The ecological implications of reconstructed historic hydrodynamic conditions in Tauranga Harbour (1852-2006).

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ABSTRACT

In order to manage, restore and mitigate the increasing anthropogenic impacts on estuarine systems in the future, it is useful to understand the magnitude and distribution of historic changes in environmental conditions that may have impacted on ecosystems through time. The general aim of this thesis is to hind cast historic environmental conditions in order to investigate the ecological implications of changes in geomorphology and hydrodynamics within the southern basin of Tauranga Harbour. This was achieved by compiling 11 bathymetries and developing a hydrodynamic numerical model.

The bathymetries produced were from 1852, 1879, 1901, 1927, 1954 and 2006 (entrance adjusted bathymetries). An additional 5 bathymetries from 1852, 1879, 1901, 1927 and 1954 were compiled which had sediment removed from the intertidal areas to simulate infilling (intertidal adjusted bathymetries). The impact of the simulated infilling on depth Investigate the by comparing the entrance adjusted bathymetries with the intertidal adjusted bathymetries of each year. Using the numerical modelling environment Delft3D a numerical model of the southern basin of Tauranga harbour was developed to simulate historical hydrodynamic conditions for each of the 11 bathymetries. The impact of the simulated infilling on hydrodynamics was investigated by comparing the results of the entrance adjusted and intertidal adjusted numerical models of each year. The modelled hydrodynamic conditions of current speed, water level range and tracer decay from the intertidal adjusted bathymetries were used to investigate temporal changes in environmental conditions that may have influenced historic ecological health and distribution of species.

The comparison of depth and hydrodynamics between the entrance and intertidal bathymetries for each year showed that the simulated infilling caused slight changes in the distribution of depth and a slight increase in the magnitude of current speed, water level range and rate of tracer decay.

The temporal changes in the environmental conditions included large magnitude small scale changes in depth and current speed occurred in the harbour entrance channels. Water level had the most significant change prior to dredging across the

Harbour potentially due to historic changes in the inlet cross-section. For depth, water level and current speed the 2006 conditions were most different to the earliest 1852 conditions. This is due to the accumulation of both large natural changes in geomorphology and hydrodynamics and changes from the anthropogenic dredging and development. The tracer decay had most difference through time in the regions with changes in the constricted entrance such as in the estuaries above Sulphur Point.

Significant ecological implications include changes in depth and water level influencing functions such as bivalve feeding times, inundation of mangroves and light attenuation for seagrass. A significant change through time as a result of the intertidal infilling is the predicted expansion of mangroves. Differences in current speeds would alter the distribution of sediment and species as well as the settlement of larvae. Residence times have had largescale changes due to the anthropogenic changes around port development. These changes would result in an increase in the retention of sediments, contaminants and larvae and a shift from bivalve dominance to polychaete's as well as altered community connectivity.

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CHAPTER ONE
Introduction

1.1 Background

Tauranga harbour is located on the east coast of New Zealand within the Bay of Plenty region and like many estuaries worldwide has experienced increasing pressures from anthropogenic processes. These processes occur within the harbour and surrounding urban areas including the development of manmade structures, reclamation of land, dredging, increased pollution, land use change, and sedimentation. Significant changes to the Tauranga Harbour entrance geomorphology and hydrodynamics have been centred around accommodating increased shipping, accessibility and growth of the Port of Tauranga located in the southern basin (De Lange et al., 2015). Another process of significant concern in the intertidal areas is sedimentation. Infilling is a natural process but has been exacerbated by the increasing sediment load from anthropogenic activities in the harbour's catchment (Britton et al., 2007, Sinner et al., 2011). These anthropogenic processes can significantly alter the harbours geomorphology and hydrodynamics which in turn influence the transport and distribution of contaminants, nutrients and sediments. There is therefore concern about these changing conditions having an impact on the overall health of the Tauranga Harbour, specifically the effect the increasing anthropogenic processes have on the ecosystem.

The increasing anthropogenic impacts on the Tauranga harbour have put a focus on the restoration of estuarine and ecological systems (Sinner et al., 2011). A key indicator of ecological health is the community composition of benthic marine invertebrates, specifically shellfish, and the distribution of these communities through the harbour as they are sensitive to physical and biological stressors in the environment. Due to the lack of historical studies on the ecological health, it is hard to quantify significant ecological changes that have occurred over longer timescales. In order to manage, restore and mitigate the impacts on estuarine systems in the future, it is useful to understand the magnitude and distribution of historic changes in environmental conditions that may have impacted on ecosystems through time.

Numerical models have been used in previous studies of Tauranga Harbour to describe the hydrodynamics of the southern basin (Tay et al., 2013), predict impacts of port development on hydrodynamics (Watson, 2016) and investigate the historic changes in morphology and hydrodynamics of the tidal delta system (Brannigan, 2009). Recent widespread ecological studies in Tauranga Harbour have looked at the distribution of benthic marine invertebrates and the biological and physical stressors which influence this distribution. However, there are no studies that have modelled geomorphology and hydrodynamics including the influence of historical infilling in intertidal areas, or hind cast changes in harbour wide environmental conditions which have the potential to influence ecological health. This thesis therefore uses numerical modelling to investigate changes in geomorphology and hydrodynamics and analyse the ecological significance of changes in these environmental conditions.

Figure 1.1: Aerial photo of the Port of Tauranga situated in the southern basin of Tauranga Harbour, New Zealand. Shows the main morphologic features of the Tauranga inlet including Mount Maunganui and Matakana Island either side of the entrance channel in the background and sulphur point which extends from the foreground. Source: Bay of Plenty Regional Council (2020)

1.2 Thesis Aims and objectives

1.2.1 Primary aim

The primary aim of this thesis is to hind cast historic environmental conditions in order to investigate the ecological implications of changes in geomorphology and hydrodynamics within the southern basin of Tauranga Harbour. This aim was achieved by developing a hydrodynamic numerical model and targeting five objectives.

1.2.2 Objectives

1. Produce 6 historic bathymetries of the southern basin of Tauranga Harbour from 1852, 1879, 1901, 1927, 1954 and 2006 which account for changes in entrance geomorphology due to human development and natural processes. Produce an additional 5 historic bathymetries from 1852, 1879, 1901, 1927 and 1954 which have sediment removed from the intertidal areas to simulate infilling.
2. Investigate the impact of the simulated infilling on depth by comparing the entrance adjusted bathymetries with the intertidal adjusted bathymetries of each year.
3. Using the numerical modelling environment Delft3D, develop a numerical model of the southern basin of Tauranga harbour to simulate historical hydrodynamic conditions for each of the bathymetries.
4. Investigate the impact of the simulated infilling on hydrodynamics by comparing the results of the entrance adjusted and intertidal adjusted numerical models of each year.
5. Use the modelled hydrodynamic conditions from the intertidal adjusted bathymetries to investigate temporal changes in environmental conditions that may have influenced historic ecological health and distribution of species.

1.3 Thesis structure

To meet the aims and objectives listed above, the subsequent chapters of this thesis are structured as follows:

Chapter Two outlines the setting and characteristics of Tauranga Harbour Southern Basin study area then reviews previous studies on geomorphology, hydrodynamics, infilling and ecological health.

Chapter Three describes the creation, of the 6 entrance adjusted bathymetries and 5 intertidal adjusted bathymetries. It also presents the resulting bathymetries and a comparison of entrance and intertidal bathymetries to investigate the impacts of the simulated infilling on geomorphology.

Chapter Four describes the hydrodynamic numerical model parameters, justifications and set up in Delft3D. It also presents the resulting hydrodynamics and a comparison of entrance and intertidal model results for each year to investigate the impacts of the simulated infilling on hydrodynamics.

Chapter Five compares results between the intertidal adjusted bathymetry numerical model runs to investigate temporal changes in geomorphology, hydrodynamics and environmental conditions which may have influenced changes in ecological health.

Chapter Six summarises the key conclusions of the study and provides recommendations for future research.

CHAPTER TWO
Previous studies of Tauranga Harbour

2.1 Introduction

This chapter outlines the setting and characteristics of Tauranga Harbour and the Southern Basin study area. It then reviews previous studies conducted on the Tauranga Harbour particularly those that have researched changes in morphology, hydrodynamics and sediment accumulation using numerical modelling. It also investigates past studies on the ecology of Tauranga Harbour in order to understand which changes in environmental conditions may influence ecological health and the distribution of species. The aim is to gather relevant information to form background knowledge so that accurate predictions of changes in environmental conditions can be made and the impacts of these changes on ecological health can be discussed.

2.1.1 Tauranga Harbour setting and the Southern Basin

Tauranga Harbour is an estuary located on the north east coast of the North Island in the Western Bay of Plenty as seen in Figure 2.1 and is one of the largest in New Zealand with an area of 851km^2 and a length of 40km (Healy et al., 1996, Hume and Herdendorf 1998, Kruger and Healy, 2006). It is classified as a barrier enclosed estuarine lagoon with the characteristics of being well mixed and shallow with extensive tidal flats (Hume et al., 2007, Tay et al., 2013). The harbour has two inlets separated by the 24 km sand barrier known at Matakana island (Spiers et al., 2009). Two rhyolite tombolos border the island with Mount Maunganui at the south-eastern Tauranga inlet and Bowentown at the north-western Katikati inlet creating a relatively stable system (de Lange et al., 2015, Hume and Herdendorf, 1992). Figure 2.1 shows the location of the inlets and the division of the Harbour into the Katikati northern basin and the Tauranga southern basin. Past studies have treated the basins separately as there is little to no exchange between the two due to the extensive shallow tidal flats separating them (Hydraulics Research Station, 1963; Tay et al., 2013). The focus of this study has therefore been solely on the Tauranga Southern Basin.

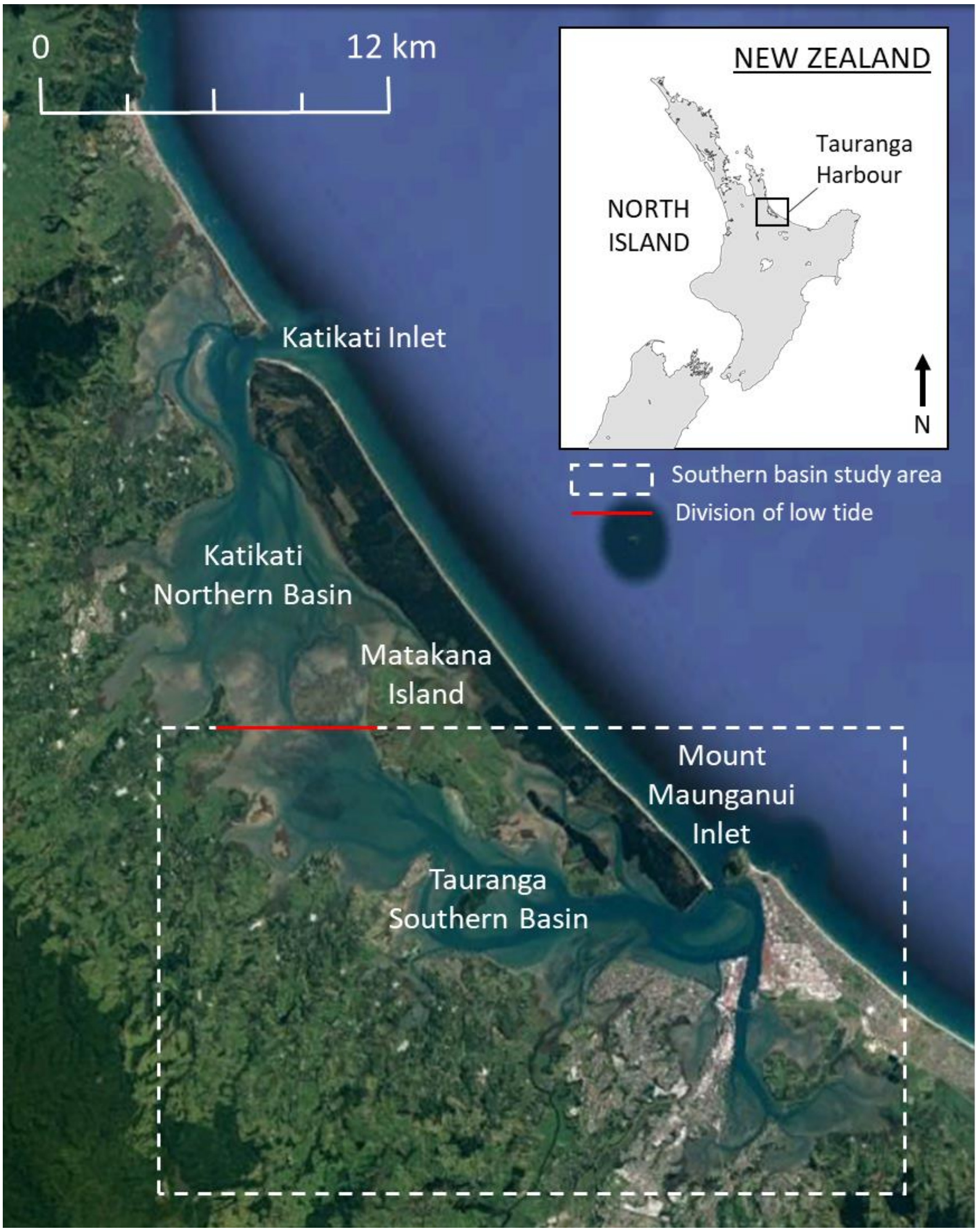

Figure 2.1: Location of Tauranga Harbour on the East coast of the North Island, New Zealand. Displays the study area of the Tauranga Southern basin. Source: Google Earth

At mean sea level (MSL), the southern basin has a total area of 95 x 106m^2 and a volume of 174 x 106m^3, with intertidal areas covering 41km^2 (Tay et al., 2013). The entrance channel through the inlet into the southern basin is roughly 500m wide and reaches depths of approximately 34m (Spiers et al., 2009). The inlet is tide current dominated with a mean tidal range of 1.4 m and mean annual significant wave height of 0.5 m (Kruger and Healy, 2006). A flood tidal delta, centre bank in Figure 2.2, dominates the entrance area of the inner harbour with majority of the tidal volume flowing through the inlet diverted through both the Western channel and Maunganui channel (Davies-Colley and Healy, 1978). The ebb and flood deltas have been modified and maintained since 1966 with dredging to improve shipping access to Sulphur point and the ports (Davies-Colley and Healy, 1978).

1	Panepane Point
2	Matakana Bank – Ebb Tidal Delta
3	Mount Maunganui
4	Entrance Channel
5	Pilot Bay
6	Cutter Channel
7	Lower Western Channel
8	Upper Western Channel
9	Centre Bank (Te Paritaha) - Flood Tidal Delta
10	Maunganui Channel
11	Stella Passage
12	Tauranga Harbour Bridge
13	Sulphur Point
14	Otumoetai Channel
15	Otumoetai Township
16	Matakana Island

Figure 2.2: Map of the Tauranga inlet of the southern basin showing main geomorphic and anthropogenic features of the tidal inlet system and surrounding area. Source: Google Earth

2.2 Previous studies of Geomorphology and Hydrodynamics

2.2.1 Hydraulic Research Station

In 1959 the Hydraulic Research Station (HRS), Wallingford England was commissioned by the Tauranga Harbour board to develop a scale model of Tauranga Harbour. Two physical models were created to investigate options for plans to extend wharf capacity at Maunganui as well as the most efficient ways to improve and maintain channel depths to allow increased shipping capacities (Hydraulic Research Station, 1963). To gather evidence, the Hydraulic Research Station (1963) conducted analysis of historical charts, field measurements and modelling runs. The simulations particularly focused on training wall schemes to increase depth on the outer entrance bar and the effects these had on inner hydrodynamics in order to identify the most effective scheme (Hydraulic Research Station, 1963).

2.2.1.1 Change in Geomorphology

In order to provide information on the durability of proposed improvements, the Hydraulic Research Station (1963) initially investigated changes in the bathymetry by comparing the first survey of Tauranga harbour in 1852 and the survey from 1954 prior to any dredging in the port. Large scale changes were concluded to have taken place in the last 100 years with the development of the lower western channel, the disappearance of the connection between the Upper Western and Otumoetai channel and the deterioration of Cutter Channel. It was speculated that the opening of the lower western channel reduced tidal flow within Cutter Channel which in turn resulted in it deepening (Hydraulic Research Station, 1963).

The Maunganui channel and Stella Passage extending south appear to have remained relatively stable over this time period (Hydraulic Research Station, 1963). The shoreline of Matakana island at the southeast end was found to have changed significantly over the study period with an extension of Panepane point towards Mount Maunganui shores reducing the distance across the entrance by 38% (Hydraulic Research Station, 1963).

The study concluded that the large-scale one directional changes in bathymetry suggested that long term equilibrium of Tauranga Harbour had not yet been reached (Hydraulic Research Station, 1963). The investigation into the Tauranga harbour noted that the development of the Lower Western channel between 1852 and 1954 had resulted in the western channel having an increase in the proportion of the tidal flows it carried, both leaving and entering the harbour (Hydraulic Research Station, 1963).

2.2.2 Davies-Colley 1976 (thesis)

Davies-Colley constructed a model of sediment dynamics for the Tauranga harbour inlet with a focus on changes hydrodynamic and sedimentological factors including the changes in tidal currents, geomorphology of the inlet and bathymetry in historical charts.

2.2.2.1 Changes in Geomorphology

Davies-Colley (1976) looked at changes in surveys from 1852, 1903 and 1966 of the Port of Tauranga and entrance prior to extensive dredging, building on studies from the Hydraulics Research Station (1963). Significant changes that were noted included the growth of Panepane point on Matakana Island which resulted in a decreased inlet width and increased depth by erosion of the entrance channel. The other change was the development of the lower western channel joining the upper western channel to the entrance channel. Previously the flow from the upper western channel was diverted to the Otumoetai and Maunganui channels which were the main tidal channels at the time. This connection between the Upper western and Otumoetai channel no longer exists (Davies-Colley 1976). The changes have been attributed to increase in current flow being diverted to the area which had eroded increasing the depth. There were substantial natural fluctuations noted in the shoreline of Matakana Island and Centre bank also changed in bathymetric configuration. In contrast, the Maunganui channel has remained relatively stable since 1852 (Davies-Colley 1976). It was also noted that the harbour's bathymetric configuration appeared relatively stable as large scale geomorphic changes has ceased, slow changes to the harbour may still occur however from sediment input, sea level change and anthropogenic effects (Davies-Colley 1976). Sediment samples of the study area had coarsely skewed grainsize which was attributed to the removal of fines by currents and the concentration of coarse material as traction load (Davies-Colley 1976).

2.2.2.2 Hydrodynamics

The investigation by Davies-Colley (1976) into hydrodynamics suggested that tidal currents dominate the motions of the water in the Harbour with wind waves having a minor effect. By measuring and plotting tidal currents on the flood tidal delta (twelve stations), it was indicated that peak ebb and flood flows at monitoring stations had asymmetric velocities in direction and intensity relating to large eddy systems (Davies-Colley 1976). Results suggested that there would be sediment transport in the net direction of dominant currents as critical erosion velocities were exceeded at most stations and during neap tides (Davies-Colley 1976).

2.2.3 Dahm 1983

Dahm 1983 continued and developed the research done by Davies-Colley (1976) into the sediment dynamics of Tauranga Harbour considering its historical development and present day processes. In particular, the Dahm study focuses on the geomorphic changes in shoreline and bathymetric surveys since they began in 1852 to understand the stability of the harbour configurations at the time. Like Davies-Colley (1976), Dahm (1983) focused on the entrance of the harbour but also continued work on the ebb tidal delta to compliment the previous works.

2.2.3.1 Changes in Geomorphology

The hydrographic surveys studied from 1852-1954 showed large shoreline and bathymetric changes; in line with Davies-Colley (1979) these were related to the development of the lower western channel. However, Dahm (1983) stated that the flow being diverted through this area was not due to deepening of the channel as hypothesized by Davies-Colley (1979), it was instead developed as a result of the extension and growth of Centre Bank flood tidal delta. The deposition of sediments from deaccelerating flood currents eventually caused the closure of the connection between the Upper Western and Otumoetai channels redirecting flow from the west of the harbour out through the western channel causing erosion of the lower western channel. This was hypothesized due to the timing of the extension of Centre bank which had already split the upper channels, before flow had increased in the lower western channel (Dahm, 1983). Dahm (1983) also concluded that the development of the lower western channel had resulted in other significant bathymetric changes including the deterioration of cutter channel, shoreline progradation at Panepane point Matakana island and the reorientation and extension of bathymetry and channels of the ebb-tidal delta.

Dahm's (1983) study of surveys from 1962 to 1979 of the lower western channel showed that the harbour had not achieved bathymetric stability after the channel had developed, which opposed Davies-Colley (1976) conclusion of stability.

2.2.3.2 Changes in Hydrodynamics

Dahm (1983) proposed that the historical bathymetric instability is caused by the conflict between flood and ebb dominated sediment transport pathways which results from the ebb flow trend from the western channel cutting across flood flow into the Harbour. It was concluded that the changes in shoreline and bathymetry indicated a complex dynamic relationship between inner and outer morphology and hydrodynamics of the harbour entrance (Dahm, 1983)

2.2.4 Tauranga Harbour study 1983

The Tauranga Harbour study (THS) was commissioned by the Bay of Plenty Harbour Board (BOPHB) to look into whether major morphological, sedimentological or hydrodynamic changes had been increased or shaped by dredging and port development (Barnett, 1985; De Lange, 1988). Specific concerns included bathymetric changes of the western channel, reduced tidal discharge in the western channel, circulation changes due to the dredging of the entrance and cutter channel, potential changes in flow and sedimentation from proposed developments (Barnett, 1985; De Lange, 1988). The general aim was to provide background for the BOPHB in order to build effective long term strategies for managing the Harbour. The major consultant organizing the report and specialist scientists was the Ministry of Works and Development (MWD) (Barnett, 1985). The report was split into five sections, Part I Overview and Part III Hydrodynamics were presented by Barnett (1985), Part II Field Data Collection and V Morphology were presented by Healy (1985) and Part IV Sediment Transport by Black (1984).

2.2.4.1 Changes in Geomorphology

Barnett (1985) prepared varying bathymetries and grids to use in the hydrodynamic model. These bathymetries were created from compiling and digitizing surveys from a variety of sources. Where data was missing it was estimated from the surrounding data in close proximity, this often occurred in areas of the upper harbour where surveys were scarce. Bathymetries from 1852, 1902, 1927, 1954, and 1970 were modelled on a 75m grid. Historic changes in the bathymetries between each of the successive years were shown by plotting accretion and erosion (Barnett, 1985). These plots showed accretion on Centre bank, instability of the lower western channel, accretion of the southeastern Matakana shoreline and the narrowing and deepening of the harbour inlet.

Induced changes from the artificial deepening due to the dredging of the main channel were identifiable in the 1970 and 1983 surveys (Barnett, 1985).

2.2.4.2 Hydrodynamic Numerical Model

The Tauranga harbour study produced a 2D numerical model using the Danish Hydraulic institute (DHI) System 21 software to simulate the hydrodynamics of Tauranga Harbour (Barnett, 1985). A larger 300x300 m grid model was used to produce a tidal signal that was used to force the boundary conditions of the smaller 75x75 m grid model of the port area. Observations from the model were found to be generally consistent with field measurements, but in certain locations the model over predicted current velocity by up to 10% (Barnett, 1985). The model predicted strongest ebb and flood currents through the entrance channel. The flood jet split between the lower western and cutter channels, while also being dispersed over the Centre Bank. Flood currents were weak through Pilot Bay and the model failed to show the flood tide eddy that occurs in the area. Ebb currents showed strength in the lower western and cutter channels and were weak over the shallow Centre bank particularly during ebb flows (Barnett, 1985).

Comparing the overall change in modelled hydrodynamics for the bathymetries from 1852-1983 found that upper harbour currents were almost identical due to the same bathymetric data being used. Other noticeable changes included that historically the flow out of the harbour was more north-south and the outer inlet ebb jet was orientated more towards the east (Healy, 1985).

2.2.5 De Lange 1988

De Lange (1988) focused on the role of wave climate on entraining and transporting sediment particularly in the Pilot Bay region which is affected by port development building on the studies of Davies (1983). Currents in the area were measured and compared to results of the Hydraulic Research Station (1963) physical model and Tauranga Harbour Study (1983) numerical model.

2.2.5.1 Comparison of Hydrodynamics

The overall circulation patterns within the Tauranga Harbour southern basin were seen in results by the HRS physical model study and the THS numerical model study. However, the Tauranga Harbour study had more similar results to the measurements of currents studied by De Lange (1988) likely due to advances in modelling since the HRS physical model. There were minor differences in circulation, for example within the Pilot Bay region both the numerical and physical models captured the ebb dominance of Pilot bay but not the long duration of ebb flows measured by De Lange (1988) which were 300-500% longer and 50-75% higher in velocity.

2.2.6 Mathew 1997

Mathew (1997) focused on long term physical impacts of the major capital dredging project from 1991-92 which removed 5 million m^3 of sediment. This was done as a part of the monitoring programme designed to identify adverse effects of dredging and dumping on flood-tidal morphology, ebb-tidal morphology, sedimentation in channels, erosion of shorelines and benthic life (Mathew, 1997).

2.2.6.1 Changes in Geomorphology due to Dredging

Pre dredging (1982-1990) geomorphological characteristics of Centre Bank, Western channel, Pilot Bay and the shipping channels from survey data were compared to during/post dredging (1990-1994) characteristics to examine changes resulting from the major dredging in 1991-1992 (Mathew, 1997). The major conclusions were that prior to dredging (1982-1990) Centre Bank was relatively stable with some shoaling in the blind flood channel. Immediately post dredging (1991-1992) there was infilling of the blind flood channel but in a relatively small area. Centre bank then seemed relatively stable in the short period (1992-1994) afterward but with some deposition on the shallowest part (Mathew, 1997). The Western channel experienced infilling pre dredging (1983-1990). Scouring then occurred after 1990 and developed a new channel before 1993. Post dredging there were no significant changes to the area (Mathew, 1997). Pilot bay did not have any significant changes during monitoring except for minor erosion that was occurring before and after the dredging (Mathew, 1997).

Mathew (1997) also made observations from survey data that the south-eastern Matakana Island shoreline and Panepane Point had accreted by 100m between 1970 and 1992 and was then stable up until the most recent survey of 1996. Therefore, it was concluded that the dredging had not impacted morphology and hydrodynamics enough to cause noticeable instability of the Matakana Island shoreline (Mathew, 1997).

2.2.6.2 Changes in Hydrodynamics due to Dredging

Near bottom current measurements were taken to investigate impacts of dredging on the current regime within the harbour by Mathew (1997) at six different locations. Measurements showed that the lower Western Channel had increased tidal current velocity post dredging and Pilot Bay had tidal flow patterns dominated by an eddy for majority of the flood tide and had a slight increase of 0.10 m/s in ebb velocity. Measurements from the edge of Cutter Channel showed that post dredging the ebb velocity had no significant change. The flood dominance that existed prior to dredging continued post dredging and had increased flood current velocities. The increased asymmetry of tidal flow velocity post 1991-1992 dredging was attributed to increase in flow from the widened and deepened channels at this site (Mathew, 1997).

The effects of dredging on tidal wave behaviour within the harbour was examined by studying tidal data collected at Salisbury Wharf and Sulphur Point stations over 7 years. From the analysis of the data, there was no significant effects identified on tidal wave characteristics within the harbour as a result of the dredged channels and widened inlet throat (Mathew, 1997).

2.2.6.3 Re-run of System 21 Hydrodynamic Numerical Model

Mathew (1997) completed a re-run of the hydrodynamic numerical model DHI System 21 using the same parameters and boundaries as Barnett (1985) modelled in the Tauranga Harbour Study but with updated post dredging 1994 bathymetry. Measured changes at the near bottom current sample sites were of good agreement with modelled results in most areas. The interpreted model results indicated decreases in peak flood and ebb velocities localized near Sulphur Point Wharf, Tanea shelf and the Western end of Cutter Channel (Mathew, 1997).

The comparison of the observed changes in morphology from bathymetric surveys to model result interpretations, suggested that the dredging did not create any extreme changes in the flood-tidal delta system during the monitoring period.

Changes observed post dredging were interpreted to be a natural continuation of the observed pre dredging changes (Mathew, 1997).

2.2.7 Brannigan 2009

Brannigan (2009) used historic hydrographic charts to investigate historic changes in the geomorphology of the Tauranga Harbour entrance delta system and hydrodynamic numerical modeling to analyse changes in peak spring flow for changes in potential net transport of sediments. The model was run for the entire Tauranga Harbour Southern Basin.

2.2.7.1 Changes in Geomorphology 1852-2006

The bathymetries from 1954, 1927, 1901, 1879 and 1852 were digitized from a variety of sources and complied using ArcMap version 9.2. The extent of the three different charts used are shown in Figure 2.3 below. The same chart for upper areas of the harbour were used due to lack of survey data and the assumption that the geomorphological change outside the tidal delta system was not significant.

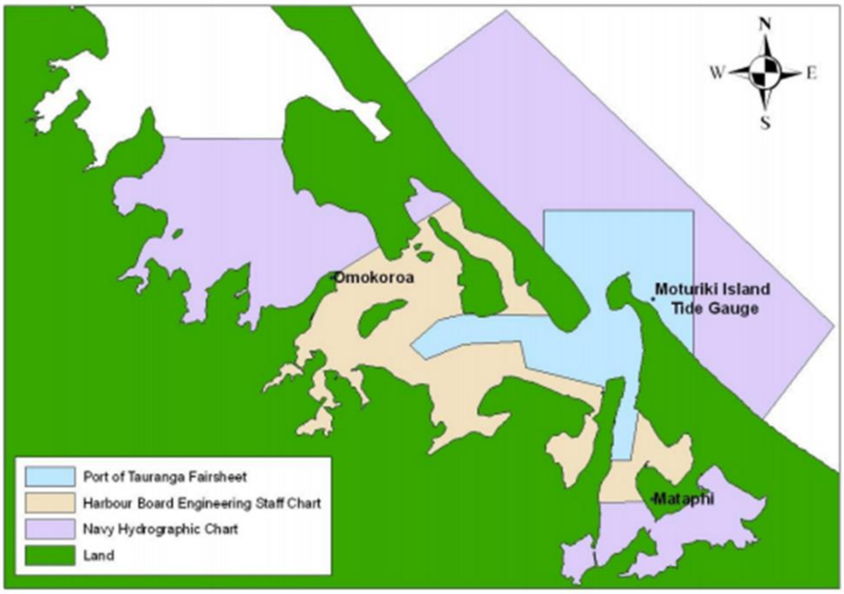

Figure 2.3: Map showing the extent of surveys and charts compiled for the creation of bathymetries. Source: Brannigan (2009).

