Mary River Project

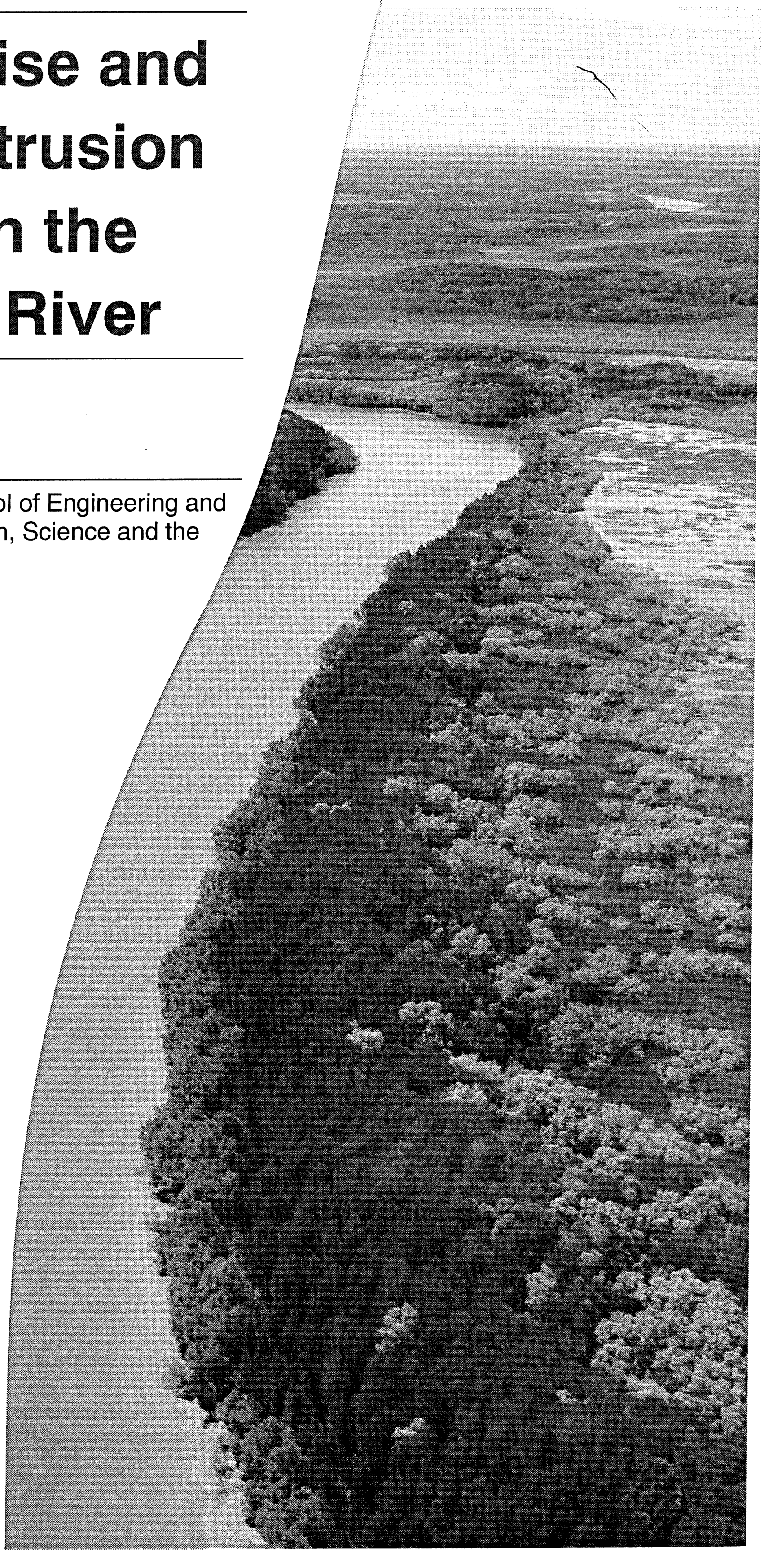
Sea Level Rise and Saltwater Intrusion Modelling on the Lower Mary River

Mike Miloshis

Eric Valentine

Environmental Hydraulics / School of Engineering and IT / Faculty of Engineering, Health, Science and the Environment

CHARLES DARWIN UNIVERSITY



Charles Darwin University – Northern Territory Government Partnership

2010 - 2013

Citation:
Miloshis, M. and Valentine, E.M. (2013) Sea level rise and saltwater intrusion modelling on the Mary River. Charles Darwin University.

