical” and can be treated as a linear wave. It also means that tidal energy is more likely to be transmitted upstream and potentially influence the dynamics of the upper estuary. But we observed that not to be the case in the Maketū Estuary and that its complex geometry and bathymetry led to a more non-linear behaviour, specifically showing tidal asymmetry in the mid and upper estuary. Our study also demonstrated how different freshwater discharge scenarios can lead to asymmetric velocities in certain areas and change in a net transport of the flow throughout the estuary, as observed for Stage 1 in the field. Furthermore, critical bed shear stress was reached two and three times at Site 2 and 3, respectively, for the pulsed scenario and was never reached for Site 4. During these instances if there are wind-induced waves, the chances of sediment erosion would be higher. The other scenarios showed a different pattern in reaching critical bed shear stress. Site 3 and 4 reached it for approximately 3 hours during the tidal cycle, indicating a higher probability of sediment erosion. Site 2, however, reached critical bed shear stress for 3 instances during the tidal cycle, and if there existed an external force such as wind, it might have led to erosion.

Notably, the model results lacked accuracy in determining the extent of flow velocities at Site 3 in the mid-estuary. Nevertheless, signs of tidal asymmetry and a shift to ebb dominance have major sediment transport indications both in the short-term and long-term depending on the grain size and bed porosity, with those sites with fine and muddy sediment being the first ones to respond to these tidal flow changes.

As part of the monitoring scheme for the Maketū restoration project, sediment erosion and accretion were recorded before and after Stage 1 by BOPRC. According to the Bay of Plenty Regional Council (2020), although it was too early to expect sediment transport after Stage 1, one site (between Site 4 and Site 6 near the Papahikahawai island) showed a response to the changes in current flows specifically a loss of fine and muddy sediment. Before Stage 1 this site was relatively sheltered and had no flows due to the presence of a causeway, which was removed as part of the restoration.

### 5.6.2 Ecological implications

Multiple studies have shown how different residence times can impact the connectivity of populations by controlling the retention and dispersal of larvae in other areas (Cowen & Sponaugle, 2009; Levin, 2006; Moffatt, 2021; Monahan, 2018). Excessive anthropogenic nutrient loading into estuaries, poor flushing rates, and longer residence times may increase primary production, resulting in eutrophication (Gonzalez et al., 2008; Savage et al., 2012; Stewart, 2021). On the other hand, short residence time (under 2 days) such as in the study by Wang et al. (2004), was one of the limiting factors that result in low phytoplankton biomass despite extremely high nutrient concentrations. It could also lead to the pollutants exerting their effects in the coastal waters outside the estuary. A pollutant will exert most of its effects within an estuary if its biochemical time scales are comparable to or shorter than the residence time. In our study, the pulsed scenario showed a residence of time lower than 2 days; specifically, Sites 3 and 4 have a residence time of 1.5 days and 1 tidal cycle, respectively.

The ecological impacts extend to water level, current speeds, and salinity levels. Differences in current speeds due to freshwater discharge would alter the distribution of sediment and species and the settlement of larvae (Moffatt, 2021). Moffatt (2021) also adds that the loss of species could impact the ecosystem and its services. For example, a decrease in the abundance of bivalves due to increased mud distribution would reduce the filtration of nutrients out of the water and potentially increase the risk of eutrophication. In our study, the pulsed scenario is the most likely to increase the mud distribution due to higher concentrations of suspended sediment entering the estuary and, due to higher current velocities, disturb most species, creating a domino effect of eutrophication and adversely impacting the ecosystem.

Moreover, different aquatic and marsh species have varying tolerances and preferences for water salinity levels. Previous studies such as Lake Waihola, New Zealand by (Schallenberg et al., 2003) showed how a slight increase in salinity could change the zooplankton community of copepods, rotifers, cladocerans, amphipods and amoebae, etc. Salinity is, therefore, a key determinant of species composition and relative abundance in tidal environments especially considering its impact on estuarine sediments; since lower salinities in estuaries allow sediments to have more ammonium but lower levels of adsorbed metals (Das et al., 2012). In our study, the pulsed scenario produced the lowest salinity levels, followed by the constant discharge scenario. It is essential to look into the specific impacts of this reduction in average salinity since the distribution and composition of fish in estuaries are influenced by the salinity regime and distance from the mouth of the estuary (Loneragan & Bunn, 1999). Moreover, changes in salinity in fishes affect the metabolic cost of osmoregulation (Morgan & Iwama, 2011) and food conversion efficiencies (Desilva & Perera, 1976; Ferraris et al., 1986). As studied by (Piazza & La Peyre, 2011), increased discharges could increase habitat accessibility for smaller species while lowered salinity down estuary could change the marine species composition. In the case Barataria estuary by (Das et al., 2012), model results indicated that river diversions strongly affect salinities only in the middle section of the estuary, which presents a challenge when designing a system of monitoring stations, both for assessing changes in the system as a whole. In the case of the Maketū Estuary, the upper estuary showed the most changes in salinity with the added freshwater flow, highlighting the need for a more detailed monitoring scheme of various species.

