IMPACTS OF SEA LEVEL RISE ON FLOODING IN AN ESTUARINE ENVIRONMENT

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ABSTRACT

This paper presents a case study of the modelling of sea level rise in flood studies, following the directive of the Victorian Coastal Strategy in 2008 to account for sea level rise of at least 0.8 m by 2100 for planning purposes. Sea level rise of at least 0.8 m must now be included in flood studies for design flood mapping and for the delineation of Land Subject to Inundation and Floodway planning overlays. This study focuses on modelling undertaken for the Port Fairy Regional Flood Study. The effect of the inclusion of sea level rise on design flood extent and levels is investigated. The balance between flood risks posed by storm surge inundation and riverine flooding under a scenario of sea level rise is also explored. We also present a method of accounting for dynamic ocean water levels in estuarine flood modelling studies.

INTRODUCTION

Coastal communities are commonly located at the interface between river catchment, estuary and ocean. This location, while providing many of the values that make our coastal towns unique, also makes them vulnerable to environmental phenomena. Coastal towns are often susceptible to flooding both from the seaward direction, as storm tide inundation, and from the landward, as riverine flooding. The combination of these two flooding mechanisms results in high flood risks for coastal communities.

Vulnerable as they already are, projected sea level rise, due to climate change, poses high risks to towns located on coastal floodplains. Under sea level rise, not only does the risk of storm tide inundation rise, but also the risk of riverine flooding, due to a higher tailwater elevation.

To ensure that future flood risks to coastal communities are minimised, the Victorian Coastal Strategy (VCS) 2008 recommended a policy of planning for sea level rise of not less than 0.8 metres by 2100. This recommendation was based on information arising from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC, 2007), which projected a sea level rise of 0.18-0.59 metres by 2090-2099, with an additional 0.1-0.2 metres from potential ice sheet melt. Adopting a precautionary approach, the Victorian Coastal Committee recommended that a minimum sea level rise of 0.8 metres (to 2100) be adopted for planning purposes. The VCS 2008 also recommended that the combined effects of tides, storm surges, coastal processes and local conditions be considered when assessing the impacts of climate change.

In this study, current and potential future flooding behaviour in Port Fairy, a coastal town in south-west Victoria, Australia, is investigated. In 2008, Water Technology completed the Port Fairy Regional Flood Study (PFRFS) and in 2010 undertook further modelling to incorporate the 0.8 m sea level rise recommended by the VCS 2008. The sea level rise scenario was based on modelling by McInnes *et al* (2009), and also accounted for a 19% increase in wind speed causing increased storm surge levels. The results of the modelling allow us to quantify the effect of projected sea level rise on design flood levels on a coastal floodplain. We identify the locations most affected by sea level rise and the upstream extent of this effect. We also investigate the balance of risks due to storm tide inundation and riverine flooding, the parts of the floodplain dominated by each mechanism and the areas subject to high risk from both.

Through this modelling we demonstrate a method of using a dynamic coastal boundary condition to simulate the combined effects of tide, storm surge and projected sea level rise. Most flood studies in coastal environments currently use a static downstream water level for design flood modelling. However, this gives an overly conservative tailwater elevation, as peak storm tide levels are generally short-lived and may not fully propagate up an estuary. A dynamic ocean water level boundary may provide a more accurate, while still conservative, estimate of tailwater conditions.

STUDY AREA

Port Fairy is located on a coastal flood plain at the mouth of the Moyne River estuary in south-west Victoria, Australia (Figure 1). The town is situated on low-lying ground just west of the river mouth. A commercial port operates on the entrance to the estuary, and the channel is dredged and protected by rock walls to allow passage of commercial and recreational watercraft. Upstream of the town, the channel widens into a shallow open water body known as Belfast Lough. The estuary is separated from the ocean by a high barrier sand dune with crest elevation 5 to 15 m above sea level. The Moyne River flows into the estuary approximately 3 km upstream of the town. Other major tributaries contributing to Belfast Lough include Murray Brook at its northern end and Reedy Creek at its southern end.