Acknowledgements

I would like to thank the staff at the Department of Land Resource Management (formally Department of Natural Resources, The Environment, The Arts and Sport) Ian Fox for backing and funding the research and Paul Jonouskas for help in the field; Larry Tessmann for his expert helicopter piloting around the Mary River floodplains; Jordan Phasey and Jon Louey-Gung for their kind help in bathymetric surveying and FUGRO for their efficient LiDAR surveying. Finally, I'd like to show my appreciation to the engineers at DHI for providing fast and helpful technical support.

Cover photo: Kate Freestone

CONTENTS

EXECUTIVE SUMMARY

The aim of this project was to improve understanding of the hydraulics of the Mary River estuary and predict how they might change with sea level rise. Unknowns highlighted in previous studies were investigated and mitigation methods such as submerged weirs, and ecological engineering were assessed. 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).

A two-dimensional computational model was used to represent the Lower Mary River system from Shady Camp Billabong to approximately 10km offshore. The model was designed to capture channel-floodplain interactions, inundation patterns, velocities and salinity while modelling weir installations and sea level rise. This required LiDAR and bathymetric survey for elevation data together with hydrographic data of ocean and upstream locations.

The model was indicative of present day conditions. It was in agreement with Tommycut and Sampan Creek mouth calibration points and inundation patterns were close to known areas of inundation. Dry season simulations were designed to reveal inundation extent and salinity patterns while wet season 'water year' simulations were utilised in velocity/erosion analysis, floodplain drainage and weir tests. Sea level rise effects were accessed in combination with all the above scenarios.

Recommendations:

- Prepare stakeholders for extensive salt water intrusion of the floodplains downstream of Shady Camp Barrage.
- Promote mangrove community establishment in areas where freshwater/brackish ecosystems are lost to salt water intrusion. 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. The low erosion resistance and low bed roughness of hypersaline mudflats lowers coastal resilience to sea level rise and if they become widespread, could lead to increased salt water intrusion upstream.
- Weirs 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. Short term erosion will be reduced but floodplain water retention is not dramatically improved and salinity still reaches sea water concentrations quickly after the runoff. Difficulty of weir construction in the area is also a concern. Past reports have estimated a construction cost in the order of 2 million dollars per weir. There is a high potential for damage around the weir due to high velocities so maintenance and emergency repairs should be accounted for.
- Natural processes of land adaption are much more effective at mitigating sea level rise. The reduction in velocities upstream of the mouth, together with higher land elevations upstream of Shady Camp will result in the slowing of headwater extension. The "big swamp" state of 5000-6000ya is a likely result of coastal inundation and will provide excellent habitat to many species of flora and fauna.
- If weirs were implemented to achieve a near-term reduction in erosion it is recommended that modelling continues with calibration and validation as well as rigorous weir position and crest height testing to increase the timespan of their value and to balance negative effects.
- Upstream, Corroboree will undergo similar changes to that which occurred to billabongs downstream of Shady Camp (Red Lilly, Sampan Billabong, Alligator Lagoon, Dead Fish Billabong and Roonees Lagoon). It is unlikely that weirs could prevent this in the event of sea level rise. There is an 8km length of semi-incised channel between Shady Camp and Corroboree so minimal erosion is required for channel formation.
- Extensive land survey or further LiDAR survey should be undertaken in areas not already covered by surveying in this project. The western plains are still fresh water habitats and elevations will give a clear indication of the fate of those areas. The estuarine plain upstream of Shady Camp Billabong to Corroboree is also a critical area for extensive elevation surveying, which will help determine the vulnerability of its freshwater habitat.