According to the Bay of Plenty Regional Council (2020) ecological impact report, macroalgal cover before and after Stage 1 (2019 and 2020) was generally reported to have increased with higher river discharge rates. They report that post Stage 1 compared to 2018, lower to the mid estuary (the area between Site 1 and Site 3) as well as Site 4 has largely cleared of macroalgae allowing improvement of sediment conditions and recovery of macrofaunal diversity. They also reported clearing of very high biomass of *Gracilaria chilensis* with patches of cyanobacteria.

Marine life has recolonised the Papahikahawai Channel (Site 5) as benthic habitat conditions have improved with the restoration of tidal flows and a re-connection to the sea. Some tuangi (cockles) had already reached a size of 25-30mm and a mean size of 18mm. Restoration of tidal flows, clearance of macroalgae and improvement in the quality of the sediments has resulted in the Papahikahawai Channel area being colonised by a range of estuarine species. One of the more prominent early colonisers has been the crabs and titiko. The restoration of tidal flows was primarily due to the removal of causeways, and not re-diversion of the lower Kaituna River.

Despite not having done ecological monitoring ourselves, it is safe to assess how the species will be impacted based on the monitoring done by the BOPRC after Stage 1. We speculate that higher freshwater discharge will keep having the positive impact already observed post Stage 1. Still, a certain level of discharge exists, which, once passed, will reverse this trend and lead to the clearing of some species. However, this does not include our pulsed scenario since it has a discharge rate of 60 $m^3$/s.

### 5.6.3 Management implications

Following de Pablo et al. (2022), to identify the most vulnerable areas within the estuary and for management purposes, Maketū estuary was divided into zones (Figure 3.1) based on morphology, hydrodynamics, and other local drivers, as these may influence the residence time of specific areas differently. Our study can be an essential tool for decision-makers to make more informed decisions, and it highlights how management decisions in one area may affect others. More specifically, we discovered that the most vulnerable regions for Stage 1 and constant scenario, regarding flushing ability, are Site 5 and 6 in the mid and upper estuary, respectively. For the pulsed scenario, this vulnerability seems to shift to Sites 3 and 4 as residence time is observed to be too short. The added freshwater flow during the pulsed scenario creates a head difference which drives the flow from the upper estuary towards the mid and lower estuary. This freshwater flow directly impacts net transport and leads to changes in residence time.

Depending on the environmental conditions, the estuary may not be able to accommodate such volumes, specifically considering its narrow and dynamic tidal inlet. Therefore, another factor to consider is accretion in the mouth segment, which is common and sometimes seasonal in many estuaries, leading to tidal energy losses creating flood dominance. Like most estuaries, the tidal inlet at Maketū is dynamic, and accretion and erosion are observed depending on environmental factors. Interventions such as reclamation, flood control measures and river discharge alterations often increase residence time due to decreased estuarine volume (Velamala et al., 2016). Hence, according to Velamala et al. (2016) one solution would be dredging in the estuary to enhance navigation at the inlet regions which can lead to positive effects by facilitating an increase in the volume of seawater entering the system. This option is viable since dregding the tidal inlet in Maketū was first done in 1926 (the first human interference with the estuary's hydrodynamics) which was deepening the Maketū tidal inlet by blasting (BOPCC, 1970). Another option would be stabilise the estuary mouth through training walls similar to Lake Illawarra in Australia (Young et al., 2014).

As previously mentioned, salinity differences in different areas of the estuary complicate monitoring and management schemes as species do not share the same tolerance regarding salinity levels and sediment characteristics. To minimise this complexity, it is suggested by Das et al. (2012) to set the discharge rate of freshwater in compatibility with the salinity tolerance range of the more essential species in the estuary. Timing of the river discharge can also play a major factor; for example, if the freshwater discharge is timed to occur during the seasons when algal bloom frequency is low, it may help control the spread of potentially toxic cyanobacterial species (Das et al., 2012). In our case, vulnerable sites regarding salinity levels remain Site 5 and 6 in the mid and upper estuary. Although a general decrease in mean salinity levels was observed with added freshwater after Stage 1, it may not be sufficient to cater to all endangered species within the region.

According to Odum et al. (1995) pulsing is considered essential for most ecosystem functioning and has been called nature's pulsing paradigm. However, the extent to which mean salinity and current velocities decrease and increase respectively, need to be considered when making restoration decisions. In our case, and as mentioned before, salinity and sediment contribute simultaneously when it comes to ecosystem health, and there needs to be a limit to how much salinity and current velocity can change before they damage the species.

