Sea Level rise and potential mitigation of saline intrusion in Northern Australia

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ABSTRACT: Australia's northern coastline is home to many coastal freshwater wetlands of international significance. They are high in biodiversity, are a large carbon store and have economic significance to tourism and pastoral production. In recent decades they have been degraded and transformed to different degrees due to sea level rise, severe storms and buffalo activity.

The Mary River estuary is modelled using 2D finite volume MIKE 21 software to assess its resilience to sea level rise and the effectiveness of engineering intervention to mitigate sea level rise of up to 0.8m. The Mary River was chosen for its long history of channel extension and widening leading to extensive saltwater intrusion.

Coastal wetlands of the Northern Territory are very expansive and low-lying. The area between 0 and 5m above mean sea level is over 10,000km^2, and a significant amount of that land is below the spring high tide level. Small thresholds in elevation are then critical to the inundation of very large areas. The Mary River is extremely vulnerable to small rises in sea level (0.3m), while a 0.8m rise will create expansive salt water environments in previously freshwater wetlands.

Submerged weirs were tested for their effectiveness in reducing the environmental consequences of sea level rise. Floodplain inundation and channel salinity levels are marginally affected by the simulation of submerged weirs in present day scenarios. As sea levels rise, weirs serve to increase both the floodplain inundation extent and salinity concentrations, relative to sea level rise scenarios without weirs. Weirs are very effective at reducing flow velocity peaks as wet season floods initiate and recede, due to dampening of the hydraulic potential. Velocities were reduced to levels below the critical entrainment velocity of 0.4ms^{-1} for the silt/sand sediment found in these areas. This would result in a reduction in channel widening and headwater extension, both key factors in sea level rise mitigation. Although weirs can reduce erosion potential, their negative properties related to inundation and increased salinity makes them a counterproductive sea level rise management tool.

It is concluded that submerged weirs may not be effective in reducing the impacts of sea level rise on wetlands of the Northern Territory.

KEYWORDS: Sea Level Rise, 2D Hydrodynamics, Coastal Wetlands, Submerged Weirs, Mitigation Techniques.

1 INTRODUCTION

Coasts around the world are experiencing the adverse consequences of sea level rise, including erosion, inundation and ecosystem losses. These negative effects will continue and increase in the coming century (Nicholls et al., 2007). Together with severe storms, sea level rise will likely cause the degradation of freshwater ecosystems, fisheries and other resources. The Mary River, located on the northern coast of Australia provides an excellent case study for these consequences and for potential sea level rise impacts of the future.

Impacts of saltwater intrusion and inundation on the Mary River have been severe in the last 70 years. In 1940, the Mary River catchment had no discrete connection to the ocean. Blocked by Chenier ridges, the two major tidal creeks, Tommycut and Sampan, did not extend more than 5km inland and tidal flows did not inundate the freshwater wetlands of the lower plain.

Over the following decades, the system has been subjected to pressure from a combination of threats; water buffalo, severe storms, sea level rise and fisherman, causing erosion and headward extension of the tidal Sampan and Tommycut creeks. Interpretation of aerial imagery shows that erosion was prolific between 1943 and 1991, during which network magnitudes exhibited exponential growth (Woodroffe and Mulrennan, 1993). By 2012, a total of 263km^2 of saltwater intrusion had occurred and the tidal creeks had developed into estuarine channels over 120m and 155m wide. The larger of the two, Sampan Creek, extends 40km inland and is barraged by a concrete weir at 35km to prevent further intrusion into Corroboree Billabong.

This study uses 2-D hydrodynamic modelling to improve understanding of the hydraulics of the Mary River estuary and predict how they might change with sea level rise. Hard structure, within channel mitigation methods for saltwater intrusion (submerged weirs) were assessed in present day and future sea level rise. The project's investigation horizon is based on conservative predictions for sea level rise over the next century, which amount to 0.8m by 2100 (Jevrejeva et al., 2010).

1.1 Area

The Mary River has an 8062km^2 catchment in the Northern Territory, Australia. It lies between the Alligator Rivers of Kakadu to the East and the Adelaide River to the West. Its source is in the south-west of the Arnhem Land Plateau from which it flows northwards along a discrete channel to the Arnhem Land Highway, creating the borders of Kakadu and Mary River National Parks. Downstream of the Arnhem Land Highway it breaks up into a discontinuous series of freshwater billabongs and creeks (Figure 1, yellow lines), including Corroboree Billabong, before passing the saltwater barrage at Shady Camp. Downstream of Shady Camp the system returns to a discrete channel called Sampan Creek that continues unbroken for 30km and discharges into Van Diemen Gulf. Tommycut Creek begins 10km downstream of Shady Camp and discharges at the coast 10km to the West of Sampan (Figure 1, red lines). This study focusses on the area downstream of Shady Camp, governed by Sampan Creek, Tommycut Creek and associated floodplains (Figure 1, green polygon).

1.2 Saltwater Intrusion

Saltwater intrusion has been an environmental issue in the Northern Territory since the 1950's (Fogarty, 1982), causing loss of freshwater wetlands, including expansive herbaceous swamp, melaleuca swamp and tidal freshwater wetlands. Many species rely on the Mary River for core breeding and nursery habitat during harsh dry seasons due to the deep billabongs of the Corroboree region. Billabongs of this type were found downstream of Shady Camp decades ago, including Alligator Lagoon, Roonees Lagoon, Dead Fish Billabong and Sampan Billabong; although all have been converted into continuous estuarine channels through tidal creek extension and widening. The Red Lilly Billabong was the latest to connect to the estuarine channel. Further upstream, Corroboree Billabong is next in line.