1. INTRODUCTION

1.1. Background

The Mary River saltwater intrusion modelling project was initiated by the Northern Territory Government to improve understanding of the dynamic processes of low-lying wetlands under threat from sea level rise and investigate potential mitigation methods. Funding was provided by the Department of Natural Resources, the Environment, the Arts and Sport (Department of Land Resource Management) for LiDAR capture and model development using existing hydrological data. Although not planned for in the beginning, after analysing the LiDAR output it was determined that a bathymetric survey was critical for model accuracy. This was carried out by CDU. The ability of the model to simulate the full water year (offset year that captures the wet season flood, i.e. December to December) is a testament to its stability and led to many novel understandings of the hydrodynamics of the system. Although the initial expected timeline was exceeded, LiDAR data collection was delayed by an early wet season and bathymetric data collection was not in the initial timeline. The level of complexity of the model and scope of its components also exceeded initial development plans.

1.2. Study site

The Mary River is 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 with its source to the south-west of the Arnhem Land Plateau flowing northwards along a discrete channel to the Arnhem Land Highway. It then breaks up into a discontinuous series of freshwater billabongs and creeks 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 (**Figure 1**). Sampan Creek has a minor hydraulic connection to Tommycut Creek called the "cutting" 25km up river from the sea. This report focusses on the area downstream of Shady Camp, governed by Sampan Creek, Tommycut Creek and associated floodplains.

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 lime green polygon signifies the area of interest. The black polygons signify the extent of Kakadu (eastern polygon) and the Mary River Coastal Reserve (western polygon).

1.3. 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 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 (**Figure 2**).

