MODELLING EFFECTS ON MARINE WATER QUALITY DUE TO URBAN STORMWATER DISCHARGES AND CLIMATE CHANGE

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ABSTRACT

In this paper the role of marine models in assessing urban stormwater discharges in relation to marine water quality is presented. A calibrated hydrodynamic model is used to quantify the dynamics of stormwater discharges along the Eastern Bays area in Auckland. The effects of future sea level rise on the dynamics of the discharges and subsequent changes in water quality in the marine receiving environment are discussed.

Traditionally, downstream static sea level conditions for urban flood models are developed based on estimates of extreme sea levels from relatively short duration tide records combined with regional estimates of sea level rise scenarios. Applying a regional estimate of future sea level rise maybe appropriate on the open coast where down-scaling effects of sea level rise may be negligible. However, in settings where complex inshore topography exists (such as the many harbours and embayments in New Zealand) regional scale sea level rise scenarios may not provide realistic estimates of local scale sea levels.

Climate change modules within the MIKE by DHI software enable the sensitivity of near shore sea level conditions to be assessed under a range of global sea level rise scenarios. Similarly, estimates of changes in precipitation can be determined from a number of global circulation models. Outputs from these modules can be used to assess the effects of changes in precipitation on stormwater discharges and to quantify local scale effects of sea level rise.

The paper discusses the effects of climate change on water quality in the marine receiving environment based on predicted changes in hydrodynamics, precipitation, mixing and the dynamic nature of the interface between the marine environment and the urban stormwater system. From a planning perspective, the need for quantifying the joint probability of extreme rainfall events and sea levels are discussed.

KEYWORDS

Urban flood risk assessment, marine models, sea level rise, climate change.

1 INTRODUCTION

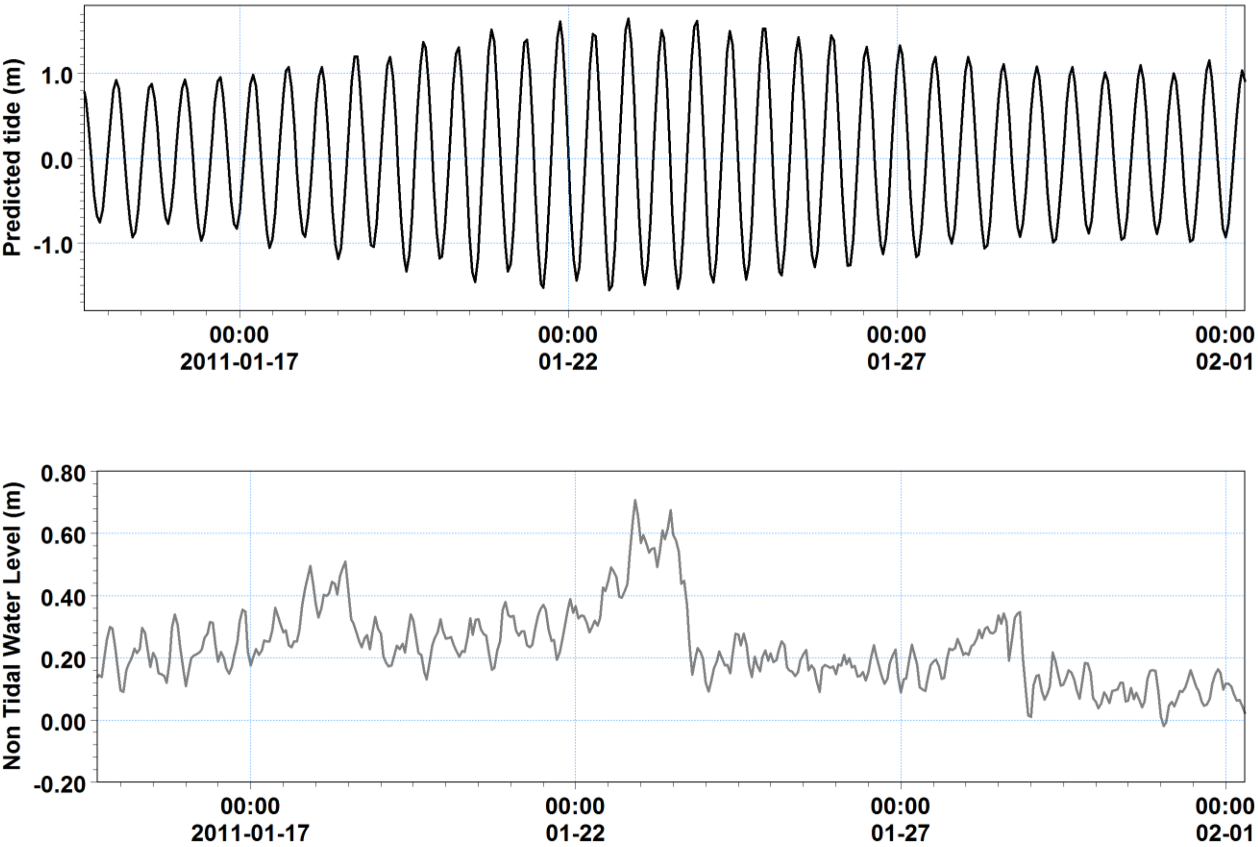
In this paper a calibrated marine model is used to assess the changes in near shore hydrodynamics under future sea level rise. The effects of climate change in terms of changes in water quality in the marine environment relating to stormwater discharges along the Eastern Bays area in Auckland are quantified.

The latest IPCC report (IPCC, 2013) predicts that globally, a sea level rise of between 0.2-0.4 m can be expected to occur by the middle of this century. This degree of sea level rise is predicted to occur under all the emissions scenarios considered by the IPCC. The New Zealand Coastal Policy statement provides guidance for managing risk in the coastal zone in terms of planning for sea level rise over at least 100 years. Through to the end of this century a base sea level rise of 0.5 m is recommended when considering planning and decision timeframes.

The well documented storm of January 2011 (Figure 1) under current climate and sea levels has been estimated to have an average recurrence interval of approximately 100 years. This event occurred when a tropical cyclone tracked over the north of New Zealand resulting in strong north-easterly winds (> 20 m/s) and associated waves in the Hauraki Gulf resulting in a non-tidal increase in water level of 0.7 m which coincided with spring tides (Figure 2). Such events are often associated with heavy rainfall which can exacerbate the effects of flooding due to coastal inundation. In thirty years' time the degree of coastal flooding that occurred in January 2011 may occur once every ten years and may occur on an annual basis by 2050 (Stephens et al. 2014).

Figure 1: Flooding in Shoal Bay near Northcote (left) and on the Auckland north-west motorway (Metservice archive).

Figure 2: Port of Auckland predicted tide (top) and observed non-tidal water level variations (bottom) for January 2011.