The area west of Tommycut Creek has a long history of inundation and freshwater vegetation loss. Once mainly Melaleuca Swamp, it is now intermittently inundated by tidal flow and has converted to hypersaline mud flats and mangrove communities. The area is low lying and intersected by even lower paleochannels, making it especially vulnerable to sea level rise. Further west in the area of the Mary River Coastal Reserve the vegetation is still in its original form. Here it comprises open forest, open woodland and low woodland melaleuca communities with *M. cajuputi*, *M. viridiflora*, *M. leucadendra* and *M. citrolens* being the dominant species.

1.3 Sea Level Rise

The issue of sea level rise (SLR) is ever increasing in governmental, environmental and economic circles around the World. On the north coast of Australia, sea level has trended upward at a rate almost three times the global average. The Australian Baseline Sea Level Monitoring Project has recorded a rise of 8.3mm per year since 1990, taking into account local land emergence of 0.2 mm/yr and barometric pressure. This equates to a total of 18.25cm of relative SLR since 1990 (BOM, 2011). The relatively high rates of sea level rise on the north coast of Australia and the low lying nature of the Mary River creates the conditions required for the rapid inundation and intrusion seen over the last 70 years.

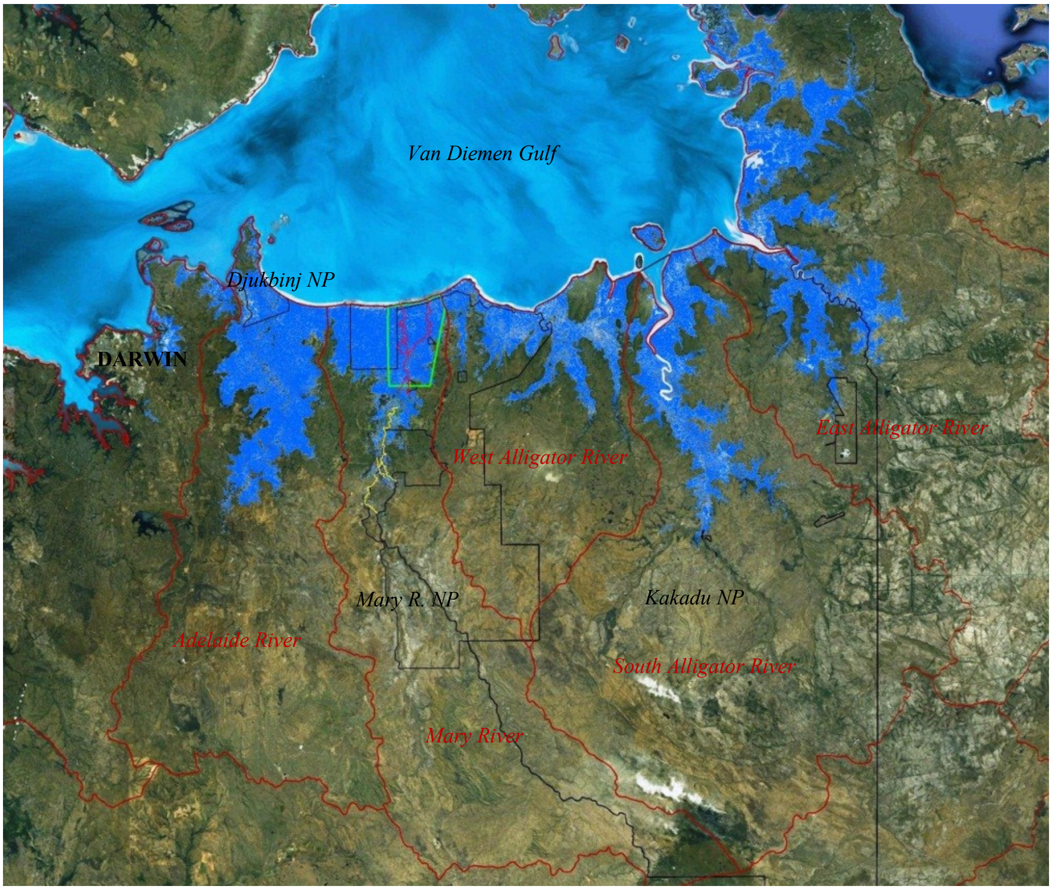

Figure 1 The river catchments associated with the closely interconnected freshwater wetlands of Van Diemen Gulf in the NT Top End, including the Kakadu wetlands of the Alligator Rivers. Areas shaded blue are low lying areas below 5m AHD. The green polygon signifies the area of interest. Black polygons signify the extent of National Parks and Reserves including Kakadu (eastern polygon), the Mary River National Park, Mary River Coastal Reserve and Djukbinj National Park at the mouth of the Adelaide River (imagery courtesy of Google Earth).

1.4 History of Interventions

The first attempt at intervention was the Shady Camp barrage. It was constructed in 1988 on a bedrock base and has remained the most successful barrage since. Others, having poor foundations on mud and clay substrate, are breached or washed away during wet-season flows.

The records show that the total number of barrages in the area include 12 small barrages east of Sampan and between Sampan and Tommycut (The Cutting etc.) and 50 structures west of Tommycut in tidal creeks, tributary creeks and paleochannels to mitigate against headwater extension.