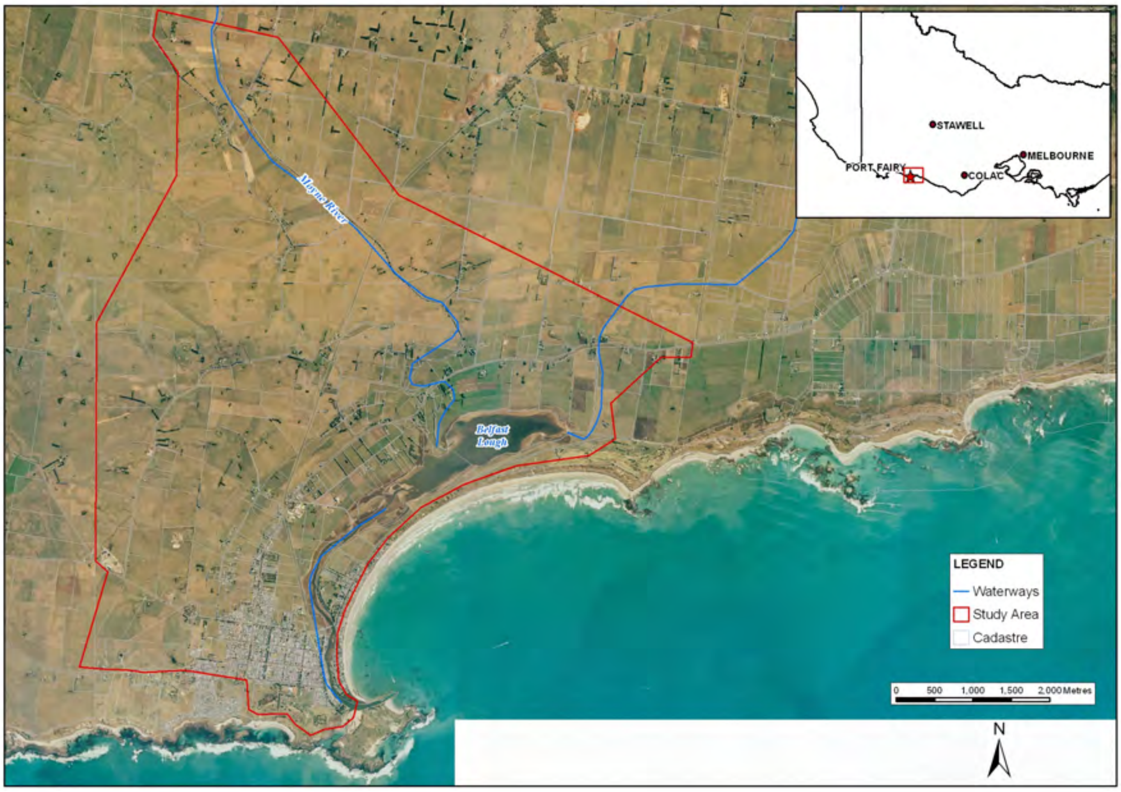

Fig. 1: Port Fairy Locality Map

The Moyne river catchment is largely rural and is characterised by gentle grades with a maximum elevation of approximately 250 m Australian Height Datum (AHD) and an average slope of 0.003. The total catchment area is 758 km^2. Large areas of wetlands and swamps exist throughout the catchment, but particularly in the lower catchment to the north-east of the township. Although many of these wetlands have been drained, they have low hydraulic efficiency under high flow conditions, and provide significant areas of floodplain storage. The low catchment slope and the large amount of active floodplain storage result in relatively small flood peaks compared to Victorian averages for similarly sized catchments (Bishop and Womersley, 2009). The 1% Annual Exceedence Probability (AEP) peak flow for the Moyne River at Toolong is approximately 260 m^3/s (Water Technology, 2008).

Port Fairy's location on a coastal floodplain at the interface of ocean, estuary and river catchment make it particularly susceptible to increasing flood risk due to sea level rise. The township is susceptible to inundation from both extreme storm tides and riverine flooding. Sea level rise will have an effect on both of these mechanisms, directly affecting storm tide levels and indirectly affecting flood levels through elevated tailwater conditions.

MODELLING APPROACH

The flood behaviour of the study area was investigated using a linked one and two-dimensional hydraulic model, based on the commercial software package MIKE FLOOD. The hydraulic model was developed and calibrated as part of the Port Fairy Regional Flood Study (Water Technology, 2008). Calibration results indicated that the model was capable of accurately reproducing observed flood and hydrodynamic behaviour at Port Fairy.

Model Structure

The two-dimensional model topography was defined by a 10 m grid, based on aerial laser survey, bathymetric data and field survey. Bridge and culvert crossings within the study areas were modelled as one-dimensional structures in MIKE 11 and dynamically coupled with the two-dimensional MIKE 21 model within the MIKE FLOOD model system. The variation in hydraulic roughness across the study area was schematised as a two-dimensional grid, representing various land uses and surface conditions. The hydraulic roughness values adopted (and verified through calibration) are summarised in Table 1 below.

Inflows to the model were applied at 9 points on the model boundary, simulating inflows from the Moyne River, Murray Brook, Holcombe's Drain, Reedy Creek and other tributaries. A downstream water level boundary was applied at the estuary mouth.

The model topography and location of structures and model boundaries is shown in Figure 2.

Tab.1: Hydraulic Roughness

Land Use Class	Manning's "n"
Open Floodplain (Pasture)	0.04-0.05
Vegetated	0.05-0.06
Port and Estuary	0.025-0.03
Roads	0.02
Paved areas (Roads)	0.015

Boundary Conditions

Four scenarios of inflow and downstream water levels were modelled to investigate the differences between current flooding behaviour and potential future behaviour with sea level rise. The scenarios, and a summary of the boundary conditions of each, are outlined in Table 2 below.

Tab.2: Boundary Conditions for Modelled Scenarios

	Scenario	Inflow Boundary Conditions	Ocean Water Level Boundary Conditions
1	1% AEP Flood Current Conditions	1% AEP (100 year ARI) design flow hydrographs	Dynamic boundary condition with CSIRO current conditions 10% AEP storm tide 0.83 m AHD at peak
2	1% AEP Flood at 2100 with dynamic ocean boundary condition	1% AEP (100 year ARI) design flow hydrographs	Dynamic boundary condition with CSIRO projection of 10% AEP storm tide at 2100 (0.82 m SLR and 19% wind speed increase) 1.86 m AHD at peak
3	1% AEP Flood at 2100 with static ocean boundary condition	1% AEP (100 year ARI) design flow hydrographs	Static boundary condition with CSIRO projection of 10% AEP storm tide at 2100 (0.82 m SLR and 19% wind speed increase) 1.86 m AHD constant level
4	1% AEP Storm Tide at 2100 with dynamic ocean boundary condition	No flow	Dynamic boundary condition with CSIRO projection of 1% AEP storm tide at 2100 (0.82 m SLR and 19% wind speed increase) 2.09 m AHD at peak

Inflow Boundaries

The inflow hydrographs were based on Flood Frequency Analysis and RORB modelling of the Moyne River catchment undertaken for the Port Fairy Regional Flood Study (Water Technology, 2008). Based on the Flood Frequency Analysis on annual flood peaks at Toolong, including an estimate of the 1946 flood, the 1% AEP peak flow at Toolong was estimated to be 258.4 m^3/s. The design flood hydrograph was developed from the calibrated RORB Model, using IFD information derived from AR&R Volume 2 (IEAust 1987) and the calibrated parameters. The design flood hydrograph was then scaled to reconcile the peak and volume to the flood frequency analysis. The design flood hydrographs for the minor tributaries were scaled using the same ratio as the Toolong flows. The 100 year flood hydrographs for the boundaries are shown in Figure 2. The inflows were unchanged between the current conditions and sea level rise scenarios (i.e., no allowance for changes in rainfall intensity or catchment wetness/losses due to future climate change were made).