## 5.7 Conclusions

We developed a validated numerical model (Delft3D) to investigate the spatial variability of flushing ability and residence time in the Maketū Estuary under 3 scenarios of freshwater discharge. The model was calibrated and validated with field data observation over one month. The model lacked accuracy in predicting the fluctuations of salinity in the mid-estuary mainly because the coastal boundary of the domain was too close to the estuary inlet, as well as model uncertainties and therefore mixing was overestimated. Nevertheless, the model still simulates the impact of increasing river discharge on residence time. Based on our findings, residence time response to freshwater discharge was not uniform throughout the estuary. The pulsed scenario achieved the lowest residence time and mean salinity levels throughout the estuary. We also discovered an increase in net transport and a shift towards ebb dominance with the added freshwater flow, especially in the mid and upper estuary. Compared to the Pulsed scenario, bed shear stress reached critical bed shear stress for longer periods for Stage 1, constant river discharge and zero discharge.

A previous monitoring report by BOPRC mentioned improvement in the estuary's ecological state, specifically reduction of macroalgae in the estuary, which led to the recovery of macrofaunal diversity. Marine life has also been able to recolonise as benthic habitat conditions have improved.

Regarding this study's management aspect, we identified the most vulnerable areas within the estuary as a function of the river discharge. Site 6, 5 and 3 are among those areas with lower flushing ability than the rest of the sites. These sites also have more muddy and soft sediments, and increased brackish water. Overall, we consider the pulsed scenario to be the most effective in flushing ability and shift to ebb dominance. Still, Stage 1 provides a better environment regarding mean salinity levels and sediment erosion. The most suitable solution would perhaps be a shorter pulse of freshwater instead of 2 weeks. We also acknowledge that in the natural environment of Maketū Estuary and Kaituna River, reaching a pulse of 60 m3/s for 2 weeks is impossible. Sediment transport and climate-induced changes such as sea level rise (SLR) are essential to water exchange and residence time in shallow mixed estuaries. Still, they are often overlooked in studies of residence time. More research is needed to investigate the interactions between sediment transport, water exchange, and SLR and how these interactions affect residence time and estuarine ecology.

# 6 CHAPTER 6 GENERAL DISCUSSION AND CONCLUSION

## 6.1 Introduction

The aim of this thesis project was to investigate the hydrodynamics and evolution of the Maketū Estuary in response to the partial re-diversion of the Kaituna River. There were four main objectives:

1. Quantify the initial response of estuarine hydrodynamics (currents, salinity, turbidity and temperature) to partial river re-diversion;
2. Establish the inter-annual changes in estuarine hydrodynamics, specifically estuarine circulation and tidal asymmetry, in response to the added freshwater flow;
3. Investigate the response of estuarine flushing and residence time to river re-diversion and
4. Determine the success of the restoration attempt in terms of water quality and management implications.

Achieving this aim and these objectives contributes to increasing knowledge on estuarine restoration and management via river re-diversion in estuaries with complex engineered interventions, utilising the Maketū Estuary as a case study. It also highlighted the importance of utilising appropriate monitoring methods for different zones of estuaries based on their flow and mixing characteristics. In particular, it addressed the knowledge gaps identified in Chapter 2.

## 6.2 Thesis objectives and outcomes

The field observations and numerical modelling identified 4 main zones within Maketū Estuary and lower Kaituna River that were characterized by different morphologies and dominant processes (Figure 6.1). The lower Kaituna River is a tidally influenced river channel; the upper estuary consists of former river channels and saltmarsh floodplains stranded by the diversion of the Kaituna River through Te Tumu Cut; the middle estuary consists of a shallow river deltaic system of braided channels and bars; and the lower estuary is a tidal inlet system with flood tidal delta and ebb tidal channels.

These zones responded differently to the re-diversion of the Kaituna River into the estuary, which reflected the distance from the inflow at Ford's Cut and the degree of connectivity. The response also changed as each stage of the re-diversion was implemented as indicated by the timeline in Figure 6.2.

The specific objectives and the thesis findings regarding the response of the Maketū Estuary to re-diversion are summarized below:

