THE HYDRAULIC AND MORPHOLOGICAL RESPONSE OF A LARGE COASTAL LAKE TO RISING SEA LEVELS

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ABSTRACT

The hydraulic and morphological response of a large coastal lake system on the Australian east coast is assessed in regards to rising mean sea levels. The relative influence of sea level rise (SLR) in relation to other significant anthropogenic perturbation to the ocean inlet is investigated. Numerical modelling techniques are used to assist in predicting the likely behaviour of tides and estuarine flushing based on a hypothetical inlet channel configuration following sea level rise.

The estuary examined in this paper is Lake Macquarie, a large coastal lake on the central coast of NSW.

The analysis indicates that the tidal range within the lake could be expected to double by the year 2100 (for a SLR scenario of 0.91 m), and is associated with a 225% larger tidal prism. The predicted increase in the volume of the tidal prism is estimated to be equally attributed to SLR and the continuation of inlet scour currently occurring in response to entrance training. Mean levels in the lake are expected to rise by an amount similar to the predicted SLR.

Lake flushing is indicated by modelling to be enhanced under sea level rise, possibly improving the water quality of the estuary but altering estuarine ecosystem characteristics.

The findings of this paper have significant ramifications for the planning and management of this and other estuaries and associated floodplains in relation to both the built and natural environments. Specific examples include the extent of land subject to inundation risk, future navigational dredging requirements and the impact on fringing ecologies.

INTRODUCTION

SLR may affect the tidal response of large estuaries by increasing the volume of the tidal prism. The feedback between the larger tidal prism and higher channel velocities may lead to accelerated rates of scour (deepening and widening) of the channel. On the other hand, the rate of SLR may be comparable with the rate of morphological evolution of the estuary and the channel will have the capacity to adapt, resulting in little or no change in the tidal prism.

The latter would require a supply of suitably sized sediment as the channel bed would need to rise at a rate similar to that of SLR.

Lake Macquarie, one of the largest coastal lakes in eastern Australia, is located between Newcastle and Gosford on the NSW Central Coast. It is characterised by a large main body of water (approximately 110 km^2) connected to the Pacific Ocean via the relatively narrow Swansea Channel (see Figure 1). The channel is 4.5 km long with an average depth of around 1.9 m and average width of around 400 m. Swansea Bridge, a low level road bridge with an opening double lifting span, crosses the channel.

Figure 1: Swansea Channel (foreground), Lake Macquarie (background). Source photo: NSW Government.

In this paper the behaviour of Lake Macquarie is examined using both measurements and modelling with the aim of making informed predictions of the future morphological change of Swansea Channel. Estimates are then made of potential changes to the tidal regime and flushing under a SLR scenario of 0.91 m for the year 2100.

ESTUARY STABILITY AND CHANNEL CONFIGURATION

Estuaries are typically in a constant state of flux responding to changes such as the spring/neap tidal cycle, episodic flood discharges, coastal storms and anthropogenic perturbations. The sensitivity of the estuarine response to such perturbations depends primarily on the size of the estuary (Nielsen & Gordon, 2008). A stable estuary is defined as having a tidal discharge and channel cross-sectional area that vary about stable average values. The apparent stability of Lake Macquarie is due to its large hydrodynamic mass. Unlike ICOLLs (Intermittently Closed and Open Lakes and Lagoons), Lake Macquarie responds slowly to perturbations and changes may go unnoticed.

The current morphology of Swansea Channel is not in a stable equilibrium state. Evidence indicates that Lake Macquarie has been in an unstable scouring mode since the construction of training walls at the entrance over 120 years ago. Prior to the breakwater construction, the inlet to Lake Macquarie was choked with littoral drift sand and barely navigable (Figure 2(a)). Since construction, there has been a long history of dredging, reclamation and foreshore protection works undertaken to address the problems caused by the slow but persistently evolving channel. The changes to the form of the channel can be seen by comparing the aerial photographs (Figure 2(b), (c) and (d)) and the survey plan prior to breakwater construction (Figure 2(a)).