There was a 75% choke of Tommycut constructed in 1996 17.5km upstream of the mouth. It remains intact to 1m below AHD but caused scour of the channel banks at both ends limiting potential resistance to the flood tide and contributing little to a backwater effect during the runoff.

Major structures in the shady camp area include barrage 45 (1km long), bobby's barrage, croc creek barrage and more recently Red Lilly Billabong barrage. Both Barrage 45 and Red Lilly Billabong barrages were breached at the time of writing. The control works programme continues to this day.

2 METHODS

The boundaries of the model were selected to cover the salt intruded areas and capture the most important hydraulic interactions of the lower Mary River. The eastern boundary was defined with land elevations above 5m AHD. The western boundary was designed to cover inundated/intruded areas. The northern boundary was tidally driven with recorded data offshore and designed to minimise boundary effects at the mouth of both creeks. The southern boundary was defined by the Shady Camp Barrage (upstream) hydrograph.

Modelling was completed with MIKE 21 FM (Flexible Mesh) HD (hydrodynamics) surface water numerical modelling package. It is a 2D depth averaged finite volume numerical model solving Reynolds averaged Navier-Stokes equations with the assumptions of Boussinesq and of hydrostatic pressure, based on the computational system System 21, “Jupiter” (Abbott et al., 1973).

Floodplain topography was obtained by LiDAR survey on the 18th of September 2011 at a vertical accuracy of 0.15m @ 67% confidence interval and horizontal accuracy of 0.25m @ 67 % confidence interval. Channel bathymetry of Sampan and Tommycut Creeks was surveyed on the 15th and 16th of October 2011 by boat using a Lawrence 10S depth sounder logging xyz points every second using identical datum's to the LiDAR survey. The channel was defined using two long-sections per channel and over 100 cross-sections.

LiDAR data was thinned from a 10m key-point digital elevation model (DEM) to a 10m gridded DEM for processing efficiency. The resulting DEM defines floodplain topography at high accuracy (Figure 2). Bathymetry was reduced to AHD and integrated into the LiDAR for incorporation into the mesh.

A variable-resolution flexible mesh was used to describe the Tommycut to Sampan geometry of the Lower Mary Plains. The resultant mesh-data derived terrain is shown in Figure 3.

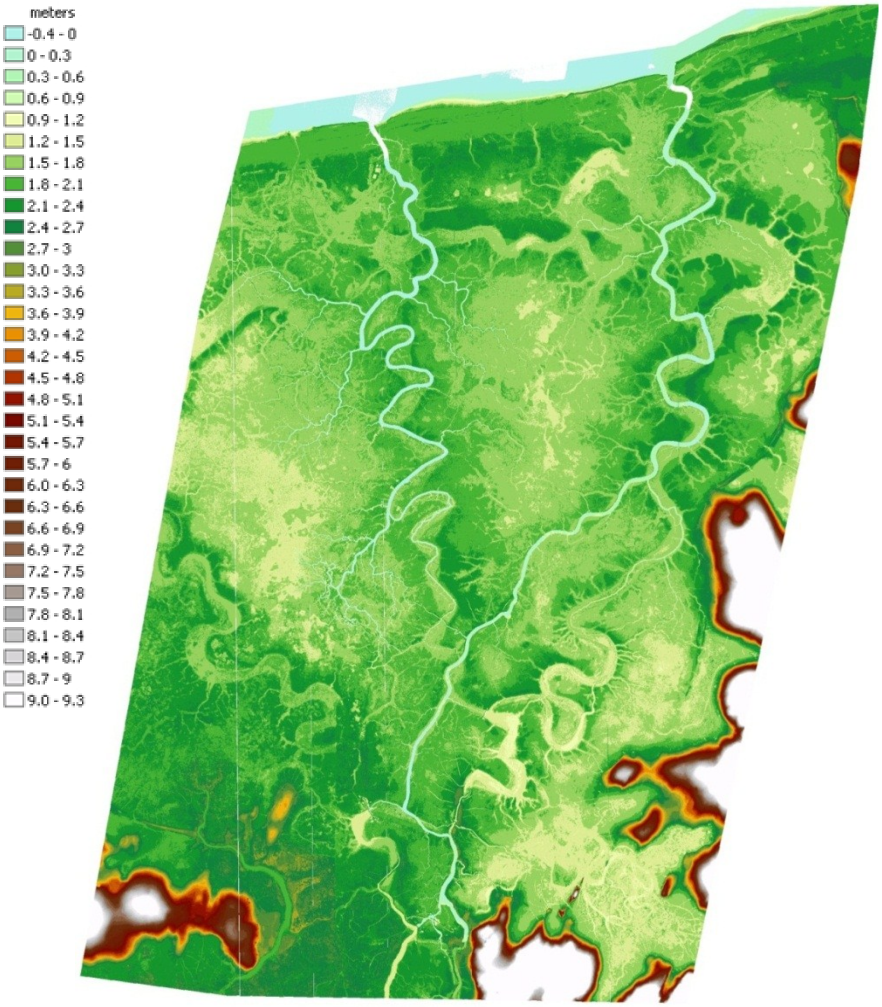

Figure 2 LiDAR derived DEM of the area of interest, mean elevation = 1.86m, standard deviation = 0.53m.