The 2006 bathymetry was sourced from Spiers et al. (2009) which had been digitized from recent surveys from the Port of Tauranga and University of Waikato combined with data from Environment Bay of Plenty for the remainder of the upper harbour. The created bathymetries are shown below in Figure 2.4.

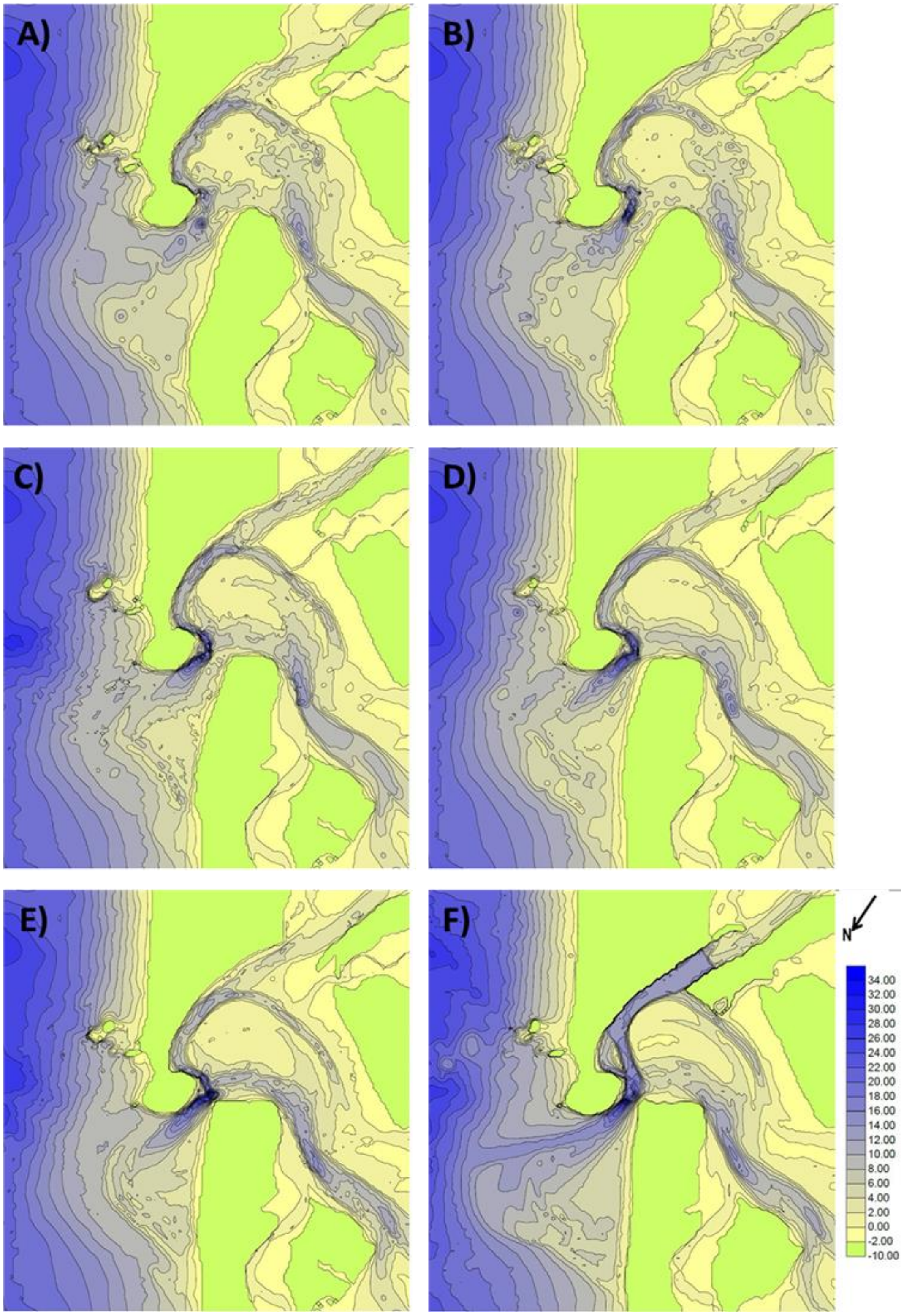

Figure 2.4: Shows the bathymetries of the Mount Maunganui inlet tidal delta system A) 1852, B) 1879, C) 1901, D) 1927, E) 1954, F) 2006. Source: Brannigan (2009).

Historic changes to the bathymetries were investigated through the use of erosion and accretion plots as well as cross-section studies of the entrance inlet and both deltas. Results from the comparison of constructed bathymetries were consistent with previous studies results with the narrowing of the inlet, accretion on Panepane point Matakana Island, accretion on Centre bank, the establishment and instability of the lower western channel. Brannigan (2009) concluded that changes in morphology due to dredging occurred in areas in immediate proximity to the modified channels. Other changes outside these directly impacted areas appeared to be consistent with naturally continuing trends as stated by Mathew (1997).

2.2.7.2 Numerical model and historic changes in Hydrodynamics

A 2D hydrodynamic model using hydrodynamic modelling environment 3DD was run to compare historic changes in current flow between the various bathymetries that were looked at in the comparison of morphology.

The model did not use river inputs as they were shown to have no effects on circulation (Hydraulics Research Station, 1963; Brannigan, 2009). As the Harbour is tidally dominated, waves were also excluded from the model runs. The 2006 model was calibrated as it had been used in studies by Spiers et al. (2009). All the subsequent model runs from previous years used the same parameters, therefore comparisons between the years were qualitative not quantitative (Brannigan, 2009).

The effects of dredging on the hydrodynamics were apparent in changes in current flows around the tidal delta system particularly in Cutter channel and less significantly in the Maunganui Roads channel and flood tidal delta. Changes in flow around Panepane Point, Matakana Island were found to be continuations of natural changes and morphological instability rather than dredging impacting hydrodynamics (Brannigan, 2009).

2.2.8 Hydrodynamics of the southern basin of Tauranga Harbour

Tay et al. (2013) simulated spatial and temporal circulation patterns of the Tauranga Harbour Southern basin using a ELCOM (Estuary Lake and Coastal Ocean Model) 3D hydrodynamic model. Previous modelling of the Tauranga Harbour hydrodynamics were not readily available and focused on studying the impacts of development in the port area. Therefore, this study aimed to understand drivers of the southern basin hydrodynamics by modelling its salinity and temperature structure as well as the effects of tides and wind.

2.2.8.1 *Hydrodynamic Numerical Model*

A variety of surveys, hydrographic soundings and fairsheets were used to construct the model bathymetry on a 75 x 75 metre resolution grid. The model had 12 layers vertically, which increased in thickness with depth. The hydrodynamic model was forced with tidal signal from offshore conditions at a Bay of Plenty Regional council wave buoy and the NIWA tidal model. The model was calibrated with field data collected using CTD casts and S4 current meters during February 1999 and validated with data from 2006 and 2008 observations. The model was allowed to "spin up" for a period of three days to reach equilibrium before data was extracted. The bottom drag coefficient was adjusted so that the modelled flow fit the observations. Spatially varying coefficients were applied across the grid with more friction (higher value) in channels and less friction (lower values) on the shallower tidal flats. The model was run under a variety of conditions including wind, no wind, and wind from two different directions to understand the impacts on patterns of temperature, salinity and residence time.

2.2.8.2 *Tides*

Tidal constituents from the model and observed data were compared using T-TIDE software which was used to extract the tidal signals. The M2 tide dominated all the compared signals for 2006, other contributing constituents were the S2,N2, K1 and O1. Amplitude and phase of the M2 tidal constituent varied across the harbour. In general, the amplitude decreased (0.73 m to 0.7 m) through the entrance, increased towards Otumoetai and the upper harbour (0.7 m to 0.78 m) and decreased moving into the estuaries above Sulphur point (0.7 m to 0.64 m). Differences in phase of the M2 were most predominant where the tidal wave was constricted through narrow channels. Time lags of up to 15 minutes occurred between low tide at the entrance and low tide at Omokoroa point as a result of the M4 overtide. Delays varied spatially across the harbour and temporally with the spring-neap tidal cycle. This has potential to impact sampling strategies and predicting the time and extent of inundation on the intertidal flats.

2.2.8.3 Residual currents and Residence time

Modelled residual currents followed the general pattern of observed circulation with ebb dominance along Omokoroa point, flood dominance in the Otumoetai channel and the entrance. Greater residual velocities were generally modelled in channels and lower velocities over intertidal flats with the exception of Centre bank which had strong flood dominance.

Modelled residence times indicated the harbour was reasonably well flushed with times of 2-4 days close to the entrance. Residence times increased moving north towards the upper harbour, within sub-estuaries that have constricted entrances and side embayments.

2.2.8.4 Controls on salinity, temperature and residence time

Figure 2.5 shows the distribution of salinity, temperature and residence time under the influence and absence of wind. The southern basin showed a weak salinity gradient which varied with the tide and had no significant changes with introduced wind. The spatial distribution of temperature varied with wind and diurnally rather than with the tides. Residence time variation in areas across the southern basin indicated it was controlled significantly by the geomorphology of the harbour.

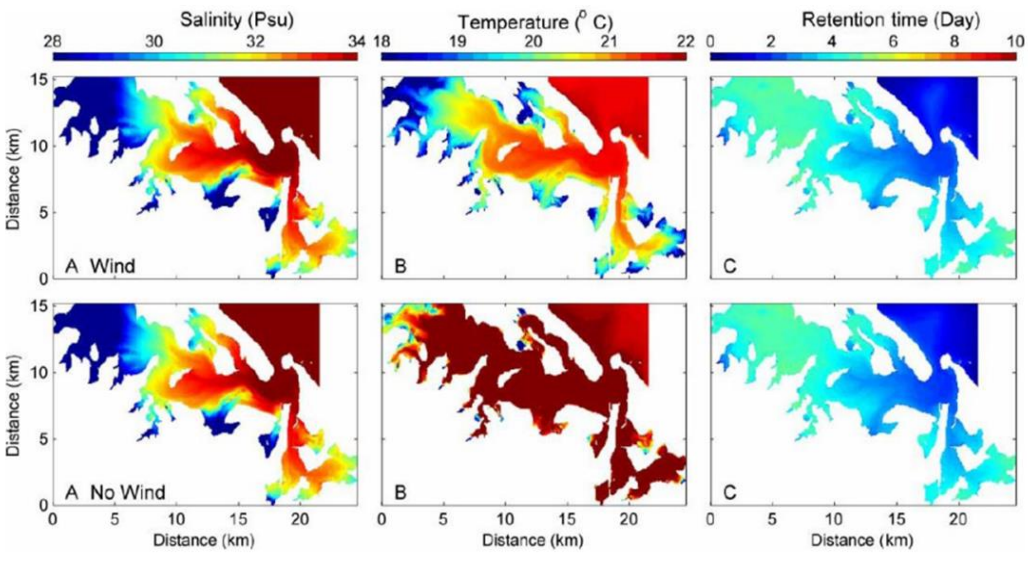

Figure 2.5: Distribution of salinity, temperature and residence time in the southern basin under the influence and absence of wind, averaged over a spring and neap tidal cycle. Source: Tay et al. (2013)

2.2.9 Impacts of Port development on Hydrodynamics

Watson (2016) developed a hydrodynamic numerical model to predict the hydrodynamic impacts in the proximity of proposed wharf extensions at the Port of Tauranga in Stella passage.

2.2.9.1 Hydrodynamic numerical model

Delft3D FLOW software from Deltares was used to set up, calibrate, verify and run the model with field data collected in 2015. The 2D hydrodynamic model used a 20 m x 20 m grid of the southern basin developed by Monahan (2018). The parameters, bathymetry and simulation time were adjusted, calibrated and verified before running the simulation. The model was allowed 2.5 days to spin-up and was run for a month to cover a full spring neap tidal cycle. Flow in the model was forced at two open water boundaries by water levels. Figure 2.6 shows the spatially varying bottom roughness map used in the model. The Chezy value was assigned based on the bathymetry and the best fit of the model results to the observed field data. The final parameters used in the model are in Table 2.1 below.

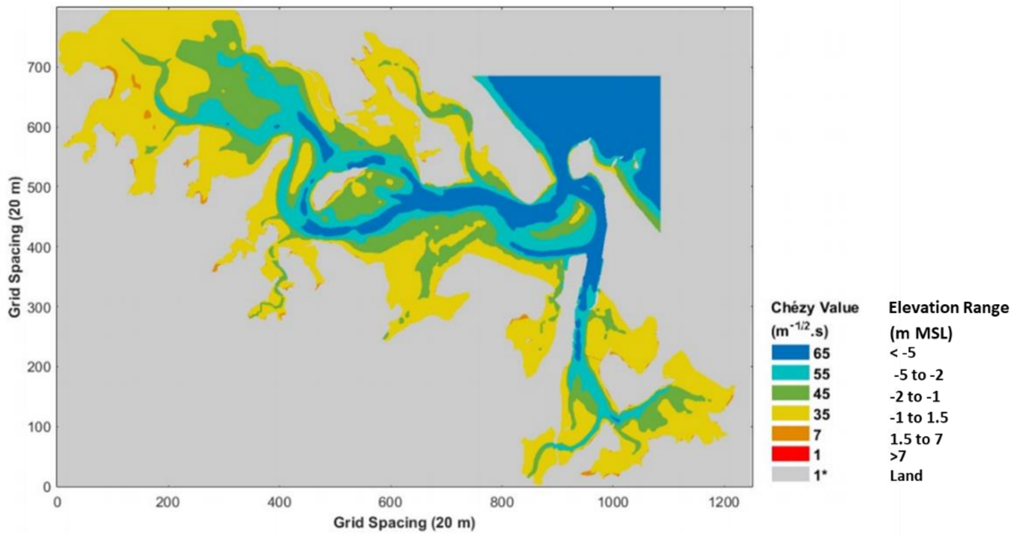

Figure 2.6: Bottom roughness map used in the Hydrodynamic model. Chézy values are based off the elevation of the Bathymetry. Source: Watson (2016)

Table 2.1: List of parameters used in the Hydrodynamic model and their final values based on calibration. Source: Watson (2016).

Parameter	Value
Time Step Interval	0.5 min
Simulation Period	32 days
Warm-up Period	3 days
Gravity	9.81 m.s^2
Water density	1025 kg.m^3
Eddy Viscosity	10 m.s^2
Threshold Depth	0.05 m
Bottom Roughness Map	Option 3 (Figure 2.6 above)
Wind Conditions	No wind

2.2.9.2 Hydrodynamics of the southern basin

The overall southern basin hydrodynamics were modelled and described by Watson (2016). During both spring and neap tides there was a lag in phase of the water level from the entrance to the upper harbour in the north-east. The lowest water levels in the north east occurred two hours later than at the entrance. There were also large differences in water level across short distances in constricted entrances and channels such as the main inlet. The maximum velocity currents occurred before high and low tides in the main channels. Overall current speeds were lowest at peak flood and ebb water levels. There was an increase in magnitude of current speeds in the main channels during spring tides compared to neap tides.

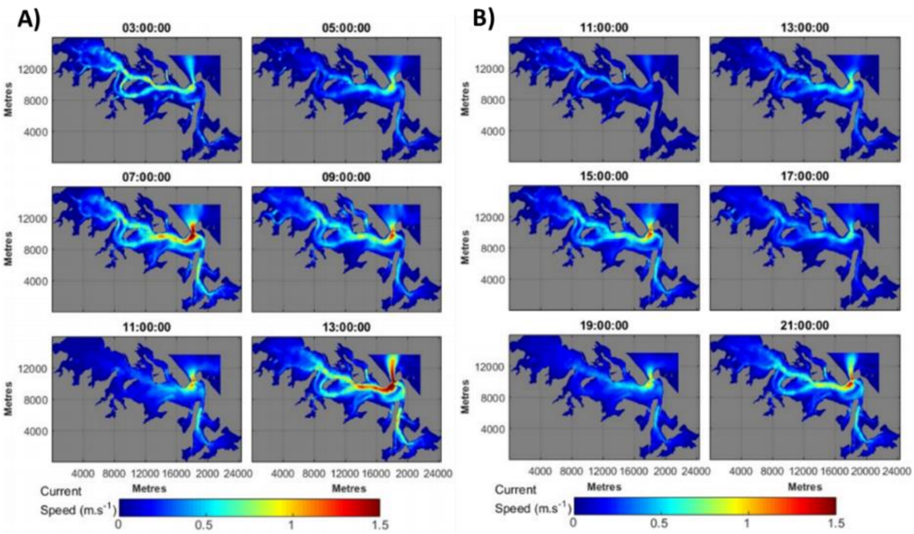

Figure 2.7: Current speeds at two hour intervals over A) a spring tidal cycle and B) a neap tidal cycle from hydrodynamic model simulations of Tauranga southern basin.

2.2.10 Conclusions on geomorphology and hydrodynamics

- Studies demonstrated that significant changes occurred in geomorphology around the entrance tidal delta between 1852-1954, prior to extensive dredging and port development. These included the accretion on Panepane point, narrowing and deepening of the inlet, accretion and extension of centre bank and the development of the lower western channel.
- Significant changes in hydrodynamics prior to dredging related to these changes in morphology. Changes in currents included the orientation of the ebb entrance jet, increased flow through the western channel, increased velocity in the entrance channel.
- Changes in the geomorphology and hydrodynamics prior to dredging were depicted to be in the immediate vicinity of the development of Cutter channel, Entrance channel and Sulphur point. Other post dredging changes were interpreted to be a continuation of naturally occurring pre-dredging changes.
- Overall the models were consistent in predicting strong currents through deeper, narrow channels and weaker current over shallower, tidal flats.
- Hydrodynamics in the upper harbour were almost identical in the modelling studies when comparing different years.
- Tauranga Harbour is a well-mixed, well-flushed, tidally dominated estuary. Freshwater input and salinity are not drivers of circulation.
- Residence time within different areas of Tauranga Harbour is controlled significantly by the geomorphology.
- Numerical modelling has been used recently to describe the hydrodynamics of the southern basin of Tauranga harbour (Tay et al., 2013).
- Most numerical modelling studies have been centred around more recent changes and immediate impacts of the dredging or port construction on hydrodynamics (eg. Watson, 2016).
- Brannigan (2009) created a hydrodynamic model and looked at historical changes in bathymetries, hydrodynamics and sediment around the Tauranga entrance tidal delta system. However, this study did not extend to the wider

reaches of the Harbour and used the same intertidal bathymetry for all years.

- No studies have modelled the geomorphology and hydrodynamics due to accounting for changes due to infilling in intertidal areas.

2.3 Previous studies of Sediment Accumulation Rates

2.3.1 Tauranga Harbour Sediment Study (NIWA)

A NIWA (National Institute of Water and Atmosphere) sediment study was commissioned by Environment Bay of Plenty (EBOP) to undertake a study on the sediment sources, characteristics, distribution, dispersal and deposition throughout the southern basin of Tauranga Harbour in order to better manage effects of sedimentation in the future. Hancock et al. (2009) conducted a literature review which collected data from 26 out of 40 identified studies. From the 26 studies, 300 samples had adequate grainsize statistics and 600 had gravel/sand/mud percentage information. The data was compiled in ArcGIS and combined with hydrodynamic and morphological information to divide the intertidal areas into 26 sub-estuaries that had common characteristics and processes. These 26 sub estuaries were classified further into 11 categories with similar catchment type and environmental (tide and wave) energy information for the purpose of modelling. The sub-estuaries exclude channels which have high velocity currents that prevent the deposition if fine sediment in these areas.

2.3.1.1 Processes affecting sediment distribution

The geomorphology of a sub-estuary and its exposure to wave and tidal energy effects the sediment dispersal, transport and erosion processes. Another key factor investigated by this study was the factor of catchment runoff inputting sediment into each sub-estuary. Most of the sub-catchments drain from areas covered with forest and agriculture in the hills to the west and south of the Harbour (Hancock et al., 2009).

2.3.1.2 Sediment distribution and sub-estuary classification

Hancock et al. (2009) found that percent mud of the surface sediment gave the best description for an accurate comparison of variation in sediments between the sub-estuaries. Figure 2.8 summarizes the sediment characteristics and classification of sub-estuaries. The sheltered muddy embayment east and west categories all lie on the west shore of the harbour and were classified as low energy, large hilly catchments and high mud content of 10.8-48.1% mud. The other categories had medium to high exposure, urban, hilly or no direct catchment and low to medium mud content (0.27-14.47%) The upper harbour transition was classified as having no immediate input from catchments, large and exposed with medium mud content. Overall the higher energy sub-estuaries trended towards having lower mud content that the low energy sub-estuaries (Hancock et al., 2009).

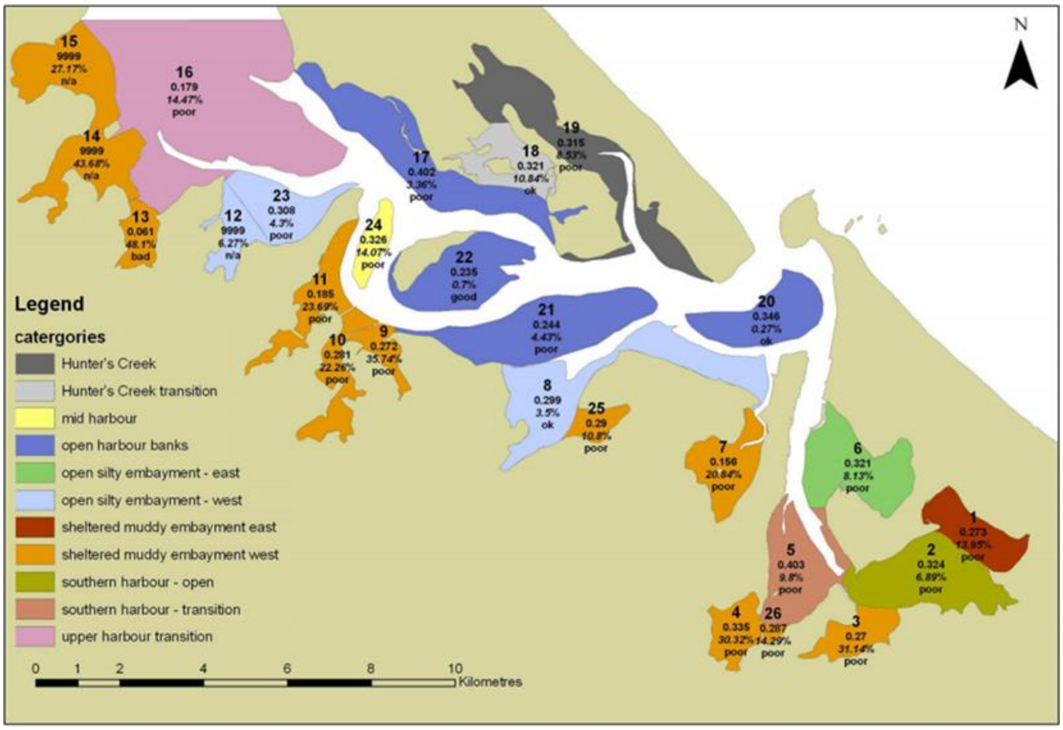

Figure 2.8: Summary diagram showing mean grainsize, percent mud and sorting parameter under each sub estuary number. The colour coding indicates the 11 categories in the legend which are based on catchment type and exposure to wind and wave energy. Source: Hancock et al. (2009)

2.3.1.3 Sediment accumulation rate (SAR)

Only one study in the literature review by Hancock et al. (2009) revealed useful information on the rates and areas of sediment accumulation in the harbour. The study from 1994 provided an estimation of 0.9mm/yr as organochlorine DDT was found at 50mm deep and was last used in about 1950. Other studies found in the review had little information on SAR and were not able to be used because the data sets were either too short, unreliable, inaccurate or undated (Hancock et al., 2009).

A selection of 10 sub-estuaries were selected for coring samples by Hancock et al. (2009) seen in Figure 2.9. Criteria for the selected sites included low mud percentage and away from freshwater input, channels, biological reworking, physical reworking, mangroves and seagrass. At each site during low tide, two replicate 10 cm diameter, 50 cm deep PVC cores were sampled. Radioisotope dating was undertaken on 6 of the 10 cores which showed signs of the least mixing. The derived SAR from three of the sub-estuaries are shown in Table 2.2. The observed sedimentation rates in the cores were low compared to other north island estuaries and had radioisotopic evidence of reworking by tides and waves. Hancock et al. (2009) hypothesized from the evidence that in the Tauranga harbour, the southern wave exposed intertidal flats are not sinks for deposition of fine material. Remobilised sediment from these areas is deposited more widely through the harbour on tidal flats, sheltered bays and mangroves or transported out to the inner shelf (Hancock et al., 2009).

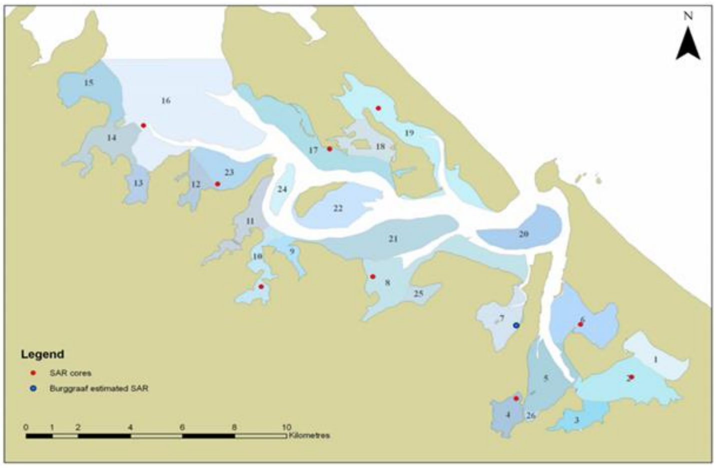

Figure 2.9 Map showing the sub-estuaries and the location of the SAR coring samples taken. The blue dot indicates the location of the one other study found to have estimated SAR (0.9 mm/yr over 58years) in the review of literature. Source: Hancock et al. (2009)

Table 2.2: Summary of the three SAR core locations, rates of accumulation and the period of time over which the SAR was calculated over.

Sub-Estuary Name	Sub-estuary Number	SAR	Period of time
Waimapu inlet	4	0.75 mm/yr	90 years
Te Hopai Estuary	16	1.57 mm/yr	45 years
Hunters Creek	8	1.33 mm/yr	23 years

2.3.2 Modelled future sediment accumulation rates

Hume et al. (2010) carried out modeled future predictions for sediment runoff from catchments and the accumulation of sediments in the harbour as a result of land-use change and climate change during the Tauranga Harbour Sediment study. The predictions were for 2001-2051 and had three scenarios with combinations of land-use and weather change. For all the Tauranga Harbour catchments, climate change is predicted to be the biggest driver of sediment runoff rather than land-use change. Increases in sediment runoff are predicted to cause increased rates of sedimentation within most sub-estuaries and the bed will become progressively finer grained. Estuaries were classified to be at ecological risk when they had high rates of fine sediment accumulation (>1 mm/yr) and existing low mud content (<10%) as the benthic macrofauna is not adapted to high presence of mud content. The at risk subestuaries for scenario three (SmartGrowth land-use and climate change influenced weather) are depicted below in Figure 2.10.

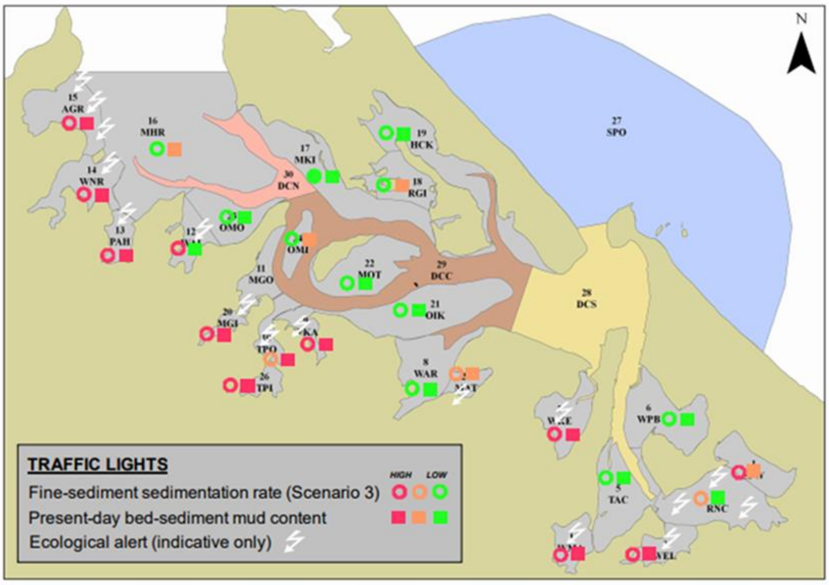

Figure 2.10: Shapes indicates sedimentation rates and Present day mud content, colours indicate high moderate and low levels for each. Ecological alert gives a rough indication of the sub-estuaries that may be at risk due to the deposition of fine sediments. Source: Hume et al. (2010).

2.3.3 Conclusions on Infilling in Tauranga Harbour

- Knowledge on the rate of sedimentation temporally and spatially in Tauranga Harbour is limited. The Tauranga Harbour Sediment Study (Hancock et al., 2009) identified only one previous study that had an approximation of SAR in one location.
- In the Tauranga Harbour sediment study 3 out of 10 cores had SAR identified, these were between 0.75-1.57 mm/yr over 23-90 years. Other cores had radioisotopic evidence of reworking and mobilisation of sediment, SAR could therefore not be inferred.
- SAR are not equal within the harbour temporally or spatially. The processes controlling sedimentation include sediment input from land, geomorphology, exposure to wave and tidal energy.
- The increased accumulation of fine sediments is expected to put a number of sub-estuaries at ecological risk.