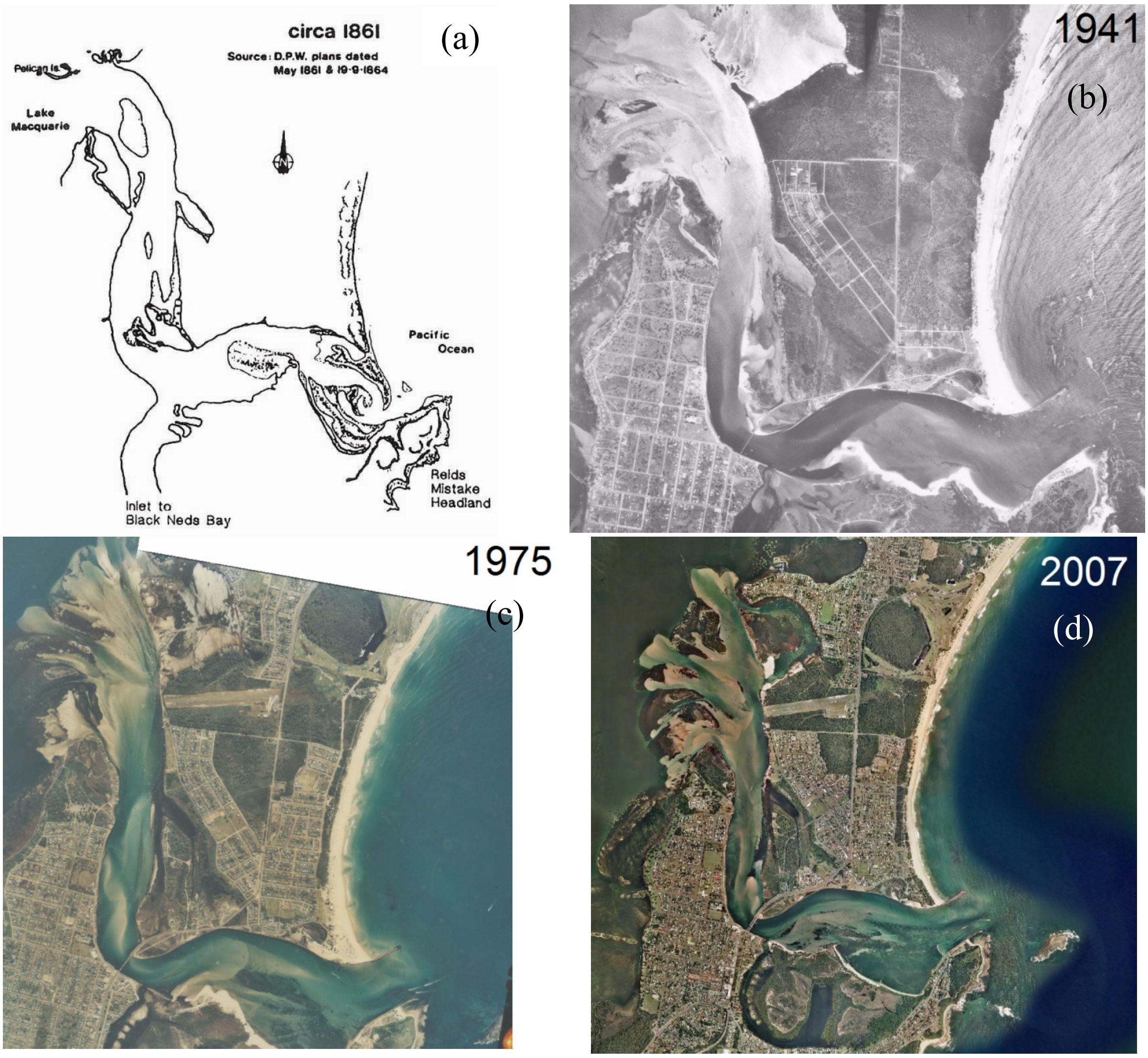

Figure 2: Swansea Channel (a) prior to breakwater construction (b) 1941 (c) 1975 and (d) 2007 (source: NSW Government).

Nielsen and Gordon (2008) recently used the time history of amplitude and phase of tidal constituents within large estuaries along with classic estuary stability theory to predict that the tidal range in Lake Macquarie could eventually reach around 77 % of the ocean tidal range. Currently the lake's tidal range is less than 10% of that in the ocean. Based on the current rate of change, this could take some 650 years. This estimated time scale indicates that morphological evolution of the inlet channel to Lake Macquarie is likely to be measured in centuries.

Observed tidal regime change

Long-term water level records are valuable in determining subtle changes in the tidal regime of an estuary.

The tidal regime of an estuary can be well described by the tidal range as calculated from the amplitude of the major tidal constituents measured within the estuary. For example, increasing amplitudes of the major constituents within an estuary (and subsequently tidal range) would indicate that the tidal prism is increasing in volume.

Tidal analysis was conducted on the long-term measured water level data available for a NSW open ocean site and two sites within Lake Macquarie.

The progression of the ratio of mean spring tidal range for both lake sites with that of the open ocean (Camp Cove) over a 22 year period is shown in Figure 3. The steady rise of this ratio for both lake sites during a time of static ocean tidal range indicates that the spring tidal range has steadily increased in Lake Macquarie over the period of record at a rate of 0.0012 per annum for Belmont and 0.0011 per annum for Marmong Point. These values agree well with the 0.0012 per annum reported by Nielsen and Gordon (2008).

In 2008, the mean spring tide range was 1.23 m and 0.12 m in the ocean and lake, respectively. The ratio of the lake to ocean mean spring tide range was 0.096, i.e., the lake experienced approximately 10 % of the typical spring tidal range observed on the open coast. If it is assumed that the tidal regime in the ocean has remained essentially static and that the rate of change of the lake to ocean ratio of 0.0012 per annum (or 0.12 %) was representative of future change, it would take approximately 80 years for the lake's tidal range to double.