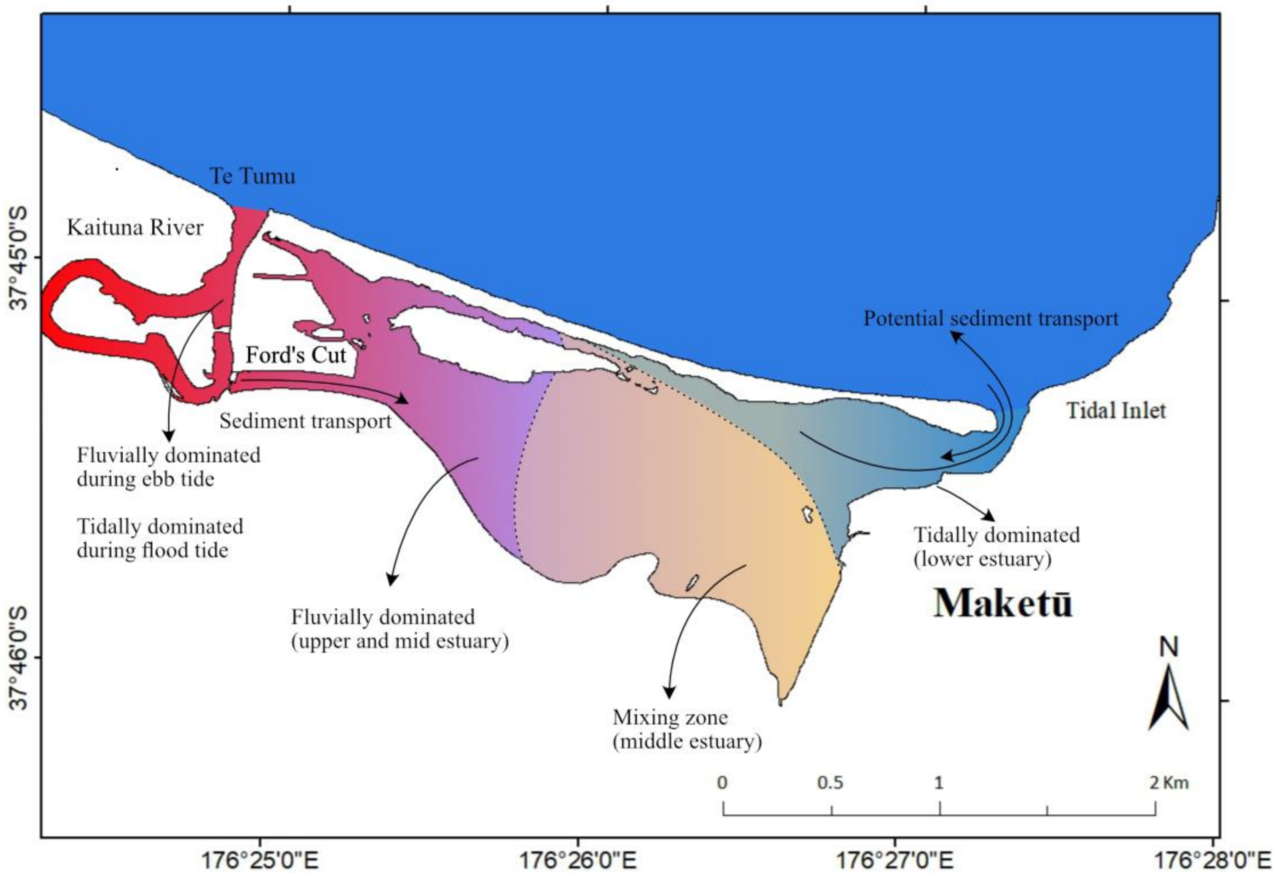



*Figure 6.1 Schematic presentation of main zones identified within the Lower Kaituna River and Maketū Estuary based on the geomorphology and dominant processes driving circulation and mixing*