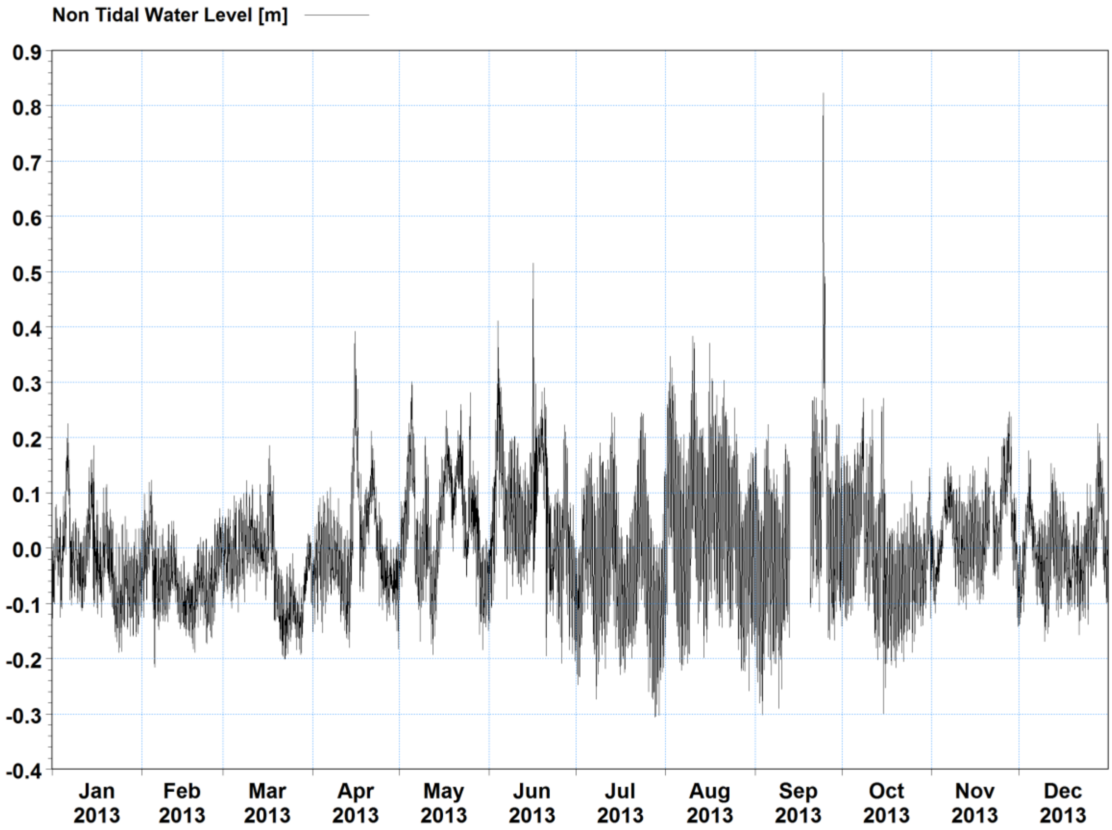


Extreme sea levels are determined by the interactions between mean sea-level rise, long-term sea-level fluctuations, tide range, changes to the frequency and magnitude of storm surges and wave conditions. The maximum observed non-tidal water level for the Port of Auckland water level record is 0.82 m (Figure 3). Non-tidal water levels of greater than 0.1 m occurred for 18% of the record and levels higher than 0.2 m occurred 4% of the time. Across the Waitemata there is significant spatial variation in predicted maximum water levels due to the tidal amplification processes - especially within the in complex bathymetry in the upper harbour. Data from Stephens et al. (2013) indicate a 0.40 m variation in extreme water levels across the Waitemata for a 200 year ARI storm event.

To provide estimates of extreme water levels a combination of calibrated hydrodynamic models and analysis on long-term sea level records are required. This is especially true when the effects of future sea level rise on tidal propagation, storm surge and wave processes need to be understood and quantified.

In this paper the effects of climate change on a stormwater system are assessed in terms of the receiving environment water quality. The changes in near shore hydrodynamics under a future sea level scenario are quantified and the implications for the hydraulic performance of stormwater outlets discussed.

Figure 3: Non tidal water level variations for Port of Auckland, 2013.



2 BACKGROUND DATA

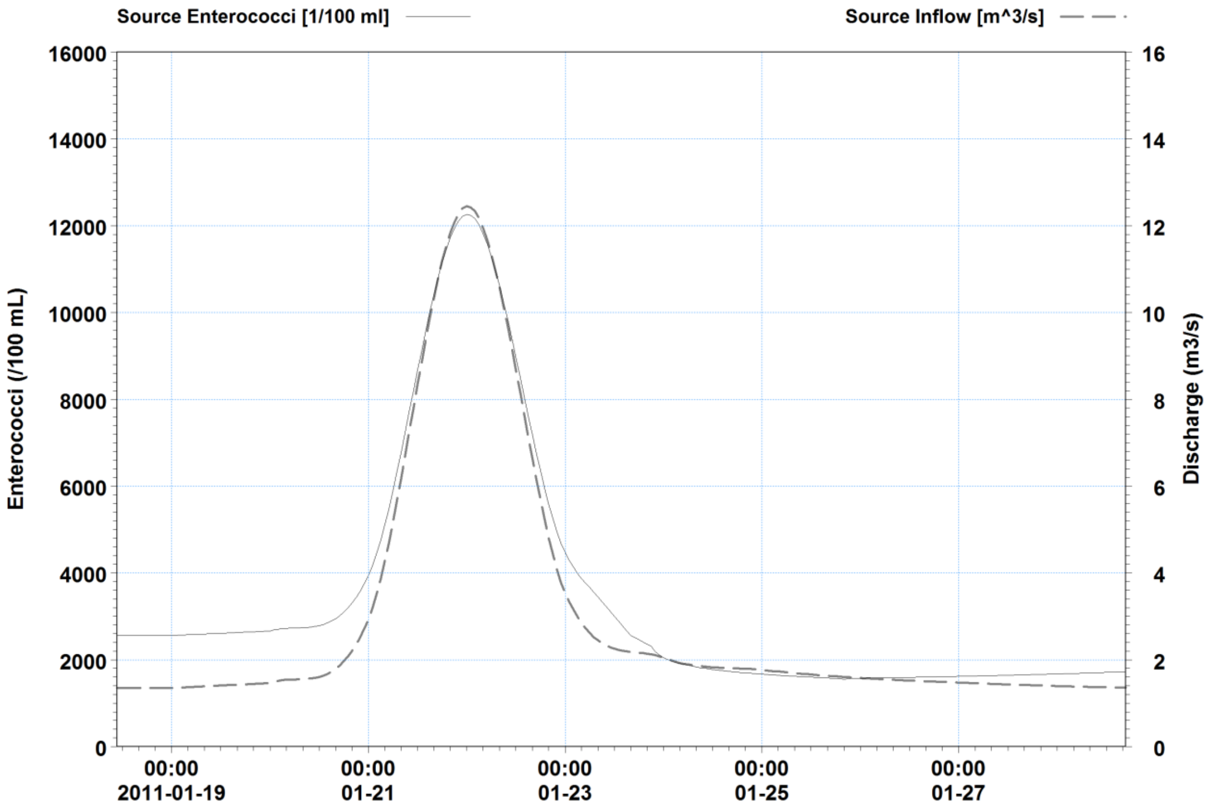
This paper builds on previous work carried out for the Auckland Council (Oldman et al. 2004) which examined the dynamics of ten small stormwater outlets within the Eastern Bays area between Okahu Bay and St Heliers Beach (Figure 4). Time-series data of stormwater quantity and quality were derived from an extensive monitoring programme carried out between November 2001 and July 2003 (Timperley and Reed, 2004) to give predicted hydrographs and enterococci time-series data for each of the outlets being considered (Table 1 and Figure 6). Units for the enterococci concentrations are all given in Enterococci count per 100 mL (Ent/100mL). Note that since this study significant improvements to stormwater systems have been implemented and water quality monitoring along this section of the coast indicates enterocooci concentrations are low during small to medium rainfall events, however high concentrations are still observed during dry weather (unpubl data Auckland Council).

Figure 4: Eastern Bays area storm water outlets (A-J) and model prediction sites (1-4).

Table 1: Predicted mean and maximum flows rates for the stormwater outlets in the Eastern Bays area. Data from data collected between November 2001 and July 2003.

Outlet Identifier	Mean inflow (m^3/s)	Maximum inflow (m^3/s)
A	0.004	1.313
B	0.021	6.414
C	0.030	9.209
D	0.004	1.320
E	0.007	2.036
F	0.002	0.640
G	0.041	12.446
I	0.015	4.583
J	0.020	6.248
K	0.006	1.748

Figure 5: Schematic hydrograph and enterococci concentration (Ent/100mL) for Outfall G, Figure 4.



3 MODEL SETUP

For this paper a calibrated MIKE 21 Flow model was established and an ECOLAB water quality template used to simulate the fate of the enterococci discharges from the ten stormwater outlets in the Eastern Bay area. The MIKE 21 flow model predicts the depth-averaged flows within coastal areas using a flexible mesh approach solving the continuity and momentum equations as well as temperature, salinity and density. It simulates the water level variations and flows in response to a range of forcing conditions (i.e. winds, tides, density gradients and atmospheric pressure). The MIKE21 ECOLAB template is coupled to the MIKE21 advection/dispersion model and simulates the transport, dispersion and biological/biochemical processes relevant to the contaminant of interest.

The grid used for this study cover the north-east continental shelf of New Zealand (Figure 6) and includes an area of high resolution elements in the inner Hauraki Gulf and outer Waitemata harbour with highest resolution in the vicinity of the Eastern Bays and Tamaki River (Figure 6). The model was forced by three-hourly wind and atmospheric pressure data extracted from the Climate Forecast System Reanalysis dataset (EMC/NCEP, 2010) along with a Flather tidal boundary condition (Flather, 1976) based on the TOPX7 Pacific Atlas tidal solution (Egbert and Erofeeva, 2002).