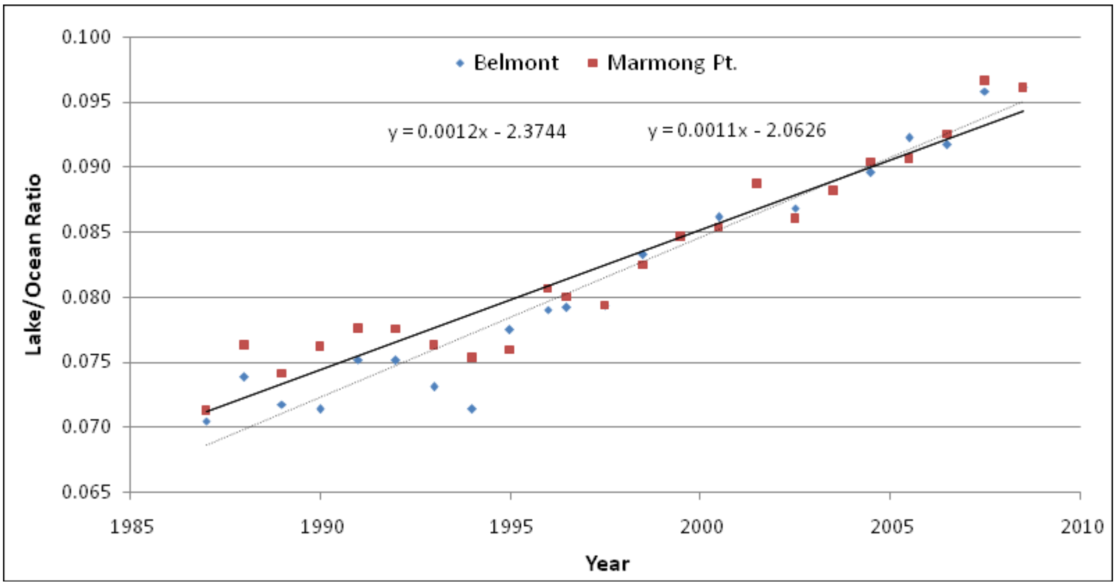

Figure 3. Lake / ocean tidal range ratio change over time for Lake Macquarie, NSW.

Observed morphological change in Swansea Channel

Two complete hydrographic surveys of Swansea Channel were available for this study. These were:

- *April 1996* hydrographic survey undertaken by the then Department of Land and Water Conservation (DLWC); and
- *August 2008* marine LiDAR survey undertaken by the Department of Environment, Climate Change and Water (DECCW).

A check of these two surveys in areas where negligible bed level change is expected (e.g., the lake proper) indicates that the surveys are sufficiently accurate to allow comparison. A snapshot of the morphological change (both natural and anthropogenic) over the 12.4 year period between surveys is provided by taking the 1996 bed levels from the 2008 bed levels (Figure 4).

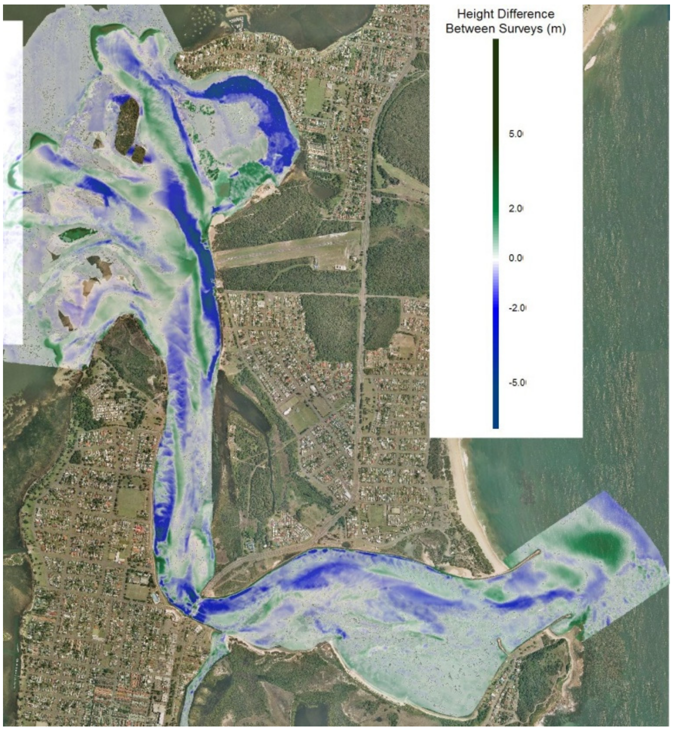

Figure 4: Bed level change between 1996 and 2008 surveys, Swansea Channel.

The general patterns of long-term morphological change observed in Swansea Channel between 1996 and 2008 can be described as:

- overall scour (and dredging) of the channel has removed sediments, making the channel more hydraulically efficient;
- there has been net export of sediment at either end of the channel. At the ocean entrance, deposition has occurred on the seaward slope of the entrance bar (Figure 5a). At the lake end, deposition has occurred on the lakeward slope of the dropovers (Figure 5b);
- deepening and widening of the main channels have occurred both downstream (Figure 5c) and upstream (Figure 5d) of the bridge; and
- shoals have generally been maintained with shifting and growth in some areas.