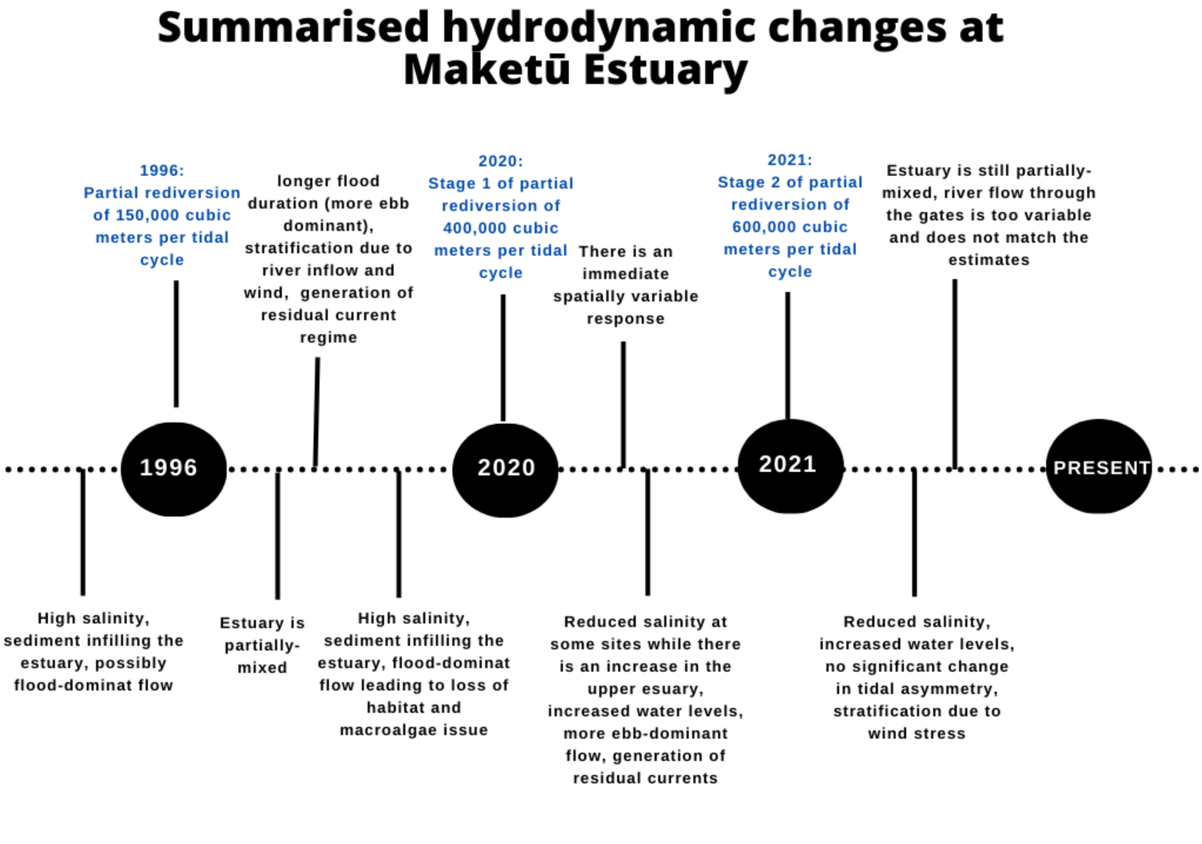



*Figure 6.2 Timeline of past and observed hydrodynamic data and analysis before and after Stages 1 and 2*

1. **What is the initial response of the estuarine hydrodynamics (currents, salinity, turbidity and temperature) to partial river re-diversion during Stage 1? (Chapter 3)**

The field data collected over approximately 5 weeks showed that the mean water level increased slightly after the gates were commissioned. The added freshwater generated an ebb-dominant flow, especially in the mid-estuary. Salinity increased in the upper estuary, but decreased elsewhere, likely due to freshwater being trapped in the upper layers and not mixing with more saline water at the bottom. While there were small changes to the estuarine Richardson number, the resulting classification did not change, and the estuary remained partially mixed. However, an asymmetry in mixing developed after Stage 1, which involved freshwater getting trapped in the upper estuary during the flood tide (when the gates open, salinity drops uniformly) and the marine water reaching the upper estuary during ebb tide. This means that most of the mixing happens in the mid estuary (mixing zone) when the tide instance is shifting and with it the tide versus fluvial dominance shift too.

2. **What are the inter-annual changes in estuarine hydrodynamics, specifically estuarine circulation and tidal asymmetry, in response to the added freshwater flow (Chapter 4)**

The main difference observed was lower overall freshwater inflow to the Estuary despite the increased number of gates, higher rainfall within the Kaituna Catchment, and a storm event during Stage 2 monitoring period. This suggests that the actual inflows into the estuary are not a simple linear function of the gate configuration and timing.

There was an increase in mean water level and flood currents at all sites, and accordingly, mean salinity declined slightly after Stage 2. The Estuarine Richardson number did not exceed the critical value for classification change, and tidal asymmetry was not as impacted as strongly as post-Stage 1. Flows were ebb-dominant after Stage 2, but the added freshwater did not increase this ebb-dominance. Maximum and minimum salinities changed before and after Stages 1 and 2, mainly due to environmental factors (rainfall, evaporation rate and wind). In comparison, Stage 1 had a stronger impact on the estuary regarding freshwater, but Stage 2 highlighted the environmental factors, such as the storm event on stratification, especially in the upper estuary.

3. **What is the response of the estuarine flushing and residence time to river re-diversion (Chapter 5)**

Chapter 5 highlighted the more vulnerable areas within the estuary regarding flushing ability. Two of the three modelling scenarios were inspired by the true nature of river activity (flow without gates and pulsed flood scenario) and the partial re-diversion (Stage 1). The simulated results showed similar flushing ability for Stage 1 and constant flow scenarios and the lowest residence time for the pulsed scenario. The tidal behaviour of the decay rate shows that with river discharge through gates, freshwater gets trapped in the upper estuary during flood tide before mixing with seawater; some of this mixed water moves to the mid-estuary before mixing again with “new” water.

4. **Is it possible to determine the success of the restoration in terms of water quality and management? (current Chapter)**

This next section of this chapter focuses on the five targets of the Kaituna River Re-diversion project set by BOPRC (Environment Bay of Plenty et al., 2009), and  evaluates whether they were achieved based on the observations and modelling presented in the previous chapters.

## 6.3 Key targets of re-diversion versus observed outcomes

### 6.3.1 To protect and improve water quality

A stream or river can support the range of uses and values for which it is required, provide for a healthy aquatic ecosystem and have the potential to meet the needs of the future. Based on our data, the freshwater entering the estuary through the gates varies in salinity depending on the tidal flow. The lower Kaituna River flow at Te Tumu becomes more tidally dominated during the flood tide and fluvially dominated during the ebb tide (Figure 6.1). Therefore, although the salinity block successfully prevented marine water (via Te Tumu Cut) from entering through the gates for Stage 1 and 2, it did not prevent mixing occurring further up the river due to salinity intrusion. The resulting brackish water bypassed the salinity block and entered the Maketū Estuary.