2.4 Previous studies on Tauranga Harbour ecology

2.4.1 Recent concerns and perceived stressors on the ecology

The impact of environmental changes on shellfish species is of particular focus in Tauranga Harbour due to not only their ecological significance and sensitivity to stressors, but also their importance as a food source. Tauranga Harbour is popular amongst locals and visitors for the gathering of edible bivalve shellfish from its extensive intertidal flats (Scholes et al., 2009). The shellfish beds also have cultural significance to the local iwi who have used them as a source of kai moana since settling in the area before European arrival (Britton et al., 2007, Taiapa et al., 2014). The local tangata whenua of Tauranga Moana have witnessed the rapid development and changes to the coastal environment over the past 150 years and the pressure it has had on the harbour's resources (Taiapa et al., 2014).

Recently there has been concerns from community groups about decreasing health, numbers and size of individual shellfish and populations (Britton et al., 2007, Sinner et al., 2011). Examples of comments raised include the disappearance of horse mussels near Otumoetai, reduction in size of cockles from increased silt distribution and in general being unsuitable to eat due to contamination (Britton et al., 2007, Sinner et al., 2011). Tangata whenua in particular have noticed long term historic changes in shellfish size and abundance.

There is no agreement on the main causes of these changes being seen however it is thought overfishing is contributing as well as other recent anthropogenic influences such as pollution and sedimentation (Sinner et al., 2011). For this study it was important to understand the recent changes in Tauranga Harbour's ecology in order to identify which biological and physical stressors control community composition and species distribution within the Harbour.

2.4.2 Environment Bay of Plenty – Ecology of Tauranga Harbour 1994

Park and Donald (1994) prepared a report on the general ecology of Tauranga Harbour as a part of environmental investigations for the Tauranga Harbour Regional Plan Project. The study in particular focused on soft-shore benthic macrofaunal communities especially in the extensive intertidal areas. Park and Donald noted that the purpose of the study was to "provide baseline data against which future changes could be reliably made". This was due to the fact previous studies of harbour ecology had been descriptive and quantitative, on small scales and quantitative, or focused on specific factors of benthic communities. Previous studies were also not comparable due to different methodologies (Park and Donald, 1994).

2.4.2.1 Intertidal study

For the intertidal study by Park and Donald (1994), samples of macrofauna were taken at 160 sites throughout Tauranga Harbour of the 1990/91 summer. Where possible sampling was done at the same locations as sediment sampling sites so that biotic and abiotic relationships could be investigated. At each site a 13cm diameter corer was used to take four replica cores to a depth of 15cm. The cores were put through a 2mm mesh sieve and the animals were sorted, counted and the cockles and wedge shells were measured (Park and Donald, 1994). Bivalves accounted for 46.3% of the total number of animals and were more numerous in the intertidal areas compared to the subtidal zones. The most common species were the *Tillina liliana* (Wedge shell) at 15.1% and *Austrovenus stutchburyi* (cockle) at 14.9%. The strongest correlation of environment conditions and species distribution was found to be that the number of species in each sample decreased with increasing silt content of surficial sediments (Park and Donald, 1994). Individual species had different relationships with silt content which determined their abundance at different sites. The trend of decreasing shellfish size from entrance sites to the upper harbour sites was also noted and species diversity decreased from high to low levels in the intertidal area. For the cockle species shell size was compared to a previous data set from 16 years' prior, the results showed no significant changes (Park and Donald, 1994).

2.4.2.2 Subtidal study

For the subtidal study by Park and Donald (1994) the same methods were used but six replicate cores were taken and a 1 mm sieve was used. Polychaetes were the dominant taxonomic group and bivalves were significantly less numerous than the intertidal areas. Species diversity at the subtidal sites had weak positive correlations with the silt content of the surficial sediments at these sites, the opposite relationship to the intertidal samples (P= 0.000). The relationship with depth was negatively correlated and also significant (P= 0.008) (Park and Donald, 1994). Park and Donald therefore concluded some species cannot survive the strong scouring currents and shifting sand in channels, slightly slower currents allow some silt settling and increase of macro fauna establishment. Higher levels of siltation in intertidal areas result in a decrease in species diversity (Park and Donald, 1994).

2.4.2.3 Impact of sedimentation

It was also stated that observable changes to intertidal areas were attributed to two main causes, one of which was the increased silt runoff and sedimentation (Park and Donald, 1994). Sheltered areas were particularly susceptible to impacts as the energy in the environment from wind and waves is not enough to prevent settlement of fine grains like in the more exposed harbour basins. The example used was the 1982 collapse of the Ruahihi Canal which resulted in several centimeters of silt smothering the Wairoa estuary of the Tauranga Harbour rapidly killing marine life (Park and Donald, 1994).

2.4.3 Bay of Plenty Benthic Macrofauna Monitoring Programme

A coastal and estuarine monitoring programme was initiated by the Bay of Plenty Regional Council in 1990 which aimed to monitor 33 sheltered and 15 exposed soft shore sites across the Bay of Plenty (Park, 2010). A 13cm diameter corer was used to take 15cm deep sediment samples, replicated 24 times at each site and put through a 1mm sieve (Park, 2010).

2.4.3.1 Tauranga Harbour Trends

The seven sites in the Tauranga Harbour seen in Figure 2.11 have shown no consistent or significant decrease in diversity of species. Community composition and sediment characteristics have shown minor changes but were attributed to natural fluctuations (Park, 2010). Waimapu estuary had the most significant increase in mud and change to dominance by polychaete worms. Density and size data was collected on the cockles within the samples. The trends in data for the five sites within the southern basin are shown in Figure 2.12. Size and density of the cockles have fluctuated at all sites for the monitoring period. Increasing trends at Town reach and Otumoetai sites were associated with the loss of seagrass beds due to swan grazing and which also resulted in a decrease in mud content.

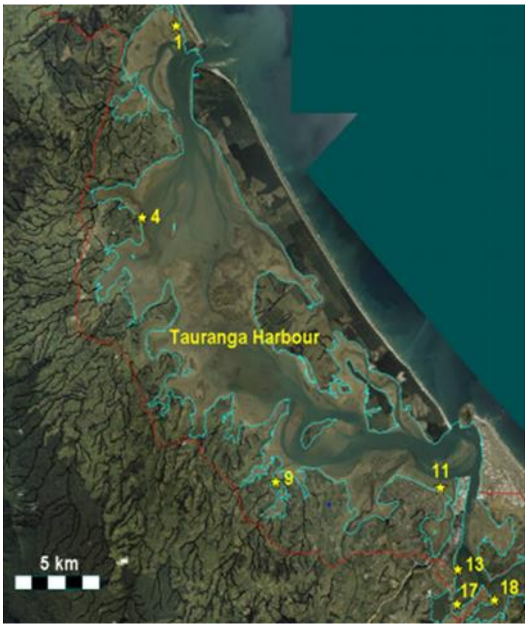

Figure 2.11: Locations of the seven sampled sites in Tauranga Harbour. Source: Park (2010)

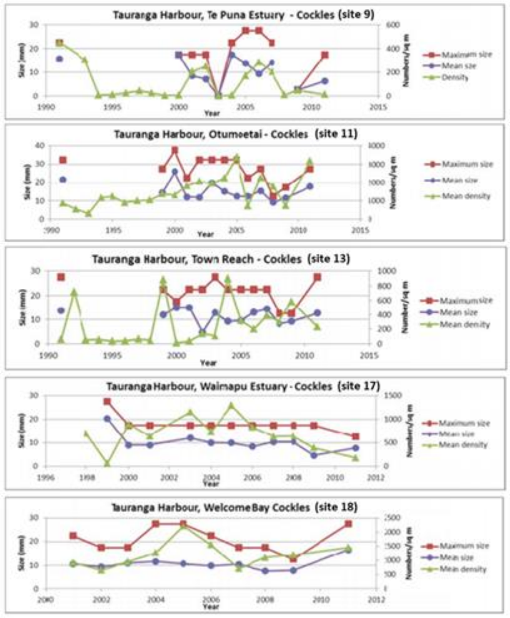

Figure 2.12: Trends in cockle size and density within each core sampled at the five sites within the southern Basin of Tauranga Harbour

2.4.4 Manaaki Taha Moana Research program

The Manaaki Taha Moana (MTM) Research program was a six-year program run from 2009 to 2015 with the overall goal of coastal ecosystem restoration and enhancement with a focus on their services of importance to iwi. Improved knowledge of the degradation processes impacting estuarine ecosystems and their services was required in order to meet this aim. The Tauranga Moana case study is run by the Manaaki Te Awanui trust with the support of other research partners, tertiary institutes, local government and local authorities (Sinner et al., 2011). It produced multiple reports over the years it was running. The initial Health of Te Awanui Tauranga Harbour and Cultural Review of Health reports summarized what is known, what knowledge gaps there are and priorities for research. This was to better identify causes of declining estuarine health and to develop restoration planning (Sinner et al., 2011).

2.4.4.1 Health of Te Awanui Tauranga Harbour (Report No.1)

The purpose of this report was to inform, identify knowledge gaps and priorities for field research by doing a literature review summarizing published scientific papers and technical reports (Sinner et al., 2011). In terms of the overall conditions of the harbour, this report summarized there is limited scientific evidence for indicators, nutrients, pollutants and benthic communities spatially and temporally. The collection of information varies greatly on a spatial scale between studies. There is also very limited information historically with time series data only available for some indicators since the 1990s (Sinner et al., 2011). In order to fill these gaps, a broad scale survey of Tauranga harbour was conducted looking at biodiversity and anthropogenic stressors. Shellfish were also highlighted for future specific case studies due to their ecological and cultural significance (Sinner et al., 2011).

2.4.4.1.1 Distribution of benthic marine macrofauna

The extent of the changes in shellfish abundance is relatively unknown due to gaps historic data with the exception of anecdotal notes (Sinner et al., 2011). Sinner et al. (2011) summarized that bivalves are the prominent taxonomic group in intertidal areas and polychaete's are the most numerous group in subtidal areas which aligns with the previous studies in Tauranga Harbour.

2.4.4.1.2 Sedimentation impacts on ecological health

Sinner et al. (2011) summarized what was known about the increasing impacts of sedimentation within Tauranga Harbour. It is known that Tauranga Harbour receives 57% of the sediments generated by erosion in the catchment, 42 % of it is transported out to sea resulting in low sediment accumulation rates on intertidal flats compared to other estuaries in the North Island. Sedimentation is not uniform across the Harbour, deposition depends on the rate of input from land, morphology of the harbour, grainsize and exposure to energy.

Observed impacts of this sedimentation in Tauranga Harbour include increased mud content in sediments, shallowing of depositional areas and increased turbidity. These have flow on effects for the ecological health and have been correlated with the expansion of mangroves, smothering seagrass beds, reduction of food availability, clogging gills of shellfish, reduced success of larvae settlement and survival (Sinner et al., 2011). Changes in community composition can also occur as a result of changes in the mud content of sediment due to certain species being better adapted to specific grainsize habitat. Benthic species play critical roles in the ecosystem as food sources, improving water quality, cycling nutrients and providing habitats. Changing the composition and distribution of these benthic species has a flow on effect on the ecology of the Harbour (Sinner et al., 2011).

2.4.4.2 Cultural review of health (report no. 3)

This report was created alongside the scientific review of health to identify historical and cultural issues that have been found significant by the tangata whenua of Te Awanui Tauranga Harbour (Taiapa et al., 2014). The aim was still to provide inform and highlight gaps in knowledge. This was done by reviewing archives, Waitangi tribunal reports, cultural impact assessments and submissions for consents. A significant concept of this report was that of Mātauranga Māori which is described as a collection of knowledge, past, present and future experiences built and developed through connection with the world, transferred through generations through first hand observation and oral tradition (Taiapa et al., 2014). Traditional knowledge of sustainably harvesting kaimoana is passed down and involves in depth knowledge of the ecosystem processes, environment, interactions and seasonal changes. This knowledge is being incorporated with science to better future restoration of Te Awanui Tauranga Harbour (Taiapa et al., 2014).

2.4.4.2.1 Observed historic ecological changes

Historic accounts from local iwi whose whanau have lived in the Tauranga Harbour area for generations have generally been consistent in recounting that the harbour was previously abundant in kaimoana and stocks have been declining for centuries (Taiapa et al., 2014). The tangata whenua have identified overfishing, change in land use, sediment input, runoff, riparian and wetland removal, port development and infrastructure as contributing factors to the historic and ongoing decline in resources (Taiapa et al., 2014). Centre bank, known as Te Paritaha is one of the only sustainable shellfish beds within the harbour. Prior to the 2015 dredging works, tangata whenua expressed concern over the previous port developments impact on the pipi bed located on Paritaha and the fears that further changes would result in the beds not recovering following interference and access being reduced. These concerns arouse after the construction of the Harbour bridge when iwi were told removed pipi beds would recover but never did (Taiapa et al., 2014).

2.4.4.3 Intertidal ecological survey of Tauranga Harbour

Ellis et al. (2017) completed a broad scale intertidal survey of macrofaunal benthic community health as well as trends in contaminants, nutrients and sediments within Tauranga Harbour. The aim of the survey was to better understand the anthropogenic stressors that were impacting on the ecology of the Harbour. Data was collected between December 2011 and February 2012 at 75 sites across the Harbour. At each site 10 replicate samples of a 130 mm diameter, 150 mm deep core were taken to quantify the macrofauna at each site. Pipi (Paphies australis) and cockles (*Austrovenus stutchburyi*) were measured as they are culturally significant species (Ellis et al., 2017).

2.4.4.3.1 Benthic health model

Using the biological and physical data from samples Ellis et al. (2017) developed a Benthic Health Model (BHM) which uses community composition to create categories of relative ecosystem health. Relative health is considered as comparing composition between sites that are affected by anthropogenic input with those that are largely unaffected. Multivariate techniques were used to determine differences in community composition with different levels of anthropogenic impacts. In this study, the health of sites in the intertidal areas were ranked using a BHM based on responses to contamination, sedimentation and nutrients.

2.4.4.3.2 Controls on ecological health

Using variance partitioning methods, Ellis et al. (2017) showed the variation in benthic community data was explained by sedimentation, specifically percentage mud (4.9%) and contamination (7.5%) with nutrients contributing less (2.7%). Community composition change was showed to have a strong gradient in response to sediment mud content (R^2 = 0.7683). Muddier sites (impacted) had higher poor ecological health ranking of 8 and sandier sites (healthy) had lower ranking of 1. Sites with the higher impacted health category (7-8) were found in inner estuaries and lower impacted health category (1-2) were found in more exposed areas of the Harbour as seen in Figure 2.13 A. Contamination (heavy metals Pb, Cu and Zn) also had a strong gradient (R^2 = 0.7075) and showed the same tendency for sites to have decreased health in inner harbour areas as seen in Figure 2.13 B. The concentrations of all heavy metals increased with increasing ecological health values (1 healthy - 5 unhealthy). The tendency of contaminants to bind with muddier sediments was reflected in the percentage mud also increasing with the contamination ecological health values. Individual species were also found to have differences in abundance between sites which correlated with one of the gradients, sedimentation was found to be the best predictor.

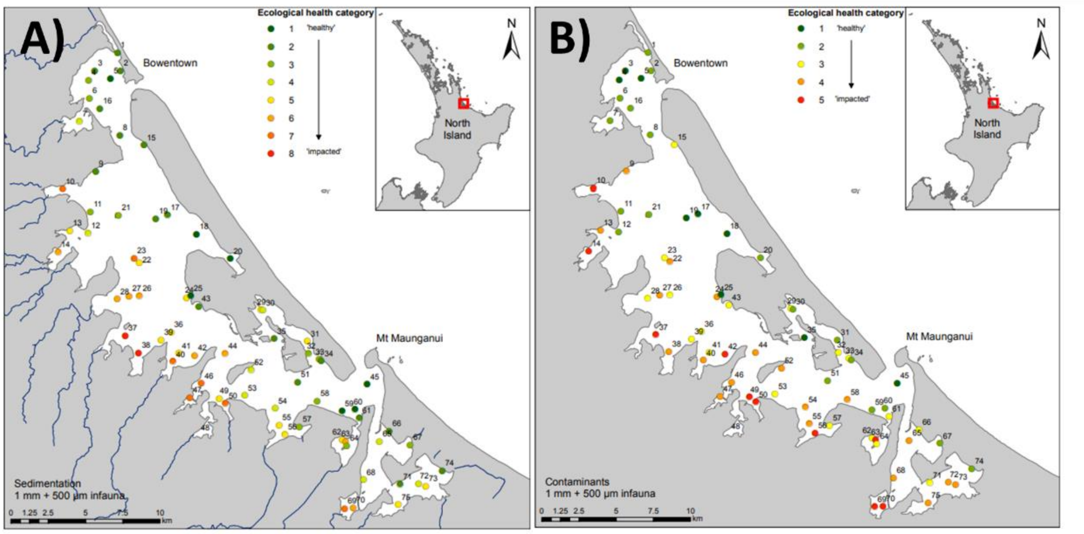

Figure 2.13: Shows the location of the 75 samples sites, colours indicate the corresponding Ecological health category with green being "healthy" or low effects and red being "impacted" or high effects. Figure 2.13 A) Ecological health category for the effects of sedimentation. Figure 2.13 B) Ecological health category for the effects of contamination. Source: Ellis et al. (2017).

2.4.5 Conclusions on the Ecology in Tauranga Harbour

- There are concerns about the increasing anthropogenic pressures within and surrounding Tauranga Harbour, this has brought a focus on management and restoration of estuarine and ecological systems.
- Changes in shellfish are of noticeable concern due to their significance as indicators of ecological health, culturally and as a food source.
- attributed increasing anthropogenic pressures on the ecology through time including dredging, sedimentation, pollution and overfishing.
- Hard to pinpoint what is responsible when there is a lack of scientific evidence spatially and temporally to show the extent of changes in community composition, shellfish populations and environmental stressors.
- In general, studies on all scales agree that bivalves are the dominant taxonomic group in intertidal areas and polychaetes dominate subtidal areas.
- Biological and physical stressors controlling ecological health and species distribution in intertidal areas include contamination, sedimentation and nutrients.

2.5 Summary

From the review of previous studies and knowledge on changes in geomorphology, hydrodynamics, sedimentation and ecology the following knowledge gaps and goals for this study have been identified.

- There have been no focused studies of hydrodynamics in Tauranga harbour southern basin accounting for historic changes in intertidal geomorphology due to infilling.
- There have been no studies investigating the historic temporal and spatial changes in harbour wide environmental conditions.
- When recreating historical bathymetries adjusted for infilling in intertidal areas and investigate whether this has an influence on depth and hydrodynamics.

- Hind cast environmental conditions using a hydrodynamic numerical model.
- Understanding the historic changes in environmental conditions will allow an estimation of the magnitude and distribution of impacts on ecological health and inform the aims of future estuarine restoration.

CHAPTER THREE
Bathymetry Compilation

3.1 Introduction

This chapter describes the creation of the historic bathymetries of the southern basin of Tauranga Harbour. The objective of this was to visualise spatial and temporal changes of the Harbour's morphology, as well as to provide rectangular model grids and bathymetries for running hydrodynamic simulations in Delft3D. The results presented are the final bathymetries with a discussion of the influence of the simulated infilling on the distribution of depth throughout the Harbour.

3.1.1 Bathymetry creation approach

The numerical modelling software Delft3D developed by Deltares has several modules and tools for creating inputs required for simulating complex 2D and 3D hydrodynamic systems. The QUICKIN module of Delft3D allows the interpolation, generation, manipulation and visualization of grid oriented depth data. Therefore, it was used to create six historical model bathymetries with the entrance bathymetry adjusted and five bathymetries with the intertidal regions also adjusted. This was achieved by combining morphological data from several different sources. The sources that were used are as follows:

Source 1: The initial template used to edit and develop the bathymetries was an original hydrodynamic model of the Tauranga Harbour southern basin comprised of 2017 multibeam sonar surveys, LiDAR (Light Detection and Ranging) from the Port of Tauranga and hydrographic charts from Land Information New Zealand (B. Stewart, pers.comm). The grid and depth files from this model provided the base data which was then subsequently altered to meet requirements for the creation of historical bathymetries. The rectangular grid had 20 metre by 20 metre resolution with 941 cells in the N direction and 1347 cells in the M direction. The bathymetry was based on mean sea level and in the cartesian coordinate system.

Source 2: The second source was bathymetric data presented by Adrian Brannigan in his Master's thesis (Brannigan, 2009) with the University of Waikato. This provided six bathymetries for reconstruction. Depth data had to be extracted from images of bathymetries from 2006, 1954, 1927, 1901, 1879 and 1852 to create digital entrance depth files that could be interpolated into the baseline-grid (source 1). The images were focused on the Tauranga entrance tidal delta system so provided detailed depth where the most significant changes in bathymetry have occurred through time. Spiers et al (2009) compiled the 2006 bathymetry which Adrian used in his thesis from single beam surveys from the Port of Tauranga, multibeam surveys from the University of Waikato, digitised charts and previous model grids from Environment Bay of Plenty. The older bathymetries (1852-1954) were digitised from fair sheets, charts from the Bay of Plenty Harbour Board Engineering staff and a Royal New Zealand Navy Hydrographic chart. All of the bathymetries were in New Zealand Map grid and depths were chart datum.

Source 3: Depth files over the whole harbour region were produced to simulate infilling over time in the intertidal areas. Intertidal areas have generally been poorly mapped historically. There were no substantial existing data to indicate what these intertidal areas were in 1954, 1927, 1901, 1879 and 1852, so the depths therefore had to be created by removing sediment from the initial Tauranga harbour southern basin bathymetry and creating an intertidal depth file for each year 1852-1954.

3.2 Methods

3.2.1 Entrance depth file creation

Original images of Tauranga harbours bathymetry back through time were obtained from Brannigan (2009) thesis on the change in geomorphology, hydrodynamics and surficial sediment of the Tauranga entrance tidal delta system. (Unfortunately Brannigan did not store the original files successfully (Brannigan, 2017, pers. comm.). Bathymetries from 2006, 1954, 1927, 1901, 1879 and 1852 were extracted and saved as JPEG files (seen in Figure 2.4). The images were then uploaded into MATLAB with the intention of creating a gridded output file that had the same depth values. The output had to be georectified (rotated, scaled and translated) into the coordinate system used in the 2006 grid so that Delft3D QUICKIN could be used for data interpolation into the baseline grid (described as source one above).

3.2.2 Image conversion to depth

Using the colours in the accompanying scales on Brannigan (2009) original images, the average colour associated with each depth was found. The mode amount of red, green and blue was found for each colour corresponding to each depth by averaging the colour values of the pixels in the colour scale. A tolerance range of 10 was set for either side of the mode for each of the red, green, and blue values associated with each depth. These ranges around the mode values were then used to find all the pixels in the original image that fell within the range for all three colours. As some colours, such as the black lines, on the original image weren't assigned depth values there were gaps in the extracted depth figure. Interpolation of existing depths was used to fill in the missing values, using the Matlab griddata routine (which uses 2-D linear interpolation).

3.2.2.1 Rotation and translation

The next step was then to rotate, scale and translate the image so that the grid was oriented with north upward and it was on a coordinate system that could be input into an existing grid of Tauranga Harbour using Delft3D QUICKIN. Calibration points were selected in both x and y coordinates from both the historic bathymetry entrance files and the baseline Tauranga Harbour Grid. These coordinates were used to find the optimal rotation, translation and scaling (evaluated using the least square error) and so match the grids made from the historic bathymetric images to baseline grid.

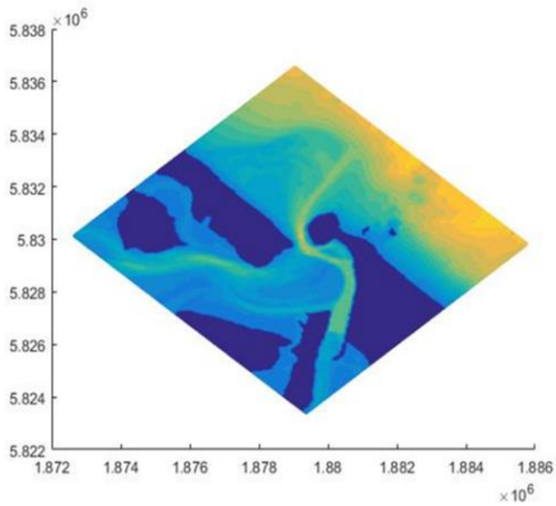

Figure 3.1 Entrance bathymetry from 2006. Extracted and rotated depth that has been translated onto axis of the Cartesian coordinate system used in Delft3D QUICKIN.

The result was then exported and saved as a depth file. This process was repeated for the years 1852-1954. The extracted, rotated, scaled and saved entrance depth from 2006 can be seen in Figure 3.1.

3.2.3 Intertidal depth file creation

To produce depth files that account for infilling over time (bathymetry source three), the baseline Tauranga Harbour bathymetry (source one, Figure 3.2) was adjusted by removing sediment from intertidal areas. The amount that was removed was based on the mean 1.22 mm/yr of deposition which was the average of the three values of 0.75, 1.57 and 1.33 mm/yr SAR found in Tauranga Harbour by Hancock et al. (2009). The amount removed for each bathymetry can be seen in Table 3.1 below which is the mean SAR multiplied by the number of years prior to 2006.

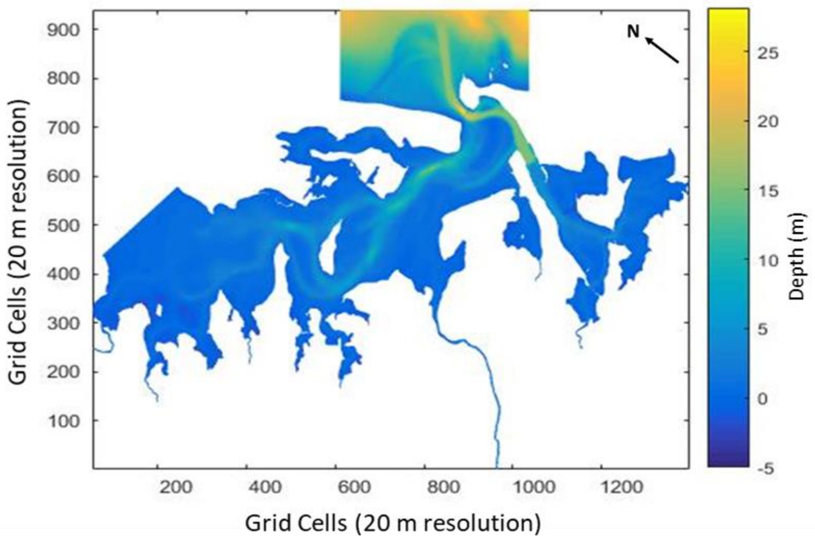

Figure 3.2: Baseline Tauranga Harbour Depth file (source one). Depth in metres indicated by the colour bar, negative values are below mean sea level. Axis shows the number of 20m resolution grid cells in the N and M direction.

Table 3.1: The total amount of sediment removed from intertidal areas for each of the bathymetries, based on multiplying the mean SAR 1.22 mm/yr by the number of years between 2006 and each bathymetry.

Bathymetry year	Number of years prior to 2006	Total amount removed from intertidal areas (mm)
1852	154	187.88
1879	127	154.94
1901	105	128.1
1927	79	96.38
1954	52	63.44

The existing depth file (Figure 3.2) from the original Tauranga Harbour bathymetry was read into MATLAB. To adjust the intertidal area for the year 1954 and simulate the removal of sediment, the original bathymetry was made deeper by 0.0644 meters. When adjusting the depth, the amount removed was tapered towards the edge of the intertidal so that the simulated removal of sediment did not create a sharp drop off in the bathymetry at the edge of the intertidal region. The result was exported and saved as a depth file. This was repeated for each of the 1852-1927 years with the appropriate depth adjustment according to the values in Table 3.1.

3.2.4 Compiling the Entrance adjusted bathymetries

The existing baseline grid of the Tauranga Harbour southern basin (described as source 1 above) was used as the basis for creating bathymetries in Delft3D QUICKIN. The final bathymetries therefore had the same grid and cell sizes.

The 2006 extracted entrance depth file from Brannigan's images was initially input into QUICKIN as samples. As there was sufficient data, grid cell averaging was applied to create depth values. Smoothing and internal diffusion were then used to even out rough contours and fill missing depth values. A uniform value of 1.10 meters was added to the depth values of the entrance in order to adjust from Port chart datum to Mean Sea Level. The original Tauranga Harbour southern basin depth file was imported as a second depth. This filled the missing depths in the upper reaches of the harbour which were not covered by the 2006 extracted entrance bathymetry. The original bathymetry was already adjusted to mean sea level so no editing was required. As two different sources of data were combined, some contours did not line up perfectly where the data met and smoothing was used to minimize the inaccuracy. The bathymetry was then exported and saved as a depth file. This process was repeated for the 1952-1954 years to create six final bathymetries which had the extracted entrance depths (source two) and the same upper harbour depths (source one).

3.2.5 Compiling the Intertidal adjusted bathymetries

To create the intertidal adjusted bathymetries, the same process used to compile the entrance adjusted bathymetries was used except that the intertidal depth files (source 3) created in MATLAB were used as a second depth rather than the baseline Tauranga Harbour depth file (source one). The intertidal adjusted depth files from 1852-1954 were combined with the corresponding entrance depth files (source 2) to create an additional five final bathymetries. The entrance depth files did not require sediment removed from intertidal areas because they had been created from charts from the appropriate year and therefore sedimentation was already accounted for. For 2006, there was no intertidal adjusted bathymetry created as this was treated as the "current" bathymetry and infilled state.

3.2.6 Limitations

There are some sources of error that may cause the created bathymetries to have some slight difference in depth compared to the original sources. One of these sources occurs as the depth values were extracted from an image using colours and interpolation, the depths may be slightly shifted in location. This slight shifting of depth could also occur when the image was rotated and translated. Joining different depth data together in QUICKIN required some smoothing along the edges where two different sources met. This means where the bathymetries were adjusted along these joins the depths may not exactly represent the true environment.

When creating the intertidal adjusted bathymetries, the sources used to map the intertidal areas were not necessarily from 2006 therefore removing sediment based on counting how many years prior to 2006 is not entirely accurate. Sedimentation accumulation rates are also not constant spatially or temporally, different areas of the harbour will have different sedimentation rates and sedimentation rates have not been constant through time. Actual sediment accumulation rates through time are unknown, the amount removed is an average and the simulated infilling is an approximation. The simulated infilling assumes that there have been some changes in depth in the intertidal areas, for some areas it may be less impacted by infilling than what's been removed, some areas may be more impacted. More comprehensive mapping and analysis of accumulation rates is needed for increased accuracy of intertidal areas when compiling historic or future bathymetries.