Downstream Water Level Boundaries

The ocean boundary conditions were adopted from CSIRO modelling (McInnes *et al*, 2009) of extreme sea levels under current conditions and four climate change scenarios to 2100. For this study, the predictions of storm tide heights at 2100 under Climate Change Scenario 2 were adopted. Scenario 2 is based on the IPCC 2007 A1F1 scenario combined with the CSIRO and BOM (2007) 'high' wind speed increase scenario. This scenario considers a sea level rise of 0.82 m and an increase in wind speed of 19% by 2100. The resulting storm tide levels are a combination of storm surge, peak tide and sea level rise. Table 3 below shows the storm tide components and peak storm tide levels for 10% and 1% AEP events at Port Fairy. The increase in the 10% AEP and 1% AEP storm tide heights by 2100 compared to current conditions was 1.03 m and 1.04 m respectively (a combination of sea level rise and storm surge increase).

Tab.3: CSIRO (McInnes et al, 2009) Storm Tide Statistics

Climate Scenario	AEP (%)	ARI (1 in yr)	Port Fairy Storm Tide Level (m AHD)	Components of Storm Tide (m)		
				Storm surge	Tide	Sea level rise
Current	10	10	0.83	0.56	0.27	0
CSIRO Scenario 2	10	10	1.86	0.77	0.27	0.82
Current	1	100	1.05	0.60	0.45	0
CSIRO Scenario 2	1	100	2.09	0.82	0.45	0.82

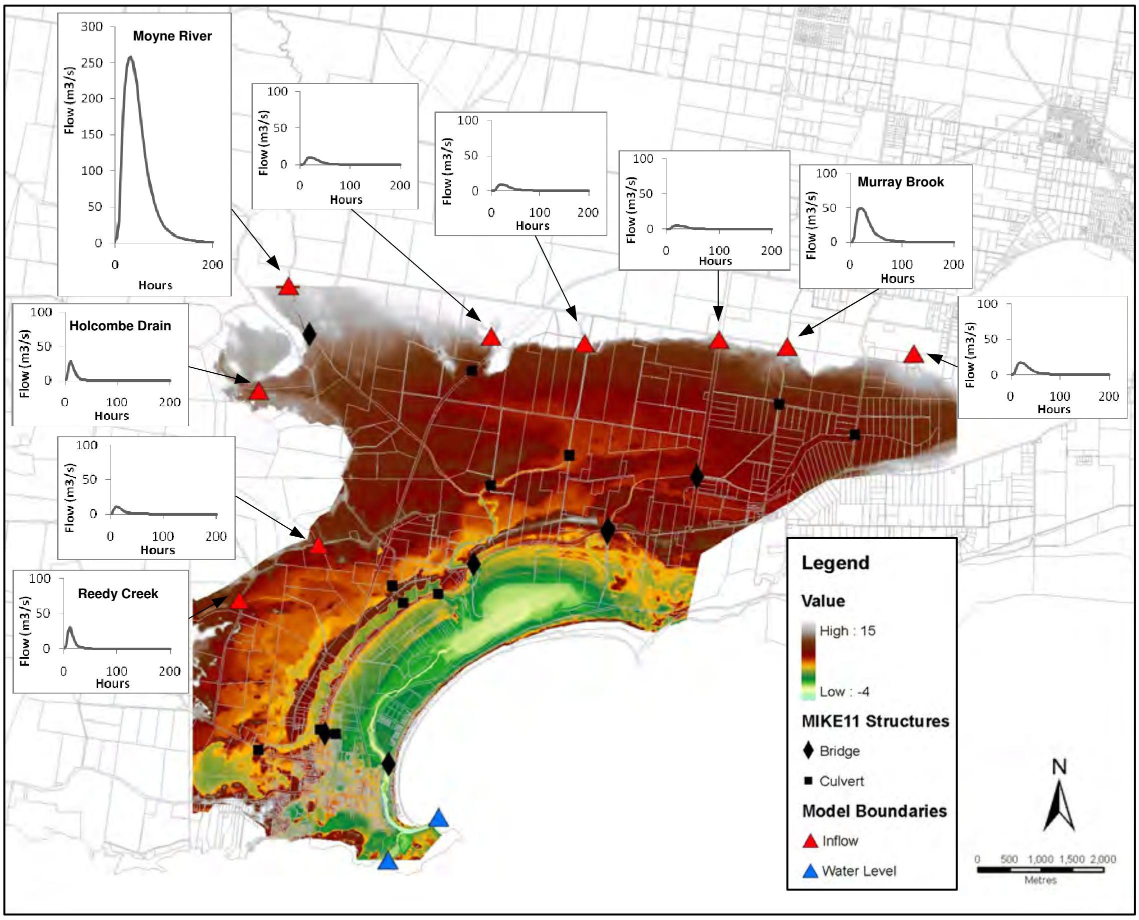

Fig. 2: Model Structure and 1% AEP inflow boundary conditions

A dynamic downstream water level boundary was employed to represent the dynamic pattern of storm surge and tide effects. Coastal flood studies commonly use a static downstream boundary set at the peak design water level. However this method results in overly conservative flood level estimates as the effect of the peak water level can fully propagate throughout the estuary. Under real storm conditions the peak water level is generally short-lived and its effect is greatest near the estuary mouth and diminishes with distance upstream. A more realistic, yet still conservative, estimate of flood levels can be obtained using a dynamic downstream boundary of simulated tide and storm surge.