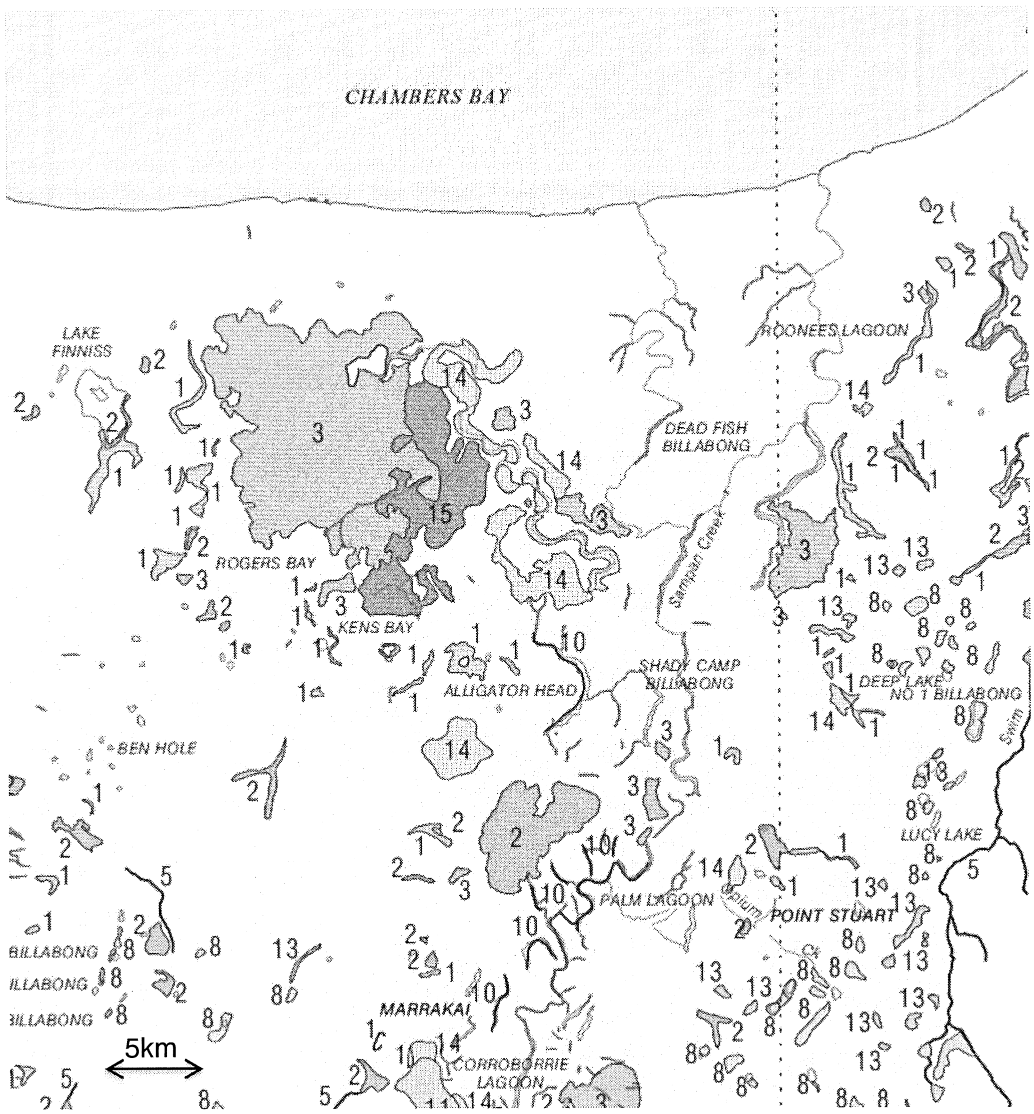


Figure 2. Melaleuca communities in the Lower Mary River Region (Brocklehurst and Kerckhof, 2002). Relevant community types: 1 *M. viridiflora, M. leucadendra;* 3 *M. cajuputi, M. viridiflora;* 14 *M. cajuputi, M. leucadendra;* 15 *M. citrolens, M. viridiflora*.

1.4. Biodiversity and ecological impacts

The Mary River Lowlands contain both fresh and salt/brackish wetlands. The freshwater systems support iconic flora and fauna species of the Northern Territory in vast numbers such as Magpie Geese, Melaleuca, Salt and Freshwater Crocodiles, White-Bellied Sea-Eagles, Egrets, Herons, Cormorants, the Arafura File Snake and White-Browed Crakes. Together there are a total of 12 threatened species reported at this site and 58 species that are endemic to the NT (Bayliss et al., 1997, Lim, 1995, Harrison et al., 2009). Freshwater systems have a higher biodiversity than saltwater marsh/swamp areas (**Figure 3**). Although the species richness of fauna is similar with fresh water areas harbouring 5% more species than saline ecosystems, flora species richness is up to 770% greater in fresh water wetlands (Bishop and Forbes, 1991). Initially, a drop in net ecosystem production of 55% can be expected when saline waters intrude on fresh water wetlands (Neubauer, 2011). If it continues the vegetation communities will transform to mangroves to accommodate the change in salinity. In some areas, such as west of Tommycut Creek, vegetation loss is dramatic and transition is slow due to low energy flow resulting in reduced rates of headwater extension (**Figure 4**).