For the enterococci water quality template two decay modes are defined one for daylight and one during the hours of darkness. Daylight decay (driven by UV levels) is dependent on both salinity (S) and water temperature (T) as follows;

$$K_l = S_{m\ast}\,(b_{t\ast}T + K_{L0})/(a_{\ast}S_m - (a-1))_{\ast}S) \qquad (1)$$

Where S_m is the reference salinity (34.5 PSU), $b_t = 0.133*10^{-3}$ [$m^2*W^{-1}*hr^{-1}*{}^oC^{-1}$] is the temperature dependency coefficient and K_{L0} is $2.124*10^{-3}$ [$m^2*W^{-1}*hr^{-1}$] is the baseline decay rate coefficient and a is the empirical coefficient of 1.54 derived from in-situ experiments.

Decay during darkness is assumed to be only temperature dependent as follows;

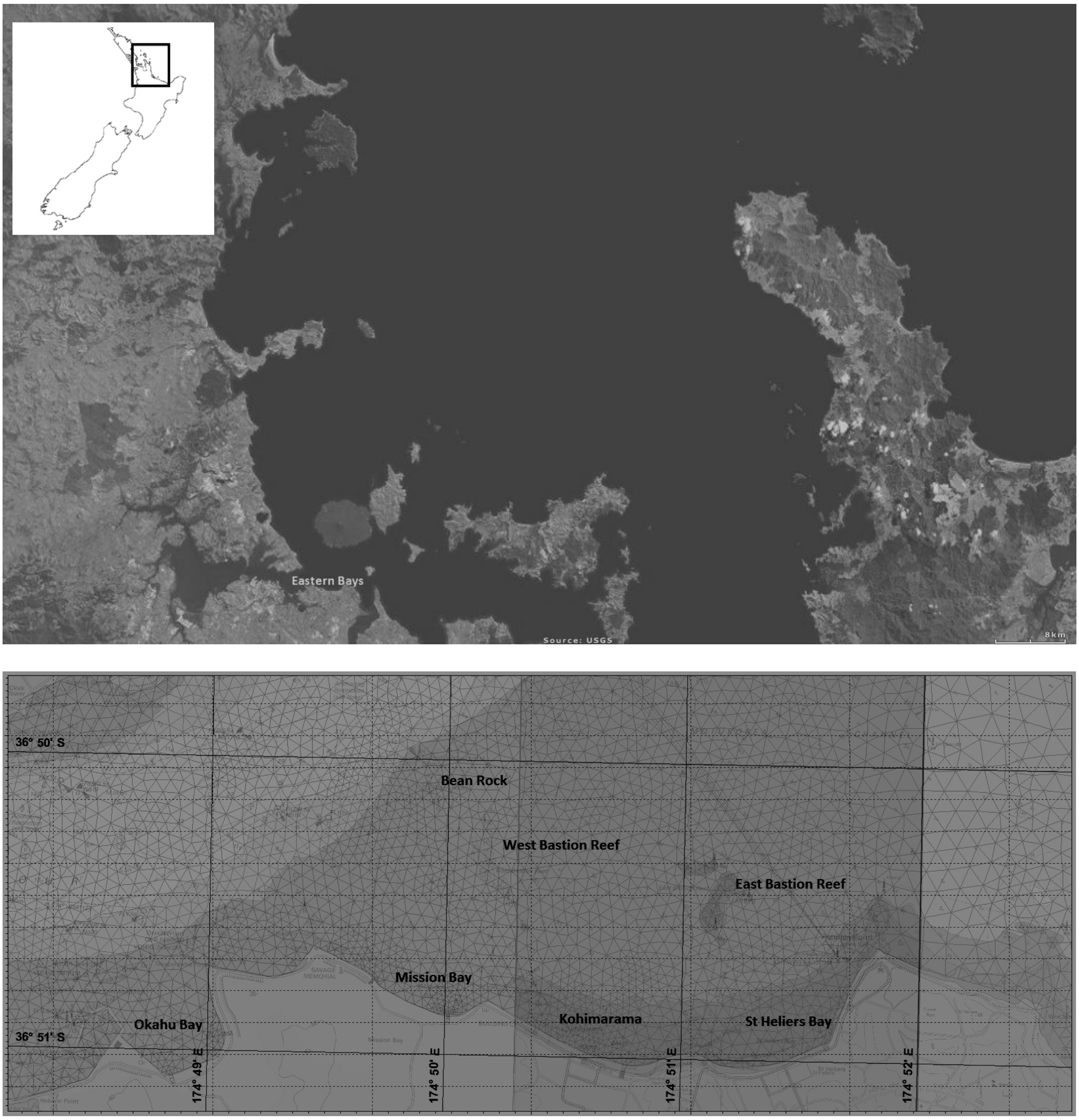
$$K_m = a_T * T - K_{mo} \qquad (2)$$

Where $a_T = 0.002425$ [$hr^{-1}*{}^oC^{-1}$] is the temperature dependency coefficient and $K_{mo} = 0.00826$ [hr^{-1}] is the temperature decay offset coefficient.

Various projections of global sea level rise (e.g. Horton et al., 2009, Grinsted et al., 2009 and Vermeer and Rahmstorf, 2009) can be incorporated into the MIKE 21 flow model boundary conditions as can the predictions of a range of Global Circulation Models (DHI, 2004), in terms of precipitation, evaporation and air temperature. Based on a chosen year and emission scenario (e.g. SRA1, SRA1B or SRA2) the MIKE Climate Change tool updates existing relevant boundary data for the range of Global Circulation Models being considered.

At each of the outlets a 1.5 m rectangular culvert was defined with an invert level set at mean sea level. The height of the culvert was set to 3.0 m above mean sea level.

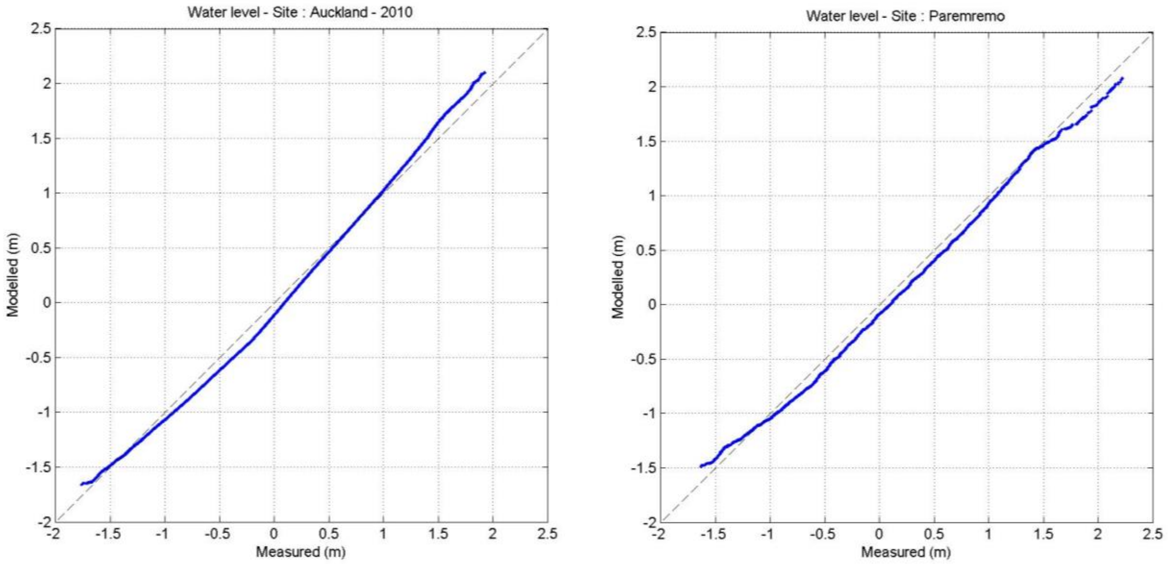
Figure 6: Extent of the hydrodynamic model grid and location of the outlets in the Eastern Bays area, Auckland (top) and details of high resolution area immediately offshore of the Eastern Bays outlets (bottom).