In order to develop the dynamic storm tide boundary, a 72 hour period storm was assumed. This is consistent with the typical storm surge durations observed along the Victorian coast. A sinusoidal storm surge curve was superimposed on a typical tidal signal and sea level rise of 0.82 m. The tidal signal was based on observed tides from the nearby Port of Portland, but with the peak tide reconciled to the CSIRO modelled Port Fairy tide as shown in Table 3 above. The peak of the surge and tide were timed to coincide producing the design sea surface elevations listed in Table 2. The peak water level was also timed to coincide approximately with the peak flood flow in the estuary. The water level boundaries for the 10% AEP storm tide for current conditions and the 10% and 1% AEP storm tide for 2100 CSIRO Scenario 2 conditions are shown in Figure 3.

The modelling was also run with a static downstream boundary at the peak storm tide level to allow a comparison with the dynamic boundary results.

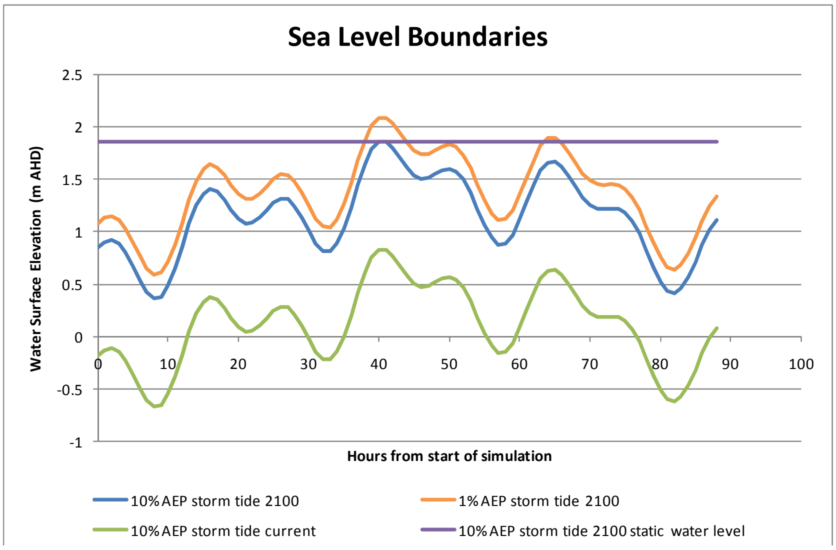

Fig. 3: Dynamic storm tide boundary for 10% and 1% AEP (10 yr and 100 yr ARI) events

Correlation of Storm Tide with Annual Flood Peaks

The incidence of heavy rain (and hence flooding) in the catchment would be expected to be correlated to some degree with increased storm surge at the catchment outlet, as they are often driven by the same meteorological processes. For this study, the 1% AEP design flood was modelled in conjunction with the 10% AEP storm surge, as recommended in Floodplain Management in Australia: Best Practice Principles and Guidelines (SCARM Report 73, 2000). To validate the use of this combination of flood and sea level conditions, a detailed analysis of sea level records and flow gauging was undertaken for the Port Fairy Regional Flood Study (Water Technology, 2008). This analysis compared recorded sea levels at Portland with peak annual gauged flows for the Moyne River at Toolong, over the period 1982 to 1998. Recently, additional sea level records from Portland have become available for 1946 that had not been previously discovered, allowing the extreme flood of March 1946 to be included in the analysis.

The March 1946 flood was a landmark event in south-west Victoria, causing major flooding across the region including the localities of Hamilton, Harrow, Casterton, Heywood, Dartmoor, Portland, Macarthur, Port Fairy and Warrnambool. It has been estimated to have a recurrence interval of between 500 and 1000 years for the adjacent Moyne River (Port Fairy) and Merri River (Warrnambool) catchments. Three day rainfall totals in the Moyne River catchment were generally between 180 mm and 260 mm. Available tidal data at Portland for March 1946 allows a unique opportunity to analyse the correlation of storm surge with a very deep low pressure system causing record heavy rainfall in the region.

Portland is located on the south-west Victorian coastline approximately 55 kilometres to the west of Port Fairy. Portland has a relatively long tidal record, and along with Port Fairy is a site for which CSIRO (McInnes *et al*, 2009) has modelled storm tides for current, 2030, 2070 and 2100 conditions as shown in Table 4 below. As can be seen, the differences in storm tide levels between Portland and Port Fairy are less than 0.1m for all scenarios, and hence the storm tide 1946 tidal record at Portland can be considered as representative for conditions at Port Fairy.

To undertake the analysis tidal predictions were made using tidal constituents derived from the observed record by a harmonic analysis, and subtracted from the recorded levels in order to compute the tidal residual (storm surge). The results indicated that there was virtually no storm surge impact at Portland at the time of the flood. Due to proximity and the open coastline between the sites, it can therefore be reasonably assumed that no significant storm-surge occurred at Port Fairy over the same period.

Tab.4: CSIRO (McInnes *et al*, 2009) 1% AEP storm tide heights (m AHD) for Portland and Port Fairy for Current Climate, 2030, 2070 and 2100 under future climate scenarios 1-4

Location	Current Climate	2030			2070			2100			
		1	2	3	1	2	3	1	2	3	4
Portland	1.01	1.16	1.22	1.21	1.48	1.61	1.71	1.83	2.05	2.11	2.41
Port Fairy	1.05	1.20	1.25	1.25	1.52	1.67	1.75	1.87	2.09	2.15	2.45

The results of the 1946 flood and tide analysis combined with the previous 1982-1998 data are shown in Figure 4 below. This suggests that the observed tide residuals for annual flood peaks are commonly less than the 10% AEP storm surge of 0.83 m (McInnes *et al*, 2009). Based on this analysis the combination of the 1% AEP flood with the 10% AEP storm surge will give a conservative sea surface elevation (and hence model tailwater).