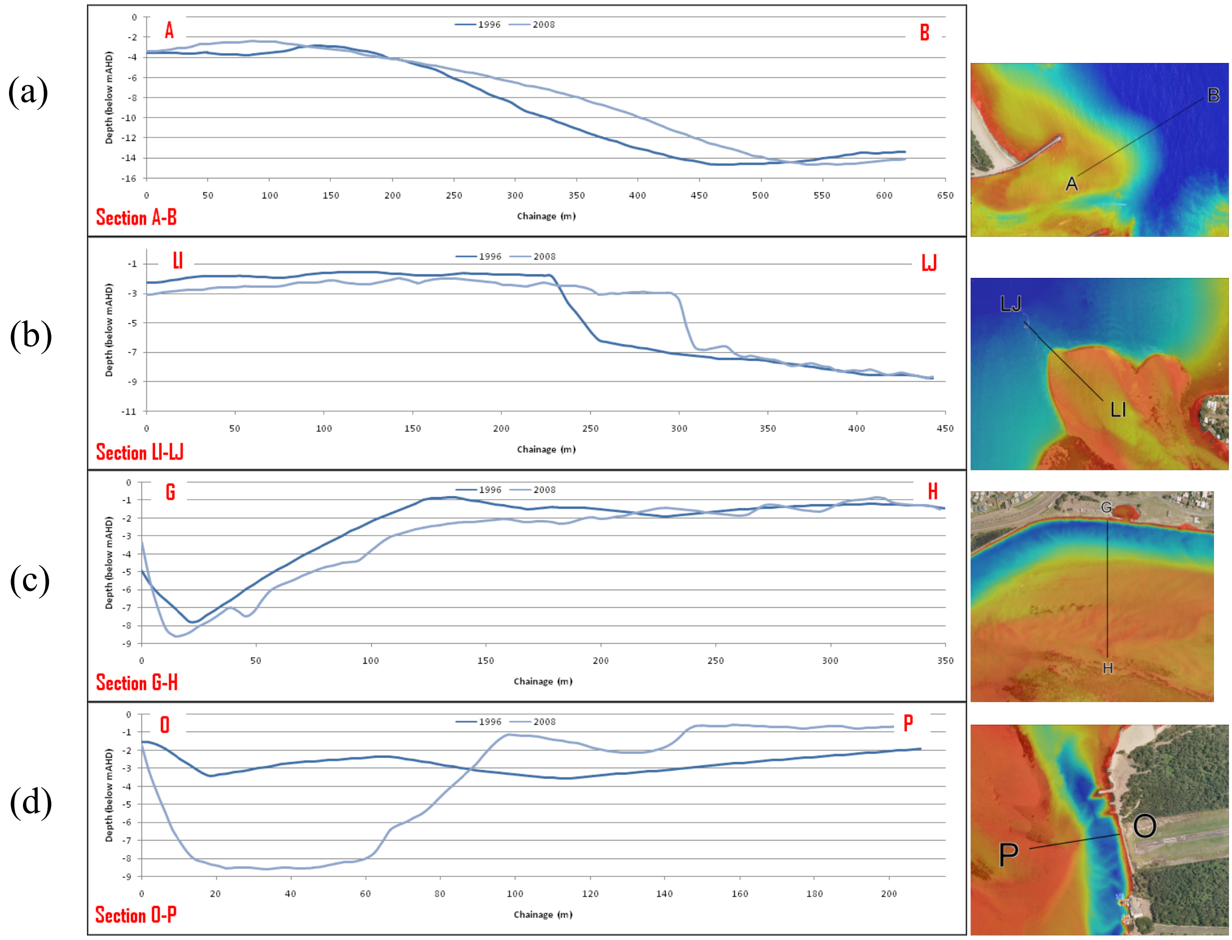

Figure 5. Cross-sectional comparison of 1996 and 2008 survey: (a) entrance bar, (b) dropovers, (c) downstream of Swansea Bridge; and (d) upstream of Swansea Bridge.

Volume changes between the 1996 and 2008 surveys were estimated using the *12D* terrain modelling software (12d Solutions, 2009). Table 1 presents the net volume change and the annual rate of volume change for the Swansea Channel area and the depositional areas observed at either end of the channel. A net loss of about 540 000 m^3 was observed within Swansea Channel over the approximate 12 year period between surveys. As indicated in Table 1, this net loss is attributed to both natural sediment loss through scour and removal by various dredging operations during this period (WBM, 2005 and Haines & Blumberg, 2007). The natural net loss of sediment from downstream and upstream of the bridge provide reasonable agreement with the net deposition observed on the entrance bar and lake dropovers, respectively. The general pattern of erosion and accretion observed indicates that Swansea Channel is experiencing scour and that sand transport is occurring in both seaward and lakeward directions.

Table 1. Net volume change in Swansea Channel between 1996 and 2008.

Location	Net Volume Change (m^3)	Rate of Volume Change (m^3/yr)
Swansea Channel	-539 700	-43 524
Natural net loss downstream of bridge	*-149 700*	*-12 073*
Natural net loss upstream of bridge	*-180 000*	*-14 516*
Removal by dredging	*-210 000*	*-16 935*
Entrance bar	+139 850	+11 654
Dropovers	+148 331	+12 361

Model system

The 2D/3D capabilities of the MIKE coastal modelling system (DHI, 2009) have been utilised to simulate free surface flows, wave and sediment transport in Lake Macquarie. The MIKE 21 model domain of Lake Macquarie covers the lake proper, Swansea Channel and extends offshore to the 100 m depth contour. As future elevated mean sea level scenarios were examined, the model included low-lying land (to a level of 4 m AHD (Australian Height Datum)) surrounding the lake and channel. The model's ocean boundary was forced using measured water levels recorded at Camp Cove tidal gauge, Sydney.

The 2D hydrodynamic model was calibrated against water level, discharge and current data collected in 1996. Verification was undertaken for 2008 conditions using measured water levels for a 37 day period over the month of August. Very good agreement was reached between modelled and measured values during the model calibration and verification periods, with errors in tidal amplitude and phase generally less than 5%. Based on the good agreement between modelled and measured data, in both calibration and verification, the hydrodynamic model of Lake Macquarie was considered calibrated and fit for further application.

Wave (MIKE 21 SW (Spectral Wave)) and sediment transport (MIKE 21 ST (Sand Transport)) modules were also employed for parts of this assessment.