3.3 Resulting Bathymetries

The compilation of bathymetries resulted in six entrance adjusted bathymetries and five intertidal adjusted bathymetries being produced as seen in Figures 3.3 and 3.4. All depths are in relation to Mean Sea Level (MSL).

3.3.1 Entrance adjusted bathymetries

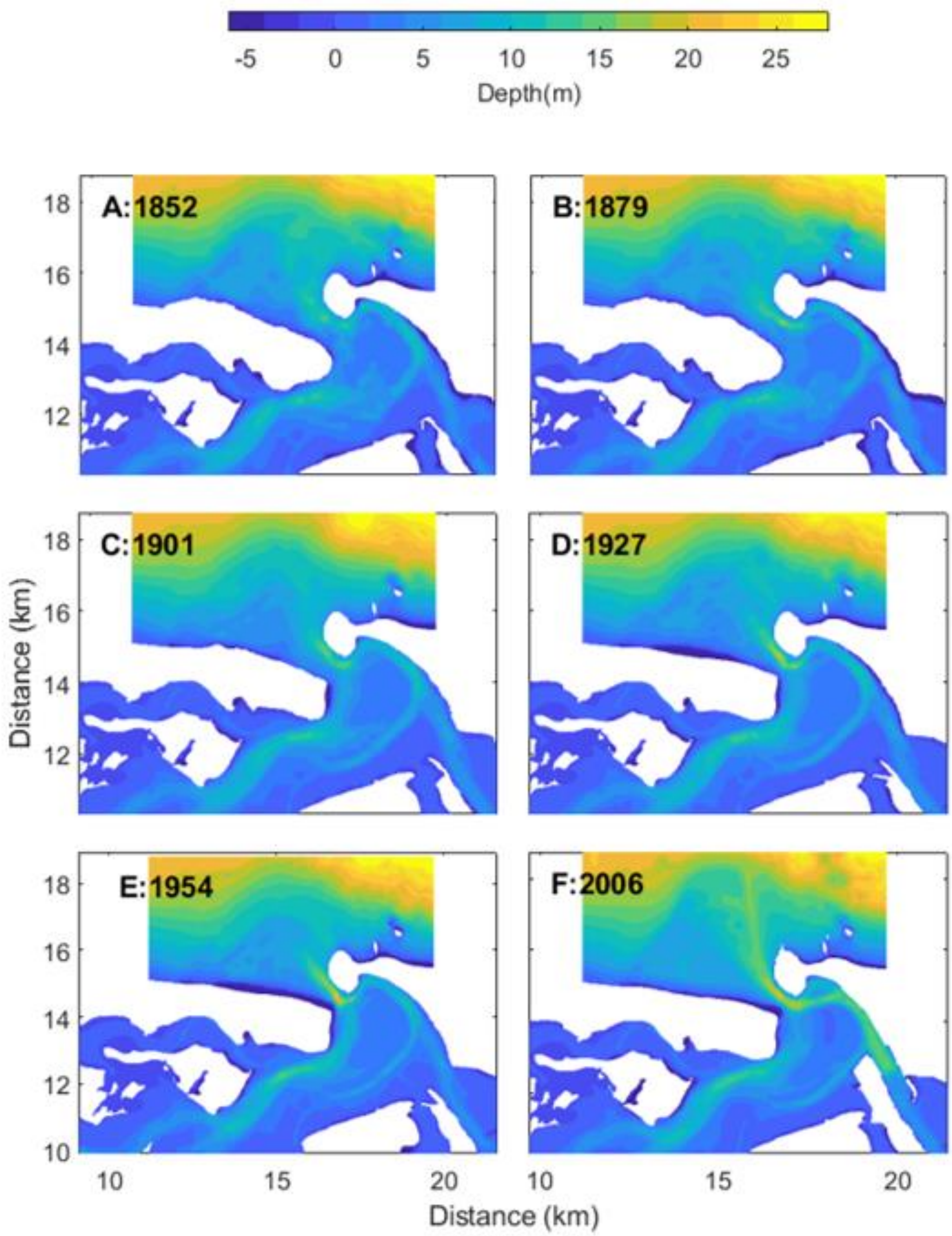

Figure 3.3 Final Entrance adjusted bathymetries (the upper harbour reaches for all years have the same bathymetry so are not shown). Depth in metres is indicated on the accompanying colour bar.

3.3.2 Intertidal adjusted bathymetries

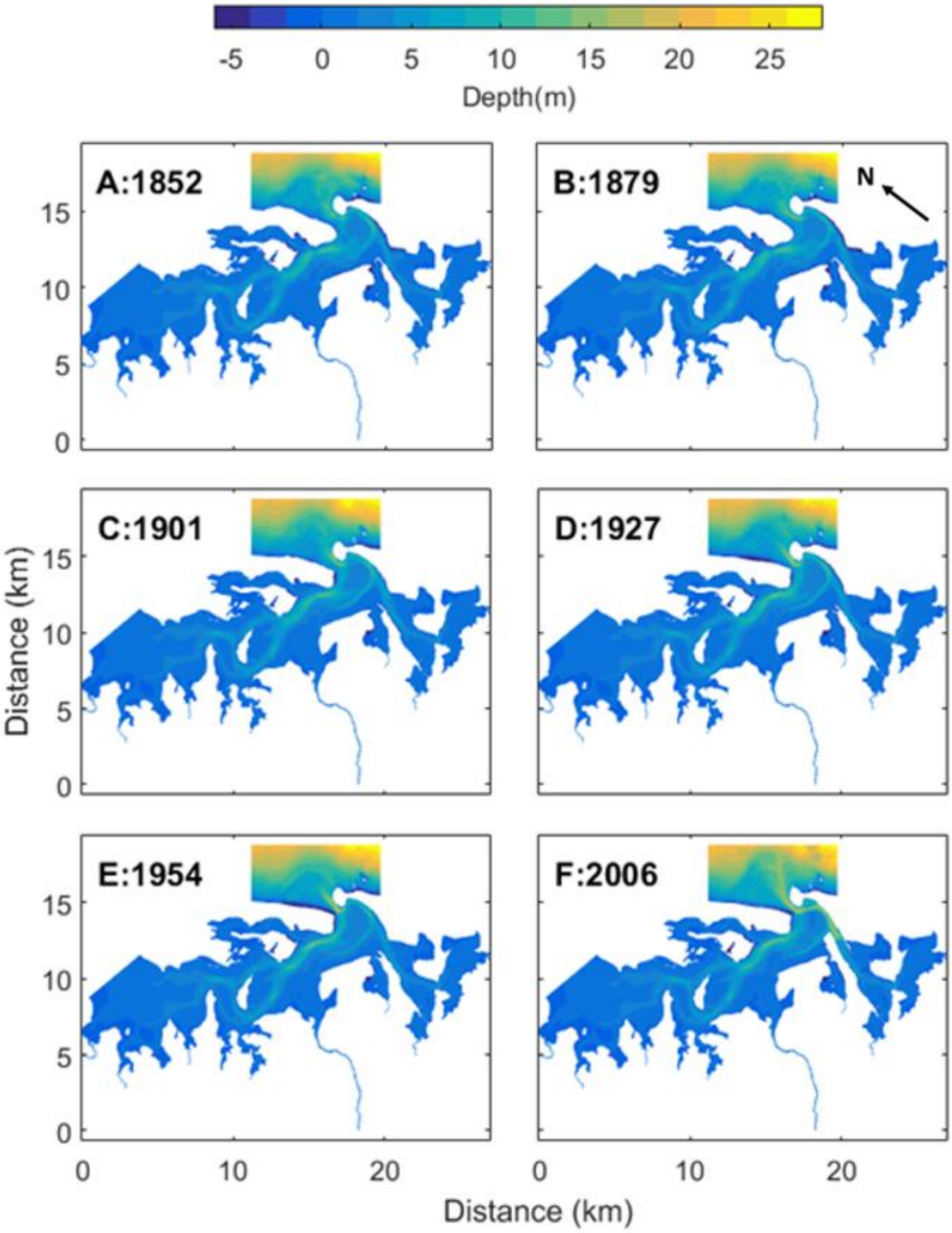

Figure 3.4 Final intertidal adjusted bathymetries. The 2006 bathymetry shown in panel F shows the upper harbour area of the 2006 entrance bathymetry, the intertidal areas have not been adjusted. Depth in metres is indicated on the accompanying colour bar.

3.4 Changes in distribution of depth as a result of simulated infilling

Simulating the removal of sediment from intertidal areas of the historic bathymetries had an influence on the distribution of depth. This can be seen in results of the analysis in Figures 3.5 and 3.6 which show depth distribution and the hypsometry for both the entrance and intertidal bathymetries. In the analysis, the 2006 entrance adjusted bathymetry is also used in the 2006 intertidal comparisons as a baseline.

3.4.1 Distribution of depth

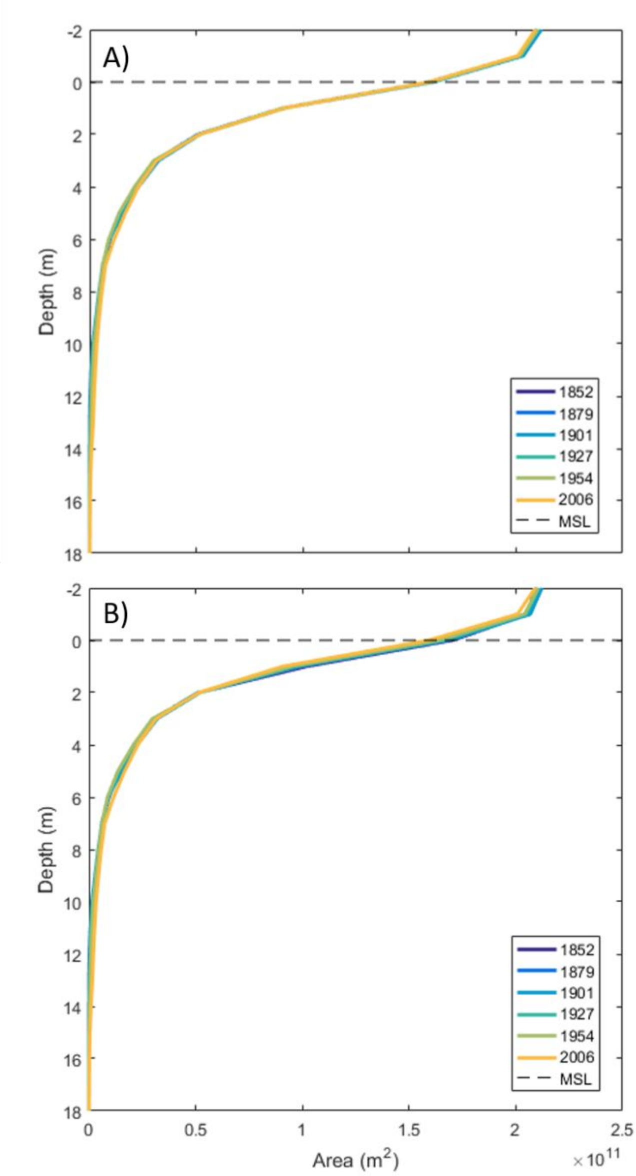

Figure 3.5 Distribution of depth at MSL as area in m2 for A) the entrance adjusted bathymetries and B) the intertidal adjusted bathymetries. MSL shown as the black dashed line and each year represented by a line as in the legend.

Figure 3.5 shows the area of the harbour that occurs at each depth for both the entrance adjusted bathymetries (A) and intertidal adjusted bathymetries (B). All of the bathymetries in Figure 3.5 have significant proportions of area between 1 metres above and 1 metres below MSL. Significantly less area is shown to be at depths below 1 metre below MSL.

The distribution of depth for the entrance adjusted bathymetries in Figure 3.5 A shows that all six of the bathymetries closely follow the same distribution of depth between 1 metre above and 2 metres below mean sea level (MSL). The distribution of area at depths greater than 2 metres varies between the six bathymetries. The 2006 bathymetry has increased area at greater depths.

For the intertidal adjusted bathymetries shown in Figure 3.5 B, compared to the entrance adjusted bathymetries, there is distinguishable differences between the six years from 1 metres above and 2 metres below mean sea level (MSL). The 1852 bathymetry has the deepest distribution in the intertidal area and the 2006 bathymetry has a shallowest distribution. The distribution of area at depths greater than 2 metres also varies between the six bathymetries and is similar to the entrance bathymetries.

3.4.2 Hypsometry

Figure 3.6 shows the hypsometry of the harbour which depicts the relative area and depth of the entrance adjusted bathymetries (A) and intertidal adjusted bathymetries (B) calculated using the equation defined by Boon & Byrne (1981). The dashed and solid lines indicate a γ value of 1 and 2 respectively. All of the bathymetries in Figure 3.6 fit roughly between these two curves indicating they have a γ value of between 1 and 2.

The hypsometry of the entrance adjusted bathymetries in Figure 3.6 A show little difference in curvature indicating all years have similar γ value. The hypsometry of the intertidal adjusted bathymetries in Figure 3.6 B shows more difference in curvature compared to the entrance adjusted bathymetries. The bathymetries still have similar curvatures but they are more distinguishable. The 2006 bathymetry is a closer fit to the γ=1 dashed line and the bathymetries move further away from this in chronological order, with the 1852 bathymetry is the closest to the γ=2 solid line. This shows that the bathymetries are decreasing in γ from 1852 to 2006.

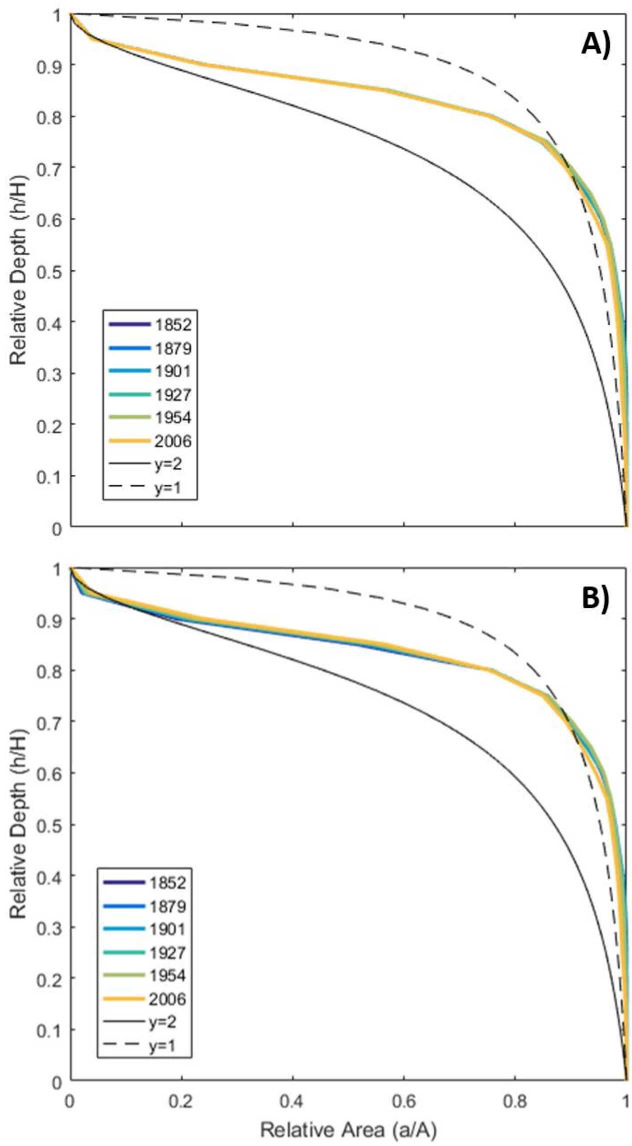

Figure 3.6 Hypsometric curves for all years for A) entrance adjusted bathymetries and B) intertidal adjusted bathymetries. Relative area is on the x-axis (a is area and A is total Harbour area), relative depth is on the y-axis.

3.5 Discussion

3.5.1 Bathymetry compilation results

The resulting bathymetries reproduced the geomorphology represented in previous studies successfully. The bathymetries illustrate the significant features of geomorphology as described in previous studies. Each of the years depict the state of Matakana Island, Sulphur Point, Centre Bank, the entrance inlet, major channels and intertidal area at that point in time.

3.5.2 Influence of infilling on distribution of depth

For both the entrance and intertidal bathymetries the general distribution of depth shows that the Tauranga harbour has extensive intertidal areas, with significant proportions of the overall area between 1 meter above and below MSL. The entrance bathymetries have almost exactly the same distribution in the intertidal depths as each of the six years used the same source to create the upper harbour areas. There is little difference in the intertidal bathymetry between the years. The variation in distribution of depth for the intertidal bathymetries shows that the simulated infilling changed the depths of the intertidal areas. The 1852 bathymetry has the deeper distribution in the intertidal areas as it had the most sediment removed during compilation of the intertidal adjusted bathymetries. The 2006 bathymetry had no sediment removed from intertidal areas and therefore has the shallower distribution in the intertidal depths. For both the entrance and intertidal bathymetries, the difference in the deeper areas between years is due the variation and changes in the geomorphology of the entrance features through time. The 2006 bathymetry has increased area at greater depths as it represents post dredging geomorphology and has artificially deepened channels (Brannigan, 2009).

For the calculation of hypsometry, the empirical parameter γ controls the curve and can be considered as an indicator of infilling as it determines the sediment in the basin as relative volume (Boon & Byrne, 1981; Dejeans, 2015). The entrance and intertidal adjusted bathymetries fit between a γ value of 1 and 2. This result is in line with analysis of Tauranga Harbour hypsometry completed by Dejeans (2015) which modelled a γ value of 1.4 using the area below average tidal level. The entrance bathymetries show little difference in curvature indicating all years have similar γ value and therefore amounts of infilling. As with the distribution of depth, this similarity between the years is due to the lack of difference in the intertidal area of the bathymetries as the same source for the depth is used for the extensive upper harbour areas. The hypsometry of the intertidal adjusted bathymetry shows that there is a decrease in γ from 1852 to 2006 as lower values of γ reflects more advanced infilling.

3.6 Summary

The compilation of bathymetries produced 6 bathymetries from 1852, 1879, 1901, 1927, 1954 and 2006 that have different entrance bathymetries and the same source for the upper harbour covering largely the intertidal areas. The 5 additional bathymetries produced for the first five years had the same differing entrance bathymetries but also had the intertidal areas in the upper harbour adjusted for infilling through time. This infilling was simulated by adding increasing amounts of depth back through time to "remove" the sediment. The 11 final bathymetries were used in the production of the hydrodynamic model in the following chapter.

The analysis of depth distribution and hypsometry allowed a comparison between the entrance and intertidal adjusted bathymetries. It was important to investigate the influence of the simulated infilling on the distribution of depth in the Tauranga harbour to make sure that the adjustments of the intertidal areas had the desired effect. The results of the analysis demonstrate that the removal of sediment from the intertidal areas of earlier bathymetries was successful. The intertidal adjusted bathymetries showed variation in distribution of depth in intertidal areas compared to the entrance adjusted bathymetries. The curvature of the hypsometry's also differed between the two sets of bathymetries with the intertidal adjusted bathymetries showing the increased influence of infilling through time with a decreasing γ value.

The simulated infilling in the creation of intertidal bathymetries has shown that although accumulation rates may not seem significant in the short term, it can have more significant implications for the distribution of depth over a longer period of roughly 150 years. Previously modelling of large scale hydrodynamic and geomorphologic changes have not considered the sedimentation on intertidal areas as there is a lack of accurate mapping in these shallower areas (Brannigan, 2009).

Having correct depths when modelling is important as there are complex feedback controls with hydrodynamics. Changing of the depth of the estuary has the potential to impact on the tidal amplitude due to changes in geomorphology and friction. This has implications for recreating hydrodynamics of the harbour as changes in the tidal flows driving circulation can affect transport processes, residence time and current velocities (Talke & Jay, 2020).

For this study and future modelling of hydrodynamics it is important to account for changes in depth caused by sedimentation within the harbour to accurately predict changes in conditions and the implications for ecological health.

CHAPTER FOUR
Hydrodynamic Numerical Model

4.1 Introduction

This chapter describes the numerical model used to recreate historical hydrodynamics of the southern basin of Tauranga Harbour. The objective of this chapter is to summarise the set-up and inputs of the hydrodynamic model which include the grid, bathymetry, initial and boundary conditions. The validity of the modelling is explored primarily by justifying values used in each of the parameters. The results presented are the averaged hydrodynamic conditions for each of the 11 bathymetries created in the previous chapter. The chapter concludes with a discussion of the influence of the simulated infilling on hydrodynamics.

4.1.1 Approach to modelling

The FLOW module of the Deltares Delft3D software was used to carry out the numerical modelling of the historical hydrodynamics in the southern basin of Tauranga Harbour. The Delft3D FLOW modelling suite is a simulation program used for computing the hydrodynamics of coastal, river and estuarine systems (Deltares Systems, 2017). As the harbour is well-mixed, shallow and vertically homogenous, depth averaged (2D) flow simulations were carried out for each of the 11 historical bathymetries (Deltares Systems, 2017). Delft3D FLOW solves the three dimensional, non-linear, shallow water Navier-Stokes equations in order to simulate hydrodynamics. The equations solved include the continuity equation, horizontal equations of motion and transport equations for conservative constituents. The flow in this model is forced at open boundaries by tides (Deltares Systems, 2017).

An original model of the southern basin Tauranga Harbour was provided by Ben Stewart as a baseline for the development of the following parameters.

4.2 Delft3D FLOW Parameters and Justifications

4.2.1 Grid and Bathymetries

The 20 x 20 m resolution grid from the original southern basin Tauranga Harbour was used for the hydrodynamic model. The resolution balances reducing computation time while providing enough detail. The grid had three open ocean boundaries away from the harbour entrance so that the flow in and out of the harbour was not interacting with the boundary and reflection was minimised (Deltares Systems, 2017). The grid was also limited to the southern basin of the Tauranga Harbour as previous studies have stated it has low water exchange with the northern basin (Barnett, 1985; Tay et al., 2013).

The compilation of bathymetries used in the hydrodynamic model are described in Chapter three. Six bathymetries from 2006, 1954, 1927, 1901, 1879 and 1852 were produced that had the entrance adjusted and five bathymetries were produced that had the entrance adjusted and the intertidal areas edited to simulate infilling (not 2006). A total of 11 final bathymetries (Figures 3.3 and 3.4) were used to run 11 simulations.

4.2.2 Timeframe

For this study, the simulation period used for each model run was a full spring-neap tidal cycle. The simulations were run from 00.00.00 on the 1st of June to 00.00.00 on the 3rd of July for each year corresponding to the bathymetries. A period of two days was included to allow a spin-up time as the hydrodynamic model began with a cold start. This spin-up allows the model to adjust to the forcing at the boundary and reach equilibrium within the harbour (Deltares Systems, 2017).

A time step of 0.5 was used in the hydrodynamic simulations. The time step controls the model stability and computation time and is dependent on water depth, gravity and grid spacing (Deltares Systems, 2017). A time step of 0.5 balances computation time and accuracy of predicted hydrodynamics in shallower areas (Watson, 2016).

4.2.3 Processes

Salinity, temperature, wave, wind and freshwater inputs and processes were not included in the setup of the hydrodynamic numerical model. As the southern basin of Tauranga Harbour is a well-mixed, shallow tidally dominated inlet, these processes do not have significant effects on the hydrodynamics or drive circulation within the Harbour (Barnett, 1965; Hydraulic Research Station, 1963). They were therefore excluded as variables in the model simulations.

One constituent with a concentration of 1 kg/m^3 was defined under the "Pollutants and Tracers" process input section of the Delft3D modelling software in order to demonstrate changes in circulation and residence time.

4.2.4 Initial Conditions

Initial conditions specify the values that the simulation will start with for each dependent variable (Deltares Systems, 2017). The values can be uniform or be set to vary spatially using an initial conditions file. For the water level and velocity components variables, the initial conditions were selected to be uniform over the whole area. The spatial distribution of the tracer constituent had to be defined in an initial conditions file. The distribution and concentration of the tracer for the 2006 bathymetry is shown in Figure 4.1. Tracer is limited to the same inner harbour area for all bathymetries. The idea behind seeding only the inner harbour with tracer is that the residence time of water in the estuary can be calculated by tracking how the tracer dilution increases with time.

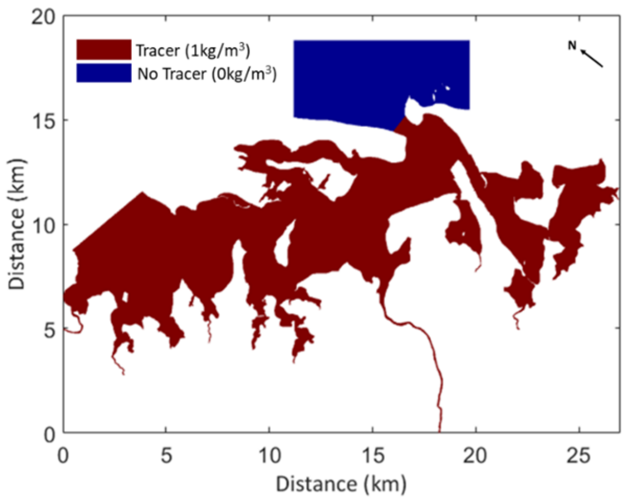

Figure 4.1: Spatial distribution of the tracer in the initial conditions file for the 2006 bathymetry. Red indicates 1 kg/m^3 tracer in the inner harbour.

4.2.5 Boundaries

The hydrodynamic model was forced at three open ocean boundaries by tidal water levels. The primary deep water constituents from the Moturiki Island tide gauge were used in the provided existing Tauranga Model and for this model. The amplitude and phase forcing conditions were interpolated between values set at the beginning and end of each boundary.

4.2.6 Physical and Numerical Parameters

The physical and numerical parameters specify values for physical conditions across the area of the model. Parameters are often adjusted through the modelling process to calibrate and verify the accuracy of results. Some values are set as constants through the whole bathymetry and others such as bottom roughness vary spatially (Deltares Systems, 2017; Watson, 2016).

4.2.6.1 Bottom roughness file

Bottom roughness is a physical parameter and determines the friction between the bed and the water passing over it. Roughness can significantly influence the behaviour of tidal waves and is therefore a common source of error within models (Deltares Systems, 2017; Tay et al., 2013; Watson, 2016). Therefore, for this study spatially varying bottom roughness files for each of the 11 bathymetries were created. The Chézy friction coefficient ($m^{-1/2}.s$) was used and the values were based off the water depth ranges used in the study by Watson (2016) shown in Table 4.1.

Table 4.1 The Chézy values assigned to each depth range to create bottom roughness maps for the 11 bathymetries. Note that the negative values are increasing depth below MSL

Chézy value ($m^{-1/2}.s$)	**Depth range (m MSL)**
65	<-5
55	-5 to -2
45	-2 to -1
35	-1 to 1.5
7	1.5 to 7
1	>7

These values were determined by Watson (2016) by calibration and verification against a series of in situe water level and current observations. Examples of the distribution of bottom roughness values can be seen in Figure 4.2 which shows the bottom roughness files for both the 1852 entrance and intertidal bathymetries. The intertidal bathymetry has higher Chézy values in the upper harbour compared to the entrance bathymetry as the depth has been adjusted for infilling.

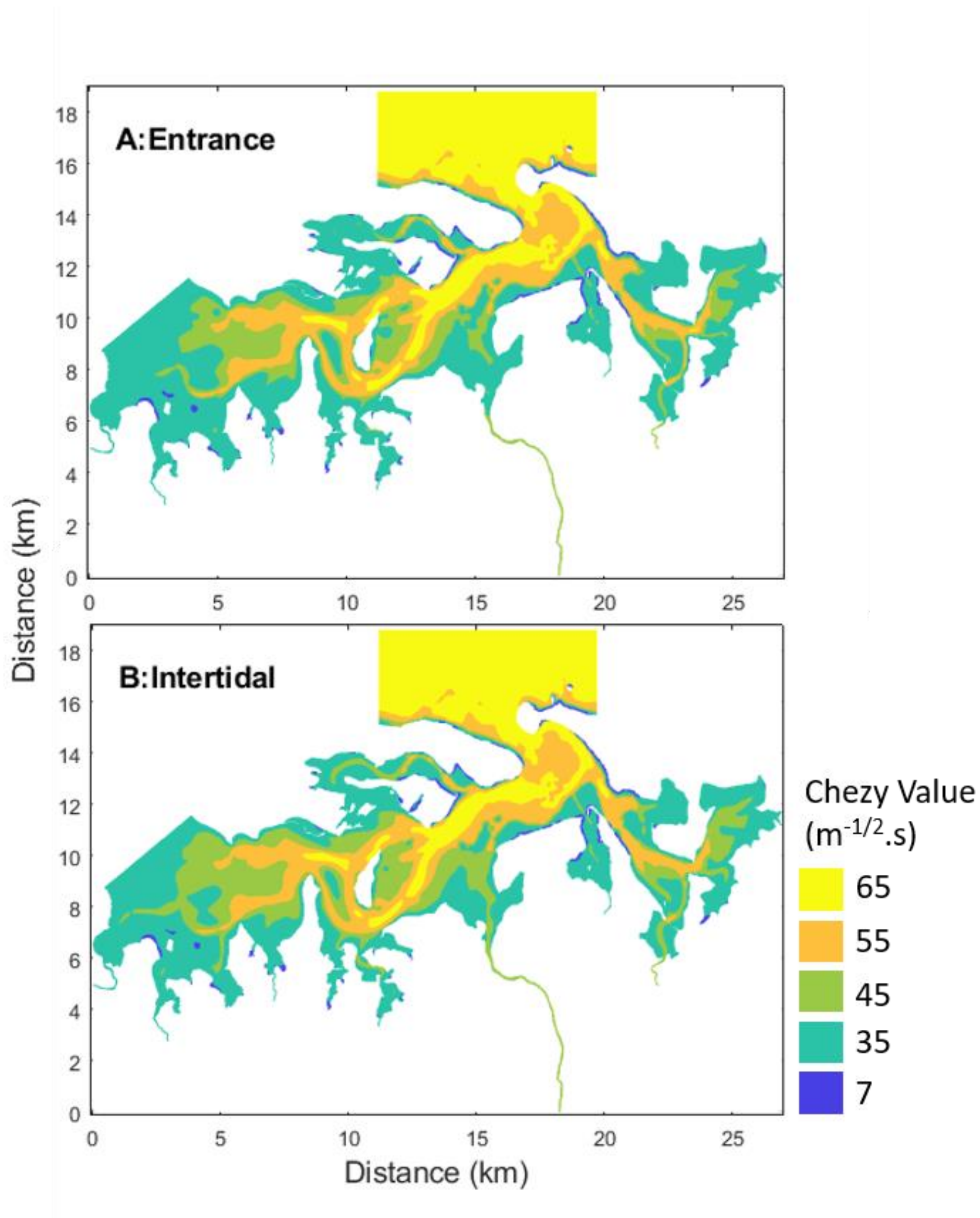

Figure 4.2 Bottom roughness map for the 1852 A) entrance adjusted bathymetry and B) the intertidal adjusted bathymetry. The special variation is based off the depth of the bathymetry and the Chézy values can be seen in key.