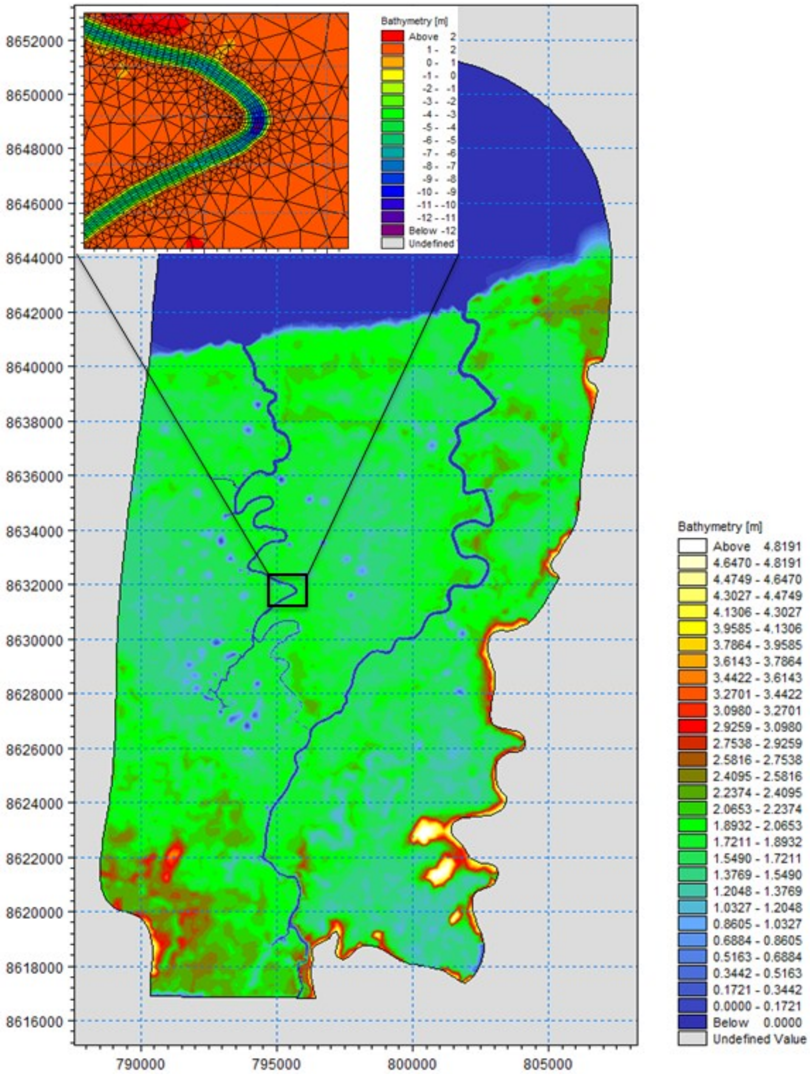

Figure 3 Mesh-derived elevations of the floodplain and channel.

3 RESULTS

Calibration is not complete although there are preliminary indications that the model is a good predictive tool for the Mary River coastal system. The recorded data from Sampan Creek mouth correlates well with the simulated data (R^2 = 0.964). The largest errors in the simulated data are those related to low tide. Surveying did not capture the full extent of the channel offshore; as such the over predicted shoaling is most likely due to shallower depths in the model at these locations than in situ.

3.1 Sea level rise and weir installation

The following analysis was of simulation outputs of dry season conditions. They are short, 10 day simulations through a spring tide cycle with $5m^3s^{-1}$ of inflow into the system at Sampan Creek.

3.1.1 0.0m sea level rise

The scenario for spring tide in present conditions has inundated the floodplain in expected areas and salinity levels are in equilibrium with the forcing conditions at each boundary (Figure 4a). At these low flows, the fresh water is flushed through Sampan Creek effectively while Tommycut increases in salinity, which is representative of recorded hydraulic conditions (unpublished data). Installing weirs in this scenario reduces the inundation extent but also serves to increase the salinity within the system. Weirs dampen the ebb tide more than the flood tide, so there is a net increase of salt transport in to the estuary together with a net decrease of fresh water transport out of the estuary. Fresh water flow accumulates upstream of "The Cutting" (Figure 4b).