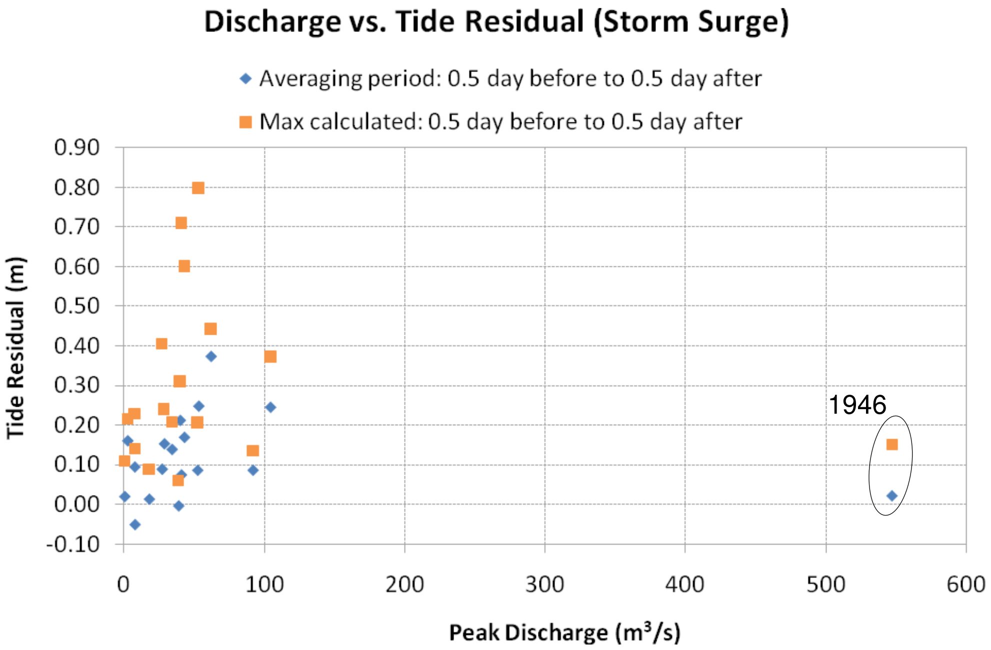

Fig. 4: Annual flood peaks and coinciding storm surge (tide residual) at Portland, VIC

RESULTS

Effect of Sea Level Rise on Flood Levels

Under the Sea Level Rise scenario, the peak ocean water level was raised by 1.03 m. The effect of sea level rise on the 1% AEP (100 year ARI) flood extent and water surface elevation is illustrated in the plan and longitudinal section in Figure 5. The sea level rise effect is most pronounced in the port section of the estuary between the river mouth and the Gipps Street bridge. On the downstream side of the Gipps Street Bridge the difference in water level is approximately 0.48 m, and decreases to approximately 0.2m in Belfast Lough. Upstream of Belfast Lough the sea level rise effect diminishes rapidly due to the steep channel gradient, as can be seen north of the Princes Highway Bridge where only minor differences in flood water level occur.

The effect of the raised water level on the flood extent is greatest around the north-western margin of Belfast Lough near Model Lane where gradients are fairly flat, along the narrow river channel through the port, and also around the low-lying wetland adjacent to the South Passage where the raised floodwater spills out of the channel onto the surrounding flat land. The flooding behaviour through the port is of particular concern because of the high level of development and habitation adjacent to the channel. Under current conditions the 1% AEP floodwaters are confined to the channel, but under sea level rise the floodplain will also be inundated by a flood of this magnitude.