4.2.6.2 Final parameters

The final physical and numerical parameters used in the model runs for all 11 of the bathymetries are presented in Table 4.2. All parameters bar the bottom roughness are constant over the entire model area.

Table 4.2 List of the physical and numerical parameters and their values used in all of the hydrodynamic model runs.

Parameter	**Value**
Gravity	9.81 m.s^2
Water density	1025 kg.m^3
Eddy viscosity	10 m.s^2
Threshold Depth	0.05
Bottom roughness	Individual spatially varying maps

4.2.7 Sources of error

Results for the hydrodynamics of all bathymetries could experience error due to a number of factors. The bathymetry and depths can contribute as they may not be representative of actual environmental conditions. This also effects the bottom roughness values that were used. This can cause error in the hydrodynamics as it influences the response of tidal currents. The mean spring tidal levels can vary on a magnitude of 0.1-0.15 metres from year to year on a 19-year cycle (LINZ, 2020). As the tidal levels were used to force the model boundary conditions, this is created a source of error in the hydrodynamic modelling. The historical hydrodynamics also have a source of error as any effects of sea level rise on the MSL over the last 150 years were not included in the original depths.

All the model runs use the same time period, physical and numerical parameters but they are not calibrated. This means the comparison of the modelled hydrodynamic results are therefore qualitative not quantitative.

4.3 Results

This section provides an overview of the results from the hydrodynamic modelling of all entrance and intertidal bathymetries. High resolution plots are provided of the entrance hydrodynamic results to provide more detail of change in these areas. Full width plots of the intertidal hydrodynamic results are presented to show the harbour wide conditions and the intertidal areas.

The hydrodynamic results presented include the mean current speed, maximum current speed, water level range and residence times. All current speed and water level plots are averaged over a 14-day spring neap tidal cycle in order to provide insight into average environmental conditions. The tracer plots are calculated over the full model run excluding the two day spin up period.

These results are presented in order to provide a base understanding of the overall patterns in conditions that occur in the Tauranga Harbour southern basin. The results will also provide context for further analysis in this chapter which involves comparison between entrance and intertidal bathymetries to investigate the influence of infilling.

The white areas in the plots are the inactive grid cells which represent land and the area outside the model boundaries.

4.3.1 Mean current speed

The distribution of mean current speed for all of the entrance and intertidal bathymetries in Figures 4.3 and 4.4 follow the same general patterns of distribution. The Entrance, Upper Western and Lower Western channels have the highest average current speeds between 0.5 and 1 $m.s^{-1}$. The rest of the harbour including the intertidal areas have mean current speeds of less than 0.2 $m.s^{-1}$.

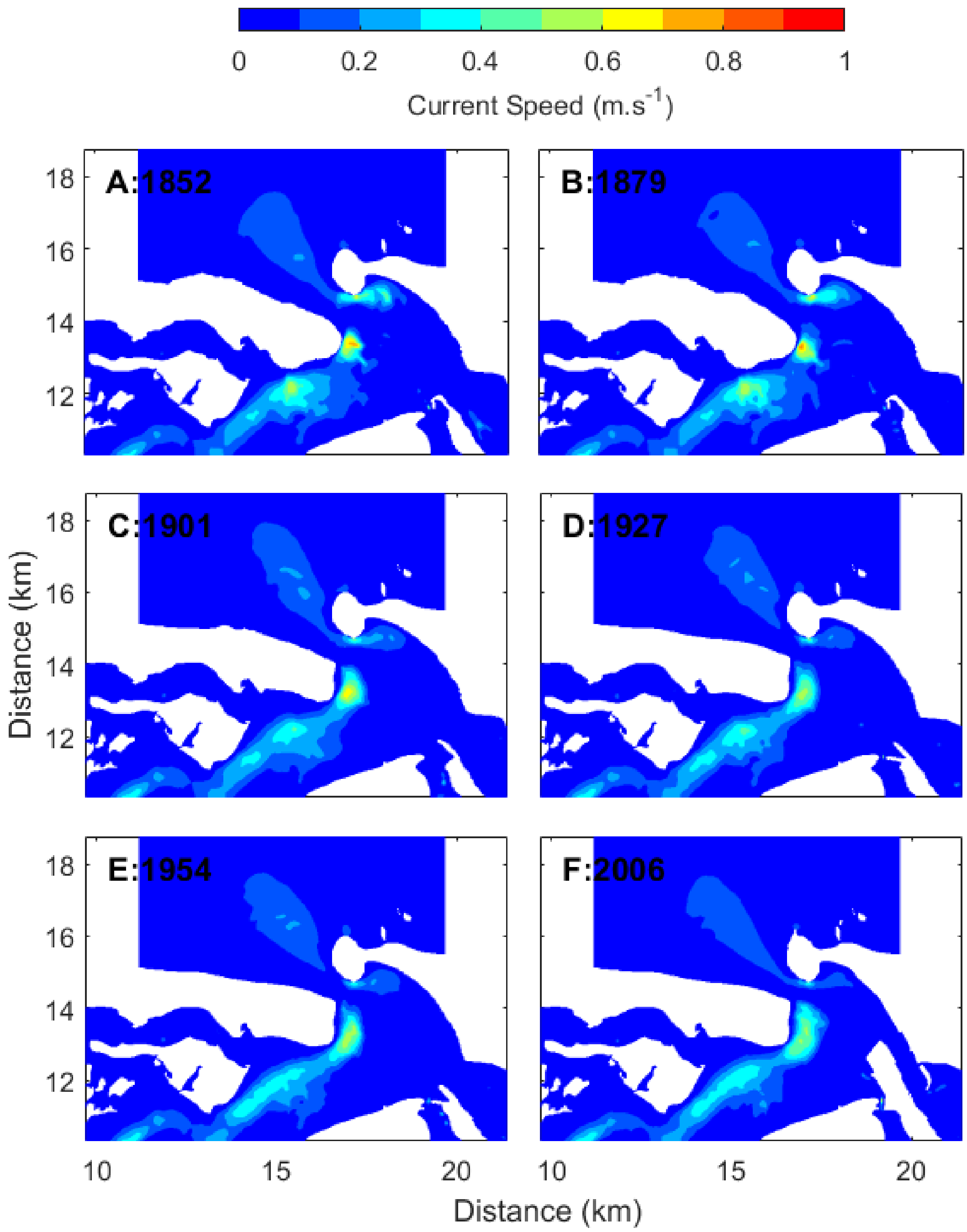

Figure 4.3 Mean current speed for the entrance adjusted bathymetry model runs A) 1852, B) 1879, C) 1901, D) 1927, E) 1954 and F) 2006. Results averaged over a spring and neap tidal cycle (14 days).

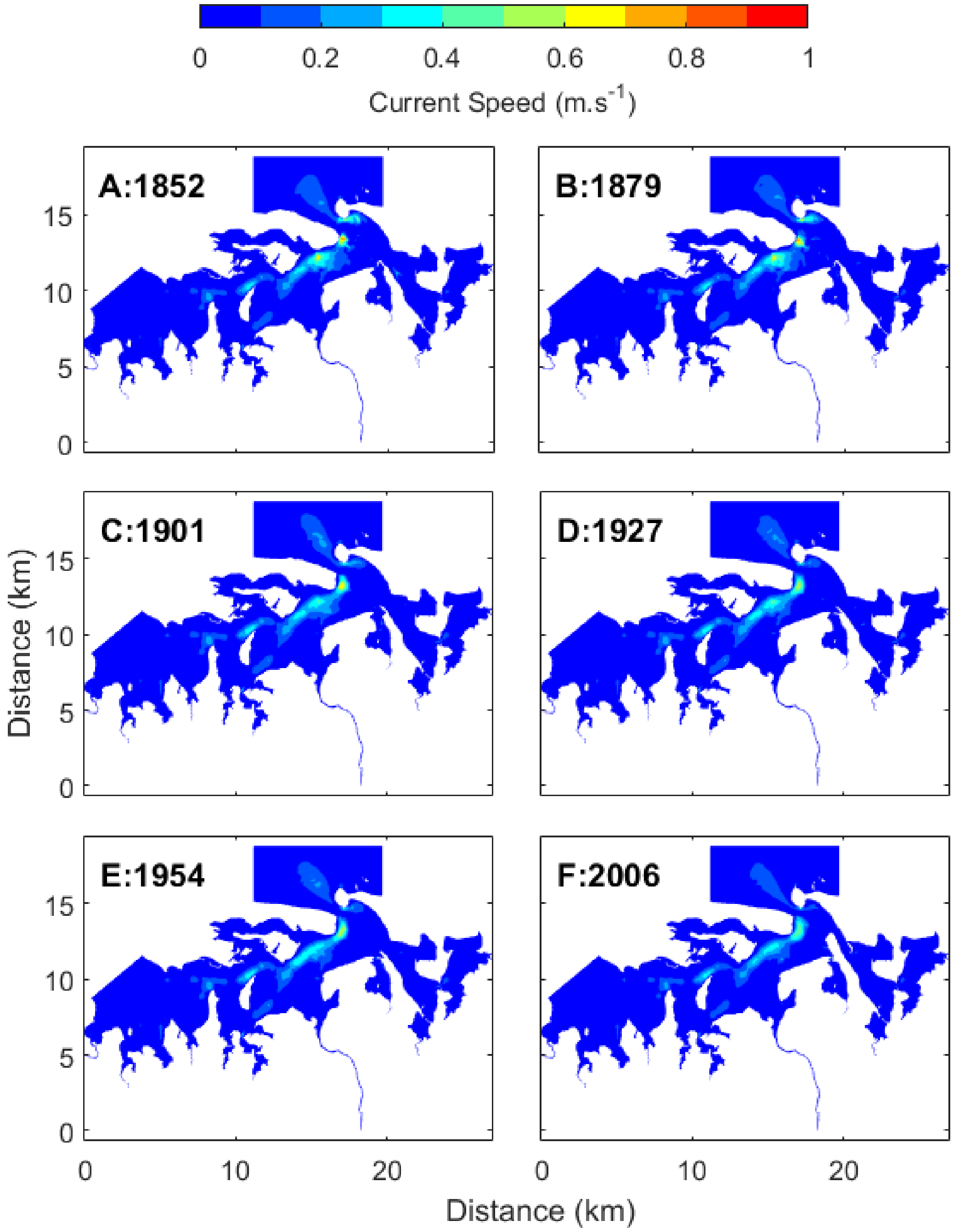

Figure 4.4 Mean current speed for the intertidal adjusted bathymetry model runs A) 1852, B) 1879, C) 1901, D) 1927, E) 1954 and F) 2006. Results averaged over a spring and neap tidal cycle (14 days).

4.3.2 Maximum speed

The distribution of maximum current speed for all of the entrance and intertidal bathymetries shown in Figures 4.5 and 4.6 follow the same general patterns of distribution. The Entrance channel and the Lower Western channel have maximum speeds greater than 1 m.s^{-1}. The other main channels reaching into upper harbour areas have maximum speeds between 0.5 and 1 m.s^{-1}. The rest of the harbour including the intertidal areas have maximum current speeds less than 0.5 m.s^{-1}.

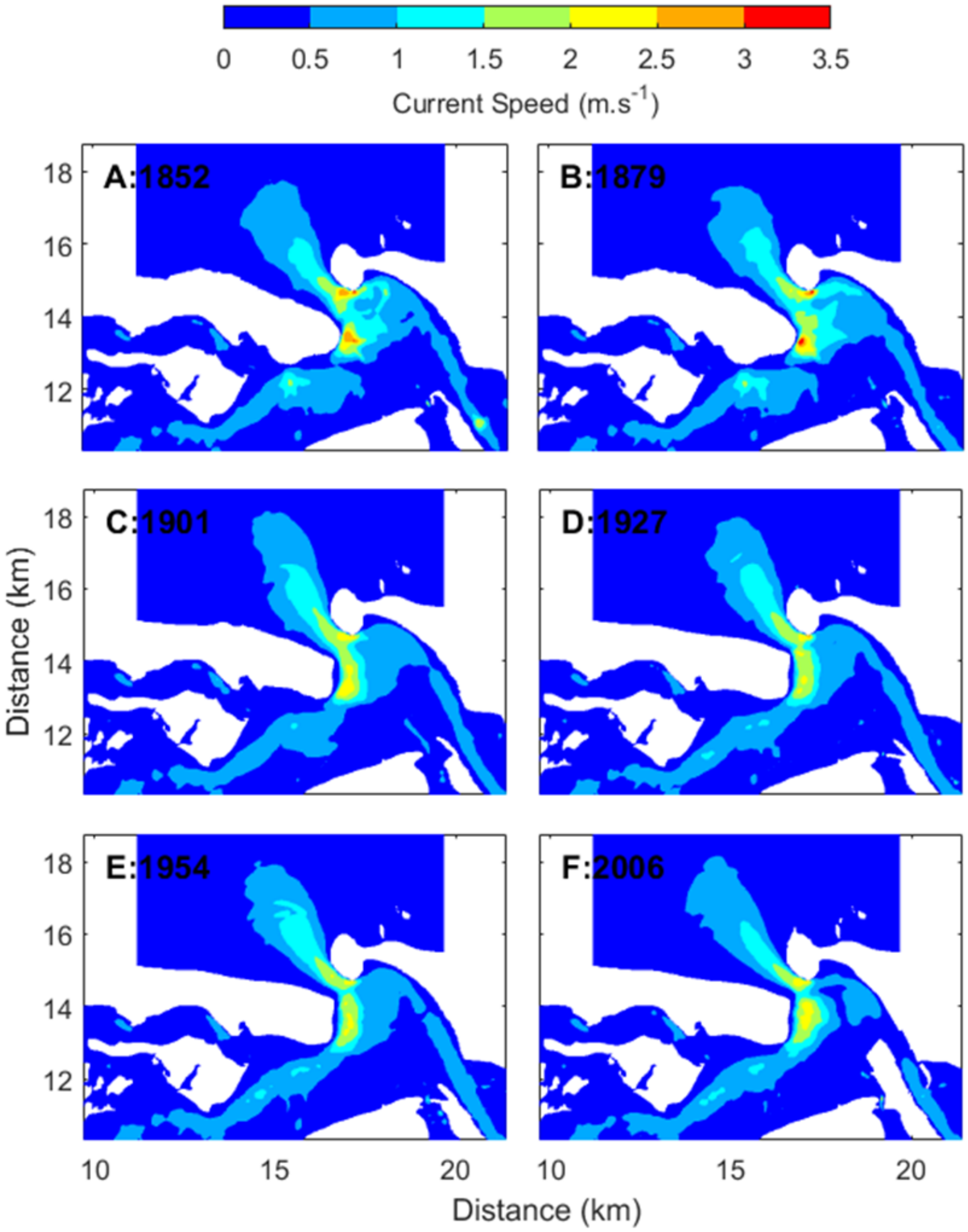

Figure 4.5 Maximum current speed for the entrance adjusted bathymetry model runs A) 1852, B) 1879, C) 1901, D) 1927, E) 1954 and F) 2006. Results are from a spring and neap tidal cycle (14 days).

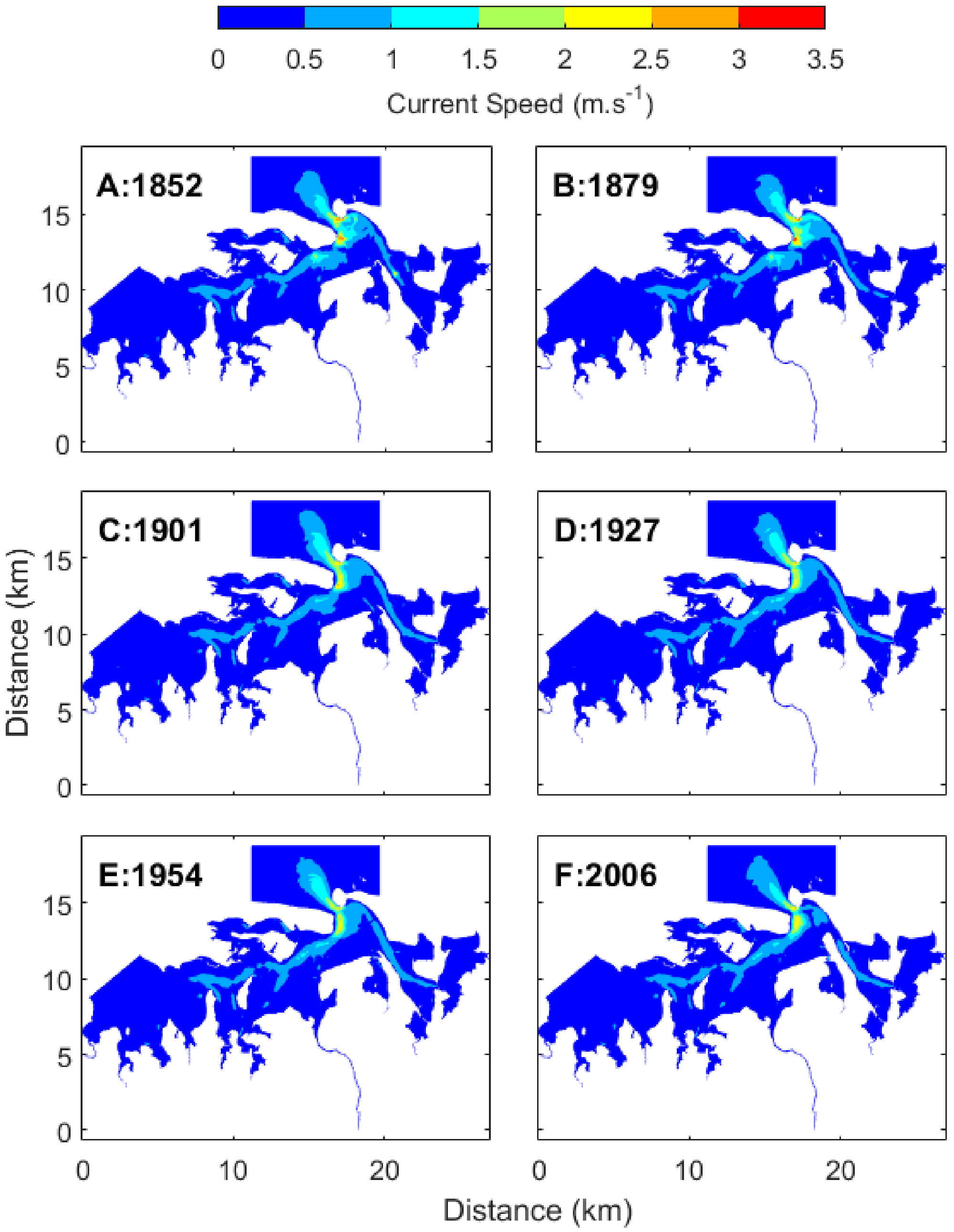

Figure 4.6 Maximum current speed for the intertidal adjusted bathymetry model runs A) 1852, B) 1879, C) 1901, D) 1927, E) 1954 and F) 2006. Results are from a spring and neap tidal cycle (14 days).

4.3.3 Water level range

The distribution of water level range for all of the entrance and intertidal bathymetries in Figures 4.7 and 4.8 follow the same general patterns of distribution. The water level range is calculated by subtracting the minimum water level from the maximum water level. The water level range decreases moving into the upper reaches of the harbour. The greatest water level range occurs outside of the harbour entrance.

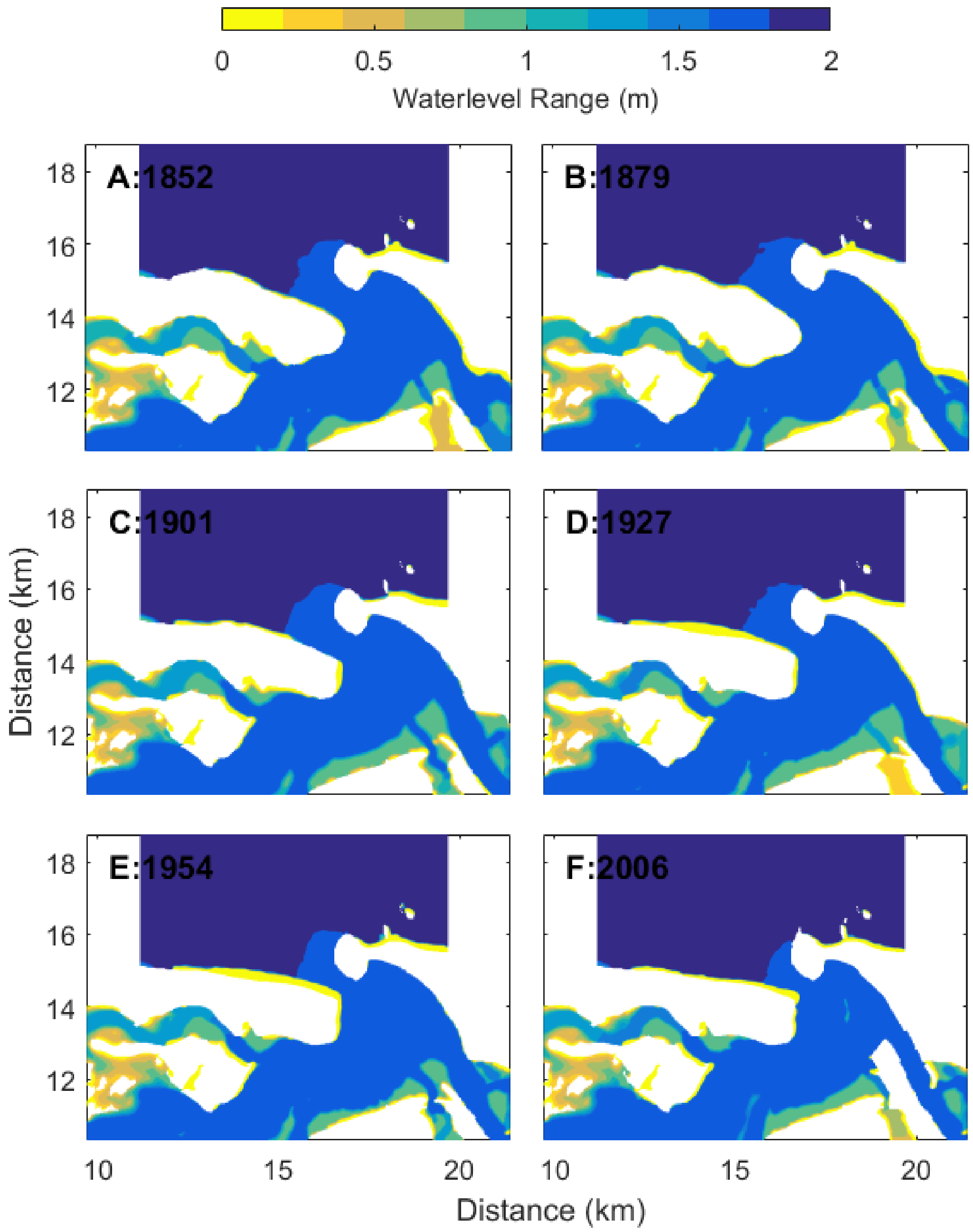

Figure 4.7 Water level range (maximum-minimum water level) for the entrance adjusted bathymetry model runs A) 1852, B) 1879, C) 1901, D) 1927, E) 1954 and F) 2006. Results are from over a spring and neap tidal cycle (14 days).

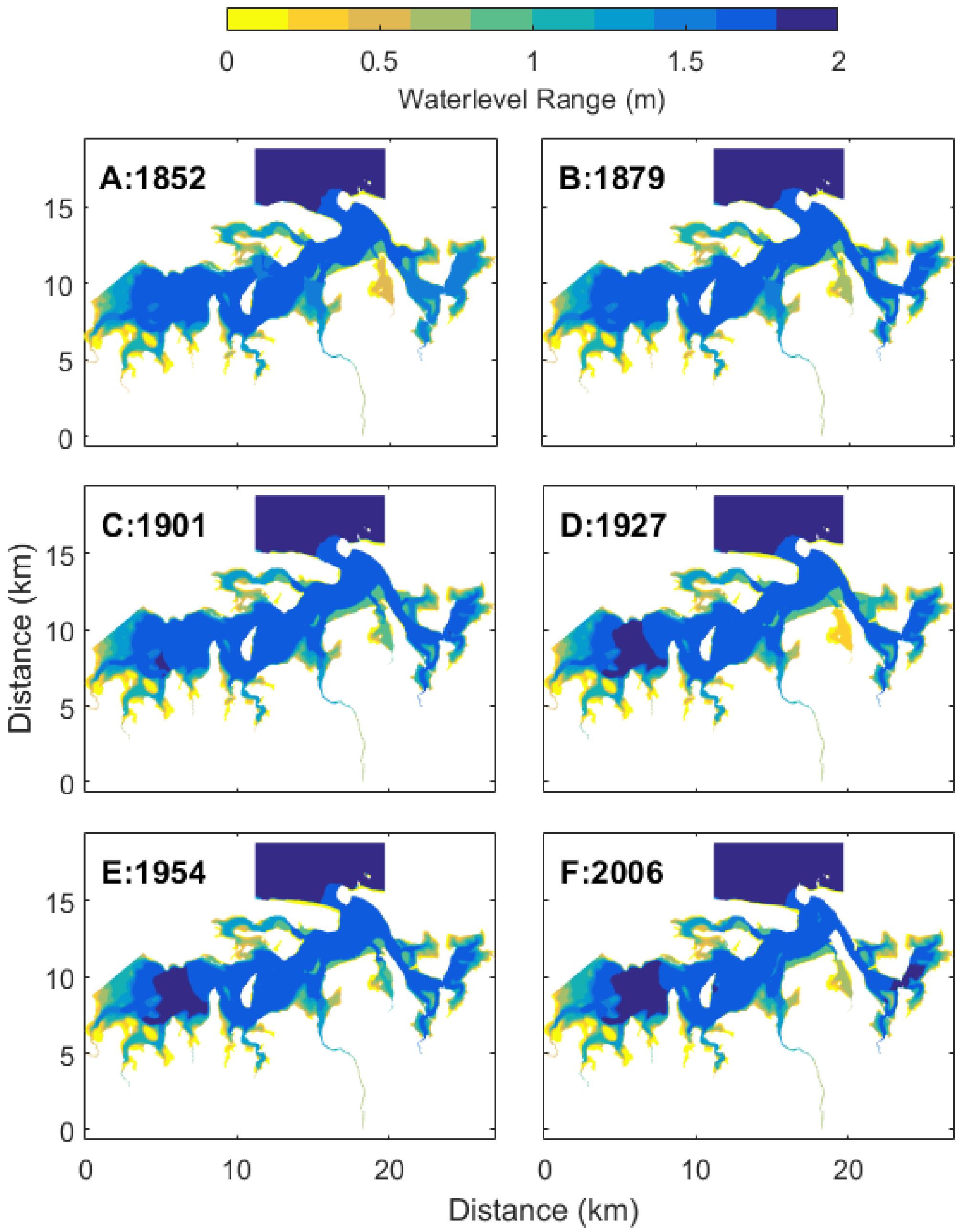

Figure 4.8 Water level range (maximum-minimum water level) for the entrance adjusted bathymetry model runs A) 1852, B) 1879, C) 1901, D) 1927, E) 1954 and F) 2006. Results are from over a spring and neap tidal cycle (14 days).

4.3.4 Tracer decay

The decay of the tracer was calculated for the five regions in Figure 4.9 by averaging the concentration of the tracer over the region for the entire simulation period (excluding the two day spin-up). The average concentrations for each region were plotted against time. A K value indicating the decay of tracer was found by fitting an exponential line to the averaged concentrations for each region. Examples for the 2006 bathymetry results of the plotted concentrations for each region and the fitted lines can be seen in Figures 4.10 and 4.11.

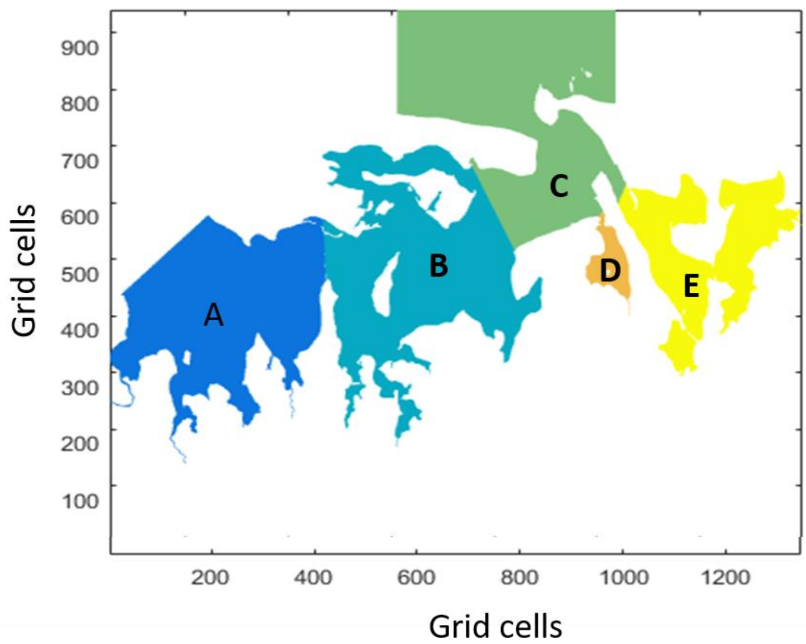

Figure 4.9 Distribution of the five regions Within the Tauranga Harbour used in the calculation for the decay of tracer.