The reduction in estuarine salinity is strongest when the discharge is high, such as occurred during Stage 1 due to higher river flows at that time. This is due to less mixing with saltwater upstream of the channel supplying freshwater to the control gates, and a higher discharge due to a greater head difference at the control gates. Overall, the degree of freshwater restoration was highly variable due the variation of inflow volumes and the degree of saltwater mixing in the Lower Kaituna River.

Circulation patterns in the estuary also highly depend on the freshwater discharge. During Stage 1 when the fluvial flow was more dominant, the flushing ability of the estuary was stronger too and freshwater flowed more easily to the lower estuary during flood tide, this reduced the salinity in the mid and lower estuary. On the other hand, while the salinity dropped sharply in the upper estuary during flood tide, it increased to a higher-level during ebb tide, causing a generally higher mean bottom salinity in this zone. During Stage 2, freshwater got trapped in the upper estuary during flood tide while marine water entered the estuary via the tidal inlet (like Stage 1), however with a less fluvially dominant flow combined with the storm winds, mixing happened in a wider zone and reduced the bottom salinity for all sites.

Tidal asymmetry was amplified by the eastward freshwater currents during both stages, with Stage 1 being more intense than Stage 2. However, this ebb-dominance did not expand to the rest of the estuary and remained in the upper and mid estuary. This suggests sediment may be flushed out of the upper estuary to the lower zone depending on the freshwater discharge. The increase in net flow and tidal prism also suggests the potential for sediment transport out of the estuary but a more detailed study is required.

Residence time was predicted to be the shortest for a pulsed flood scenario while creating an enhanced ebb-dominant flow, possibly leading to immediate sediment transport. This further highlights the need to recreate the natural behaviour of the river (pulsed floods) to enhance restoration of the estuary. Different estuary zones respond differently to the river re-diversion (in terms of flushing ability, mixing patterns and tidal propagation), and the mixing zone border moves further up the estuary with lower freshwater inflow; this border was expected to be closer to the tidal inlet with the BOPRC estimated discharge through the gates (Figure 6.1). Therefore, monitoring schemes need to accommodate the more vulnerable zones and species.

In sum, although Stage 1 and Stage 2 had an impact on the hydrodynamics and the water quality of the estuary, they were only partially successful in restoring the water quality due to the high variability in freshwater discharge and the lack of harmony with the natural behavior of the river.

### 6.3.2 To ensure navigability at Te Tumu and improvement in the tidal inlet while keeping Te Tumu open for flood hazards

This target is focused on erosion/accretion at Te Tumu Cut, which connects the vessel launching facilities (boat ramp) near Ford's Cut with the open ocean. Previous studies have shown the stability of the channel at Te Tumu is dependent on the longshore sediment transport rate and the ebb discharge from the lower Kaituna River (Bruun et al., 1974; Gao & Collins, 1994; Mawer, 2012; O'Brien & Dean, 1972). The operation of the gates is intended to divert water into the estuary during flood tide conditions, to avoid reducing the ebb discharge.

However, this mode of operation may allow the flood tidal flow to transport sediment further upstream than before re-diversion. It was also previously noted (KRTA, 1986; Mawer, 2012) that the ebb tidal delta tends to accrete and close off Te Tumu Cut, until swept away by a flood event (> 400 cusecs). This study did not assess the response of Te Tumu Cut to the re-diversion Stages 1 and 2, but did observe that the inflows through the gates did not match the theoretical discharges. No data was obtained during flood events requiring the closure of the gates. Further study into the timing of these gates and their impact on Te Tumu is necessary.

### 6.3.3 To restore a healthy ecosystem:

This study did not investigate the ecological response to the re-diversion. However, it is generally accepted that the response to re-diversion is related to the changes to the circulation and water quality responses, which were investigated. As mentioned before, the observed changes were not large enough to impact the main body of the estuary in the long-term and model results further confirmed that higher rates of river discharge are required.

Previous studies (Murray, 1978; Loomis, 1984; KRTA, 1986) indicated that most of the ecological changes concerning the community involved salt marshes and tidal wetlands fringing the estuary. The restoration of Maketū Estuary is tackling these areas with other measures separate from the re-diversion. It is beyond the scope of this theses to assess these measures. However, as discussed in Chapter 5, the ecological improvements reported by the BOPRC after Stage 1 appear to be largely a consequence of the removal of causeways connecting the Papahikahawhai block (island) to the mainland.