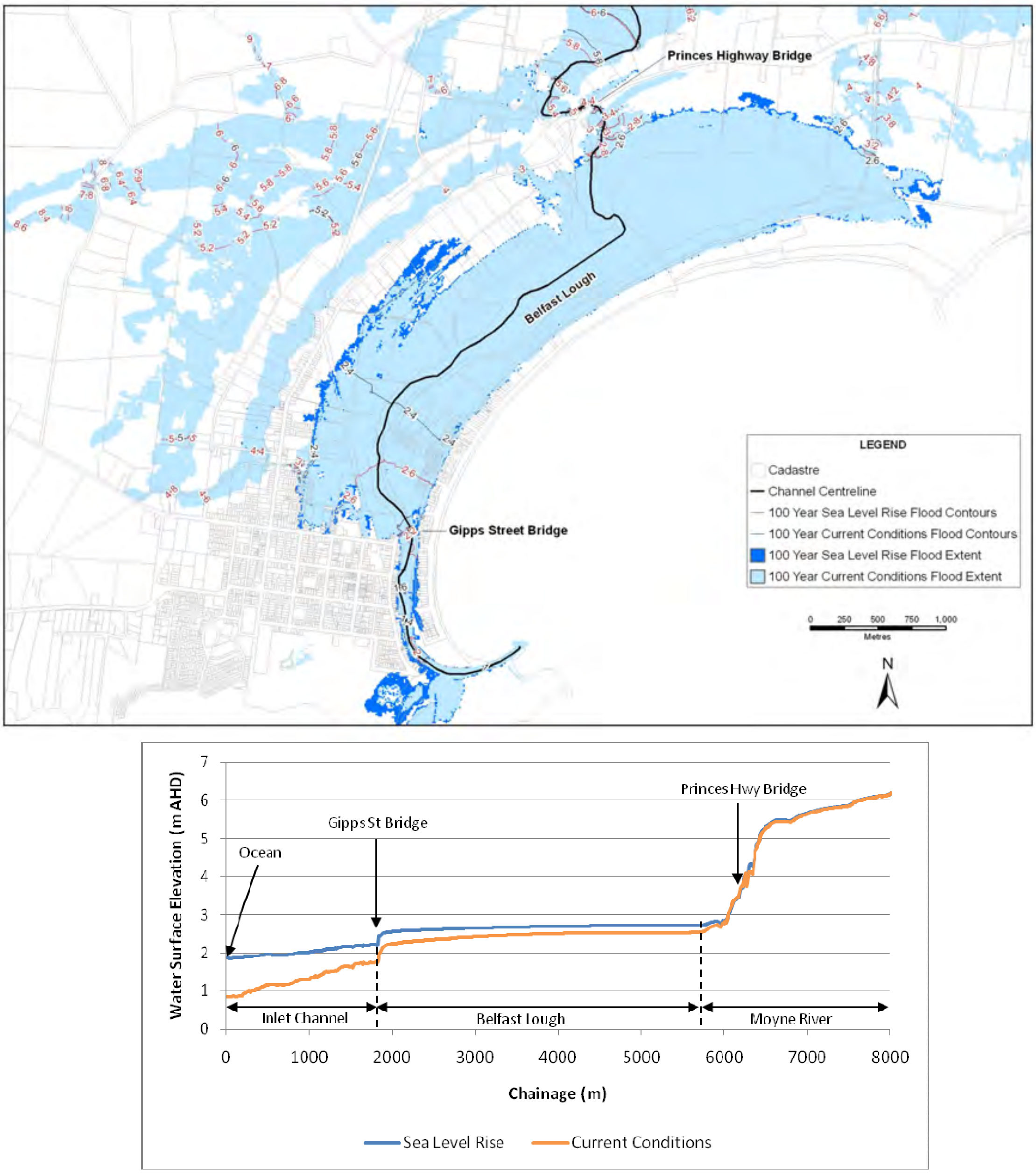

Fig. 5: Comparison of the extent and level of the 1% AEP (100 year ARI) flood under current conditions and with sea level rise. The longitudinal section is taken along the channel centreline from chainage 0 at the ocean outlet.

Effect of Dynamic Ocean Water Level Boundary

The use of a dynamic ocean water level boundary simulating tide and storm surge patterns leads to a less conservative estimate of flood levels in the estuary. The modelled 1% AEP flood levels with a static and dynamic boundary condition are compared in Figure 6. The use of the dynamic downstream ocean water level results in lower peak flood levels, with these increases greatest in Belfast Lough and tapering to zero downstream of the Gipps Street bridge. Modelled water levels within the Lough are lowered by up to 0.10 m. Modelled extents are decreased slightly by using a dynamic water level, mostly around the north-western margin of Belfast Lough.