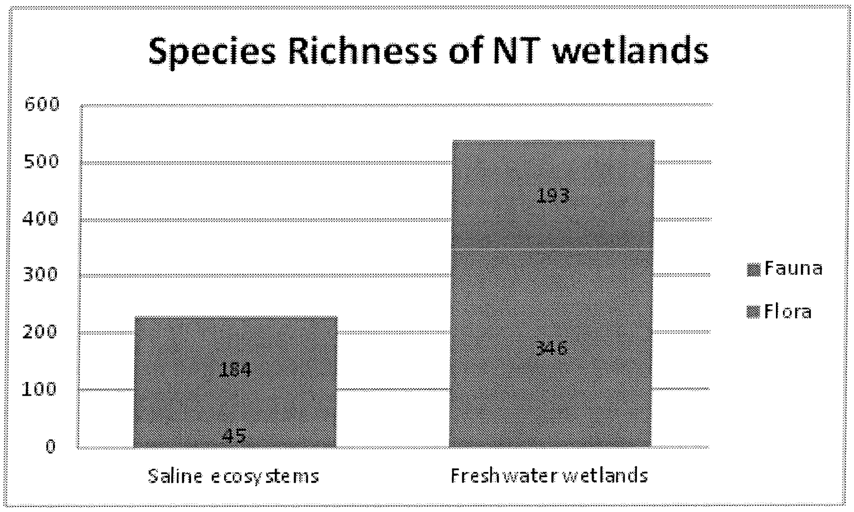


Figure 3. Saline ecosystems data (combines the nearshore, mangroves and hypersaline mudflats) compared to freshwater ecosystems. Invertebrates are not included although it is expected that freshwater ecosystems have a higher species richness of invertebrates.

The Victorian government recently accessed the biodiversity levels of wetlands in transition to salt marshes and found a marked drop in biodiversity. The conceptual diagrams in **Figure 5** show the importance of thresholds in salinity levels and their effect on wetlands of different morphology. Type 1 is reminiscent of the area between Tommycut and Sampan and type 2 resembles the area west of Tommycut Creek. Over time the ecosystem recovers from the hypersaline conditions of type 2. In the Tommycut area this is dependent on changes in morphology through the formation of tidal creeks.

1.5. 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). This relatively short term dataset is heavily influenced by El Nino/La Nina effects and the Pacific Decadal Oscillation as well as the effects of climate change. Over longer periods the eustatic sea level pattern will reveal itself. Although local land subsidence/emergence is accounted for in this dataset, the effects of the tectonic movement of the Indo-Australian plate are not reduced to a datum. This could be achieved if local benchmarks were tied to the International Terrestrial Reference Frame (Altamimi et al., 2002, Ballua et al., 2011).

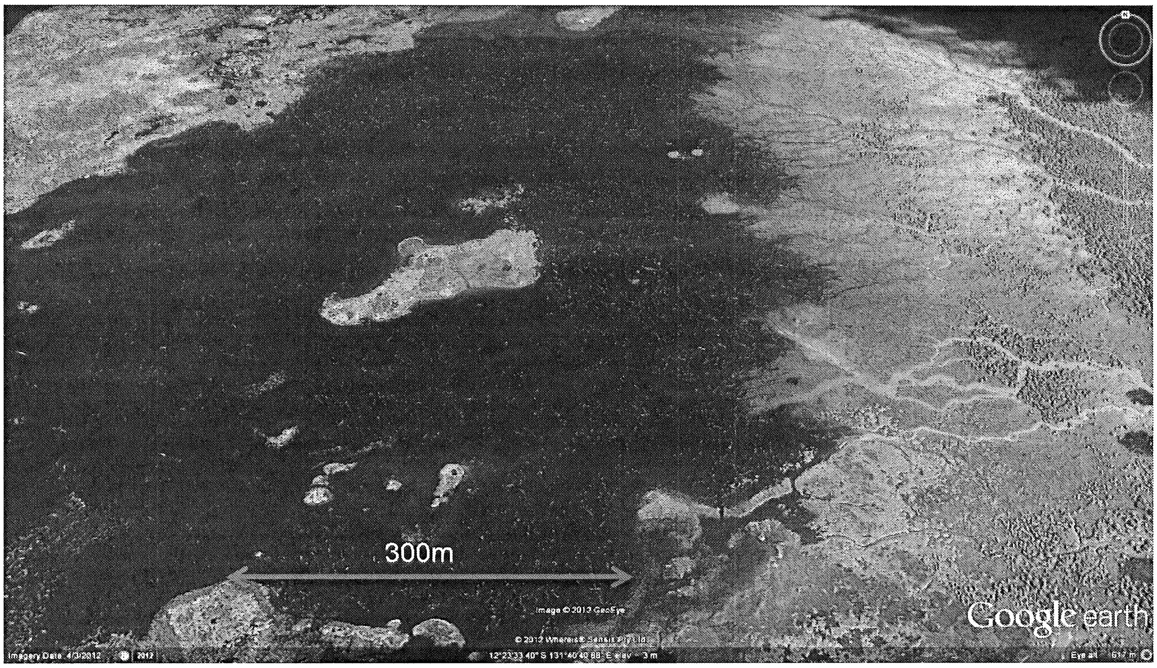
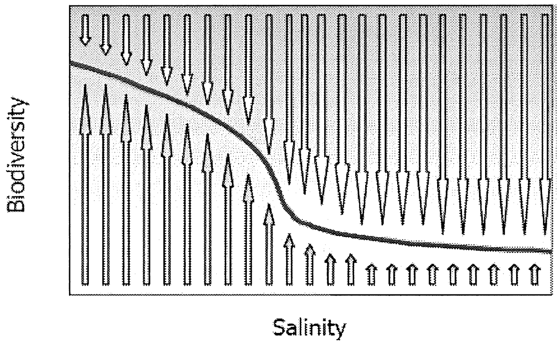
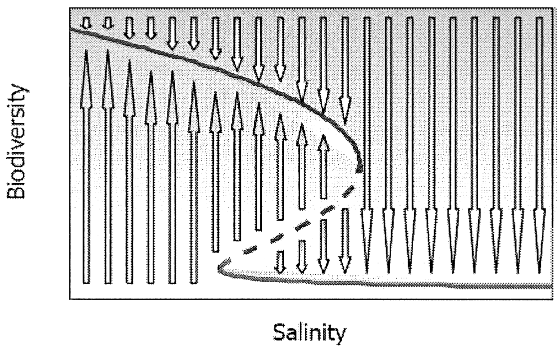