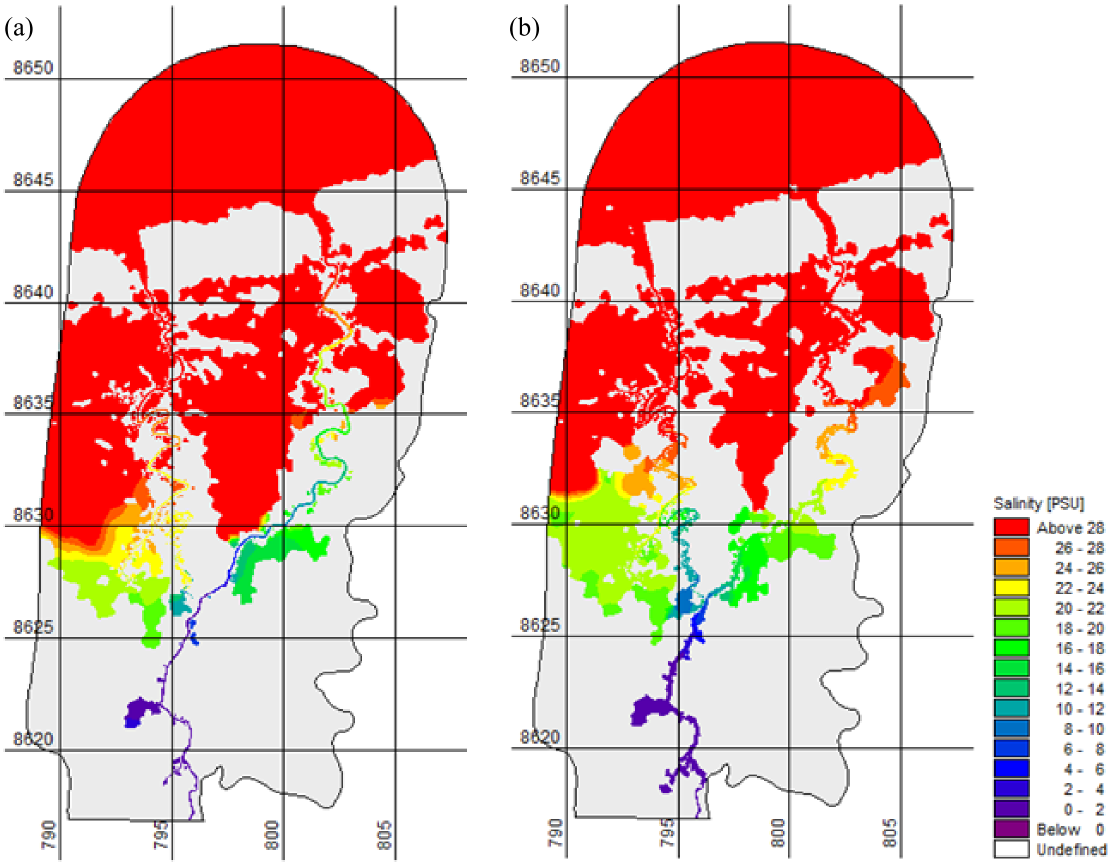

Figure 4 (a) Run030 (0.0m SLR, No Weirs), whole area output of salinity after 7 days of tidal flow; (b) Run033 (0.0m SLR, Weirs at TCM and SCM), whole area output of salinity after 7 days of tidal flow.

3.1.2 0.3m sea level rise

Inundation of most of the lower plains will occur after 0.3m SLR as the area will be below MWHS. The $5m^3s^{-1}$ flow is small, but still much greater than end of dry season flows, which can reduce to zero. The buffer zone from salt to fresh is very narrow (Figure 5a). Adding weirs slows down the ebb flow and the backwater effect causes the fresh inflow to flood in the upper floodplains, reducing its buffering effect. This allows the salt water to push further upstream. The backwater effect also increases inundation of the Melaleuca Station area and deeper inundation downstream of "The Cutting" (Figure 5b).

3.1.3 0.8m sea level rise

As sea level increases, inundation spreads to the upper reaches. The channels are more saline and freshwater flow is forced onto the floodplain adjacent to Shady Camp Billabong (Figure 6a). Adding weirs only exacerbates the problem of inundation and saltwater intrusion. Channels are no longer definable in the flow field and the fresh water inflow is obstructed by tidal flow over the Shady Camp Barrage (Figure 6b).

3.2 Velocities

Velocities were investigated to determine the most likely flow conditions that lead to erosion of the channel banks and headwaters. Upstream locations were again focused on as headwater extension has been the major cause of saltwater intrusion in the resent past (Knighton et al., 1992). Firstly, the present conditions were analysed.