4 MODEL CALIBRATION

For the purposes of this paper the calibration of the model in terms of water levels is presented. Figure 7 shows the quantile-quantile plots of predicted and observed water levels for the Port of Auckland (for all of 2011) and a site near Paremoremo Creek (for the period October-November 2002). It can be seen that overall the model is a good predictor of water levels but tends to slightly over predict higher water levels at the Port of Auckland site and under predict higher water levels at the Paremoremo Creek site. The skill score (Zhang et al. 2010) for the two sites are 0.81 (Port of Auckland) and 0.76 (Paremoremo).

Figure 7: Quantile-quantile plot of the predicted and observed water levels at the Port of Auckland for 2011 and Paremoremo Creek (Oct-Nov 2002).



5 SCENARIOS

Two different model scenarios were simulated all spanning the period of the January 2011 storm event. These scenarios were;

- Existing mean sea level including wind and atmospheric pressure fields,
- 2050 mean sea level conditions including wind and atmospheric pressure fields.

Both models were run with background salinity set to 34.5 PSU with an initial uniform sea temperature of 20 ^{o}C across the model domain. Freshwater inflows were assigned a salinity of 0 PSU and temperature of 18 ^{o}C – typical for spring conditions (Neale, 2012). Simulations were carried out over a 14-day period from the 18th to the 31st of January 2011, with the peak of the hydrograph (Figure 6) timed to coincide with a spring high tide of the 22nd of January.

Using the range of projections for global sea level rise through to 2050 (Table 2) the boundary conditions for the existing sea level simulation was increased by a value of 0.32 m for the 2050 simulation. Using the range of Global Circulation Models embedded in the MIKE Climate Change tool the average increase in precipitation for 2050 was estimated to be 8%. The hydrographs for the 2050 simulation were increased by this factor. For this paper it was assumed that the enterococci load off the catchment would be the same as present day levels. The time-series of enterococci concentrations were therefore decreased by 8% due to the assumed increase in outlets discharges for the 2050 scenario.

Table 2: Range of sea level rise estimates to 2050 from various emission scenarios and global scale predictions.

Prediction Reference	**SRA1B emission scenario**	**SRA2 emission scenario**	**SRB1 emission scenario**
IPCC AR4	0.12 – 0.24 (0.18)	0.12 – 0.20 (0.16)	0.10 – 0.21 (0.16)
Horton	0.21 – 0.30 (0.25)	0.22 – 0.29 (0.25)	0.20 – 0.28 (0.22)
Grinstead	0.35 – 0.48 (0.41)	0.36 – 0.49 (0.42)	0.31 - 0.43 (0.37)
Vermeer	0.36 – 0.51 (0.43)	0.36 – 0.51 (0.43)	0.33 – 0.47 (0.39)

6 RESULTS

The focus of the discussion of the modelling results relate to the predicted depth-averaged Enterococci concentrations for the two scenarios being considered.

To assist in the analysis of the predicted differences in Enterococci concentrations a brief discussion of the hydrodynamics in the vicinity of the Eastern Bays area is provided here.

6.1 HYDRODYNAMICS

Maximum currents in the vicinity of the Eastern Bay area occur within the entrance to the Waitemata Harbour and Tamaki River during both the mid-ebb and mid-flood tide (Figure 8). Offshore of Okahu Bay peak ebb and peak flood tide currents mirror those of the currents in the entrance to the Waitemata. Within Mission Bay a zone of relative low currents occur with an easterly directed current during the peak ebb tide and an onshore directed current during the peak flood tide. Along the rest of the Eastern Bays area currents tend to be directed to the east on both the peak ebb and flood tide.

For the 2050 sea level rise scenario the overall pattern of depth averaged currents does not change dramatically. Increases in mean current speeds of around 1% occur within the approaches to and entrance of the Waitemata Harbour. Increases in mean current speed of around 8% occur on the inter-tidal areas within the Tamaki River while speeds in the main channel of the Tamaki River are reduced by around 2%. Offshore of the Eastern Bays area mean current speeds are predicted to reduce by between 2% and 5% under the 2050 sea level rise scenario.

Immediately offshore of the Eastern Bay area water levels under the 2050 scenario increase by 0.37 m (compared to the 0.32 m applied on the boundary). Under existing sea level conditions inundation of the inter-tidal area along the Eastern Bays occurs on average for 68% of the tidal cycle. For the 2050 sea level scenario inundation of this inter-tidal area occurs for more than 80% of the time. Such increases in water levels and inundation times will lead to greater near-field dilution of the discharges under the 2050 sea level rise scenario compared to the current sea level scenario.

This increase in water level and associated increase in inundation times in the near shore zone may result in an increase in saline intrusion into the culvert during higher states of the tide. As configured in the model, offshore water levels exceed the culvert crest level for an extra hour under the 2050 sea level rise scenario. The actual degree of saline intrusion into the culvert will depend on the actual configuration of the culvert and the connection through to the upstream stormwater system. The predicted salinity within the culvert at Outlet G (Table 1) for the two scenarios considered are shown in Figure 9. Maximum predicted salinities occur at high tide. At the start of the model simulation (when there are only baseflow outlet discharges) salinity increases of around 5 PSU occur under the 2050 sea level rise scenarios. During the peak of the outlet discharge the volume of freshwater entering the culvert (12 m^3/s, Table 1) is sufficient to prevent any intrusion of saline water into the culvert. On the recession of the hydrograph the predicted differences in salinity between the two scenarios begins to increase to around 2 PSU.

6.2 ENTEROCOCCI CONCENTRATIONS

The time series of the predicted enterococci concentrations at a site 300 m offshore of Mission Bay (Site 1, Figure 4) show the reduction in enterococci concentrations that occur under the 2050 sea level rise scenario at all states of the tide (*Figure 10*). The maximum predicted concentrations at this site occur at low water when the near field dilution is at a minimum. Under the existing sea level scenario the maximum predicted concentration at this site is 2995 Ent/100mL while under the 2050 sea level scenario the maximum predicted concentration is 2370 Ent/100mL. This reduction is much more than just the 8% reduction in source concentration and gives an indication of the overall increase in dilution that would occur under the 2050 sea level scenario.

At a site 1200 m offshore of Mission Bay (Figure 11, Site 2 in Figure 4) the maximum predicted concentration (which occurs at low water following the peak discharge) under the existing sea level scenario is 920 Ent/100mL while under the 2050 sea level scenario the maximum predicted concentration is 1060 Ent/100mL. Note that at high water (when minimum concentrations occur) concentrations under the 2050 sea level scenario are also higher than those predicted to occur under the existing sea level rise scenario.

Similar increases in predicted concentrations occur at a site 2400 m offshore of Mission Bay (Figure 12, Site 3 in Figure 4) under the 2050 sea level rise scenario. Note that at this site the maximums occur during the peak currents that occur on the mid-ebb and flood tide which transports the discharge plumes from the entrances of both the Tamaki River and Waitemata Harbour to the site.

In the entrance to the Tamaki River the time-series of predicted enterococci concentrations (Figure 13, Site 4 in Figure 4) show that the peak predicted enterococci concentrations (which again occur during the peak currents on the mid-ebb and flood tide) are highest under the 2050 sea level rise scenario. During peak flows, maximum increases in predicted enterococci concentrations of around 230 Ent/100mL occur under the 2050 sea level scenario. During other stages of the tide predicted enterococci concentrations are always higher under the 2050 sea level rise scenario compared to the existing sea level scenario. As a result, the average predicted enterococci concentration over the full simulation period is around 40 Ent/100mL higher under the 2050 sea level rise scenario than under existing sea level at this site.

The spatial distribution of the predicted mean concentrations over the full period of the model simulation are shown in Figure 14 for the existing sea level scenario and Figure 15 for the 2050 sea level scenario. The figures show that overall the pattern of dispersion of the plume is very similar. However, as noted above concentrations at selected sites under the 2050 sea level scenario are generally lower in the near shore zone (e.g. Figure 12) and that further offshore (e.g. Figure 12 and Figure 13) peak concentrations can be higher. The difference in mean concentrations for the two scenarios (Figure 16) reflect these general findings with a zone of reduced mean concentration immediately offshore of the outlets and increased concentrations in the Tamaki River.