The resulting K values for each region from both entrance and intertidal bathymetries of all years are displayed in a bar graph (Figure 4.12). The K values indicate that for all of the bathymetries, the rate of decay between regions follows similar patterns. Region C has the lowest K values and therefore fastest rate of decay. Region A has the highest K values and therefore the slowest rate of decay. Region D has the greatest variation in decay between the years.

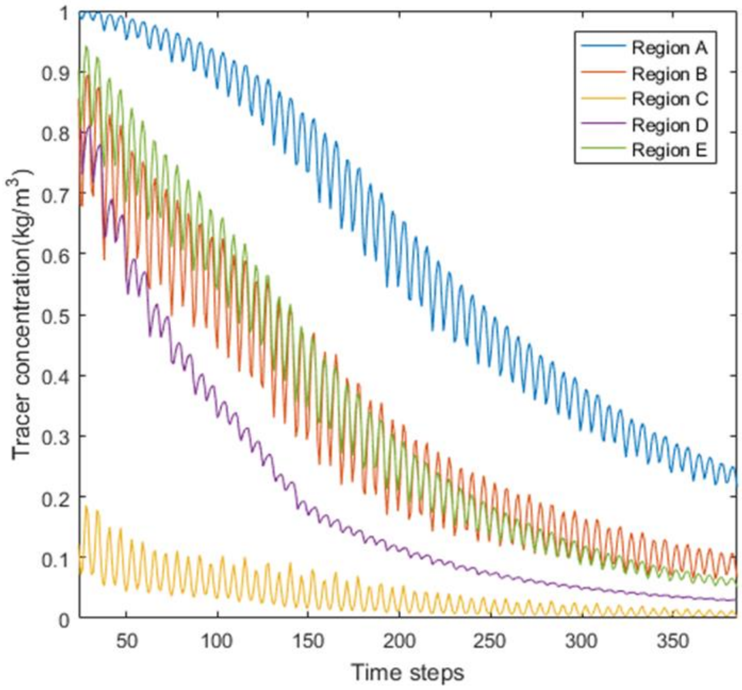

Figure 4.10 The 2006 entrance bathymetry average concentration of the tracer in kg/m^3 through time for each of the regions (as shown in the key). Each time step is two hours.

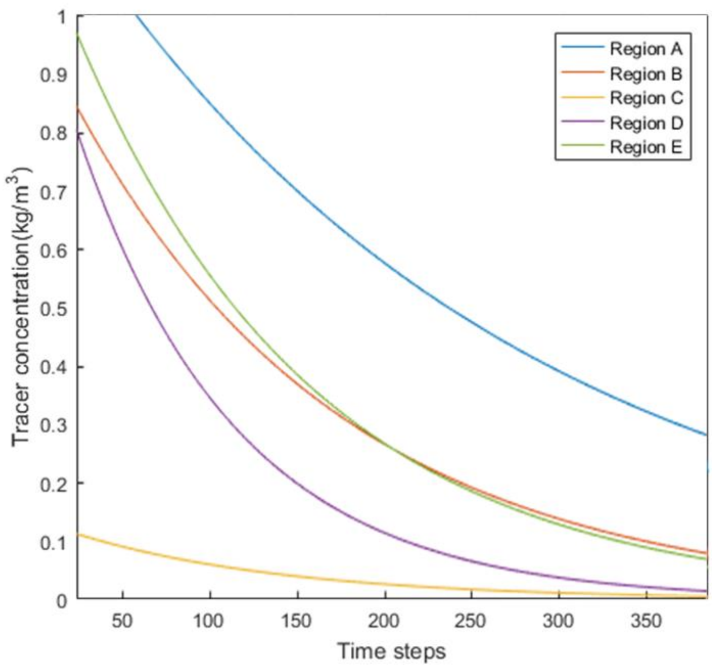

Figure 4.11 The 2006 entrance bathymetry fitted concentration of the tracer in kg/m^3 through time for each of the regions (as shown in the key). Each time step is two hours.

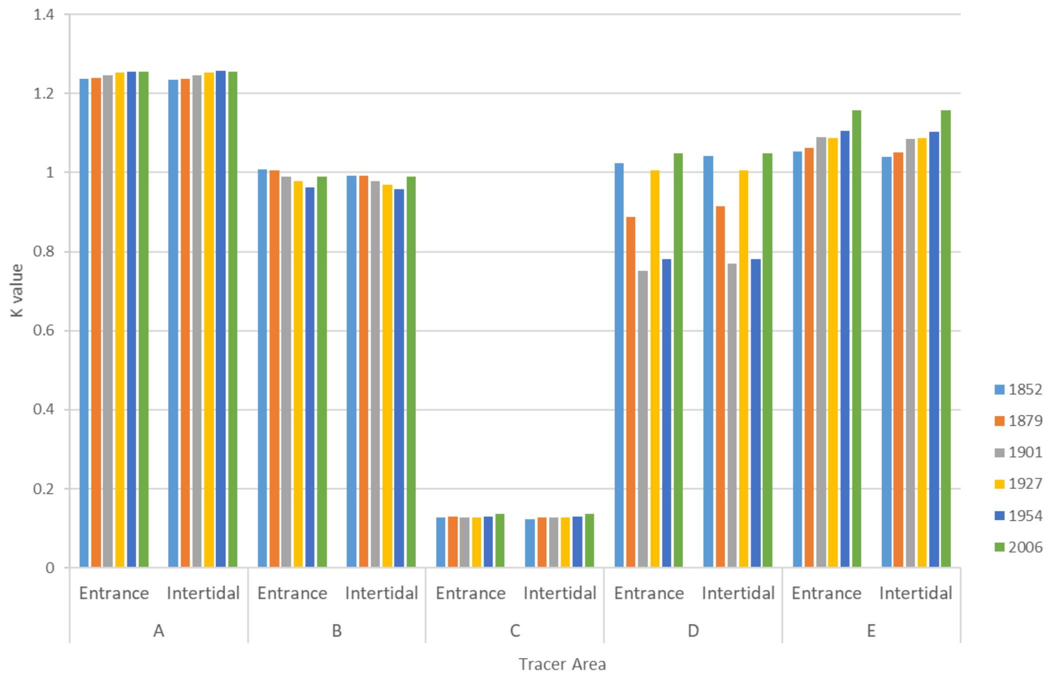

Figure 4.12 Bar graph of K values for all 11 bathymetries plotted by region. Colours represent each year as presented in the key.

4.4 Changes in hydrodynamics as a result of simulated infilling

The previous chapter illustrated that simulating the removal of sediment from the intertidal areas of the historic bathymetries had small influence on the distribution of depth. In order to investigate the influence of infilling on hydrodynamics, the modelled results for the intertidal bathymetries were subtracted from the modelled results for the entrance bathymetries. This demonstrates the changes caused solely by infilling as the entrance and intertidal bathymetries from each year have the same entrance bathymetries but different depths of the intertidal areas.

The distribution of changes in mean current speed, maximum current speed, water level and tracer decay are presented in Figures 4.13 to 4.16. Positive values indicate an increase in the magnitude of the element as a result of the simulated infilling.

The 2006 bathymetry results are shown as a baseline. No changes are observed as the 2006 entrance bathymetry is also used as the 2006 intertidal bathymetry.

4.4.1 Mean current speed

Figure 4.13 demonstrates the difference between the mean current speed of the entrance and intertidal bathymetries of each year. Removing the sediment to simulate infilling resulted in an increase in mean current speeds. All of the year's show the same general pattern of change but have different magnitudes. Changes above 0.01 $m.s^{-1}$ were limited to more channelized areas. The greatest change of 0.05 $m.s^{-1}$ in mean current speed occurred in the Western channel for all years. The 1852 bathymetry has the greatest distribution of changes and the 1954 bathymetry had the smallest distribution of changes.

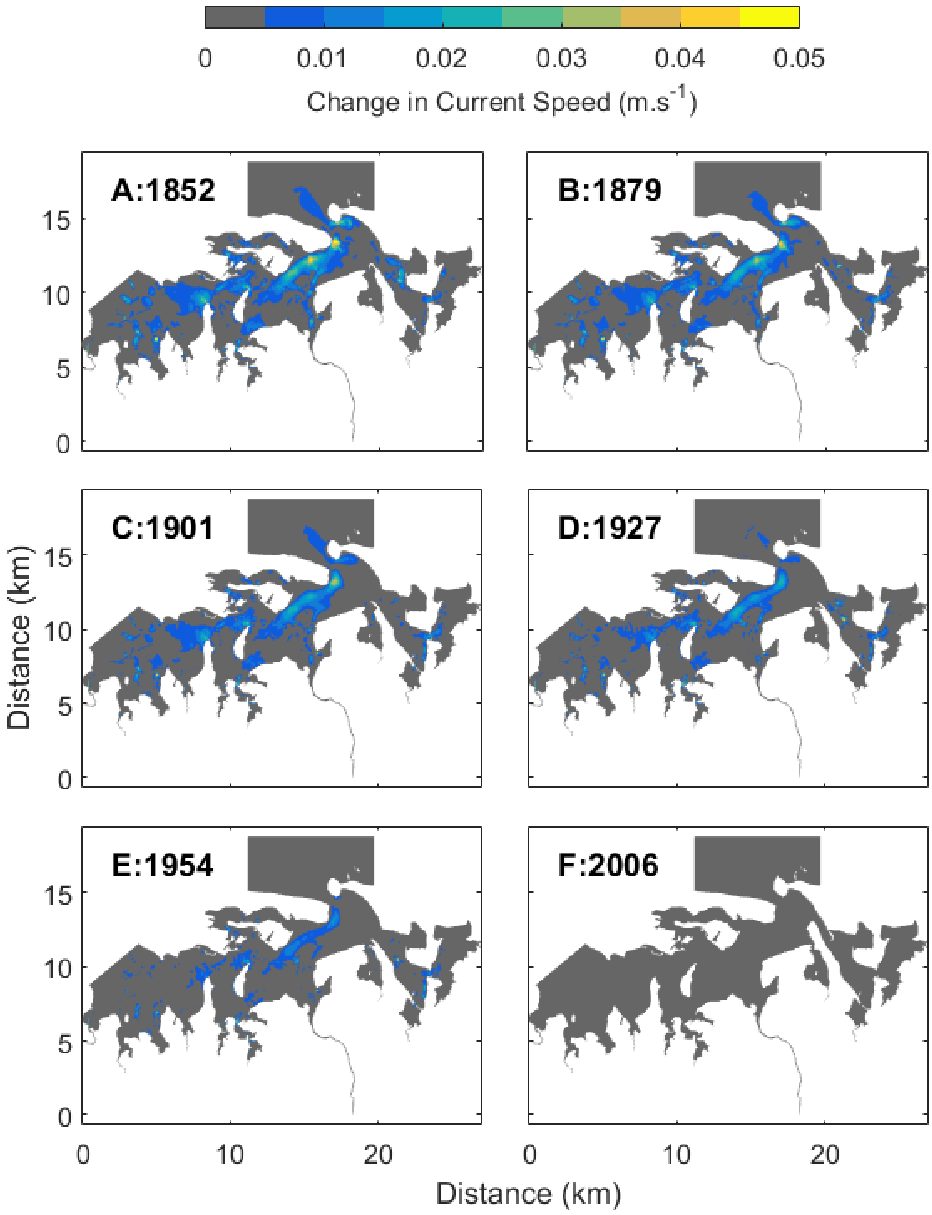

Figure 4.13 Change in mean current speed between the intertidal and entrance bathymetries for each year A) 1852, B) 1879, C) 1901, D) 1927, E) 1954 and F) 2006.

4.4.2 Maximum current speed

Figure 4.14 demonstrates the difference between the maximum current speed of the entrance and intertidal bathymetries of each year. Removing the sediment to simulate infilling resulted in an increase in maximum current speeds. All of the year's show the same general pattern of change but have different magnitudes. Changes above 0.025 $m.s^{-1}$ were limited to more channelized areas. The greatest change of 0.2 $m.s^{-1}$ in maximum current speed occurred in the Western channel. The 1852 bathymetry has the greatest distribution of changes and the 1954 bathymetry had the smallest distribution of changes.

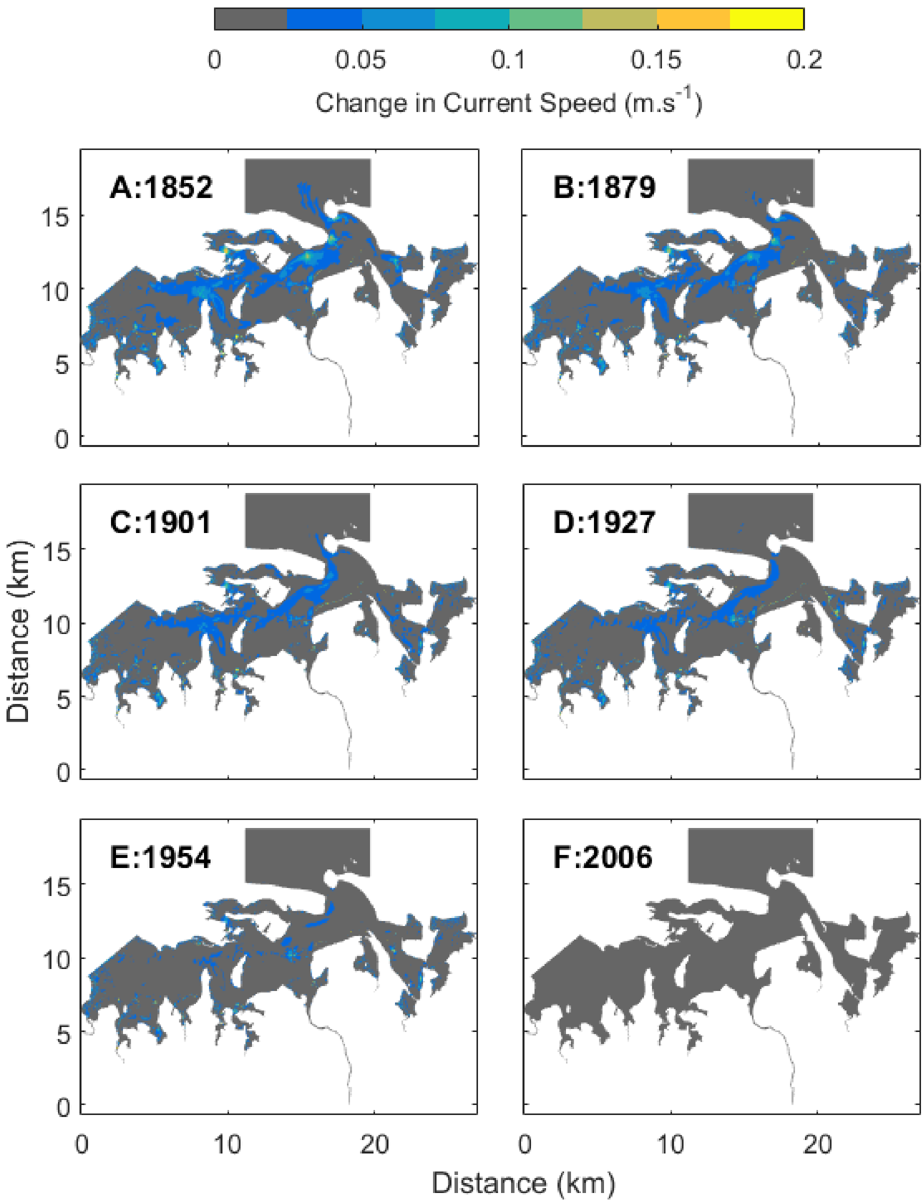

Figure 4.14 Change in maximum current speed between the intertidal and entrance bathymetries for each year A) 1852, B) 1879, C) 1901, D) 1927, E) 1954 and F) 2006.

4.4.3 Water level range

Figure 4.15 demonstrates the difference between the water level range of the entrance and intertidal bathymetries of each year. Removing the sediment to simulate infilling resulted in an increase in water level range. All of the year's show the same general pattern of change but have different magnitudes. Changes above 0.08 m were limited to the shallow intertidal areas. Changes below 0.04 m occurred in deeper areas and closer to the entrance. The 1852 bathymetry has the greatest distribution of changes and the 1954 bathymetry had the smallest distribution of changes.

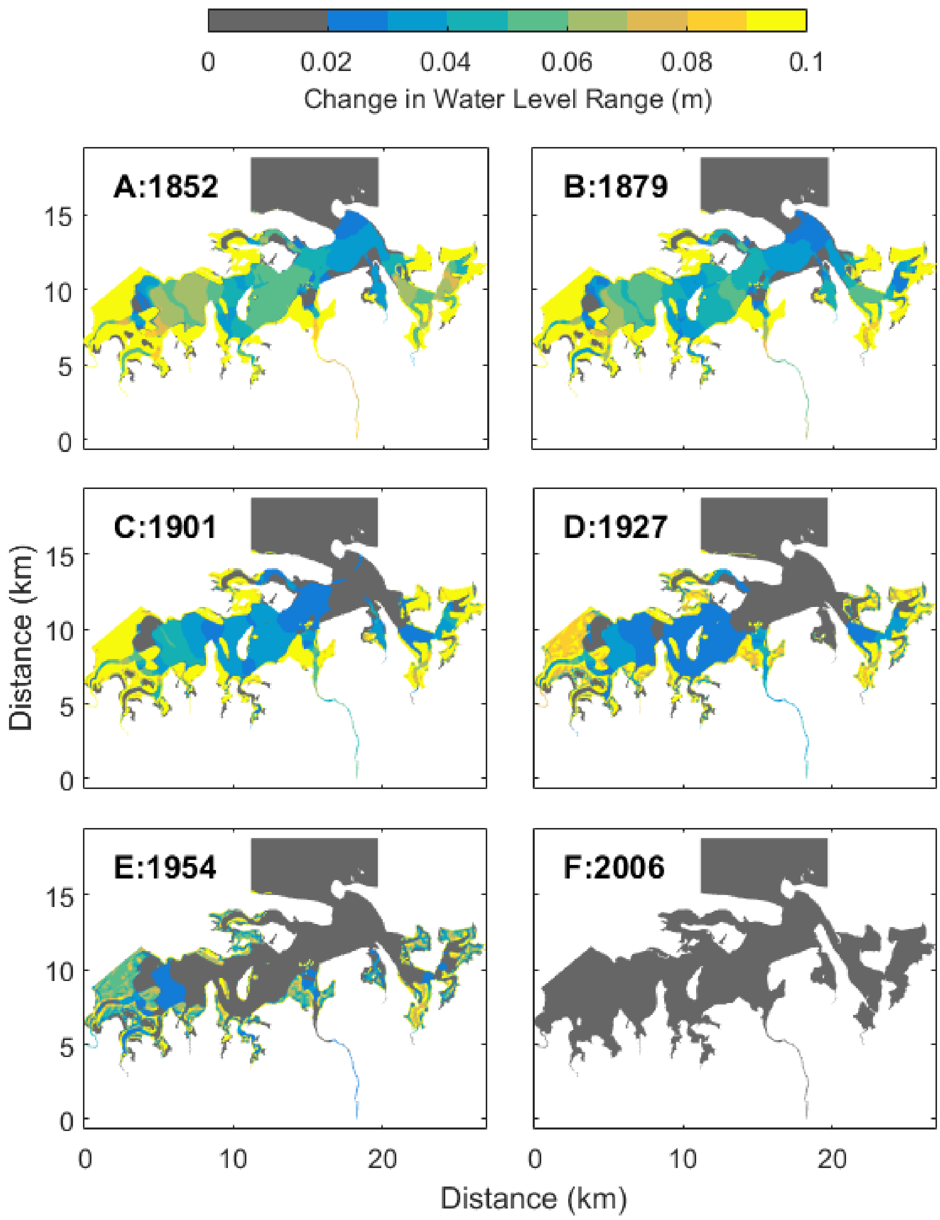

Figure 4.15 Change in water level range between the intertidal and entrance bathymetries for each year A) 1852, B) 1879, C) 1901, D) 1927, E) 1954 and F) 2006

4.4.4 Tracer decay

Negative values indicate that the infilling caused a decrease in the K value and therefore an increase in the rate of decay of the tracer. Figure 4.16 demonstrates that regions A, B, C and E mostly had decreasing K values for all years. Region D had the greatest change between entrance and intertidal bathymetries and had more increasing K values. Within each region the 1852 bathymetries showed the largest change in K and the 1954 year showed the least change.

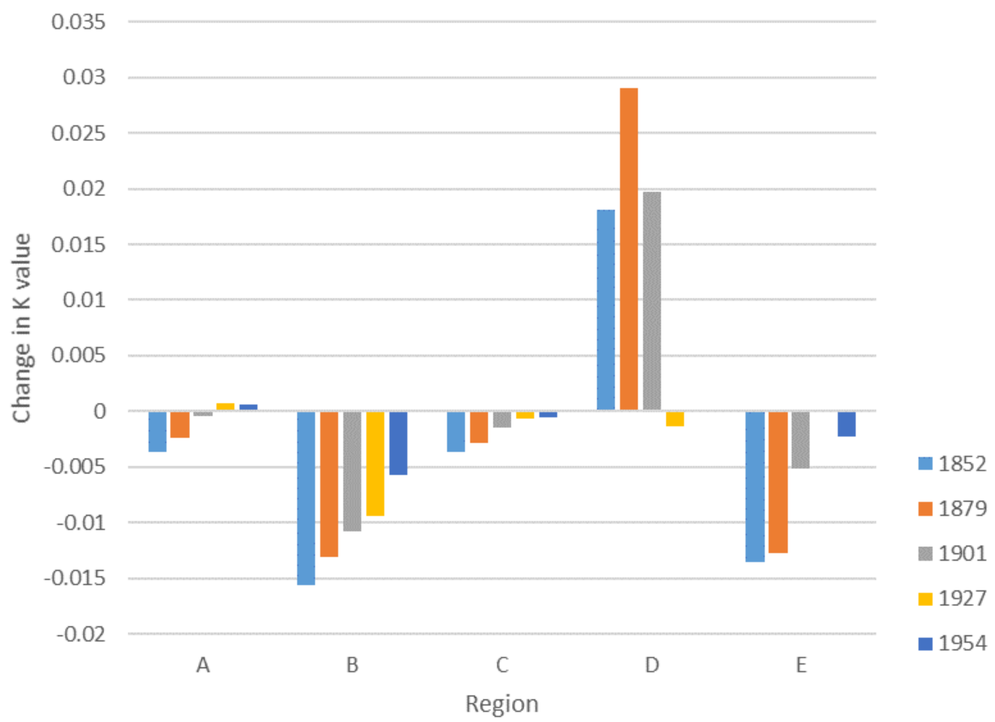

Figure 4.16 Bar graph of difference in K values (entrance-intertidal) for all years plotted by region. Colours represent each year as presented in the key.

4.5 Discussion

4.5.1 Hydrodynamic model results

The results from the hydrodynamic numerical modelling in this study agree with findings in previous studies of the Tauranga Harbour southern basin. The observed patterns are what is expected in the environment.

The strongest currents observed through the entrance channel and lower western channel were also found in the Tauranga Harbour Study (Barnett, 1985) and by

Watson (2016). Currents were also observed to be weaker over the shallower intertidal areas (Barnett, 1985).

The distribution of water level range generally fits what is expected to be observed in the environment. The largest range within the estuary is between 1.6 and 1.8 meters which corresponds to the spring tidal range of 1.75 meters as stated by Land Information New Zealand (2020) for the Port of Tauranga standard tidal levels. Water level range decreases in the intertidal areas as the minimum water level occurs when the tide goes out and the bed is exposed.

The study of the Southern Basin hydrodynamics by Tay et al. (2013) demonstrated that residence times vary spatially across the harbour and are controlled greatly by the geomorphology of the Harbour and sub estuaries. This study reflected the same patterns in distribution with quicker decay closer to the entrance and slower decay further from the entrance and in sub-estuaries with constricted entrances. The K values for regions A, B and C demonstrate that tracer decay rates increase moving away from the entrance which is exposed and has a high exchange of water. The regions D and E have higher K values and show variability as these regions have restricted entrances and varying levels of exposure to the entrance through time with the development of Sulphur point.

4.5.2 Influence of infilling on hydrodynamics

Infilling resulted in the increase of current speeds and water level range. It also resulted in the increase in the rate of decay. The increase in water level in the intertidal areas can be attributed to the deepening caused by the simulated infilling. The minimum water level (dry bed level) for the intertidal adjusted bathymetries deepened resulting in an increase in the overall water level range. The channels decreased in depth relative to intertidal areas resulting in increased magnitude of current speeds. This is due to the increased volume of flow forced through a smaller channel area. The K values generally decrease with the removal of sediment in the intertidal adjusted bathymetries, indicating the tracer concentration is decreasing more quickly through time. This is due to the increased water level range and current speeds transporting increased amounts of tracer out of each region with the ebb and flow of the tide.

The 1852 year had the greatest distribution of changes between the entrance and intertidal bathymetries and the 1952 bathymetry had the smallest distribution in changes between the entrance and intertidal bathymetries. This is because the 1852 bathymetry had the greatest amount of depth increase in intertidal areas as it needed the greatest amount of sediment removed to simulate infilling. The changes in hydrodynamics due to the influence of the simulated infilling increase in magnitude back through time.

4.6 Summary

Delft3D FLOW was used to create a numerical model in order to predict the historic hydrodynamics of the 11 entrance and intertidal bathymetries compiled in in the previous chapter. The hydrodynamic numerical modelling produced expected patterns in the current speed, water level and tracer decay results. The results also represented observations in previous studies of the hydrodynamics of Tauranga Harbour.

The analysis compared the entrance and intertidal bathymetries for each year in order to investigate the influence of infilling on hydrodynamics. The changes in the intertidal area depth due to the simulated infilling were shown to increase the magnitude of current speed, water level range and rate of tracer decay.

The adjusted geomorphology of the intertidal bathymetries had an influence on the hydrodynamics of the Tauranga Harbour southern basin. Therefore, the intertidal adjusted bathymetries and hydrodynamic results are used in the following chapter to investigate ecological implications of changes in environmental conditions.

CHAPTER FIVE
Ecological implications of Changes in Environmental Conditions

5.1 Introduction

This chapter aims to use the modelled hydrodynamic conditions from the intertidal adjusted bathymetries to investigate changes in environmental conditions that may have influenced historic ecological health and distribution of species. The results presented analyse changes by comparing the hydrodynamics of historic bathymetries with the most recent bathymetry (2006). It also compares pre-dredging changes with post dredging changes to analyse the influence of the anthropogenic alterations to the bathymetry. The chapter concludes with a discussion on the ecological significance of the changes in hydrodynamics and environmental conditions.

5.2 Changes in environmental conditions

For the environmental conditions of depth, water level range, mean current speed, maximum current speed and tracer decay two figures are presented. The first is the results for each of the 1852, 1879, 1901, 1927 and 1954 bathymetries subtracted from the 2006 bathymetry results. The second shows the changes between 1852 and 1954 bathymetries (pre dredging) and the changes between 1954 and 2006 bathymetries (post dredging).

For all figures, positive values indicate an increase between the earlier bathymetry and 2006, negative values indicate a decrease between the earlier bathymetry and 2006. Greyscale is used to represent areas that have had no change or very low change in order to highlight the distribution of area with more significant changes. The white areas in the plots are the inactive grid cells which represent land and the area outside the model boundaries. Changes in the area of land reclamation at Sulphur Point aren’t shown as this area is classified as land and is outside of the grid boundary for the later bathymetries.

5.2.1 Difference in Depth

<u>1852-2006</u>

The most significant differences in depth between the 1852 and 2006 bathymetries seen in Figure 5.1 (A) include increases in depth of up to 10 metres occur in Stella passage, Cutter Channel, Entrance Channel, and Upper Western Channel. There is also accretion of 10m or more at Panepane Point. Centre Bank has accretion of between 2-6 metres and the intertidal areas are shallower by up to 0.2 metres. Upper harbour channels have minimal difference in depth.

<u>1879-2006</u>

The most significant differences in depth between the 1879 and 2006 bathymetries seen in Figure 5.1 (B) include increases in depth of up to 10 metres occur in Stella passage, Cutter Channel, Entrance Channel, and Upper Western Channel. Accretion of 10m or more occurs at Panepane Point narrowing the inlet. Centre Bank has accretion of between 2-6 metres and intertidal areas get shallower by up to 0.2 metres. The upper harbour channels have minimal difference in depth.

<u>1901-2006</u>

The most significant differences in depth between the 1901 and 2006 bathymetries seen in Figure 5.1 (C) include increases in depth of up to 10 metres occur in Stella passage and Cutter Channel. Accretion of 10m or more occurs at Panepane Point narrowing the inlet. Centre Bank has accretion of between 2-4 metres and the intertidal areas get shallower by up to 0.2 metres. The upper harbour channels have minimal difference in depth.

<u>1927-2006</u>

The most significant differences in depth between the 1927 and 2006 bathymetries seen in Figure 5.1 (D) include increases in depth of up to 10 metres occur in Stella passage and Cutter Channel. Accretion of 10m or more occurs at Panepane Point narrowing the inlet. Centre Bank has no significant difference and the intertidal areas get shallower by up to 0.2 metres. Upper harbour channels have minimal difference in depth.

1954-2006

The most significant differences in depth between the 1954 and 2006 bathymetries seen in Figure 5.1 (E) include increases in depth of up to 10 metres occur in Stella passage and Cutter Channel. No significant difference at Panepane point and Centre Bank. Intertidal areas get shallower by up to 0.2 metres. Upper harbour channels also have minimal difference in depth.