Tidal velocity asymmetry

Estuarine morphology is to a large extent determined by the residual (or net) sediment transport patterns. Inversely, residual sediment transport depends on differences in the magnitude and duration of ebb and flood currents. Such differences ('tidal asymmetry') are produced by distortion of the tidal wave in the shallow waters of the coastal shelf and as it enters an estuary. As such, estuaries experience a feedback relationship between their morphology and the current velocities generated inside them. The nature of this feedback is investigated for Lake Macquarie so that the implications of sea level rise can be deduced in a broad sense.

The modelled pattern of peak spring tidal current speed differences for existing conditions (2008) (Figure 6) was calculated for Swansea Channel by vector addition. In terms of peak tidal currents, Swansea Channel can generally be described as having ebb dominance downstream of Swansea Bridge and a strong flood dominance upstream of the bridge.

The comparison of peak tidal velocities does not take into account the duration of such velocities. In order to overcome this, net tidal excursion was calculated for four locations along the channel (Figure 6). To exclude times when there is negligible sediment movement (i.e., at relatively low velocities), a threshold was introduced ($V_{critical}$ = 0.5 m/s) and the area under the velocity curve above the threshold was calculated to find respective flood and ebb excursions. Taking the difference between the flood and ebb values gives the net excursion, with positive values indicating flood dominance and negative values ebb dominance. Net tidal excursion was calculated for both existing conditions (2008) and predicted future conditions in the year 2100 based on a 0.91 m SLR scenario (LMCC, 2008). The resulting estimates of ebb, flood and net tidal excursion values are presented in Table 2.

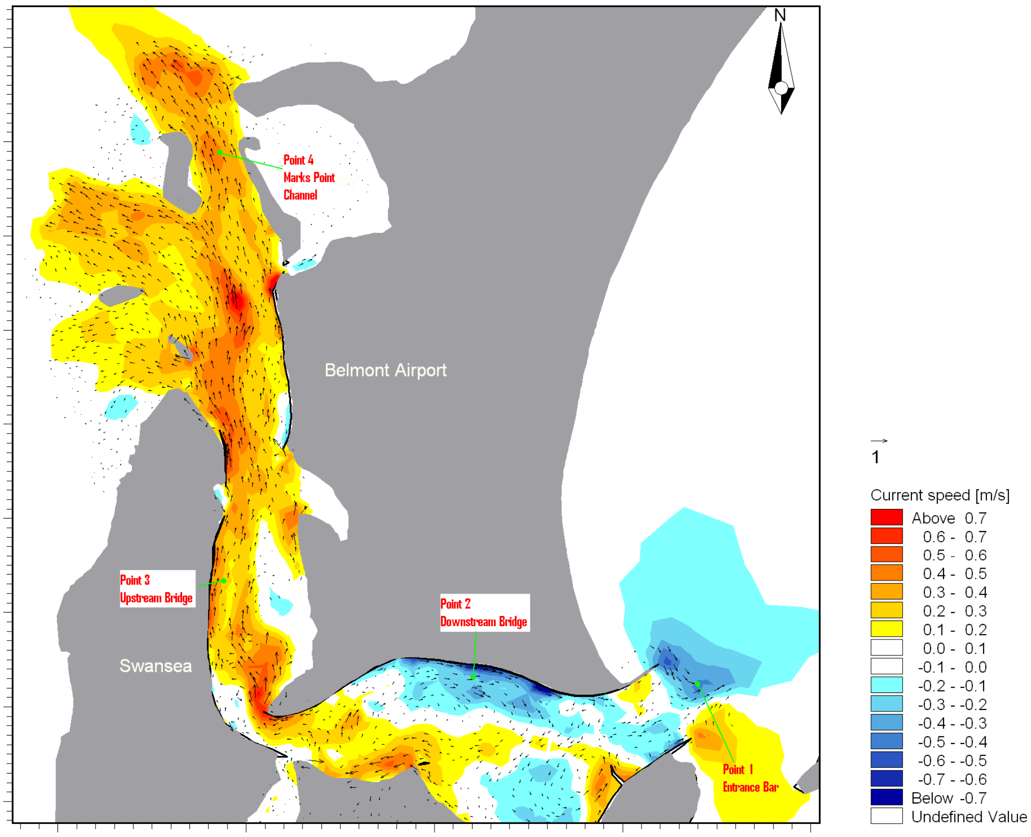

Figure 6. Peak current speed difference in Swansea Channel for existing conditions (2008).

Table 2. Tidal excursions for existing (2008) and SLR (2100) conditions

Scenario	Parameter	P1 Entrance Bar	P2 Downstream bridge	P3 Upstream bridge	P4 Marks Point Channel
Existing Conditions (2008)	Flood Excursion (m)	0	+2,500	+40,400	+68,430
	Ebb Excursion (m)	0	-20,450	-27,750	-47,640
	Net Excursion (m)	0	-17,950	+12,650	+20,790
	Dominance	-	**Ebb**	**Flood**	**Flood**
SLR Conditions (2100)	Flood Excursion (m)	0	+3,300	+78,350	+141,500
	Ebb Excursion (m)	-3,430	-10,760	-37,210	-94,080
	Net Excursion (m)	-3,430	-7,460	+41,140	+47,420
	Dominance	**Ebb**	**Ebb**	**Flood**	**Flood**

From Table 2, the pattern of ebb and flood tide dominance observed in Swansea Channel is the likely cause of the general pattern of observed erosion and deposition. The large flood tidal excursions seen upstream of the bridge (i.e., at P3 and P4) explains the net direction of sediment transport in this section of the channel. Progradation of the dropovers with sediment scoured from upstream of the bridge is a well documented observation in Swansea Channel (WBM, 2003).