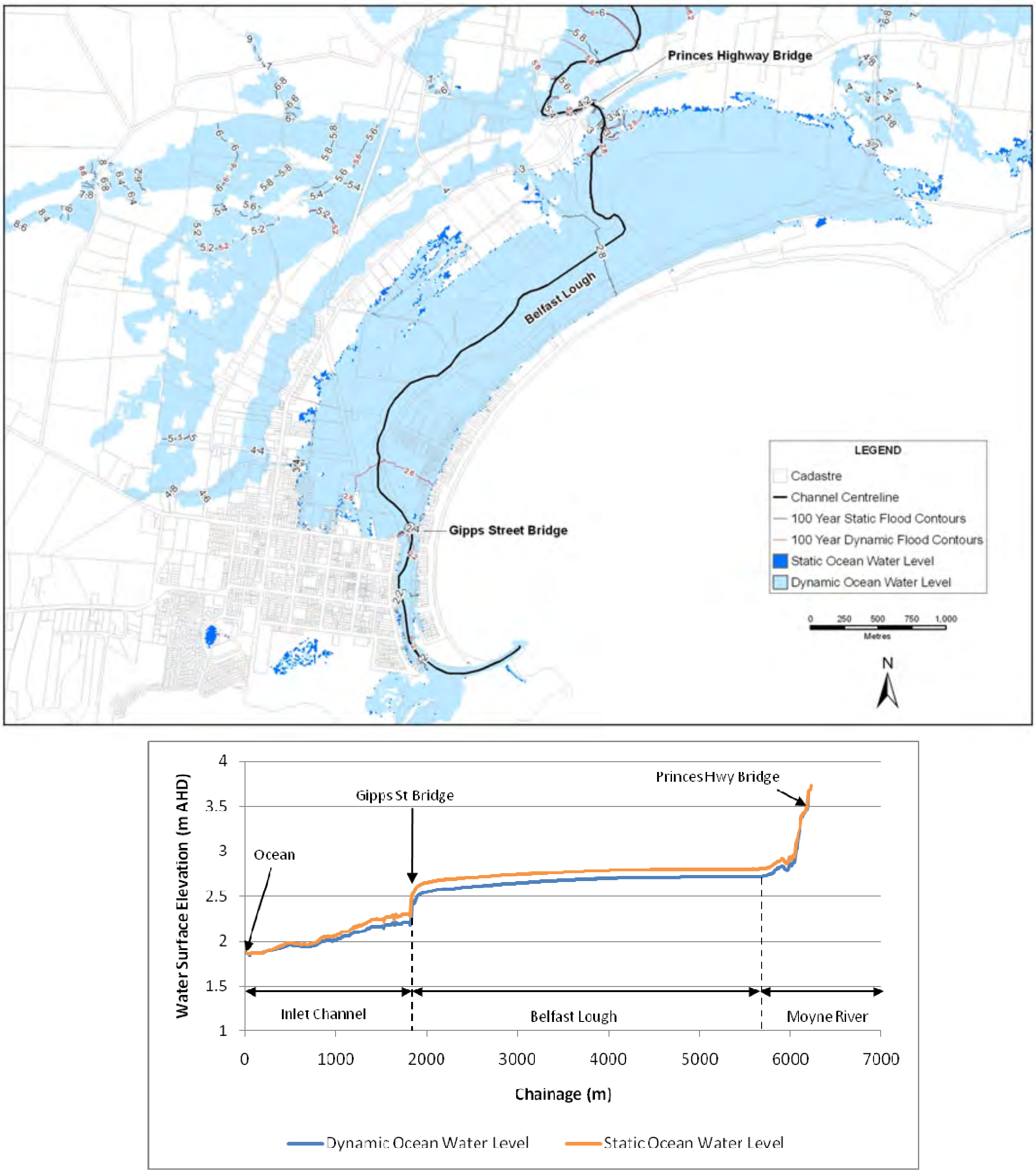

Fig.6: Comparison of the 1% AEP (100year ARI) flood with sea level rise with a static and dynamic ocean water boundary condition. The longitudinal section is taken along the channel centreline from chainage 0 at the ocean outlet.

Balance of Flood and Storm Tide Risk under Sea Level Rise Conditions

The modelled 1% AEP (100 year ARI) flood and storm tide extents and levels are shown in Figure 7. The storm tide causes a much flatter water surface profile through the estuary than the flood. Due to the transient nature of the peak storm tide level and constrictions posed by the Gipps Street bridge and narrow river channel through the port, there is not enough time for the peak level to completely propagate into Belfast Lough. Figure 7 shows that peak storm tide levels in Belfast Lough are around 0.1 m lower than at the ocean entrance of the Moyne River.

The storm tide is the dominant flooding mechanism between the river mouth and a point opposite Cox Street in the narrow port section of the river channel – that is, the 1% AEP storm

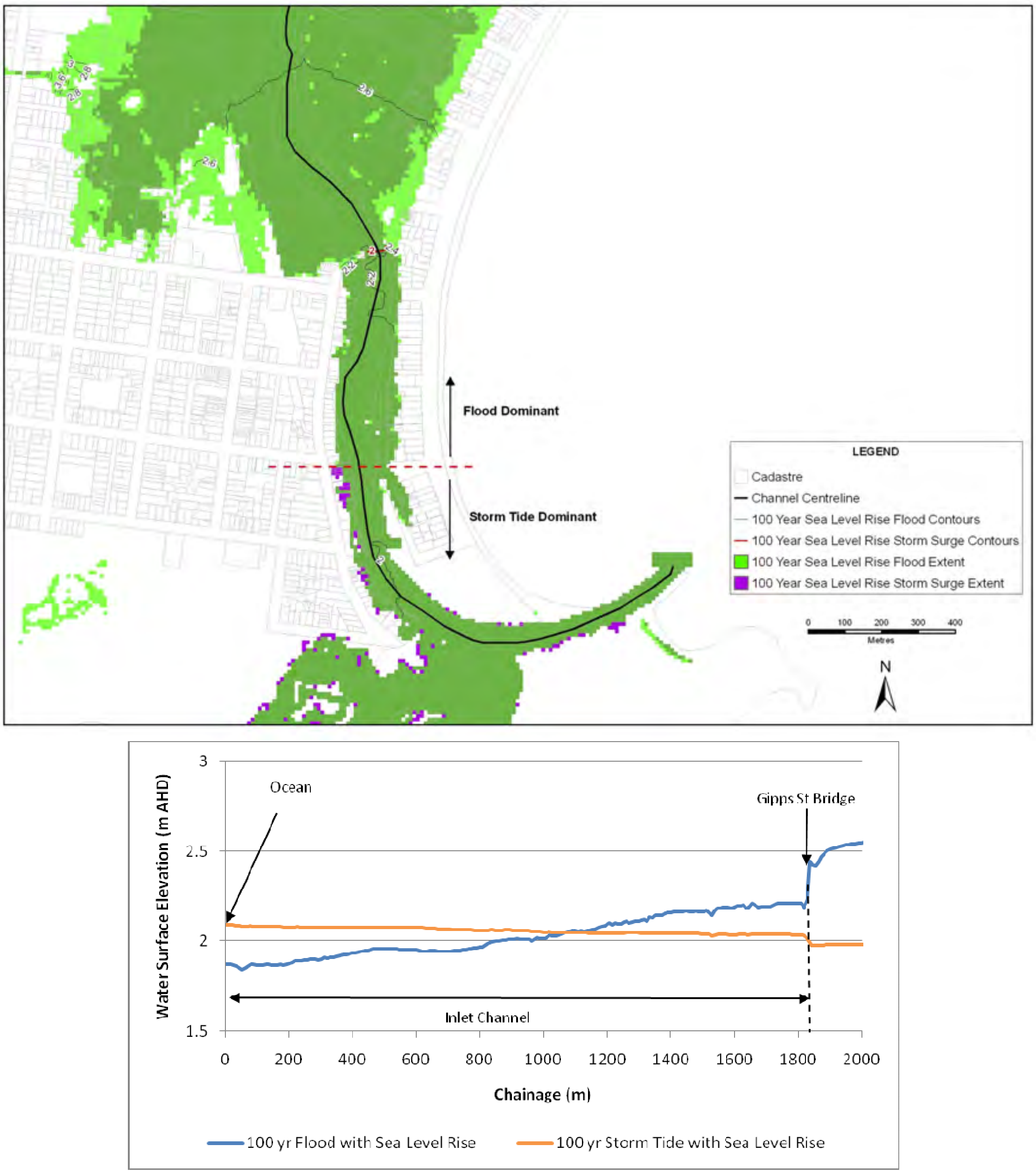

Fig.7: Comparison of the 1% AEP (100year ARI) flood and storm tide inundation with sea level rise. The longitudinal section is taken along the channel centreline from chainage 0 at the ocean outlet.

tide inundation levels are higher than the corresponding catchment-sourced flood levels - as indicated in Figure 7. Upstream of this transition point the catchment-sourced riverine flood is the dominant flood mechanism. However it must be noted that areas subject to inundation from both flood and storm tide have a greater risk of inundation than those subject to one or the other (given that our analysis suggests these two flood mechanisms, at the extreme range, can be considered mutually exclusive). This applies particularly to properties adjacent to the river channel between the Gipps Street bridge and the river mouth, where risk associated with both mechanisms is high.