Figure 4. Google Earth image taken in March, 2013, west of Tommycut Creek headwaters. This area was once completely dominated by Melaleuca Swamp (Fogarty, 1982, Story, 1969, Story et al., 1969). The Top left of the image shows diverse freshwater/brackish vegetation; the middle black areas are hypersaline mudflats littered with melaleuca tree stumps due to dieback; the right side of the image shows tidal creek extension into the mudflats and associated mangrove colonisation. This is a slow process in this area of the system, taking over 20 years for the transition (Fogarty, 1982 compared to present).



The predicted relationship between wetland biodiversity and salinity for type 1 wetlands.



The predicted relationship between wetland biodiversity and salinity for type 2 wetlands.

Figure 5. Conceptual diagrams of freshwater wetlands in transition to salt. Type one: freshwater area to mangrove habitat. Type two: freshwater area to hypersaline mudflat (Victorian Government DSE, 2006).

1.6. NT issues

There are over 10,000km^2 of coastal wetlands in the Northern Territory at elevations below 5m AHD (Australian Height Datum) (**Figure 6**). Many of these are experiencing salt water intrusion to some extent. The Finniss, Adelaide, Mary, Alligator Rivers and Arafura Swamp have experienced various rates of reduction in fresh water wetlands and billabongs due to tidal creek extension and resultant salt water intrusion since the 1950s (Fogarty, 1982, Knighton et al., 1991, Knighton et al., 1992, Cobb et al., 2007).