The term "restoration" implies a return to some previous condition (Verdonschot et al., 2013). However, it is difficult to define what this previous condition was for the Maketū estuary (Loomis, 1984). However, with the proper physical and biological conditions being restored, one also expects to see improvement in the overall state of the ecosystem. The main hydrological factors influencing these conditions are current velocity, mixing (salinity) and turbidity. While this study observed an increase in current velocity, a reduction in salinity and a shift towards ebb dominance (indicating a potential for sediment transport out of the estuary), it is impossible to conclude that they guarantee an improvement to the ecosystem. As Verdonschot et al. (2013) mentioned, more comprehensive and long-term monitoring is essential to underpin quantitative assessment of management measures. The aquatic literature has demonstrated that restoration is unique to specific sites, time and organism groups and that, as a consequence, generalisations on recovery processes are challenging.

### 6.3.4 To ensure sustainable land-use development:

This outcome is focused on making sure that resources in the Kaituna River and Ōngātoro/Maketū Estuary are managed and used in a way that protects and enhances the things we value – views, collecting kaimoana, and enjoying the natural features that the Kaituna River and Ōngātoro/Maketū Estuary offer. Although out of the scope for this study and not wholly measurable, this target somewhat includes the previous two. At the same time, some of the features of Maketū Estuary's historic state cannot be achieved, such as larger scale fishing, navigation for bigger vessels, etc.

Mitigating the more recent issues such as eutrophication and sedimentation is possible. Specifically, improving the flushing ability of the estuary with higher rates of freshwater that imitate natural flood events (pulsed scenario) could trigger a chain of events that start with sediment being flushed out and eventually lead to the clearing of macroalgae and increase in macrofauna population. After all, reducing the most visual signs of ecological decline, such as algal blooms (Elliott et al., 2016), may indicate the restoration's success. On the other hand, from expert opinion and discussion, if Te Tumu is left in its natural state, 600,000 $m^3$/tidal cycle (Stage 2) is likely the maximum volume that will flow from the river to the estuary irrespective of the size of the diversion structure. Te Tumu could be constricted by constructing a western training wall to force more water through the estuary (Environment Bay of Plenty, 2009).

### 6.3.5 To support kaitiakitanga and local people's stewardship

The Maketū estuary and Kaituna River are extremely important to mana whenua (Environment Bay of Plenty, 2009). This target is out of the scope of this study and it would be for mana whenua to determine if this target has been achieved.

## 6.4 Discussion

Generally, estuarine and coastal waters have long periods of recovery of at least a decade (Borja et al., 2010), with recovery implying that a system will return to a previous condition after being in a degraded or disrupted one, which is often interpreted as being in poor ecological health (Simenstad et al., 2006). Moreover, determining the attainment of the desired or targeted system is impossible without an agreement and criteria for the restoration goals of the system (Simenstad et al., 2006). Many studies on restoration attempts are focused on single pressures and do not include time-series data analysis (Verdonschot et al., 2013). It is not possible to assess if the targets above are met without a proper analysis of the extent of this improvement.

One concern mentioned by BOPRC was the uncertainty with how river flows go through the estuary, with the possibility that higher discharge through the gates would be required because the estuary is so full of sand. The consensus of previous studies and the available evidence indicate that the natural pre-diversion state of the river-mouth estuary at Maketū was a deltaic system of shallow braided channels and sandbars. Removal of these will probably require dredging and further disruption of the estuary. Morphological impacts to the river channels and sandbars will be hard to predict, especially when high river flows occur, i.e. estuary fringe erosion or spit blow-out could readily occur. Furthermore, other concerns include: potential flooding and erosion of the road to Maketū potential needs for flood protection/mitigation of Maketū infrastructure; loss of boating access through Te Tumu; potential breaching of the spit; and scour along the Papahikahawai Channel.

BOPRC has suggested options to mitigate these concerns, including but not limited to a new highly efficient channel between the river and the estuary to replace or augment Ford's Cut; or the creation of flood storage further upstream (to avoid a rise in flood levels in the upper catchment); or a spill weir at Te Tumu (providing flood release). These would be feasible if land could be obtained, or the proposals were undertaken in conjunction with wetland creation if multi-purpose use was acceptable. Overall, since a full re-diversion is likely inconsistent with several BOPRC policies, pulsed flood flows with higher discharge rates seem to be the more conservative option.

## 6.5 Summary and conclusion

The Maketū Estuary has had a long history of engineering works and interventions relating to its overall structure and freshwater inflow. When the river flow was removed, it changed from a dynamic river mouth to a more tidally dominated lagoon. This, combined with its community and cultural significance, made its restoration attempt more complex. This study evaluated the impact of the 2020/2021 river re-diversion on the hydrodynamics of the estuary.

Global studies have emphasised setting clear and specific targets (measurable and consistent) for restoration schemes to assess their success fairly. More precisely, laying out a range for change in the physical parameters that the re-diversion would achieve is essential. Since that was not the case for the Kaituna Re-diversion, this study focused on the increase in the flushing ability, current velocity and decrease in salinity levels as indicators of physical impact.