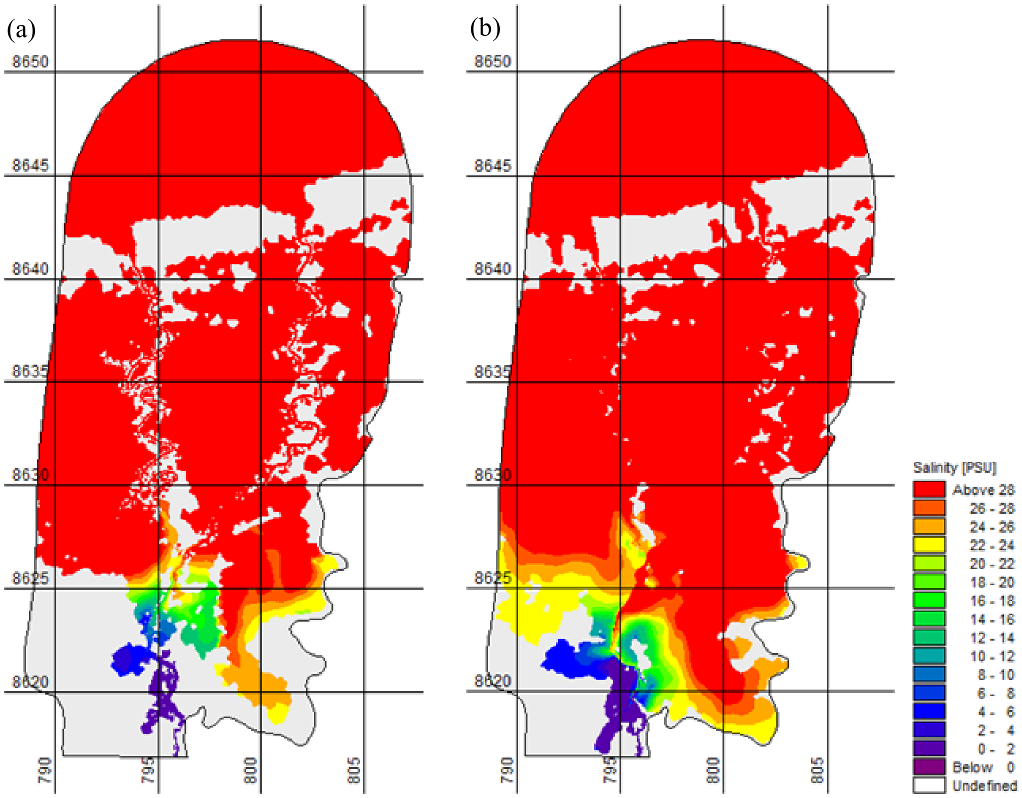

Figure 5 (a) Run038 (0.3m SLR, No Weirs); (b) Run041 (0.3m SLR, Weirs at TCM and SCM).

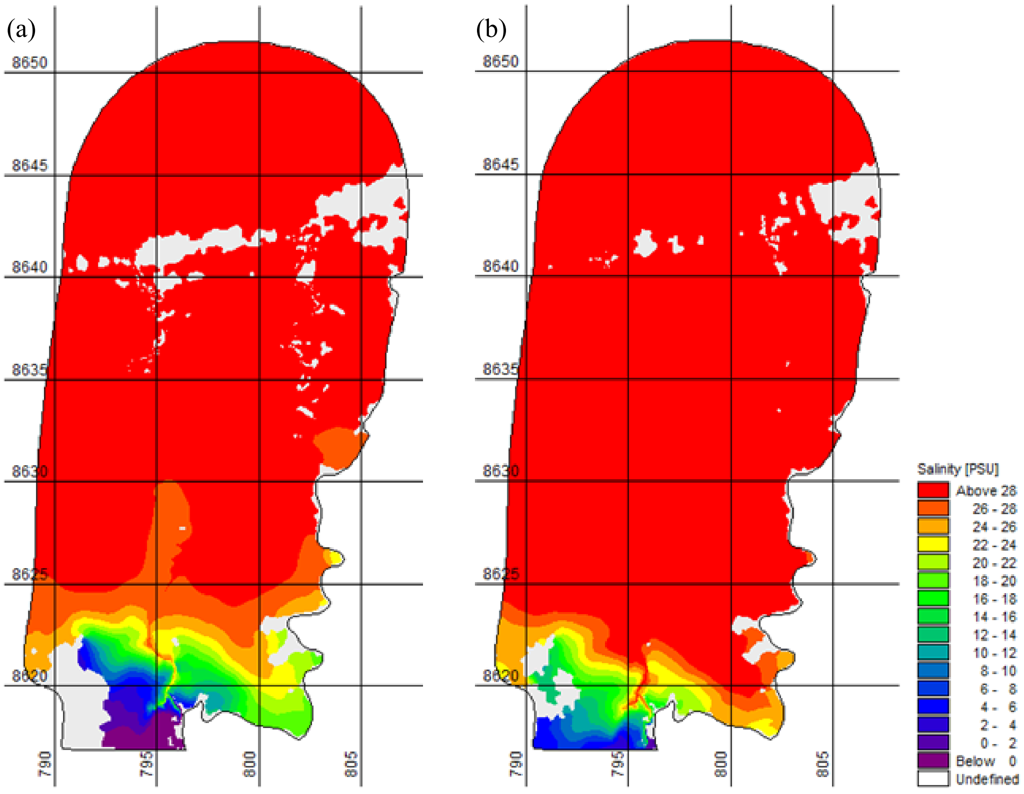

Figure 6 (a) Run046 (0.8m SLR, No Weirs); (b) Run049 (0.8m SLR, Weirs at TCM and SCM).

Throughout the water year max velocities of 1.5ms^{-1} occur during flood inception when flow is at bankfull height (Figure 7). As flow drops to bankfull height again in the runoff period, tides again affect the water level upstream causing a second peak in velocities at similar magnitudes. Both peaks are associated with low tides. This relationship between high discharge and an increasing tidal influence can cause a 100% increase in velocity with a low tide induced increase in velocity head of 560mm. Maximum dry season velocities are between 0.5 and 0.75ms^{-1} during flood spring tides and below 0.5ms^{-1} for ebb tidal flow. There is a transition phase from low tide induced high velocities and high tide induced low velocities to mid tide high velocities and slack tide low velocities depending on the inflow discharge. The first point of reverse flow due to the flood tide occurs when water levels are 2.18m AHD at the inflow and tidal amplitude is 2.08m.

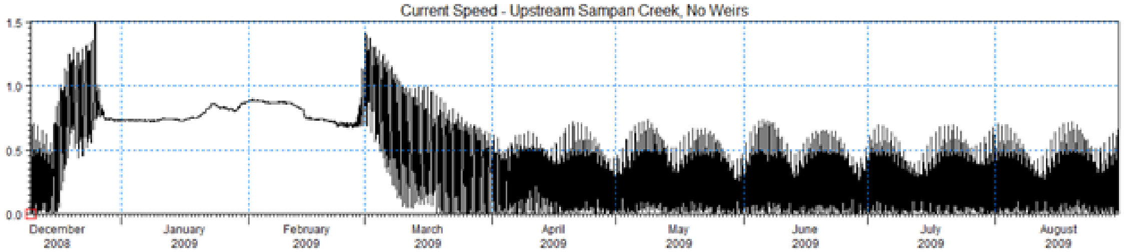

Figure 7 Current speed time series extracted 2km downstream of Shady Camp Barrage (795800, 8620400). Present state.