The ebb tidal excursion found downstream of the bridge may provide an explanation for the observed scour occurring in this location and the deposition observed on the seaward side of the entrance bar. Under tidal conditions only, current speeds at P1 (entrance bar) are less than that required for significant sediment transport, and are indicative of an area of deposition. However, it is noted that an ebb dominant peak current regime over the entrance bar is indicated by the model. Wave penetration and relative importance of wave induced sediment transport are discussed in the next section. For SLR conditions, this general trend is predicted to continue, however, there is a reduction in the ebb dominance in the downstream sections of the channel and an increase in the magnitude of the flood dominance upstream of the bridge.

Wave penetration and sediment transport

While tidal currents are the primary mechanism for sediment transport in an estuary, in some areas wave action is also important in mobilising and transporting sediments. The entrance area of Swansea Channel is exposed to ocean waves and is potentially affected by wave action. This paper examines the potential influence of ocean waves on sediment transport processes at the entrance to Swansea Channel.

As sand sized sediment supply from the catchment is very limited, the availability of sediments to the channel from the ocean side is a key issue in determining the morphological response of Swansea Channel to SLR. Sediment transport potential can be enhanced by wave action, which increases the bed shear stresses particularly during wave breaking, acting to mobilise sediments. Once mobilised, sediments are transported by the prevailing current. Waves also create residual currents that can transport sediments. A example of a residual wave driven current is an alongshore current caused by waves approaching at an angle incident to the shoreline.

An uncalibrated coupled modelling approach was used to investigate the relative influence of waves on sediment transport in the entrance area. The uncalibrated nature of this modelling means that it can be used to assess the relative change in entrance currents and sediment transport but that absolute values cannot be considered reliable. Simulations were conducted for a range of significant wave heights (H_s) for waves originating from the dominant SSE swell direction and with the mean peak wave period (T_p) of 10 s. The modelled sediment transport flux through the entrance area over five typical spring tidal cycles is plotted in Figure 7. Table 3 gives the flood, ebb and net sediment transport loads through the entrance channel calculated by the model over five typical spring tide cycles. A net ebb sediment transport was calculated for all the wave conditions examined. Under the median wave condition, the net ebb sediment transport load was reduced by approximately 25 % (as compared to *'no wave'* or tidal only conditions), this ranged up to a reduction of almost 70 % for larger waves (H_s = 3.5 m).

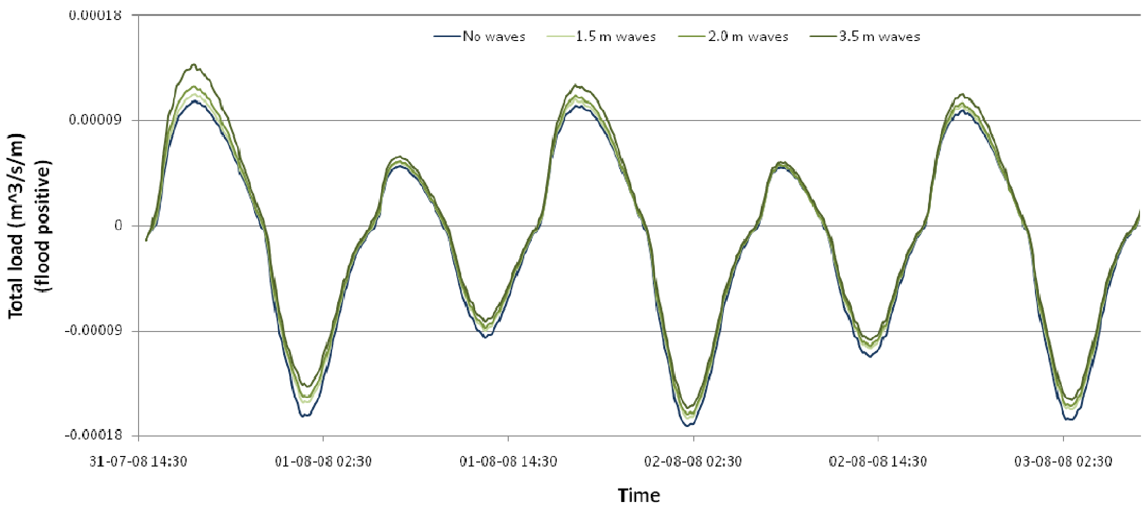

Figure 7. Modelled sediment transport rates across the entrance area for range of SSE wave conditions.