The reasons for the higher concentrations in this area relate to the predicted increases in velocity across the inter-tidal areas in the entrance of the Tamaki River. These increases in current speeds and increased water depths on the inter-tidal area lead to greater advection of the discharge plume as it is transported firstly south along the western inter-tidal areas of the Tamaki River on the flooding tide and further into the Tamaki River at high water and then onto the eastern inter-tidal areas of the Tamaki River during the ebbing tide (Figure 15).

Other areas where there are predicted to be increases in enterococci concentrations under the 2050 sea level rise scenario include the eastern end of Ngataringa Bay (in the Waitemata) and the areas around Bean Rock and the Bastion Point reefs. For these areas the increases in predicted enterococci concentrations relate to the changes in plume visitation at these sites due to the increase in mean sea level.

Figure 8: Peak ebb (top panel) and flood (bottom panel) tide velocities for the existing sea level conditions.

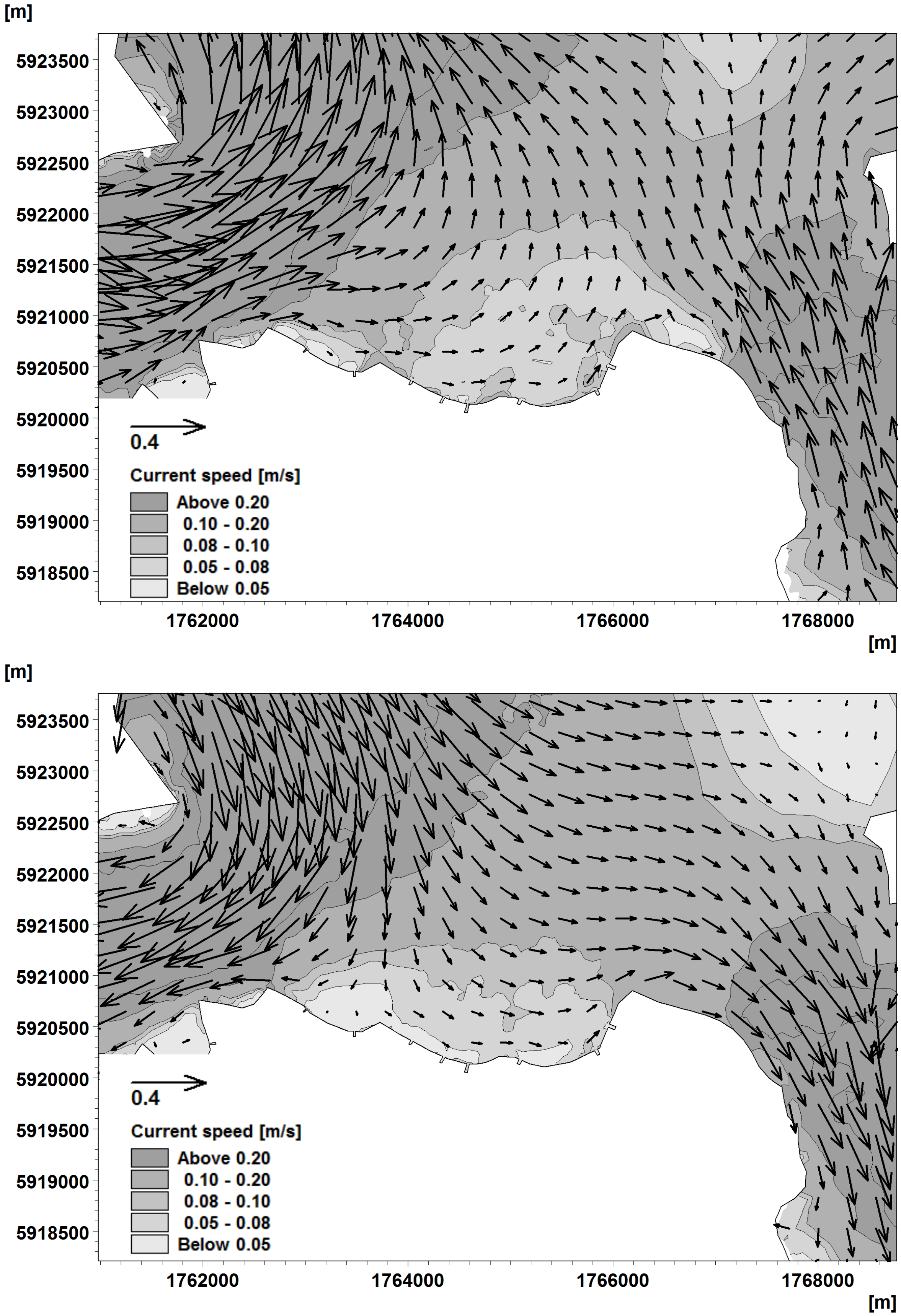


Figure 9: Time-series of predicted salinities just landward of the culvert for outlet G (Figure 4). Offshore water levels for the existing sea level scenario are also shown to illustrate the state of the tide.

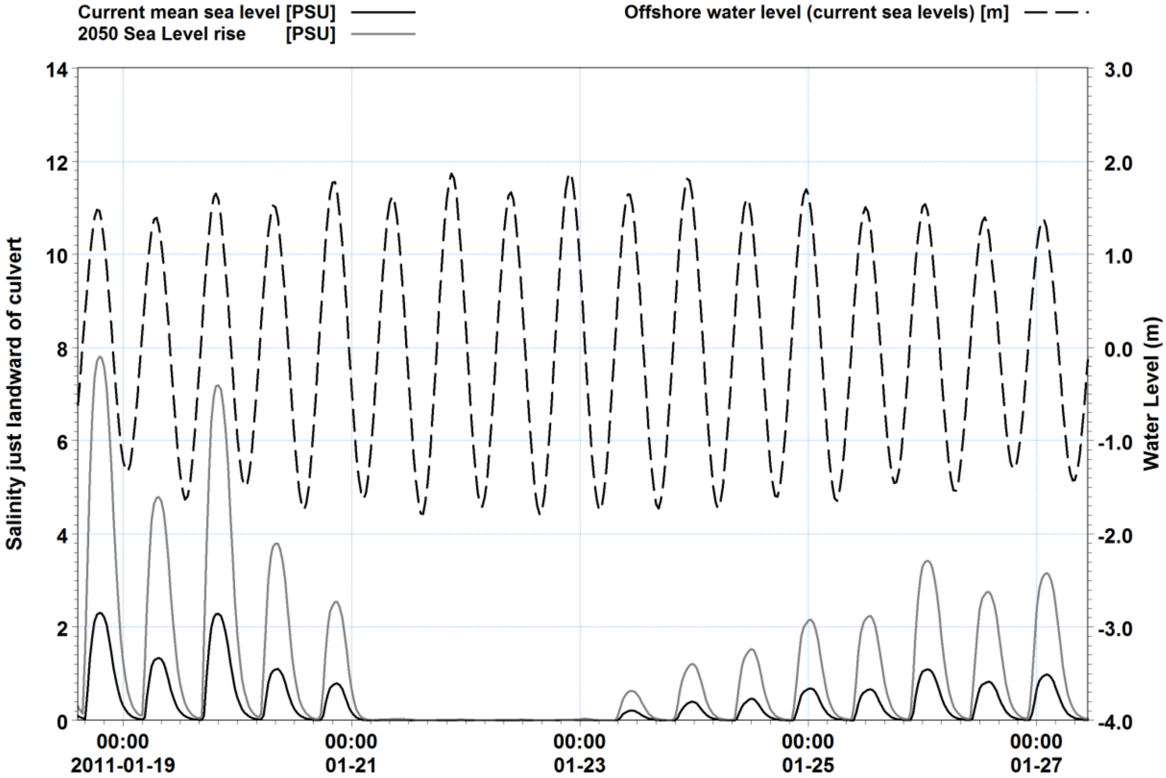


Figure 10: Predicted depth-averaged enterococci concentrations at a site 300 m offshore of Mission Bay (Site 1, Figure 4) under existing and 2050 sea level scenarios.