Weirs have little effect on channel velocities during overbank flood conditions (January – February) but a dramatic effect on peak velocities during flood inception and runoff, almost cancelling out the previous effect of high inflow and velocity head. Dry season velocities are kept below 0.25ms^{-1} (Figure 8). Slower velocities in the channel overall causes a delay in tide by 2hrs at Shady Camp Barrage.

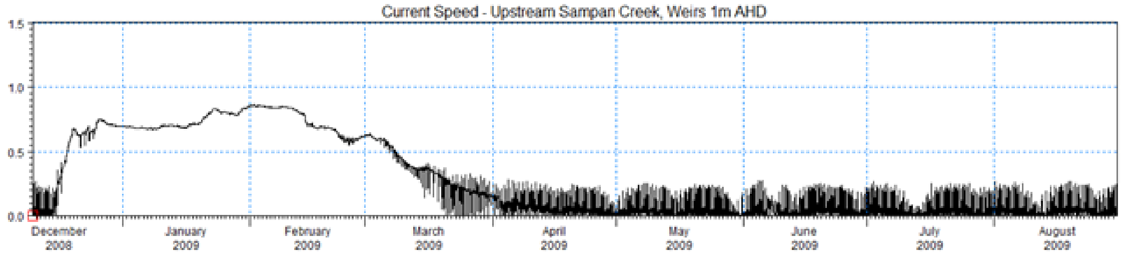

Figure 8 Time series extracted 2km downstream of Shady Camp Barrage (795800 8620400). Present sea level, weirs at 1.0m AHD in the mouths of Tommycut and Sampan Creeks.

3.2.1 Velocities after Sea Level Rise

Modelling sea level rise of 0.3m and analysing the bankfull flow event revealed very interesting results. The efficiency of ebb tide flows in bankfull conditions was slightly diminished. The beginning of the ebb flow is weaker due to flooding of the floodplain at high tides. The excess tidal flow out of the estuary takes longer to drain due to attenuation on the floodplain driven by increased resistance at the channel/floodplain boundary (Knight and Brown, 2001), causing the water level at 795800, 8620400 to remain above 2m for longer. As such the water level drop is not as great as present day conditions. The result is a drop in maximum velocities to 1.39ms^{-1} after sea level rise of 0.3m. This is expected to drop further with 0.8m sea level rise.

Weirs continue to be extremely effective at reducing velocities after SLR. Maximum velocities are kept below 0.9ms-1, similar to present overbank flow conditions with velocity peaks dampened out by a reduction in tide induced velocity head. With further SLR (0.8m) the tidal flow is high enough to cause reverse peaks in the water level with the flood tide and a resultant drop in velocity (Figure 9). Spring tides serve to drop the current speeds down to zero even before water levels have returned to the channel during the runoff.

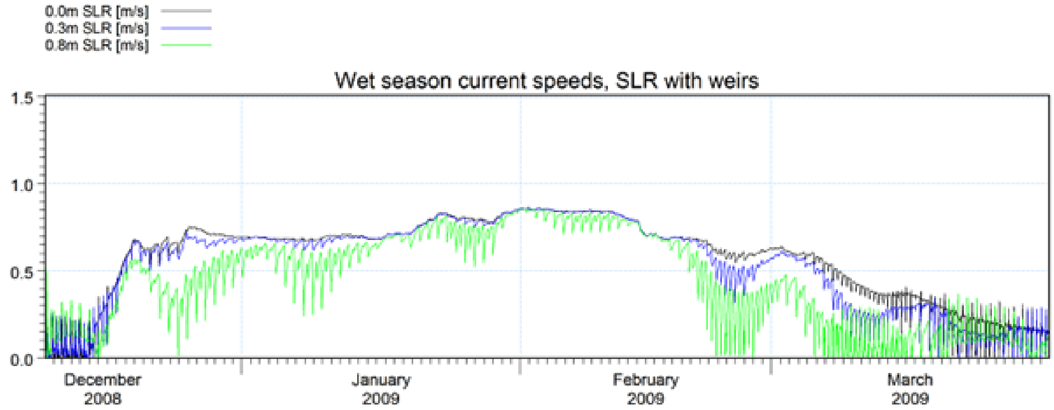

Figure 9 Full wet season outputs for all three sea level rise scenarios with submerged weirs at 1.0m AHD.

4 DISCUSSION

The lower floodplains of the Mary River are very vulnerable to SLR. Only small increases to 0.3m are needed to surpass an elevation threshold that creates extensive inundation (Figure 5). Any small scale barrage intervention efforts in this area would not be sustainable in the near future as inundation frequency of large areas becomes too great. After 0.8m SLR the problem of inundation is exacerbated. It is evident that inundation as expansive as the area in Figure 6 will lead to dramatic changes to the morphology and biodiversity. Increased flood tide action with reduction in current velocities upstream of the mouth will promote sediment accumulation via marine sediments (Wolanski and Chappell, 1996), while vegetation will transition from saline, brackish and fresh communities to saline mangrove communities and possibly coastal mud flats.

Inundation from salt water increases with weirs installed. The ebb tide slows while the flood inundates the same areas with or without weirs so any further blocking of the tide only increases floodplain inundation and salinity within the system.