Table 3. Comparative sediment transport through the entrance area over five spring tides

	No waves	Median waves (H_s = 1.5 m)	75%ile waves (H_s = 2.0 m)	98%ile waves (H_s = 3.5 m)
Flood transport (m^3)	+2 262	+2 372	+2 463	+2 748
Ebb transport (m^3)	-3 853	-3 568	-3 467	-3 271
Net transport (m^3)	-1 591	-1 194	-1 004	-524
Direction of net transport	**ebb**	**ebb**	**ebb**	**ebb**

The results of the wave penetration and sediment transport modelling in the entrance area (Table 3) indicate that the direction of net sediment transport in this area is dominated by tidal currents. Wave action only significantly affects the net sediment transport direction for large waves and these only occur for a small percentage of the time. Average wave conditions tend to reduce the magnitude of net seaward sediment transport loads out of the entrance. This result, although not conclusive, suggests that significant supply of sediment to the channel from the ocean is not likely under its current configuration. Only very large storm waves are able to force entrance bar sands into the entrance. In addition, onshore movement of sediment at the entrance has a northward bias either being transported to the adjacent Blacksmiths Beach, or forming the sand shoal attached to the northern breakwater. The sediment in this shoal is likely recirculated to the entrance bar by the ebb dominant tidal flow. The coastline directly to the south of the entrance to Swansea Channel is characterised by a rocky nearshore with numerous exposed reefs. As such, net northerly littoral drift is unlikely to provide significant sediment supply to the entrance area.

The above would suggest that Swansea Channel may not have the ability to adapt to SLR by keeping pace with the rising mean sea levels via channel infilling and a resultant nil net change in channel depths.

Predicted channel configuration

A predicted channel configuration based on a 0.91 m SLR scenario for the year 2100 was defined for use in the hydrodynamic model of the future tidal prism. The predicted channel form was based on assumptions of:

- continued scour of the channel at the same rate as observed over the 12 years between hydrographic surveys. This is supported by the steady linearly increasing trend in the tidal prism of the lake observed over the 22 years of available water level data. It is believed that the most reasonable explanation for this steady trend is morphological evolution of the channel toward a stable equilibrium following entrance training over 120 years ago. It follows that this trend is likely to continue if there are no other major alterations in the coming 90 years. The flows and sediment transport mechanisms (primarily the pattern of tidal asymmetry) via which the observed channel scour occurs are shown to persist under the predicted future SLR conditions.
- ongoing maintenance dredging at a similar level as occurred in the period 1996 to 2008.
- a similar pattern of erosion and deposition as observed from 1996 to 2008 survey differences. Shoals in the channel maintained at similar level relative to the mean.

Based on the above, the 2100 predicted channel includes a net removal of approximately 4 million cubic meters of sediment from the existing channel bed. This equates to a reduction in the bed level in the channel of approximately 1 m. However, the volume was not removed uniformly, being mainly removed from the deeper main channel areas.

Although every effort has been made to provide reasonable predictions of the likely behaviour of the channel in the future and in response to SLR, the predicted channel configuration remains a hypothetical representation of the future channel. There are a large range of variables and scenarios that could affect the future channel configuration.

TIDAL SIMULATIONS

Tidal model simulations for two channel configurations under an adopted SLR scenario of a 0.91 m increase by the year 2100 were completed. The existing condition (2008) was included for comparison. The existing channel configuration was also used for SLR simulations and represents a lower bound for change in the lake tidal regime. A more realistic configuration for SLR scenarios is provided by the predicted channel configuration as this channel configuration includes the expected continuation of channel scour.

Based on the calibrated MIKE 21 FM two-dimensional hydrodynamic model of the lake system, all tidal simulations covered a 37-day period. SLR was simulated by raising the ocean boundary and water level by 0.91 m.

In general, rising sea levels are expected to increase the tidal velocities in the channel and the volume of the tidal prism of the lake. This is due to two main factors:

- a combination of a slightly increased flow area and slight decrease in the friction in the channel due to higher mean water levels increases the hydraulic efficiency of the channel, which allows more of the ocean tide to exchange during a tidal cycle; and
- additional areas are inundated by tidal waters when mean water levels increase, and this additional tidal storage allows for a greater tidal prism.

Table 4 provides a comparison of the modelled tidal ranges for the lake proper permanent water level gauge site at Belmont. It shows that the spring tidal range is expected to more than double (approximately 215 % increase) by 2100 under a SLR scenario of 0.91 m based on the predicted channel configuration. A comparison of the two channel configurations simulated under SLR conditions shows that approximately half of this increase in tidal range is due to SLR, and half a result of ongoing channel scour.

Table 4. Modelled tidal ranges for existing conditions (2008) and 0.91 m SLR conditions (2100) for Belmont, Lake Macquarie.

Tidal range	Existing conditions (2008)	0.91 m SLR boundary condition	
		Existing channel	Predicted channel
Spring range (MHWS-MLWS)	0.12 m	0.19 (+0.07) m	0.26 (+0.14) m
Neap range (MHWN-MLWN)	0.08 m	0.12 (+0.04) m	0.17 (+0.09) m

Based on modelled discharges at the entrance to Swansea Channel, mean tidal prisms for existing conditions (2008) and the 0.91 m SLR with the predicted channel configuration scenario are provided in Table 5. The tidal prism was calculated here as the volume under the discharge curve between successive zero crossings. The values presented in Table 5 are based on a 28-day period within the 37-day simulation. The mean spring tidal prism in that lake is expected to increase by approximately 225 % for a SLR of 0.91 m.

Table 5. Tidal prisms for existing conditions (2008) and 0.91 m SLR scenario for the predicted channel configuration

Year	Tidal Condition	Tidal Prism ($x10^6$ m^3)	Percent of Lake Volume (%)
2008	Mean Spring Tide	14.6	5.2
	Mean Neap Tide	9.7	3.5
	Mean Overall Tide	12.0	4.3
2100	Mean Spring Tide	32.7	9.9
	Mean Neap Tide	22.2	6.8
	Mean Overall Tide	27.3	8.3

TIDAL FLUSHING MODELLING

Tidal flushing refers to the replacement of water within the lake with water from outside the lake as the tide brings seawater through the channel on the flood tide and carries out lake water on the ebb tide. Quantitative investigations into flushing can be used to describe the likely character of water quality responses of a coastal water body. Flushing times are typically defined in terms of e-folding times. The e-folding time refers to the time taken for a conservative tracer initially applied at a uniform concentration of 1 to reduce to 1/e, or 0.368.