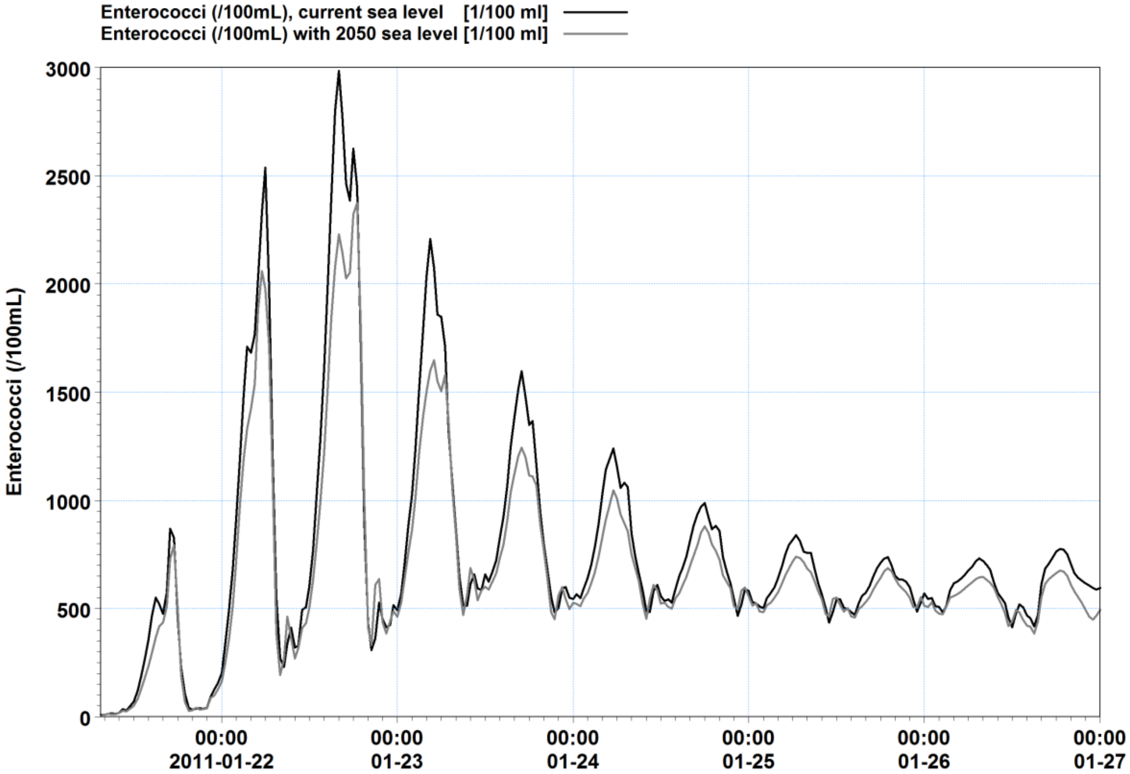


Figure 11: Predicted depth-averaged enterococci concentrations at a site 1200 m offshore of Mission Bay (Site 2, Figure 4) under existing and 2050 sea level scenarios.

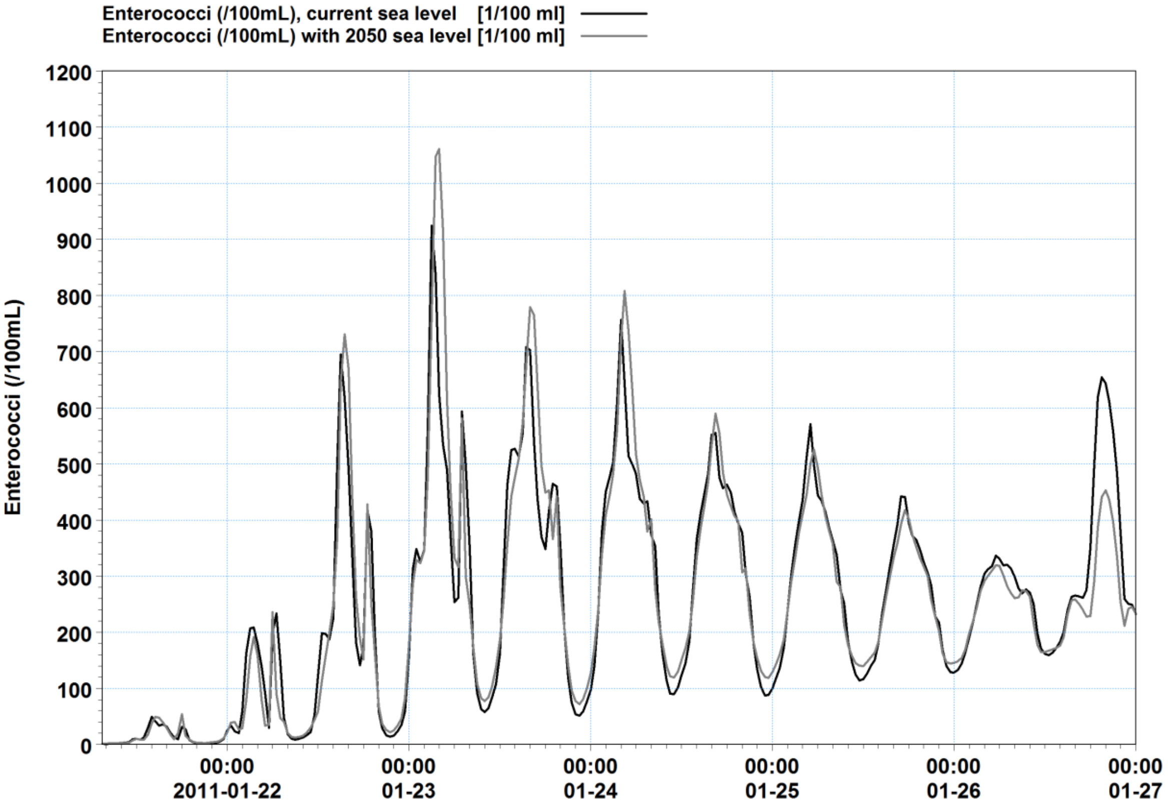


Figure 12: Predicted depth-averaged enterococci concentrations at a site 2400 m offshore of Mission Bay (Site 3, Figure 4) under existing and 2050 sea level scenarios.