Velocity investigations have found the timing and dominant conditions in which erosion occurs. Wet season flood inception and runoff are times of erosive conditions in upstream locations. It is governed by the ebb tide and bankfull inflows and the low lying nature of the Mary River system allows strong tidal action in areas far upstream. For high velocities to occur tidal action must prevail while inflows are at bankfull height, creating a large velocity head and erosive conditions. In the past 70 years this process has been very active. Upstream of Shady Camp, elevations are higher, in the range of 3.0-3.2m AHD (Lim, 1995), so it is possible that conditions for rapid head water extension will ease.

The reduction in velocities after a peak at bankfull flow is caused by the inefficient transport of flow over the floodplains and attenuation of the ebb tide due to increased resistance at the channel/floodplain boundary (Knight and Brown, 2001). Simulation of a SLR of 0.3m leads to a drop in velocities upstream. This suggests that the rapid channel extension in recent decades is due to the fact that the floodplain elevations have been matched to ebb tidal flow. Modelling shows this will reduce with only slight increases in SLR. Whether or not the floodplain accumulates enough sediment to retain this effect or turns into an extensive mangrove swamp that will dampen the tides further is unknown.

Submerged weirs also reduce the ebb tide effect and cancel out the wet season bankfull velocity peaks. Their effect is not lost when SLR occurs. Figure 9 shows, as sea level increases, velocity drops further due to greater inundation and attenuation on the floodplains.

Submerged weirs are effective at reducing salinity in the short term but become increasingly counter effective as sea levels rise. The flood tide bias pushes highly saline water further inland with weirs installed and the channels quickly increase to sea water concentrations (32 PSU). During spring high tides the entire area downstream of Shady Camp is inundated and fresh water flow is not enough to buffer salt water extending over the Shady Camp Barrage (Figure 6b). It should be noted that this is indicative only and that in the time it takes for 0.8m of SLR to occur, floodplain accumulation, channel morphodynamics and mangrove vegetation will alter the hydrodynamics.

The model has dramatically improved the understanding of the effects of sea level rise on coastal floodplain systems but its limitations should be considered. This model is not effectively calibrated to rely on for explicit decisions on weir dimensions or to be used as a definitive source of exact salinity levels or inundation extent. It should be used as an indicative and comparative tool. Higher accuracy could be achieved with the correct velocity and water level data for calibration. The model is indicative of the changes likely to occur with predicted sea level rise and in its present state serves as a tool to understand the general responses of the system. The use of present topography/bathymetry in large sea level rise simulations (0.8m SLR) is also an indicative analysis, as great system changes will have occurred. The model has shed light on the probable changes due to 0.8m SLR but there are others that may be unforseen due to the complex processes in a rapidly evolving system like the Mary River. The authors recommend that assessments on the response of other vulnerable coastal wetlands are approached separately as small variations in morphodynamics can alter how sea level rise affects a system and it is unlikely that another wetland will respond in the same way to the Mary River.

5 CONCLUSION

Submerged weirs are not effective at reducing the effects of SLR. They are not recommended based on their limited effectiveness as sea levels rise. Although they do reduce velocities upstream they also increase inundation and salinity concentrations. The natural response of this system is to become more stable with sea level rise so in effect the positive effects of weirs will be reduced in the future. The major issue with ecosystem transition is potentially long periods of hypersaline mudflats before mangrove colonisation (similar to what is happening west of Tommycut Creek). Actively promoting mangrove community establishment in the downstream area as freshwater/brackish ecosystems are lost to salt water intrusion would be a more reliable and beneficial response to sea level rise.

6 REFERENCES

Abbott, M. B., Damsgaard, A. & Rodenhuis, G. S. 1973. System 21, "Jupiter" (A design system for two-dimensional nearly-horizontal flows). Journal of Hydraulic Research, 11, 1-28.

Australia. Bureau of Meteorology 2011. Annual sea level data summary report. The Australian Baseline Sea Level Monitoring Project.

Fogarty, P. 1982. A preliminary survey of environmental damage associated with activity of feral buffalo. Tech Report. Feral Animals Committee, Conservation Commission. Darwin, NT.

Nicholls, R.J., P.P. Wong, V.R. Burkett, J.O. Codignotto, J.E. Hay, R.F. McLean, S. Ragoonaden and C.D. Woodroffe, 2007: Coastal systems and low-lying areas. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 315-356.

Jevrejeva, S., Moore, J. C., Grinsted, A 2010. How will sea level respond to changes in natural and anthropogenic forcings by 2100? Geophysical Research Letters, 37.

Knight, D. W. & F. A. Brown 2001. Resistance studies of overbank flow in rivers with sediment using the flood channel. Journal of Hydraulic Research 39, 283-301.

Knighton, A. D., Woodroffe, C. D. & Mills, K. 1992. The evolution of tidal creek networks, Mary River, northern Australia. Earth Surface Processes and Landforms, 17, 167-190.

Lim, R. 1995. Report into matters relating to environmental protection and multiple use of wetlands associated with the Mary River system. Darwin, NT: Legislative Assembly of the Northern Territory.

Wolanski, E. & Chappell, J. 1996. The response of tropical Australian estuaries to a sea level rise. Journal of Marine Systems, 7, 267-279.

Woodroffe, C. D. & Mulrennan, M. E. 1993. Geomorphology of the Lower Mary River Plains, Northern Territory, Darwin, Australian National University, North Australia Research Unit.