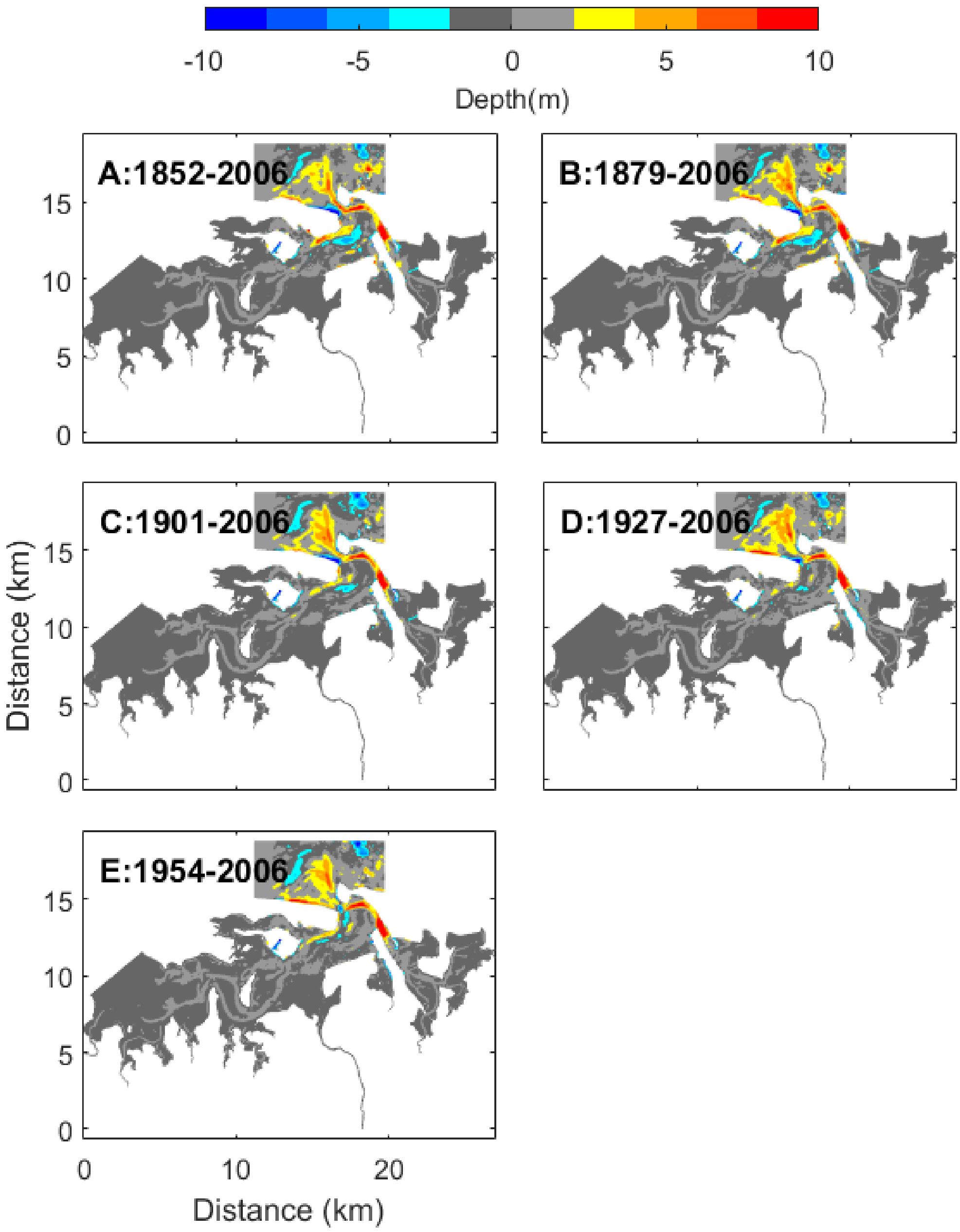

Figure 5.1 Difference in depth for A) 1852-2006, B) 1879-2006, C) 1901-2006, D) 1927-2006 and E) 1954-2006.

5.2.1.1 Pre and post dredging changes

The most significant differences in depth between the 1852 and 1954 bathymetries (prior to dredging) seen in Figure 5.2 (A) include an increase in depth of up to 10 metres through the entrance channel and accretion of 10 metres or more at Panepane point. The western channel increases in depth by 4-8 metres and Centre bank gets shallower by 2-4 metres. Differences in depth between the 1954 and 2006 bathymetries seen in Figure 5.2 (B) (post dredging) include an increase in depth of up to 10 metres in Stella passage and Cutter Channel. No significant differences appear at Panepane point and Centre Bank. Sulphur Point and the Harbour Bridge are constructed creating land. There is a greater distribution of accretion in the intertidal areas prior to dredging compared to post dredging.

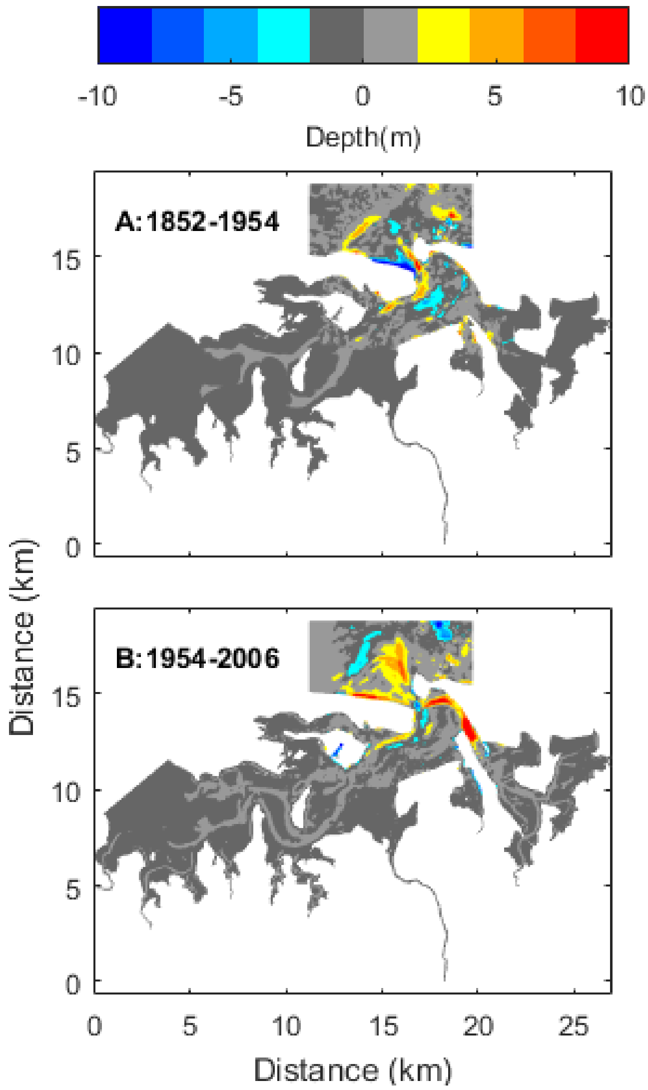

Figure 5.2 Difference in depth for A) 1852-1954 (pre dredging) and B) 18954-2006 (post dredging).

5.2.2 Difference in water level range

1852-2006

The most significant differences in water level range between the 1852 and 2006 bathymetries seen in Figure 5.3 (A) include an increase in range of 0.1-0.2 metres from the entrance towards the upper harbour and a decrease of 0.1-0.2 metres in the intertidal areas. The estuary above Stella Passage had an increase of 0.3-0.4 metres.

1879-2006

The most significant differences in water level range between the 1879 and 2006 bathymetries seen in Figure 5.3 (B) include an increase in range of 0.1-0.2 metres from Otumoetai towards the upper harbour and a decrease of 0.1-0.2 metres in the intertidal areas. The estuary above Stella Passage had an increase of 0.1-0.2 metres.

1901-2006

The most significant differences in water level range between the 1901 and 2006 bathymetries seen in Figure 5.3 (C) include a decrease of 0.1-0.2 metres in the intertidal areas and 0.2-0.3 metres in Waikareao Estuary.

1927-2006

The most significant differences in water level range between the 1927 and 2006 bathymetries seen in Figure 5.3 (D) include a decrease of 0.1-0.2 metres in the intertidal areas and an increase of 0.3-0.4 metres in Waikareao Estuary. There is also an increase of 0.4-0.5 metres in the area behind the Tauranga Harbour bridge.

1954-2006

The most significant difference in water level range between the 1954 and 2006 bathymetries seen in Figure 5.3 (E) is an increase of 0.3-0.4 metres in Waikareao Estuary.

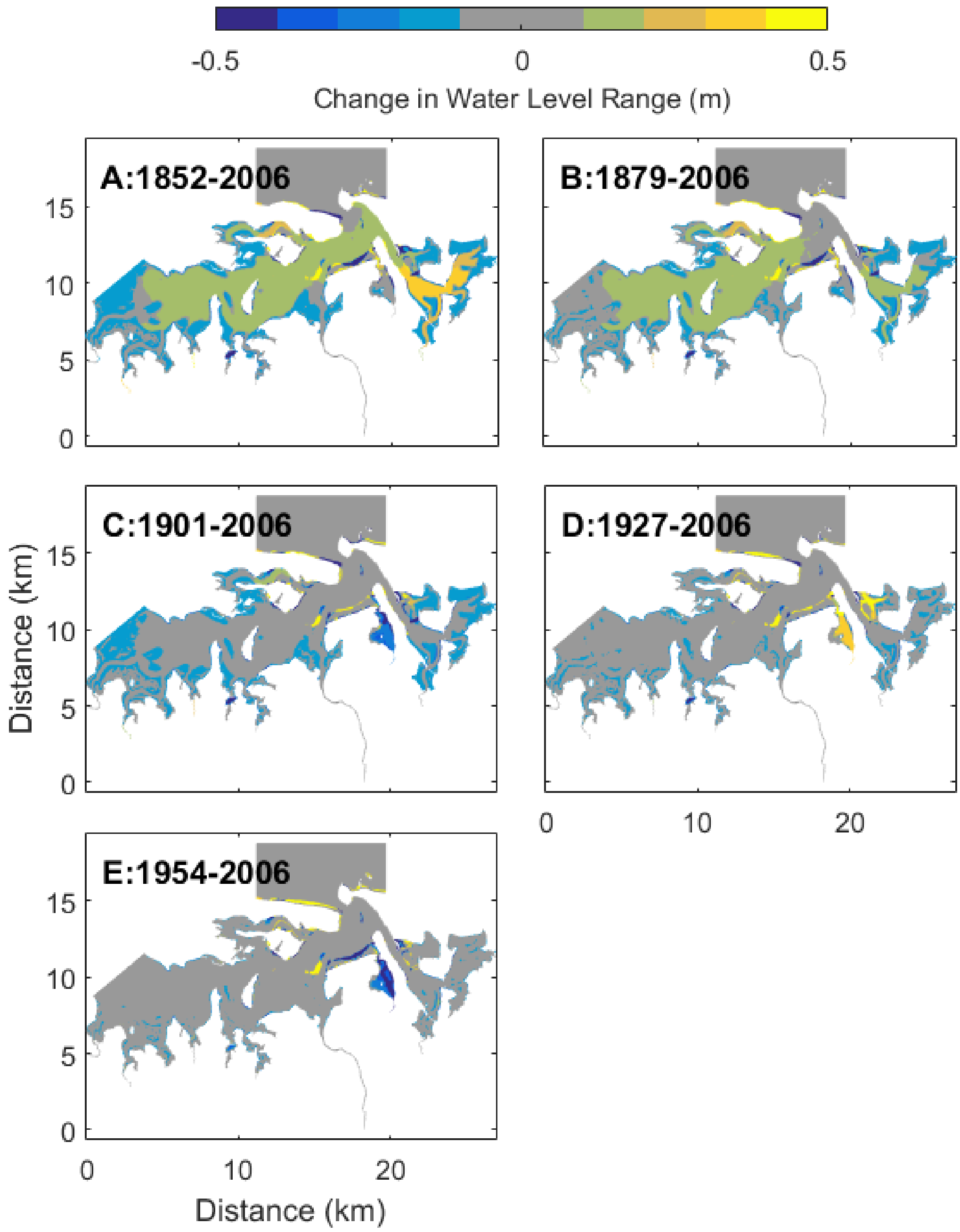

Figure 5.3 Difference in water level range for A) 1852-2006, B) 1879-2006, C) 1901-2006, D) 1927-2006 and E) 1954-2006.

5.2.2.1 *Pre and post dredging changes*

The most significant differences in water level range between the 1852 and 1954 bathymetries (prior to dredging) seen in Figure 5.4 (A) include an increase in range of 0.1-0.2 metres from Otumoetai towards the upper harbour, an increase of 0.4-0.5 metres in Waikareao Estuary and 0.2-0.4 metres above Stella Passage. There is also a decrease of up to 0.1 metres in the intertidal areas.

Differences in water level range between the 1954 and 2006 bathymetries seen in Figure 5.4 (B) (post dredging) include an increase in range of 0-0.1 metres from Otumoetai towards the upper harbour and in the estuary above Stella Passage. There is a decrease of 0.4-0.5 metres in Waikareao Estuary and decrease of up to 0.1-0.2 metres in the intertidal areas.

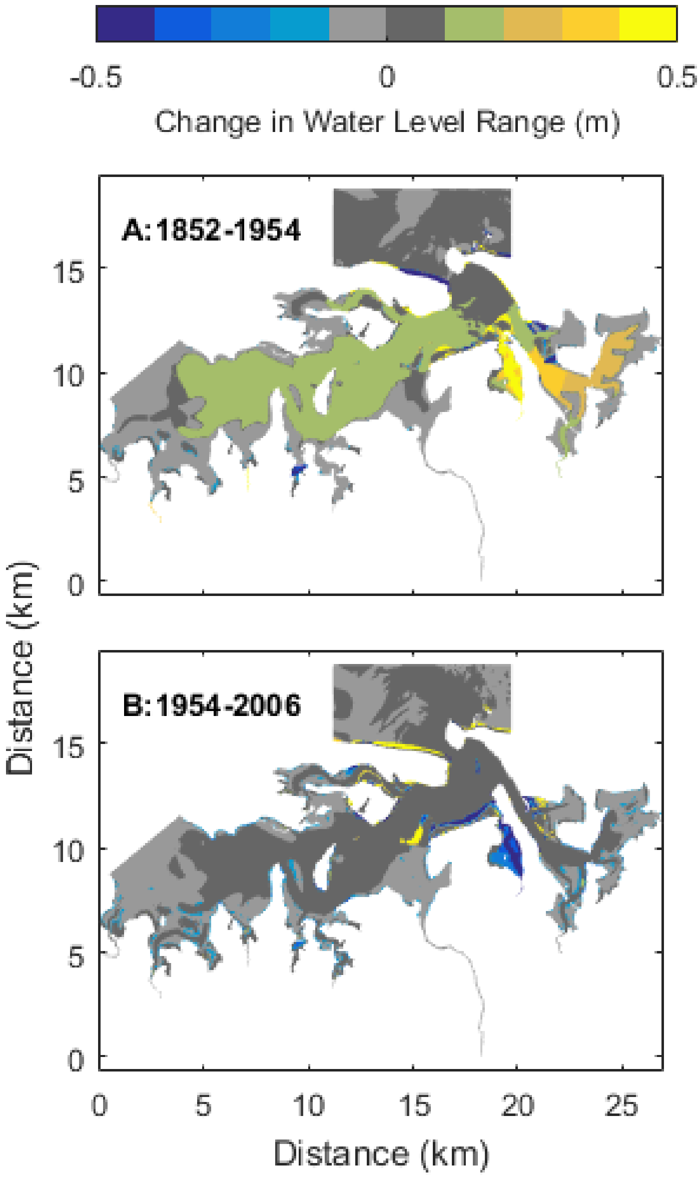

Figure 5.4 Difference in water level range for A) 1852-1954 (pre dredging) and B) 18954-2006 (post dredging).

5.2.3 Difference in mean current speed

1852-2006

The most significant differences in mean current speed between the 1852 and 2006 bathymetries seen in Figure 5.5 (A) include decreases in speed in the entrance channel of up to 0.6 $m.s^{-1}$ and in the Upper Western channel of 0.1-0.3 $m.s^{-1}$. The Lower Western channel has areas of speed increase and decrease of up to 0.4 $m.s^{-1}$. There is a slight decrease in speed over Center Bank of 0.1-0.2 $m.s^{-1}$. A small distribution of 0.1-0.2 $m.s^{-1}$ speed increase occurs in proximity of the Harbour Bridge. The majority of the harbour has less than a 0.1 $m.s^{-1}$ difference in speed.

1879-2006

The most significant differences in mean current speed between the 1879 and 2006 bathymetries seen in Figure 5.5 (B) include decreases in speed in the entrance channel of up to 0.6 $m.s^{-1}$, outside the entrance of 0.1-0.3 $m.s^{-1}$ and in the Upper Western channel of 0.1-0.3 $m.s^{-1}$. The Lower Western channel has areas of speed increase and decrease of up to 0.4 $m.s^{-1}$ and there is a slight decrease in speed over Center Bank of 0.1-0.2 $m.s^{-1}$. A small distribution of 0.1-0.2 $m.s^{-1}$ speed increase occurs in proximity of the Harbour Bridge. The majority of the harbour has less than a 0.1 $m.s^{-1}$ difference in speed.

1901-2006

The most significant differences in mean current speed between the 1901 and 2006 bathymetries seen in Figure 5.5 (C) include decreases in speed through and outside the entrance channel of up to 0.4 $m.s^{-1}$. The Lower Western channel has areas of speed increase and decrease of up to 0.3 $m.s^{-1}$. The majority of the harbour has less than a 0.1 $m.s^{-1}$ difference in speed.

1927-2006

The most significant differences in mean current speed between the 1927 and 2006 bathymetries seen in Figure 5.5 (D) include decreases in speed outside the entrance channel of up to 0.2 $m.s^{-1}$ and the Lower Western channel having a small area of speed increase of up to 0.3 m.s^{-1}. The majority of the harbour has less than a 0.1 m.s^{-1} difference in speed.

<u>1954-2006</u>

The most significant difference in mean current speed between the 1954 and 2006 bathymetries seen in Figure 5.5 (E) include decreases in speed outside the entrance channel of up to 0.2 m.s^{-1} and the Lower Western channel having a small area of speed increase of up to 0.3 m.s^{-1}. The majority of the harbour has less than a 0.1 m.s^{-1} difference in speed.

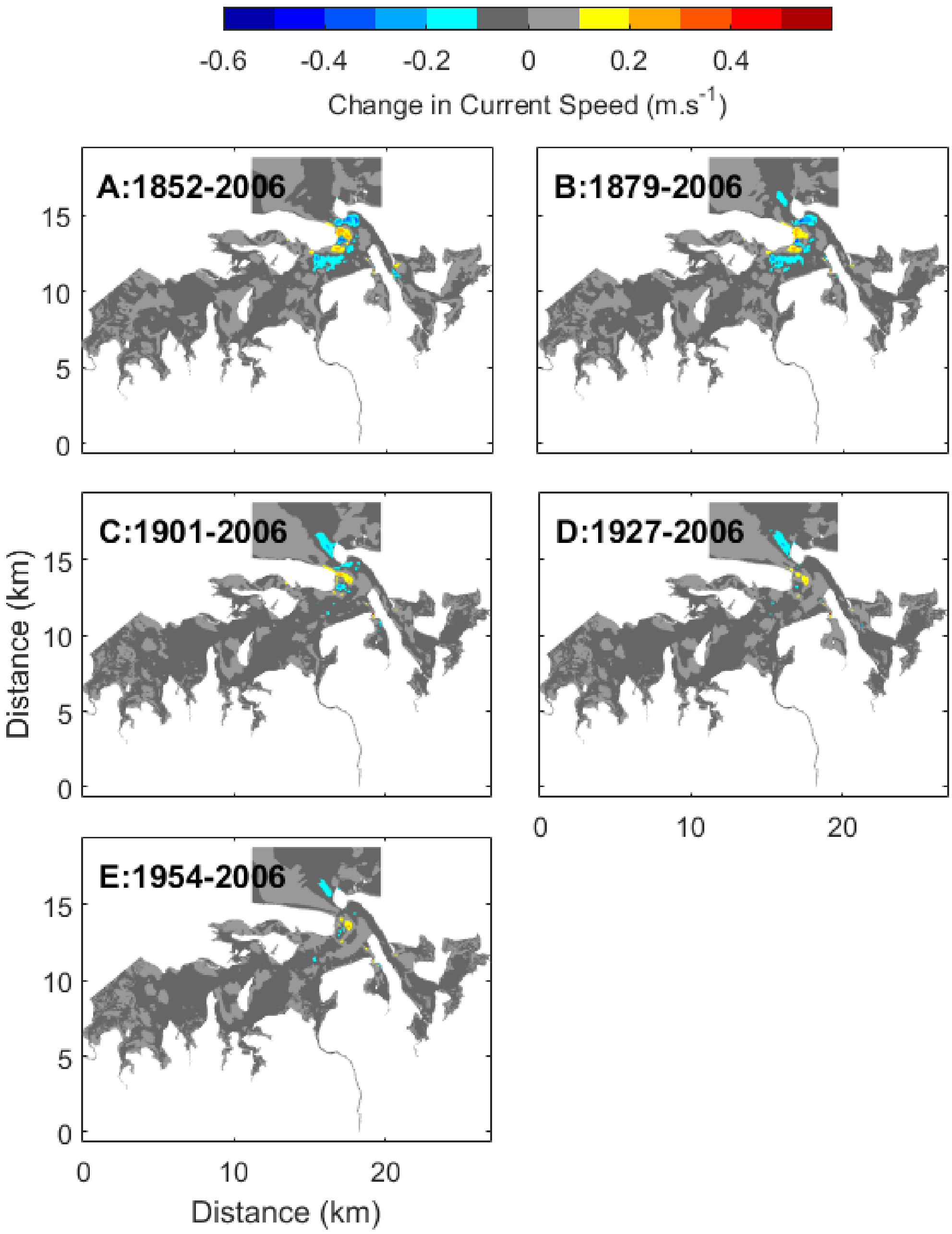

Figure 5.5 Difference in mean current speeds for A) 1852-2006, B) 1879-2006, C) 1901-2006, D) 1927-2006 and E) 1954-2006.

5.2.3.1 *Pre and post dredging changes*

The most significant differences in mean current speed between the 1852 and 1954 bathymetries (prior to dredging) seen in Figure 5.6 (A) include decrease in speed of up to 0.5 $m.s^{-1}$ within the entrance channel and the Upper Western channel. There are areas of increase and decrease within the Lower western channel of 0.1-0.3 $m.s^{-1}$. Differences in mean current speed between the 1954 and 2006 bathymetries seen in Figure 5.6 (B) (post dredging) include small area of increase within the Lower Western channel and a decrease in the outer entrance channel of 0.1-0.2 $m.s^{-1}$. The post dredging plot shows a greater distribution of decrease in speed of up to 0.1 $m.s^{-1}$ in the upper harbour and intertidal areas compared to the pre dredging plot.

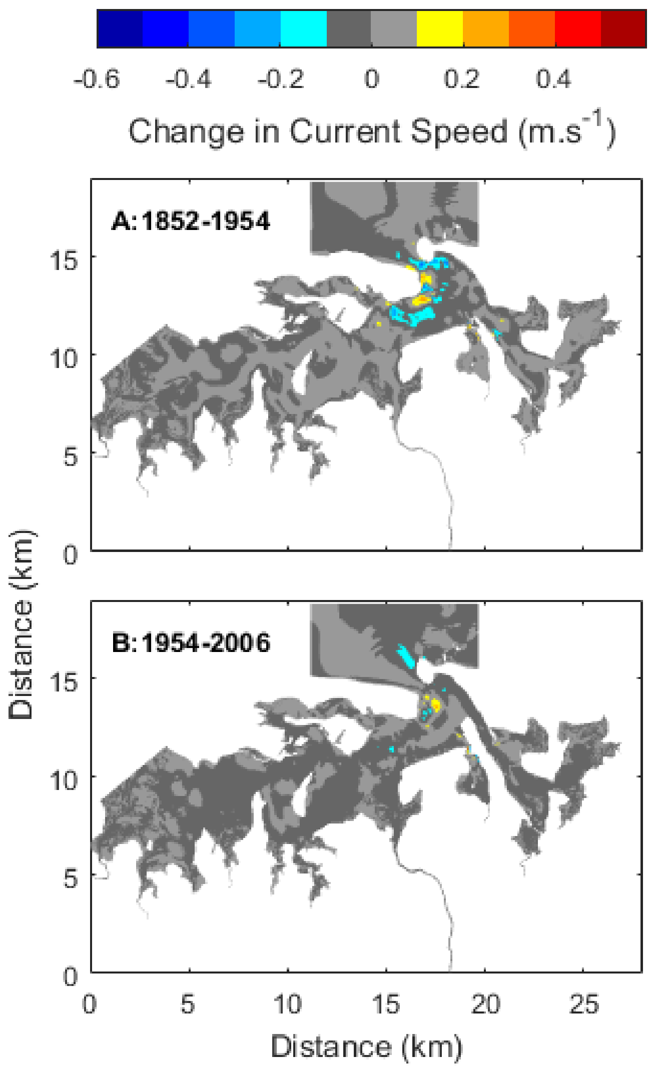

Figure 5.6 Difference in mean current speed for A) 1852-1954 (pre dredging) and B) 18954-2006 (post dredging).

5.2.4 Maximum current speed

1852-2006

The most significant differences in maximum current speed between the 1852 and 2006 bathymetries seen in Figure 5.5 (A) include decreases in speed in the entrance channel of up to 1.4 $m.s^{-1}$ and increase in the Lower Western channel of 0.6-0.8 $m.s^{-1}$. There is a decrease in speed over Center Bank, in the Upper Western channel, Cutter Channel and Stella Passage of up to 0.6 $m.s^{-1}$. Increases and decreases up to 0.4 $m.s^{-1}$ occur in several channels above Stella passage. The majority of the harbour has less than a 0.2 $m.s^{-1}$ difference in speed.

1879-2006

The most significant differences in maximum current speed between the 1879 and 2006 bathymetries seen in Figure 5.5 (B) include decreases in speed in the entrance channel of up to 1.4 $m.s^{-1}$ and increase in the Lower Western channel of 0.6-0.8 $m.s^{-1}$. There is a decrease in speed over Center Bank, in the Upper Western channel, Cutter Channel and Stella Passage of up to 0.6 $m.s^{-1}$. The majority of the harbour has less than a 0.2 $m.s^{-1}$ difference in speed.

1901-2006

The most significant differences in maximum current speed between the 1901 and 2006 bathymetries seen in Figure 5.5 (C) include decreases in speed in the entrance channel of up to 0.8 $m.s^{-1}$ and increase in the Lower Western channel of 0.4-0.6 $m.s^{-1}$. There is a decrease in speed over Center Bank, Cutter channel and Stella Passage of up to 0.6 $m.s^{-1}$. The majority of the harbour has less than a 0.2 $m.s^{-1}$ difference in speed.

1927-2006

The most significant differences in maximum current speed between the 1927 and 2006 bathymetries seen in Figure 5.5 (D) include decreases in speed in the entrance channel of up to 0.8 $m.s^{-1}$ and increase in the Lower Western channel of 0.4-0.6 $m.s^{-1}$. There are decreases in speed within Cutter channel and Stella Passage of up to 0.6 $m.s^{-1}$.

1954-2006

The most significant difference in maximum current speed between the 1954 and 2006 bathymetries seen in Figure 5.5 (E) include decreases in speed in the entrance channel of up to 0.8 $m.s^{-1}$ and increase in the Lower Western channel of 0.4-0.6 $m.s^{-1}$. There are decreases in speed within Cutter channel and Stella Passage of up to 0.6 $m.s^{-1}$.

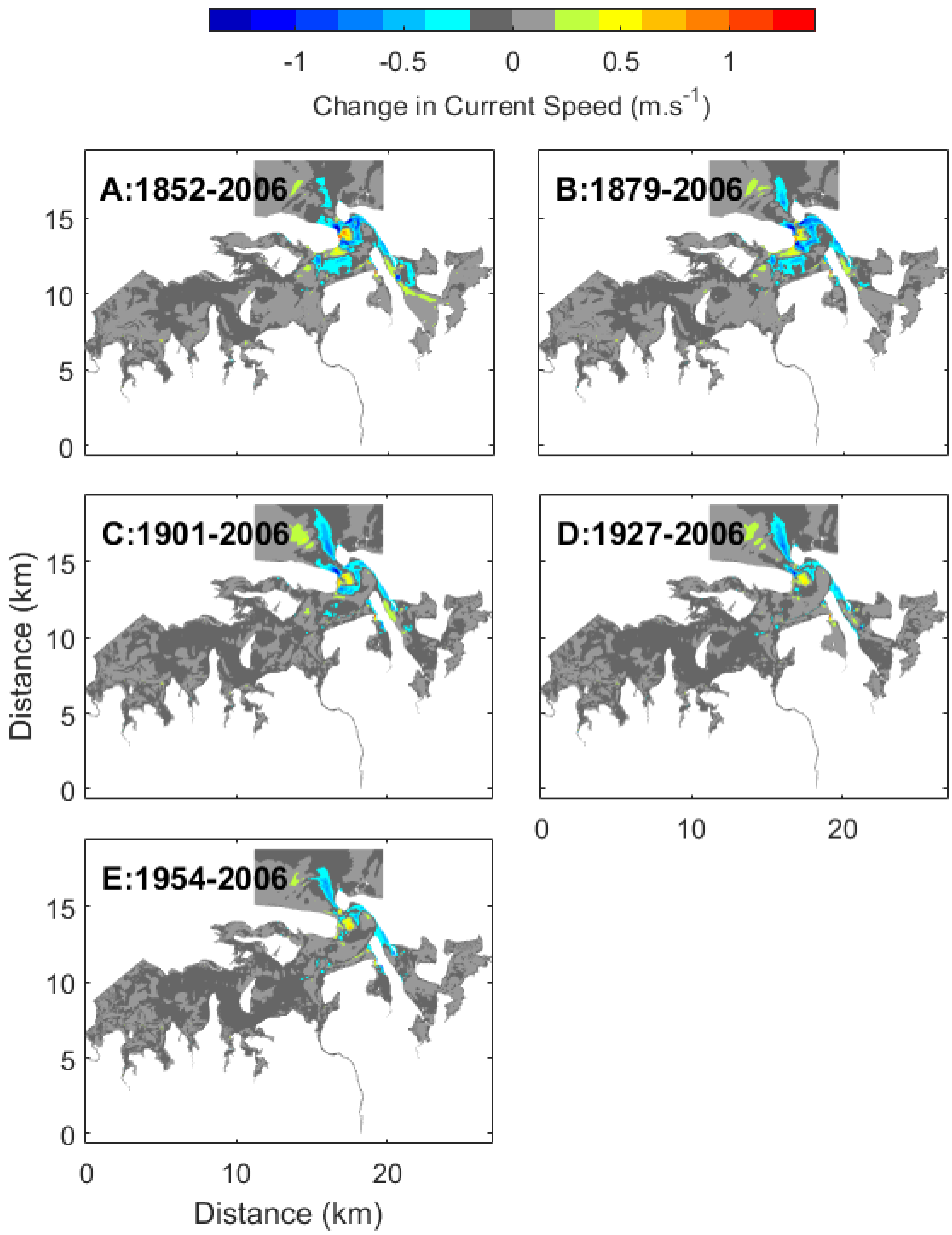

Figure 5.7 Difference in maximum current speeds between A) 1852-2006, B) 1879-2006, C) 1901-2006, D) 1927-2006 and E) 1954-2006.