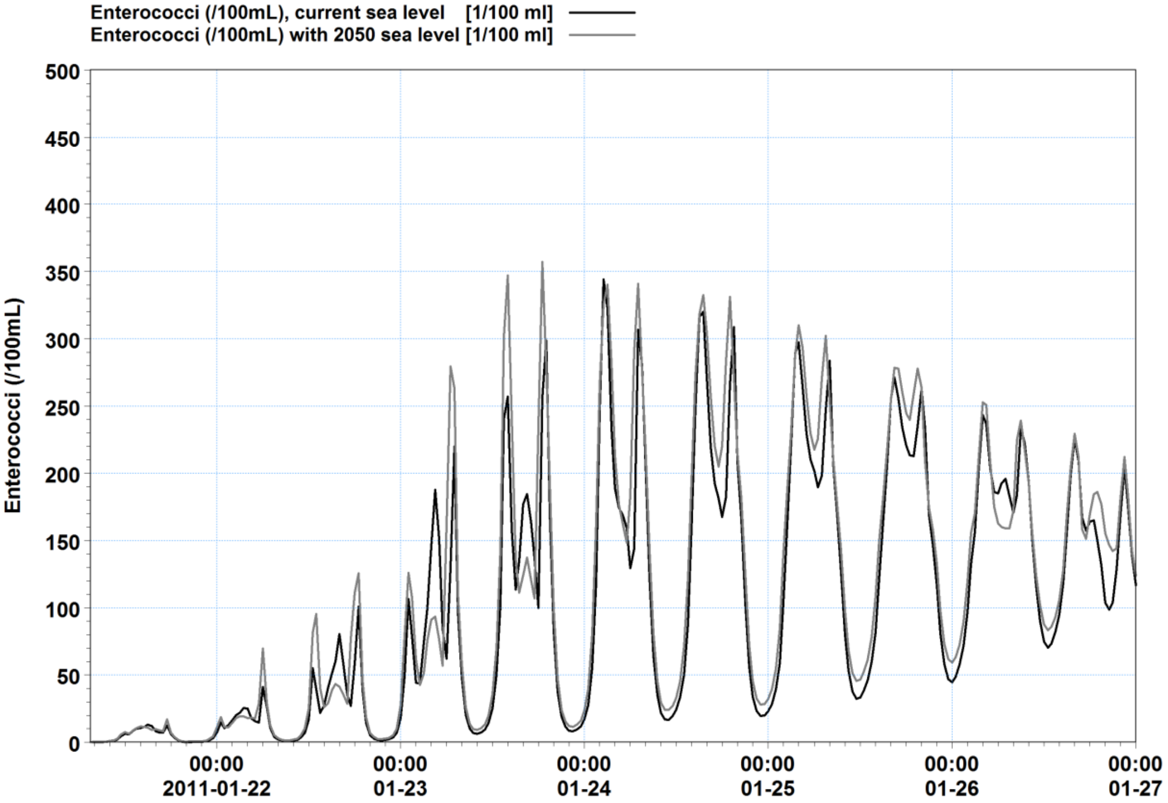
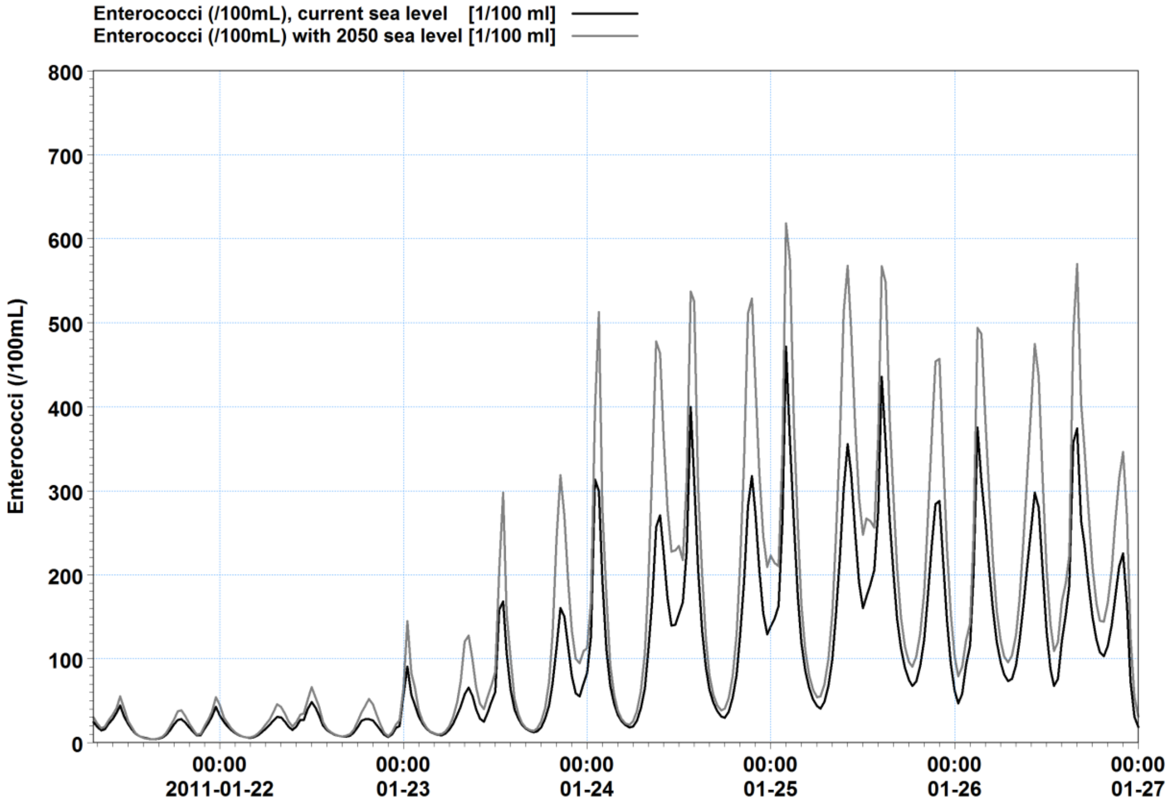


Figure 13: Predicted depth-averaged enterococci concentrations within the entrance to the Tamaki River (Site 4, Figure 4) under existing and 2050 sea level scenarios.



Figure

Figure 14: Predicted mean enterococci concentrations over the period of the model simulation (18th-31st January 2011) for the existing sea level scenario.

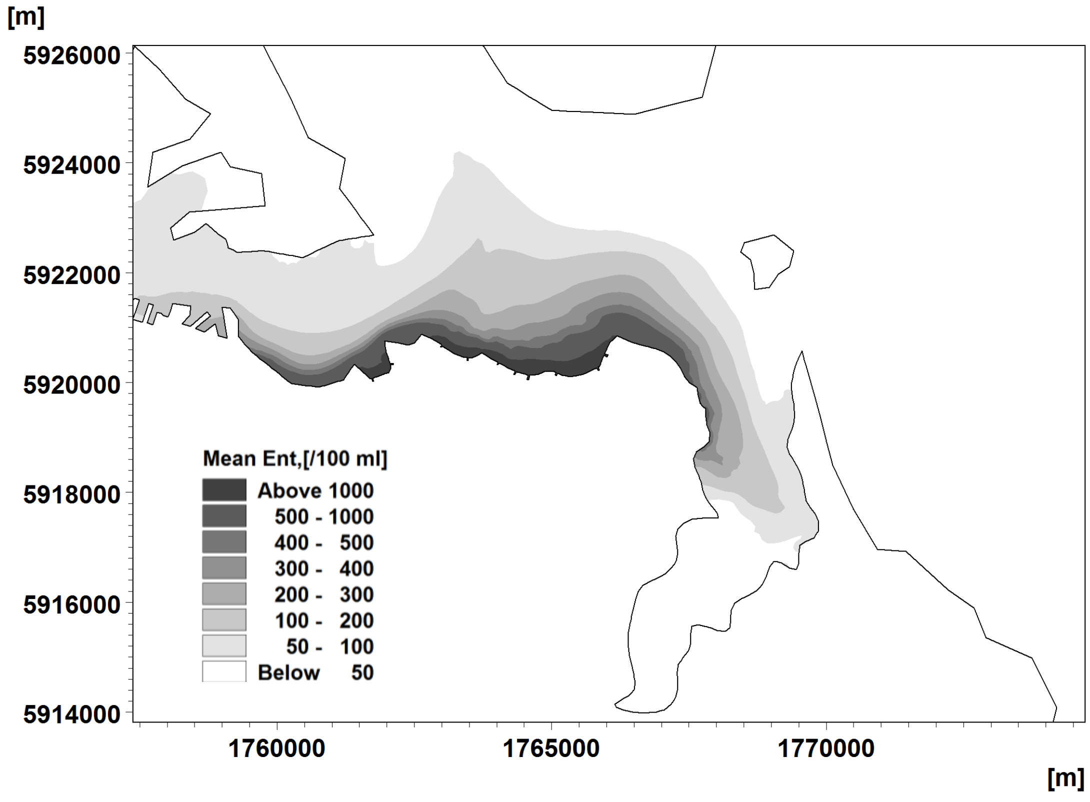


Figure 15: Predicted mean enterococci concentrations over the period of the model simulation (18th-31st January 2011) for the 2050 sea level scenario. Pathway of increased advection on the incoming and outgoing tide shown.