DISCUSSION AND CONCLUSIONS

These investigations show that predicted sea level rise may have a significant local impact on peak flood levels within an estuary. The impacts are non-linear and may be dramatically over-estimated if, for example, an increase in tailwater level is applied uniformly to existing flood levels within an estuary. As demonstrated in Fig. 5, sea level rise impacts for the Moyne River at Port Fairy progressively diminish from the ocean entrance heading upstream through the estuary. In this case, the sea level rise effect extends 6 kilometres upstream.

The extent of sea level rise impact through an estuary will be determined by the hydraulics of each particular system. Estuaries with good hydraulic connectivity to the ocean and low flood surface gradients will tend to be more effected that those with more hydraulically constricted floodplains that exhibit steeper backwater flood profiles.

The peculiarities of the Port Fairy estuary – the narrow channel, Gipps Street bridge constriction and Belfast Lough – may limit the applicability of specific results of this study to other areas. In two other flood studies undertaken by Water Technology in south-west Victoria, similar results were found in the hydraulically similar Merri River estuary [Water technology 2007], (which has a narrow channel between the river mouth and the extensive Kelly's Swamp, crossed by a number of bridges), while in the dissimilar Surry River estuary [Water technology 2008b] the steep flood gradient at the river mouth results in only very minor local increases in flood levels and extents due to sea level rise.

The use of a dynamic ocean level boundary condition has been shown to reduce over-estimation of flood levels by up to 0.10 metres in the Port Fairy case study, however the resulting flood levels are still considered to be conservative because of the use of a 10% AEP storm tide boundary condition coinciding with the peak flood flow.

The implications of sea level rise for coastal townships are significant given that development situated on the flood fringe is typically sensitive to relatively small changes in flood level. The relationship between flood level and flood risk is highly non-linear, so that a small rise in flood levels can result in a large increase in flood risk. Flood risk is sensitive to water level increase where the following occurs:

- Floor levels are currently only slightly above the current 1% AEP flood level.
- Constructed flood mitigation levees or natural ridgeline barriers are only marginally above current 1% AEP flood levels
- Land fringing the current known 1% AEP flood extent has a flat gradient

The impact on planning can subsequently be dramatic as a 0.8 m rise would exceed the typical freeboard allowance of 300 to 600 mm above the present 100 year ARI flood levels. Inclusion of investigation of sea level rise in flood studies for coastal communities will enable flood risk to be identified in line with the 2008 Victorian Coastal Strategy, and allow land use and development planning to be proactive in light of increasing flood risk due to sea level rise.

Due to increases in flood level over time flood mitigation options designed for 2010 conditions may not be appropriate for conditions expected in 2100, however investigation of the effect of sea level rise on flood levels (particularly if 2030 and 2070 scenarios are also included) may identify the areas impacted first as sea levels rise, and hence allow prioritisation and staging of mitigation works. It must also be considered that some works to mitigate riverine flood effects, such as increasing the hydraulic capacity of the Gipps Street bridge at Port Fairy to reduce riverine flood levels in Belfast Lough, may also result in increasing storm tide flood risk, in this case upstream of the bridge.

In areas susceptible to both catchment flooding and storm tide inundation, flood risks may be compounded when these two mechanisms are largely independent, as demonstrated at Port Fairy. Even though storm tide levels were found to be lower for most of the Moyne River Estuary, its contribution to flood risk needs to be acknowledged. Current 1 in 100 year flood extents for planning purposes consider only the probability of catchment sourced flooding, but ideally the two mechanisms should be considered in a joint probability analysis. For example, a property outside the current 1 in 100 year (1% AEP) flood extent might actually have a greater than 1% chance of flooding in any year due to the combination of flood and storm surge probabilities. It should also be investigated whether current freeboard allowances are enough to account for this elevated flood risk in estuarine areas.

Flood warning systems in estuarine areas need to be designed to consider these two flooding mechanisms (storm tide and catchment-sourced flooding). This also has implications for data collection – more tidal gauges may be warranted to collect baseline data, enable analysis of correlation between storm tides and catchment based flooding for particular flood events in particular river systems, and to facilitate storm tide flood warning.

At this point in time it is as yet unclear whether Land Subject to Inundation Overlay (LSIO) and Floodway extents should reflect 2010 (current) or 2100 (a snapshot of potential future climate change) flooding conditions. As an increasing amount of flood data including the effect of sea level rise is now becoming available, guidance from State Government on this issue is timely to ensure flood-related planning scheme amendments can proceed. While the increases in flood levels can be significant, they are also projected to occur gradually over decades, and hence councils and floodplain management authorities have many years to implement flood risk mitigation strategies. The most effective strategy is to avoid development in locations that will become increasingly flood-prone over time, and hence recognition of flood risk in the planning scheme within the short term is paramount.

With respect to allowance for predicted sea level rise associated with climate change it is useful to note that the selection of 2100 as a reasonable planning horizon is somewhat arbitrary. Under present IPPC advice, sea level rise is predicted to continue well beyond 2100 and indeed the rate of rise is expected to accelerate significantly after this time. This suggests that testing of a range of climate change scenarios (in the same way that a range of flood ARI's are generally incorporated into flood modelling studies) should be undertaken. This will inform a deeper understanding of risk to the floodplain by analysing likelihood and consequences over a range of inundation scenarios.

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