Flushing simulations of Lake Macquarie were carried out using a calibrated MIKE 3 FM model including the advection dispersion module. The model was forced with an ocean tide along the seaward boundary and a spatially uniform wind field. Wind speed and direction data was sourced from the Bureau of Meteorology's Williamtown Airport weather station. A full year was simulated with wind forcing based on 2007, selected because the wind climate in this year was close to the long term average in terms of both magnitude and direction.

Figure 8 displays the e-folding times calculated for Lake Macquarie under existing conditions (2008) and 0.91 m SLR with the predicted channel configuration (2100) scenario, respectively. Under existing conditions (2008), the lake average flushing time (in terms of an e-folding time) was estimated as 277 days, with a considerable variation across the lake, e.g. with the southern lake area experiencing the longest flushing times (up to a year or more). For the predicted 0.91 m SLR conditions (2100), tidal flushing times in the lake are expected to be significantly reduced, with a simulated lake average e-folding time of 167 days, and the relative pattern of flushing time variation across the lake is expected to be generally maintained.

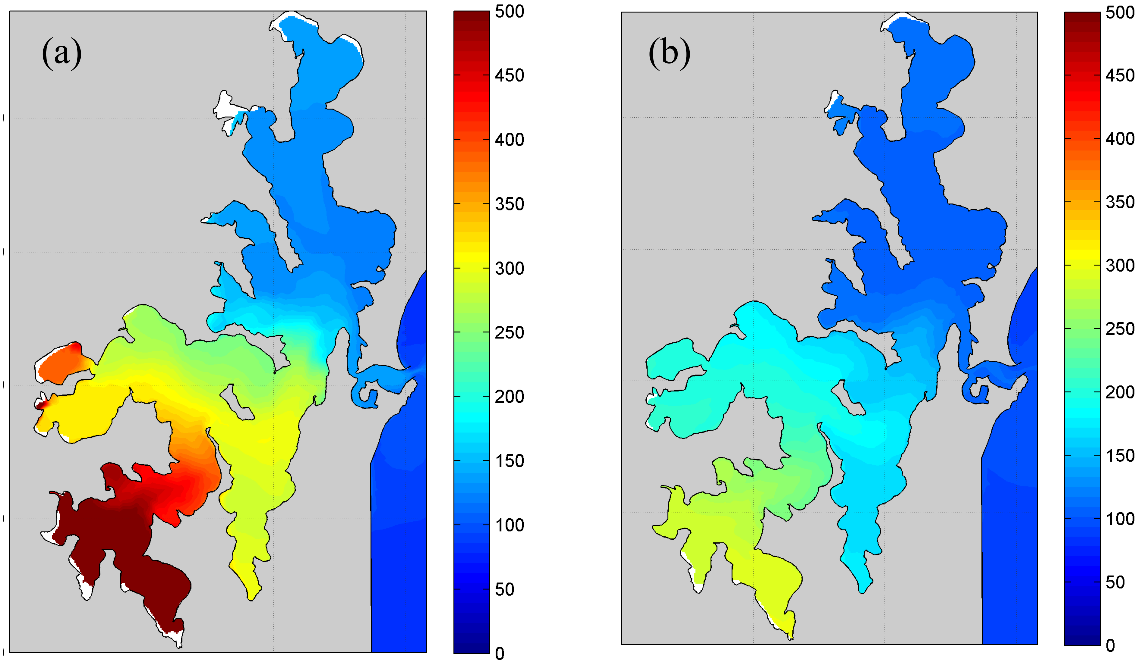

Figure 8. Map of e-folding time in days for (a) existing condition (2008) and (b) predicted SLR conditions (2100)

CONCLUSIONS

The behaviour of the hydrodynamics and sediment transport in Swansea Channel, Lake Macquarie, was modelled in order to investigate likely patterns of change under SLR. Based on the predicted channel configuration for the year 2100, the spring tidal range in the lake is indicated to more than double (approximately 215 % increase) under SLR of 0.91 m. Approximately half of this increase in tidal range is attributed to SLR and half a result of ongoing channel scour. Mean water levels in the lake are expected to rise by an amount similar to the predicted SLR. The average flushing time (in terms of e-folding time) of the lake is indicated to be reduced by approximately 40% under the SLR scenario.

The findings of this study have significant ramifications for the planning and management of this and other estuaries and associated floodplains in relation to both the built and natural environments. The implications of this assessment include continued scouring of Swansea Channel potentially associated with progressive failure of the rock rubble revetments and groynes on either side of the channel. The indicated overall increase in channel depths is likely to be associated with ongoing formation of shoals and it is likely that future navigational dredging will be required in the channel. Increased mean lake levels and a greater tidal range will significantly affect the fringing ecologies of Lake Macquarie and greatly increase the land subject to inundation risk. Unprotected shorelines within the lake are likely to recede. Lake flushing is likely to be enhanced, possibly improving the water quality of the estuary but altering estuarine ecosystem characteristics.

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