5.2.4.1 Pre and post dredging changes

The most significant differences in mean current speed between the 1852 and 1954 bathymetries (prior to dredging) seen in Figure 5.4 (A) include decreases in speed in the entrance channel of up to 1.4 $m.s^{-1}$ and increase in the Lower Western channel of 0.6-0.8 $m.s^{-1}$. There is a decrease in speed over Center Bank and in the Upper Western channel of up to 0.8 $m.s^{-1}$. Increases and decreases up to 0.4 $m.s^{-1}$ occur in several channels above Stella passage. Differences in mean current speed between the 1954 and 2006 bathymetries seen in Figure 5.4 (B) (post dredging) include a decrease in speed in Stella Passage, Cutter channel and the outer Entrance channel of up to 0.8 $m.s^{-1}$. The Lower Western channel increases in speed up to 0.6 $m.s^{-1}$. The post dredging plot shows a greater distribution of decrease in speed of up to 0.2 $m.s^{-1}$ in the upper harbour and intertidal areas compared to the pre dredging plot.

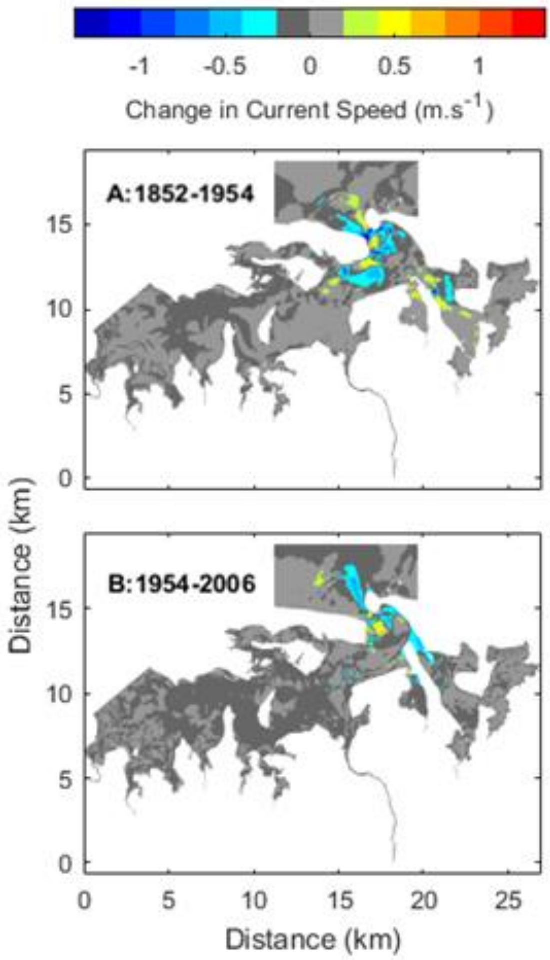

Figure 5.8 Difference in maximum current speed between A) 1852-1954 (pre dredging) and B) 18954-2006 (post dredging).

5.2.5 Tracer decay

In general, 2006 had higher K values compared to all of the years in all of the regions as seen in the bar plot of Figure 5.9. This indicates that the rate of decay was slower for the 2006 bathymetry.

Region A

The pattern in region A is that the difference in K decreased through the years. The 2006 model was more similar to 1954 than 1852. The difference between 1954 and 2006 was negative indicating 1954 actually had a slower decay rate of tracer. All the differences in K are less than 0.025.

Region B

The pattern in region B is that the difference in K increased through the years. The 2006 model was more similar to 1852 than 1954. The difference between 1852 and 2006 was negative indicating 1954 actually had a slower decay rate of tracer. The difference between 1879 and 2006 was also negative. All the differences in K are less than 0.035.

Region C

The pattern in region C is that the difference in K decreased through the years. The 2006 model was more similar to 1954 than 1852. All the differences in K are less than 0.015.

Region D

There was no pattern in region D for the difference in K. This region had the most variability in the difference of K. The difference between 1852 and 2006 was less than 0.01. The difference in K between 2006 and both 1901 and 1954 was greater than 0.25.

Region E

The pattern in region E is that the difference in K decreased through the years. The 2006 model was more similar to 1954 than 1852. Differences are higher in this region with all five years having a difference in K between 0.05 and 0.12.

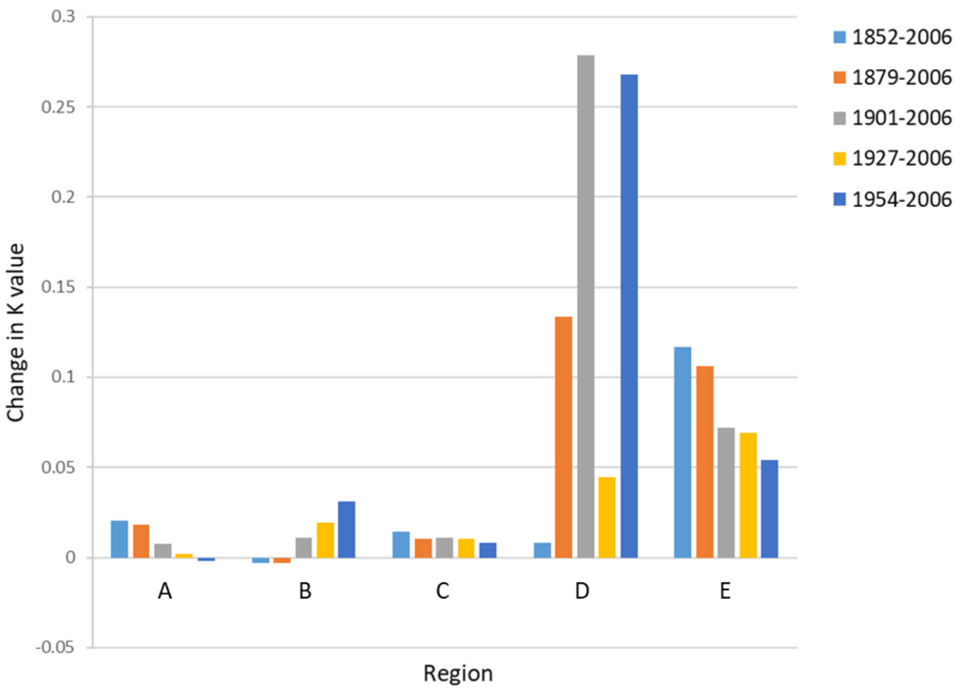

Figure 5.9 Bar graph of change in K values between 2006 and each year for intertidal bathymetries, plotted by region. Colours represent each year as presented in the key.

5.3 Discussion

5.3.1 Changes in environmental conditions

The spatial extent of the region where the water level range increased changed in the years prior to dredging compared to post dredging. This indicates that the widespread historic changes in water level range of up to 0.2 m were due to natural changes in the geomorphology of the entrance rather than changes due to dredging or land reclamation (also shown in Brannigan, 2009). Brannigan investigated cross sections of the inlet gorge for all six bathymetries from Mount Maunganui across to Matakana Island. The entrance channel deepening between 1852 and 1954 increased the cross sectional area of the inlet, allowing an increase in tidal discharge and amplitude of water level range within the harbour as observed in the results (Hume & Herdendorf, 1992; Watson, 2016). Changes to water level range above the Sulphur Point reclamation were controlled by the changing cross sectional areas and constriction of entrances into the sub-estuaries. The decrease of water level range in intertidal areas of less than 0.1 m can be attributed to decrease of depth and decrease in the minimum water level.

The most significant changes in depth and current speeds occurred through the entrance and tidal inlet system. Differences between 2006 conditions and previous years were a result of natural and anthropogenic processes and were limited to the main channels and areas of port development (Brannigan, 2009). The contrast in environmental conditions were the greatest between 2006 and the earliest bathymetry of 1852 as the differences were an accumulation of long term natural changes and short term anthropogenic changes caused by dredging. The contrast in environmental conditions were the least significant between 2006 and the more recent bathymetry of 1954 as the differences were mainly a result of the short term anthropogenic changes caused by dredging.

Natural changes to the entrance geomorphology and current speeds observed in this study were more widely distributed than the changes caused by dredging. Previous studies by HRS (1963), Davies-Colley (1976), Dahm (1983), THS (1983), Mathew (1997) and Brannigan (2009) have observed these changes. The narrowing and deepening of the entrance channel and accretion at Panepane point resulted in a decrease in current speeds through the inlet. There was great variability in the Lower Western Channel depth and current speed. This instability occurs due to the extension and accretion of Centre bank closing the connection between the Upper Western and Otumoetai channels. The accretion on Centre bank resulted in the slowing of flood currents and further deposition of sediment. The deepening of the Entrance channel, Cutter channel and Stella passage through dredging resulted in decreases in current speeds in the areas directly impacted. The changes in depth and current speed outside of these areas post dredging, such as those in the Lower western channel, are continuations of changes observed pre dredging (Brannigan, 2009; Mathew 1997).

Minimal changes in the depth and current speeds were observed in the intertidal areas. As the intertidal areas are extensive, changes are widely distributed however the differences were not of great magnitude. Changes to depth in the intertidal areas occurred as a result of the simulated infilling which meant they were observed getting shallower through time with a total change of 0.188 mm accumulation over the 150 years. There were no distinct patterns to changes in current speeds, all differences in mean speeds were less than 0.1 $m.s^{-1}$. Areas of increase and decrease varied spatially and temporally indicating that the localized changes to depth from the infilling were more likely to be responsible for the differences rather than any large scale changes in environmental conditions.

The differences in tracer decay are indicative of how residence time has changed within different regions of the harbour. Regions A, B and C all had the lowest differences in K value as the geomorphology of these areas did not change a lot through the years, they remained open and with high level of exchange. Regions E and D were sub estuaries in the upper harbour above the development and land reclamation at Sulphur Point. There were large differences between 2006 and previous years and variability in K as the entrance constriction to these regions changed through time and affected the rate at which water was flushed through (Tay et al., 2013).

5.3.2 Ecological implications

The changes to water level, current speed and rates of tracer decay though time have the potential to impact the distribution of species, ecological functions and estuarine health. The ecological implications of changes in the above environmental conditions for Tauranga Harbour are discussed in the following section.

5.3.2.1 Water level range

The changes in water level seen in this study have the potential to change the distribution of species through time. Water level range is indicative of the tidal levels and determines the amount of time areas of the Harbour spend under water with the rise and fall of each tide (Peterson, 1991). Changes to the water level and tidal ranges within the harbour mean that the distribution of inundation times will be altered. This then impacts species that rely on certain water levels for ecological functions.

5.3.2.1.1 Bivalves

The distribution of bivalves has the potential to be impacted by changes in water level range as biological and physical stress is created as a result of exposure, feeding behaviour and food supply (Dobbinson et al., 1989; Legendre et al., 1997;

Peterson 1991). The amount of time the organisms spend under water and their elevation on the shore has controls on the feeding time as they filter nutrients out of the water column. The study by Legendre et al (1997) in the Manukau Harbour demonstrated that there is a relationship between the elevation on the shore and the abundance of *Austrovenus stutchburyi* and *Macomona liliana*. Greater numbers of both species and most size classes were found in areas that had increased periods of submersion. This can be linked to the biological stress of feeding times and nutrient content of the water decreasing with increased elevation. Changes in the levels of immersion and emersion with each tidal cycle will cause changes in the levels of stress.

The differences in water level hind-cast by modelling in this Chapter has potentially changed the distribution of both *Austrovenus* and *Macomona* as they are common bivalve species in the Tauranga harbour (Ellis et al., 2017; Park & Donald, 1994; Sinner et al., 2011;). The intertidal areas adjusted for infilling through time and experienced an increase in elevation and decrease in water level range. This would be expected to result in a decrease in the abundance and size of these and other shellfish in the areas with increased elevation.

5.3.2.1.2 Mangroves

The distribution of mangroves has the potential to be impacted by water level range as their habitats are restricted by specific inundation regimes, amongst other processes. The growth rate of mangroves responds to flooding, therefore the upper and lower limits of distribution are related to water levels and depth. Growth of mangroves is modelled using equations which account for the inundation stress factor and multiplier ‘I’ which ranges between unlimited growth (1) and no growth (0) (Van Maanen et al., 2015). Maximum growth rates would occur with optimal inundation regime ($I=1$) and reduced growth rates ($I<1$) would occur when the mangroves are flooded for longer or shorter periods of time. Growth, size and distribution of mangroves is therefore dependent on inundation time and subsequently the elevation of the bed.

The mangrove species found in New Zealand estuaries is *Avicennia marina var. australasica* and occupies the upper half of the intertidal areas and are limited in seaward extent to 20-30 cm above mean sea level as their roots need to be uncovered for at least half of every tidal cycle (Park, 2004). Investigations into Tauranga Harbour mangrove distribution by Park (2004) have shown support for the hypothesis that sedimentation of estuaries is contributing to the acceleration of mangrove spread. The decrease in depth from accumulation of muddier sediments increases the range of habitat for mangroves by reducing the water level range and inundation time.

With the simulated infilling of 18.88 mm over 150 years in this study, the intertidal areas have decreased in depth and water level range. It would be expected that this would have had the potential to cause significant changes and expansion of mangrove forests seaward through time as even small raises in wide shore profile and a sedimentation rate of 2mm per year could result in an additional 1 metre of colonisation. This expansion was shown by Park (2004) as mangrove areas had doubled in the last 50 years. Mangroves have ecological significance as they enhance diversity, increase complexity of habitats, increase productivity, trap fine sediments, provide nursery habitats and improve water quality.

5.3.2.1.3 Benthic plants

The distribution of benthic plants such as sea lettuce has the potential to be impacted by water level range as light is required for photosynthesis and attenuation is impacted by the depth of the water column. Light attenuation is described with the coefficient K_d m−1 which describes the rate of light intensity decrease with depth. Sea grass is considered to be sensitive to changes in light penetration as it is a high light adapted, benthic primary producer. A study by Cussioli et al. (2019) investigated light penetration in Tauranga Harbour and the implications for the *Zostera muelleri* species of seagrass present. This species colonizes areas of intertidal flats within the average tidal range. The K_d coefficient was shown to fluctuate naturally with the tide, with high levels of light penetration at low tide and lower levels at high tide. This species has a minimum light requirement of 36% surface irradiance in order to sustain growth. It was demonstrated that in the intertidal zones 28-76% of the surface light reached the bed when submerged indicating that photosynthesis is not limited in these areas but growth may be more impacted in the deeper channels where light availability is more limited.

The implications of these observations for the historic changes in water level range and depth are that the decreases in range in the intertidal areas are not likely to have caused significant changes to the distribution of *Zostera muelleri* as light attenuation would remain high. However, the increases in water level range across the rest of the Harbour area are likely to have an impact as any changes in water depth would result in changes in K_d. In the subtidal areas even a small decrease of light penetration would have resulted in the minimum levels of light required to sustain growth not being reached and the potential loss of seagrass beds. Seagrass beds are important ecologically as they are productive habitats which stabilise sediments, enhance structural complexity and therefore biodiversity as well as provide habitat for juvenile fish (Park, 2016). Historic changes in seagrass beds would have therefore had flow on effects for other aspects of ecological health. Recent losses of seagrass beds have been attributed to smothering caused by increased sedimentation within the Tauranga Harbour, increased turbidity decreasing light availability and grazing from swans (Ellis et al, 2017; Park, 2016).

5.3.2.2 Current speeds

Current speeds can control the distribution of species directly and indirectly as species are adapted to different energy environments and sediment type. Previous studies of the distribution of benthic species in Tauranga have been limited temporally and spatially. However, they have consistently identified that the dominant taxonomic group in intertidal and subtidal areas are bivalves and polychaetes respectively (Park and Donald, 1994; Park, 2010; Sinner et al., 2011).

5.3.2.2.1 Distribution of mud

Changes in current speeds affect the transport and distribution of sediments. Stronger currents result in fine sediments being removed and transported while the coarser sediments are left behind (Davies-Colley & Healy, 1978). With decreases in currents speeds there would be less energy in the environment and so finer grains would deposit (Hancock et al., 2009). The changes in sediment distribution can result in changes in community composition and the distribution of species as organisms are sensitive to the suspended sediment and energy.

Thrush et al. (2003) developed specific models for 13 common species based on probability of occurrence to predict broad scale changes in Macrofauna in response to changes in sediment type. The species represented common, dominant members of intertidal flat communities. Increasing mud content resulted in positive effects for the occurrence of *Helice crassa* (tunnelling mud crab), *Scolecolepides benhami, Nicon aestuariensis* and *Heteromastus filiformis* (surface deposit feeder polychaetes). Strong negative effects of increasing mud content were found for *Austrovenus stutchburyi*, *Macomona liliana, Nucula hartvigiana (*bivalves), *Aonides oxycephala* and *Anthopleura aureoradiata* (mudflat anemone). Deposit feeders are more numerous in muddier sediments as the organic content of the sediment is higher and ingested more efficiently. Suspension and filter feeding bivalves and anemone are found in coarser sediments as food in the water column is replaced faster and there are less suspended fines that would clog gills (Peterson, 1991). In a study by Jones and Simmons (1981) of the *Helice crassa* mud crab, it was found that the resided above mid tide in well-drained and compacted sediments. This is due to its feeding preference and adaptations for burrowing requiring a stable substrate.

Current speed in intertidal areas is significant as it determines where fine sediments accumulate once they stop being transported in suspension in the water column. Areas of lower energy have less potential for transportation and erosion so tend to accumulate fine sediments and have higher mud content (Hancock et al., 2009). The changes in current speed in the intertidal areas were not consistent temporally or spatially and were of low magnitude (maximum less than 0.2 m.s-1). Therefore, any changes in mud distribution due to current speed changes through time are hard to predict. Changes would have to be investigated at a smaller scale in order to distinguish whether there was potential for a shift in community composition. In areas of reduced current speeds and increased accumulation of mud it would be expected that there would be a shift away from general bivalve dominance in intertidal areas and increase in polychaete's and mud crabs.

In the entrance, channels with the greatest current speeds such as the Lower Western channel have coarse shell coverage. The observed differences in current speeds in this study would result in shell coverage changing through time. Decreases in speed observed over Centre bank and in surrounding channels would result in increased areas of medium and fine sand as observed in studies by Brannigan (2009). The decrease in scouring currents and shifting sand may have allowed establishment of some communities that would not have normally existed in the higher energy environment (Park and Donald, 1994).

5.3.2.2.2 Larvae settlement

Hydrodynamics also have controls on population dynamics of benthic marine invertebrate species. The dispersal, transport and settlement of pelagic larvae is influenced by current circulation and speeds as the larvae are small and have poor swimming abilities (Cowen & Sponaugle, 2006; Monohan, 2018). These dispersal processes are essential for the survival and persistence of populations as they allow connectivity, recruitment and genetic diversity between and within populations. Similar to sediment, the transport distance and settling of larvae out of the water column is influenced by the current speeds (Legendre et al., 1997). Small areas of increased or decreased current speeds have the ability to impact where larvae are deposited. Therefore, any localised differences in current speed modelled within the intertidal areas has the potential to impact the survival and distribution of populations. In general, increased current speeds would be expected to decrease settlement and reduce rates of recruitment to that area (Levin, 2006). On the other hand, increases in current speeds could result in increased dispersal distance of larvae (Cowen & Sponaugle, 2006; Monohan, 2018).

5.3.2.3 Tracer decay

Although Tauranga Harbour is a shallow well flushed estuary, the complex morphology, tidal flows, channels and flats can create complicated circulation patterns which in turn affect the residence times of different areas in the Harbour (Monohan, 2018; Tay et al., 2013). In this thesis changes in residence time of the harbour was demonstrated by calculating rates of tracer decay (K). Increases in K value and residence time affects how quickly contaminants and sediments are flushed out of different regions of the harbour (Tay et al., 2013). It also has controls on biological stressors such as food supply and larvae retention as it controls the rate of exchange between the water within the estuary and the outer shelf (Dobbinson et al., 1989; Peterson, 1991; Tay et al., 2013).

The general patterns of residence time observed were that it decreased with proximity to the entrance (low decay in A to high decay in C) and increased in entrance restricted estuaries (low decay in regions D and E) (Tay et al; 2013, Monahan, 2018). The results showed that the regions E and D with restricted entrances had the most changes in the decay of tracer through the years. This is significant for the ecology in these regions as it means that there is reduced exchange with water from outside the harbour as a result of increased development of Sulphur Point and the Port. The A, B and C regions had minor changes (less than 0.05) in K value between years. This indicates that these regions did not have significant changes in residence time and were unlikely to have had significant changes to the retention and trapping of larvae, sediments and contaminants.

5.3.2.3.1 Larvae retention

Different residence times can impact on the connectivity of populations by controlling the retention and dispersal of larvae in different areas of the harbour (Monohan, 2018; Levin, 2006; Cowen & Sponaugle, 2006). Monohan (2018) demonstrated through numerical modelling of larvae dispersal that retention of released larvae around Centre Bank was always low and retention in the upper harbour areas were higher. Retention in sub estuary regions was also lower. Most larvae retention also depended on the time of release in relation to tidal levels, with lower retention during spring high and low tides. These patterns indicate that retention in upper harbour regions and sub estuaries is influenced by tidal circulation and morphology (Monohan, 2018). Changes to the harbour that have influenced tidal circulation include the dredging and land reclamation at Sulphur point. The rate of decay of tracer in Regions D and E has decreased through time as a result of changes in the constriction of the entrances. This would result in them having higher retention times of larvae, recruitment and durability within populations of these sub estuaries. Populations in other areas may have suffered as a result of the decrease in dispersal of larvae out of these regions due to the loss of connectivity (Monohan, 2018). Changes in the connectivity due to alterations in morphology and residence time would influence the historic distribution and abundance of benthic populations.

5.3.2.3.2 Trapping of sediment and contaminants

The potential for sediment and contaminants to become trapped increases in areas with low levels of tracer decay as they are not flushed quickly. Increased mud content has also been correlated with increased concentration of contaminants as they tend to bind to muddier sediments (Ellis et al., 2017). Ellis et al. (2017) observed that sediment, nutrient and heavy metal concentrations were found to be higher in the inner areas of the harbour where there was depositional environments and reduced flushing rates.

Recent broad scale studies by the MTM research programme have been used to develop Benthic Health Models which uses community composition to create categories of relative ecosystem health. Biological and physical stressors controlling species distribution in subtidal tidal areas were identified as mud, total organic content (TOC), loss on ignition (LIC) and mean current speed (Clark et al., 2018). Controls on species distribution in intertidal areas were identified as contamination, mud content and nutrients (Ellis et al., 2017). An increase in sedimentation and contaminants would mean that the area shifts to a more impacted Ecological Health category as depicted in the Benthic Health Models by Ellis et al (2017). The ecological implications of this are that the general ecological health of these areas declines with a shift in community composition to species that have more tolerance to increased sedimentation and pollution impacts.

5.4 Summary

The intertidal adjusted bathymetries and hydrodynamic results from the modelling in the previous chapter were used to investigate differences between environmental conditions of historic bathymetries.

The analysis compared 2006 with previous year’s results and the pre and post dredging changes. For depth, water level and current speed the 2006 conditions were most different to the earliest 1852 conditions. This is due to the accumulation of both large natural changes in geomorphology and hydrodynamics and changes to the anthropogenic dredging and development. Differences in tracer decay were more predominant in the regions with changes in entrance constriction. The open harbour regions had minimal differences between years.

The changes in environmental conditions would have had some ecological significance and implications for distribution of species back through time. Changes in depth and water level have implications for species that rely on certain water levels for ecological functions such as bivalve feeding times, inundation of mangroves and light attenuation for seagrass. Current speeds would control the distribution of sediment and species as well as the settlement of larvae which would have to be investigated on a smaller scale. Residence times have had largescale changes due to the anthropogenic changes around port development. These changes influenced the distribution and retention of sediments, contaminants and larvae which in turn control the community composition and connectivity.

The loss of species which complete key ecosystem services and increase biodiversity would have flow on effects for other aspects of estuarine health. An example of changes in ecosystem services would be a decrease in abundance of bivalves due to increased mud distribution would reduce the filtration of nutrients out the water and potentially increase the risk of eutrophication. Mangroves and seagrass provide diverse habitat for a range of species, increases or losses of these areas have implications for the survival of other species.

CHAPTER SIX
Conclusions

6.1 Overview

The primary aim of this thesis was to hind cast historic environmental conditions in order to investigate the ecological implications of changes in geomorphology and hydrodynamics within the southern basin of Tauranga Harbour. Previous studies had not modelled geomorphology or hydrodynamics including the influence of historical infilling in intertidal areas, or hind cast changes in harbour wide environmental conditions. The aim of this thesis was achieved by completing five objectives and the conclusions are summarised in this chapter. Recommendations are then given for future areas of study.

6.2 Summary of Objectives

6.2.1 Chapter Three - Bathymetry Compilation

There were two main objectives for this chapter. The first was to produce 6 historic bathymetries of the southern basin of Tauranga Harbour from 1852, 1864, 1870, 1879, 1901, 1927, 1954 and 2006 which account for changes in entrance geomorphology due to human development and natural processes. Produce an additional 5 historic bathymetries from 1852, 1864, 1870, 1879, 1901 and 1927 which have sediment removed from the intertidal areas to simulate infilling. The second objective for this chapter was to investigate the impact of the simulated infilling on depth by comparing the entrance adjusted bathymetries with the intertidal adjusted bathymetries of each year.

The first objective was achieved with the compilation of bathymetries which produced 6 bathymetries from 1852, 1879, 1901, 1927, 1954 and 2006 that have different entrance bathymetries and the same source for the upper harbour covering largely the intertidal areas. The 5 additional bathymetries produced for the first five years had the same differing entrance bathymetries but also had the intertidal areas in the upper harbour adjusted for infilling through time. This infilling was simulated by adding increasing amounts of depth back through time to “remove” the sediment.

The analysis of depth distribution and hypsometry allowed a comparison between the entrance and intertidal adjusted bathymetries in order to complete the second objective. The intertidal adjusted bathymetries showed variation in distribution of depth in intertidal areas compared to the entrance adjusted bathymetries as a result of the simulated infilling. The curvature of the hypsometry's also differed between the two sets of bathymetries with the intertidal adjusted bathymetries showing the increased influence of infilling through time with a decreasing γ value.

6.2.2 Chapter Four – Hydrodynamic Numerical Model

This chapter focused on the third and fourth objectives for the study. These were using Delft3D to develop a numerical model of the southern basin of Tauranga harbour to simulate historical hydrodynamic conditions for each of the bathymetries. Then investigated the impact of the simulated infilling on hydrodynamics by comparing the results of the entrance adjusted and intertidal adjusted numerical models of each year.

Delft3D FLOW was used to create a numerical model in order to predict the historic hydrodynamics of the 11 entrance and intertidal bathymetries compiled in in the previous chapter. The hydrodynamic numerical modelling produced expected patterns in the current speed, water level and tracer decay results. The results also represented observations in previous studies of the hydrodynamics of Tauranga Harbour.

The analysis compared the entrance and intertidal bathymetries for each year in order to investigate the influence of infilling on hydrodynamics. The changes in the intertidal area depth due to the simulated infilling were shown to increase the magnitude of current speed, water level range and rate of tracer decay.

6.2.3 Chapter Five – Changes in Environmental Conditions

This chapter focused on the final objective of using the modelled hydrodynamic conditions from the intertidal adjusted bathymetries to investigate temporal changes in environmental conditions that may have influenced historic ecological health and distribution of species.

Large magnitude small scale changes in depth and current speed occurred in the harbour entrance channels. Water level had the most significant change prior to dredging across the Harbour potentially due to historic changes in the inlet cross-section. For depth, water level and current speed the 2006 conditions were most different to the earliest 1852 conditions. This is due to the accumulation of both large natural changes in geomorphology and hydrodynamics and changes from the anthropogenic dredging and development. The tracer decay had most difference in the regions with changes in the constricted entrance.

The changes in environmental conditions had some ecological significance and implications for altering the distribution of species back through time. These changes influenced the distribution of sediments and contaminants which in turn control the community composition.

6.3 Implications for Ecological Restoration and Management

In order to look at how to manage, restore and mitigate the impacts on estuarine systems in the future, it is useful to understand the magnitude and distribution of historic changes in environmental conditions that may have impacted on ecosystems through time. As observed in this study many changes occurring through time have been from natural processes rather than as a result of short term anthropogenic processes. Changes in depth and water level have implications for species that rely on certain water levels for ecological functions such as bivalve feeding times, inundation of mangroves and light attenuation for seagrass. Current speeds would control the distribution of sediment and species as well as the settlement of larvae which would have to be investigated on a smaller scale. Residence times have had largescale changes due to the anthropogenic changes around port development. These changes influenced the distribution and retention of sediments, contaminants and larvae which in turn control the community composition and connectivity. The loss of species which complete key ecosystem services and increase biodiversity would have flow on effects for other aspects of estuarine health. As high mud content and contamination in benthic health models determine poor ecological health it is important to focus on preventing the accumulation of these in the estuaries. An area of focus would be to ensure the maintenance of large scale flushing processes especially within estuaries with constricted estuaries and increased residence time. More local changes in community composition would have to be looked at a smaller scale in order to determine which processes have resulted in the changes and are a focus for restoration.

6.4 Future studies

Future research could be undertaken using more accurate sediment accumulation rates to adjust the intertidal areas for infilling. Different rates of infilling could be applied to different areas of the harbour in order to more accurately predict historic and future changes in hydrodynamics. Residence time of smaller areas could be investigated in order to understand which areas may have changed more significantly through time and have been more ecologically impacted by the accumulation of sediments and contaminants. Small scale changes in current speed may be observed by smaller grid sizes in the numerical model in order to predict any localised changes in community composition that may have occurred historically. Using the changes in current speed to predict actual changes in the distribution of sediment type would provide significantly more information on how ecology may have been effected as mud content can be used to model ecological health.

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