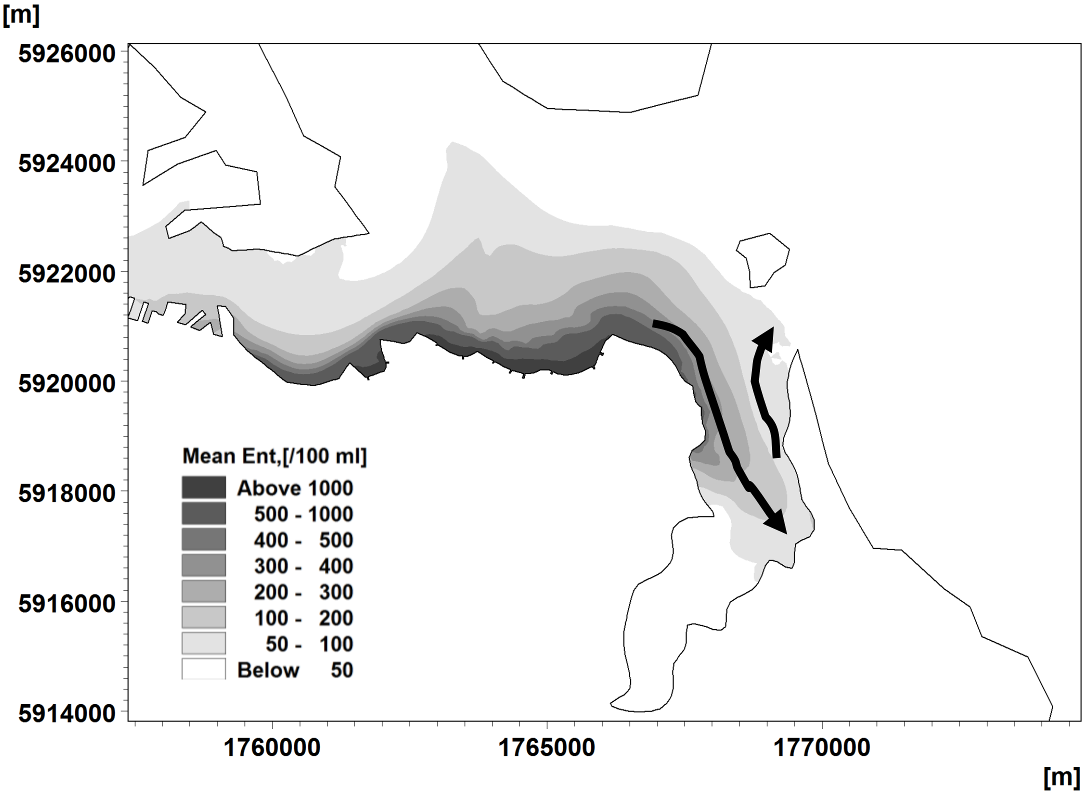
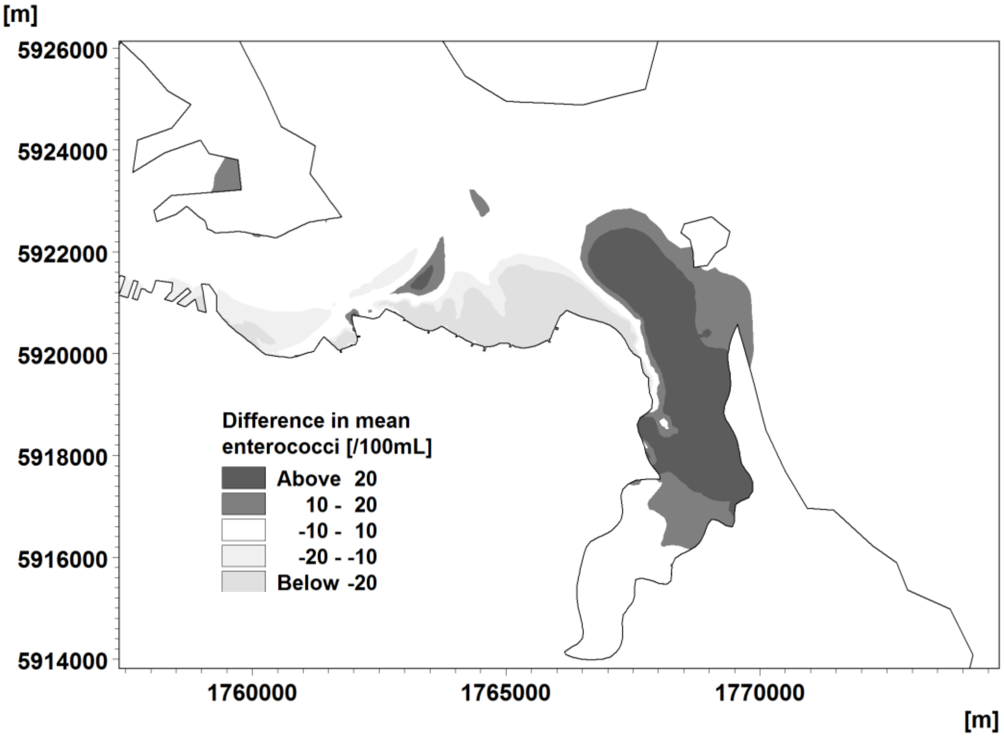


Figure 16: Predicted change in mean enterococci over the period of the model simulation (18th-31st January 2011). Positive values indicate mean enterococci concentrations under the 2050 scenario are higher than under existing sea levels.



7 CONCLUSIONS

In this paper the use of calibrated hydrodynamic and contaminant models have been used to illustrate the potential effects of future sea level rise on the dynamics of the interface between the marine environment and urban stormwater systems and changes to predicted water quality in the marine receiving environment.

Based on estimated contaminant loading and inflows from ten small stormwater outlets within the Eastern Bays area between Okahu Bay and St Heliers Beach, Auckland, the dynamics of the outlet plumes under current sea level conditions and those expected in 2050 are simulated. It has been assumed that future contaminant loadings will not change but that inflows will increase due to increased precipitation due to climate change. This paper does not addresses the potential for continued reductions in contaminant loading into the future and how these may be offset by predicted population growth.

The modelling of the Eastern Bays area outlets has shown that increases in contaminant levels may be expected in the Tamaki River under a 2050 sea level scenario (assuming no decrease in contaminant loading). The combined effect of the Eastern Bays outlet discharges, stormwater inflows within the Tamaki River and other stormwater outlets in the vicinity would also need to be considered before a more representative picture of the effect of climate change on water quality could be determined.

Results from the modelling have shown the importance of considering local increases in sea level driven by regional scale sea level rise. Even in the relatively exposed, open coastline along the Eastern Bays area local sea level estimates through to 2050 increase by 5 cm over the open boundary sea level rise applied in the model. Across the Waitemata extreme sea levels of up to 0.4 m higher than those expected near the entrance to the Waitemata could occur during extreme storm events.

Factors effecting the dynamics of the outlet plumes within the receiving environment include the increase in sea level (which provides greater degree of dilution), the increases in inundation time in the inter-tidal area in the vicinity of the outfall (which can dramatically increase dilutions for lower states of the tide) and changes to the advection of the plume due to ambient currents. The performance of the outlet itself will be a function of the increase inflows that may occur to the system (due to increased precipitation), the change in frequency of higher rainfall events (which will have an influence on the enterococci loading that may occur) and the hydraulics of the stormwater system under increased sea levels.

The results from the modelling indicate that under the same contaminant loadings as occur at present and a 2050 sea level rise scenario there could be expected to be a reduction in the near-field contaminant concentrations along the Eastern Bay area. This is a result of a combination of a reduction in source contamination, an increase in water level and associated increase in inundation times in the near shore zone.

In the far-field, contaminant concentrations offshore of the area of the outlets are predicted to be very similar in 2050 compared to those occurring today. However, contaminant concentrations in the Tamaki River are predicted to increase due to changes in the exchange of water across the inter-tidal areas of the Tamaki. This leads to greater advection of the discharge plumes across the inter-tidal areas and into the main channel of the Tamaki River. Other areas in the vicinity of the outlets where there are predicted to be increases in contaminant concentrations are reef areas and other inter-tidal sectors of the Waitemata where, under current sea level conditions, the dynamics of the contaminant plume is limited by the shallow water depths and limited plume visitations.

The modelling presented in this paper uses the January 2011 storm event to illustrate the potential effects of future sea level rise. This event consisted of a spring tides coinciding with high winds from a tropical cyclone resulting in elevated water levels and associated high rainfall. From a planning perspective the need to carry out a joint probability analysis of extreme rainfall and sea levels needs to be considered. Work carried out in the England (DEFRA, 2005) show that the dependency between extreme rainfall and sea levels is very site specific and a function of catchment size, coastal orientation and exposure and catchment characteristics. Quantifying the dependence can only be carried using long term sea level and flow data (e.g. Aijaz et al. 2011). The dependency can then be quantified by comparing the frequency of extreme flows occurring that occur simultaneously with extreme storm surges, with the frequency of extreme flows that occur regardless of the size of surge. In most urban systems the greatest risk from extreme events is due to rainfall (e.g. Lian et al. 2013). Work carried out on the Rhine Delta in the Netherlands (Kew et al. 2013) found that the probability of an extreme sea level event following an extreme rainfall event was three time lower if they are considered to be independent. Such changes in the probability of extreme events has clear implication in terms of the design of urban stormwater systems.

The modelling has shown the potential for increased saline intrusion into stormwater systems under future sea level rise scenarios. The actual impact of this in terms of the performance of stormwater systems can only really be addressed through the use of fully integrated dynamically linked marine and urban models. Only when the changes in the exchange of saline and freshwater and the subsequent changes in hydraulics of the stormwater system have been quantified can the performance of an outlet be assessed under future sea level rise scenarios.

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