Although the added freshwater flow impacts the circulation and tidal asymmetry to some degree, the river discharge through the gates is highly constrained. Depending on the meteorological conditions, it may not have the expected impact, at least not in the long term. To maintain the health of the estuary, it is vital to address the flushing issue in the vulnerable zone (Sites 5 and 6) and to do so, a higher rate of river discharge is required.

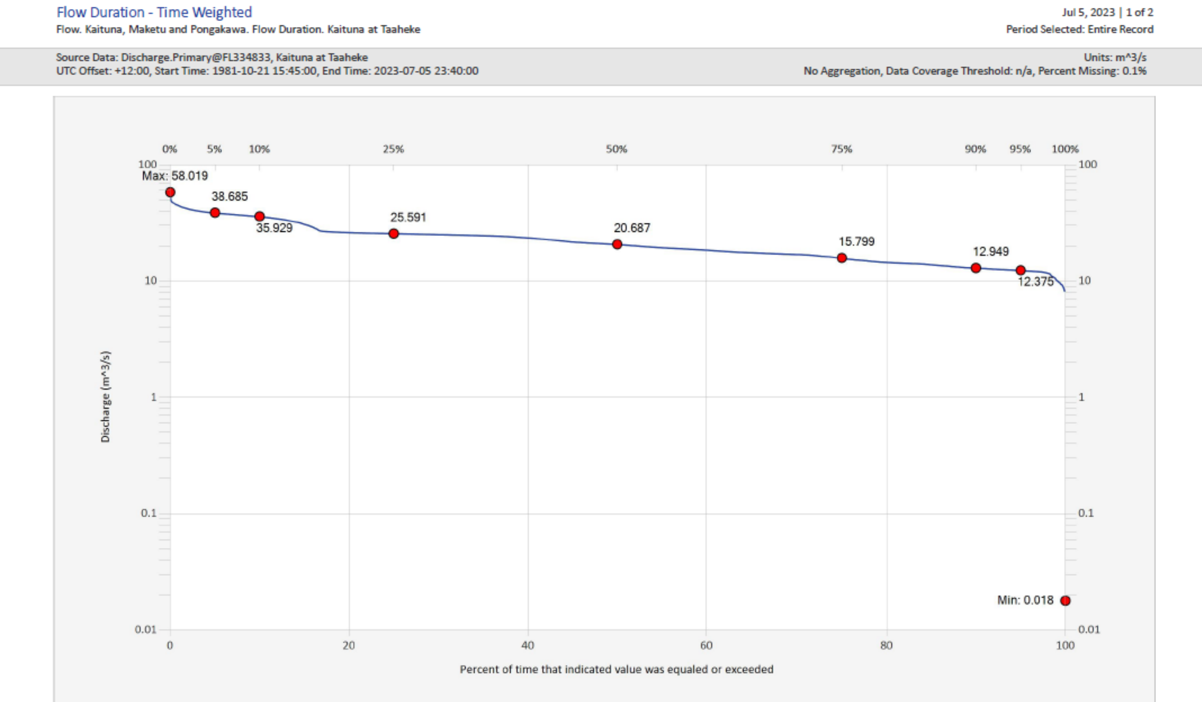
Our pulsed scenario was showed to be more efficient in targeting the flushing ability, tidal asymmetry and salinity reduction within the estuary, especially in the more vulnerable zone. This plan can be modified depending on the season and meteorological conditions while avoiding flooding in the upper catchment or Maketū region. Depending on the scenario's main aim, such as sediment transport out of the estuary or just enhanced flushing ability, the frequency of the pulsed flood can differ (ranging from 4 hours, similar to Stages 1 and 2 or days). It is important to note that weir construction at Te Tumu may not be needed if a suggested dam in the upper catchment allows more water to flow in the Kaituna River, but dredging the tidal inlet may be necessary depending on the season. With a higher flow rate in the Kaituna River, the question of flood storage may become an issue and affect the wetlands in the region.

There are still significant gaps in estuarine restoration and management knowledge, specifically those related to setting and achieving realistic targets. It is vital to note the multi-dimensional impact of these attempts and how a linear mindset will not improve the understanding and implementation of estuarine restoration and management. Improving the knowledge in setting realistic physical targets and defining success in restoration will lead to more informed decisions.

Despite observing the immediate and inter-annual impact of the re-diversion on salinity, tidal asymmetry and the flushing ability, there remains uncertainty about how long the recovery of the estuary will take and whether it can adapt to sea level rise in the long term. With that in mind, it is too early to decide if the restoration attempt satisfies the community's needs, and further monitoring and research are required. For example, long-term morphological change in the estuary combined with future sea level rise scenarios would fill the gap in estuarine restoration knowledge for sites such as the Maketū Estuary, with a long history of engineering works. Considering applying the pulsed flood scenario, there needs to be more research on determining the specific flows that will trigger sediment transport out of the estuary but not flush out nutrients too fast, while minimising the chance of floods in the area.

# APPENDIX

*Figure A1. Kaituna flow probability at Taaheke from 1954 until 2023 by BOPRC in 2023*



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