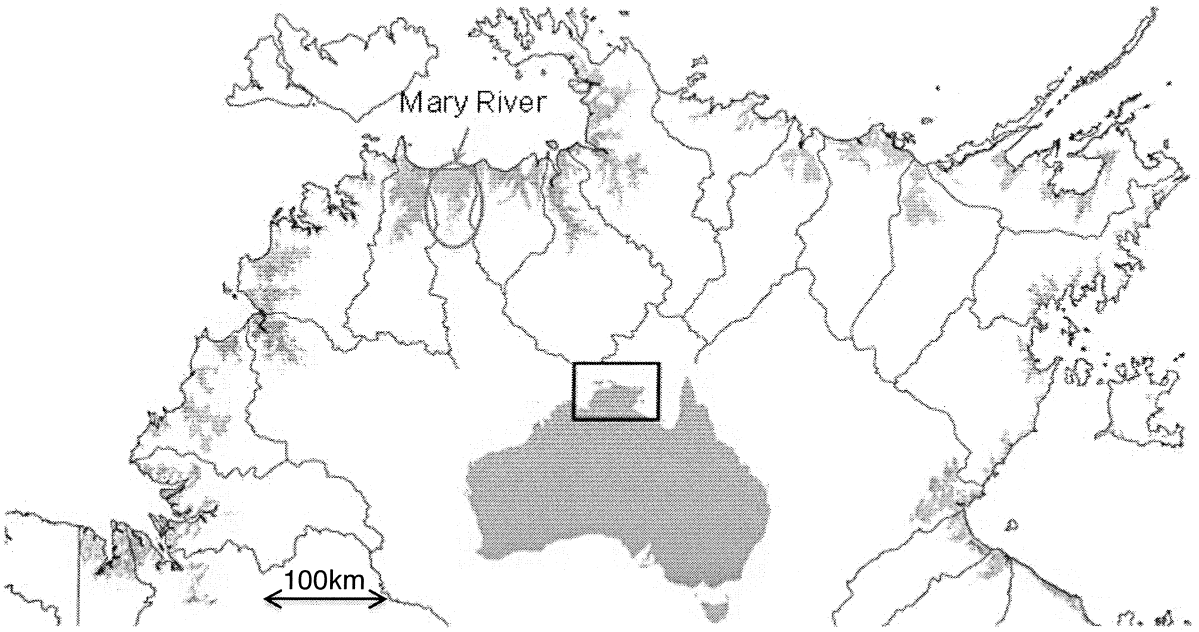


Figure 6. The Northern Territory Top End, low lying wetlands vulnerable to sea level rise. Wetland environments with elevations below 5m AHD (Based on STRM data).

1.7. History of saltwater intrusion in the Mary River

In 1940, the Mary River catchment had no discrete connection to the ocean. Blocked by Chenier ridges, the two major creeks, Tommycut and Sampan, did not extend more than 5km inland. Tidal flows did not inundate the freshwater wetlands of the lower plain and extensive melaleuca forest and swamp dominated the coastal areas west of Sampan Creek (**Figure 7**).

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 expansion of the tidal Sampan and Tommycut creeks. Interpretation of aerial imagery shows that erosion was prolific between 1943 and 1991, the network magnitudes exhibiting exponential growth (**Figure 8a, b**).

Between 1943 and 1950, the western Tommycut Creek extended with four tributaries leading to the Western Palaeochannel (Woodroffe and Mulrennan, 1993). These four tributaries were the first example of headwater extension into the Melaleuca and herbaceous swamps, beyond the fringe of the freshwater wetlands. Little of the change was recorded until 1963 when the Roonees Lagoon gauge station, at 12km upstream, detected a tidal influence during spring tides. It remained a tidal freshwater wetland until 1967 when saline water was found in the area.

Shady Camp was not affected by tides before 1976. By 1977 the fresh water billabong was connected to Sampan Creek and exposed to saltwater intrusion. The first structure at Shady Camp Billabong was a causeway built in 1978 but it was later washed out by the 1980 wet season floods (Fogarty, 1982). In 1987 the Northern Territory Government began a salt water intrusion control programme, which led to the construction of the Shady Camp Barrage in 1988. Made with concrete supported by the only bedrock base in the lower plains, it is still in commission today (Applegate, 1999).

Following the Woodroffe and Mulrennan (1993) geomorphological study and the NT Government wetland workshop in 1994, an attempt was made in 1995 to partially block Tommycut Creek at Dead Fish Billabong. It proved too difficult and was abandoned after 75% of the channel was blocked. It remains in place today with a crest height at approximately 1m below AHD. The constriction has served to increase current velocities at the bank leaving a large oval shaped scour of the channel, an indication of the potential issues following any major intervention works in the area. Overall the salt water intrusion programme has been successful to date, rehabilitating 20km^2 of degraded wetlands near the Chenier coast and vast freshwater wetlands upstream of Shady Camp Barrage (Jonauskas and Applegate, 2002).

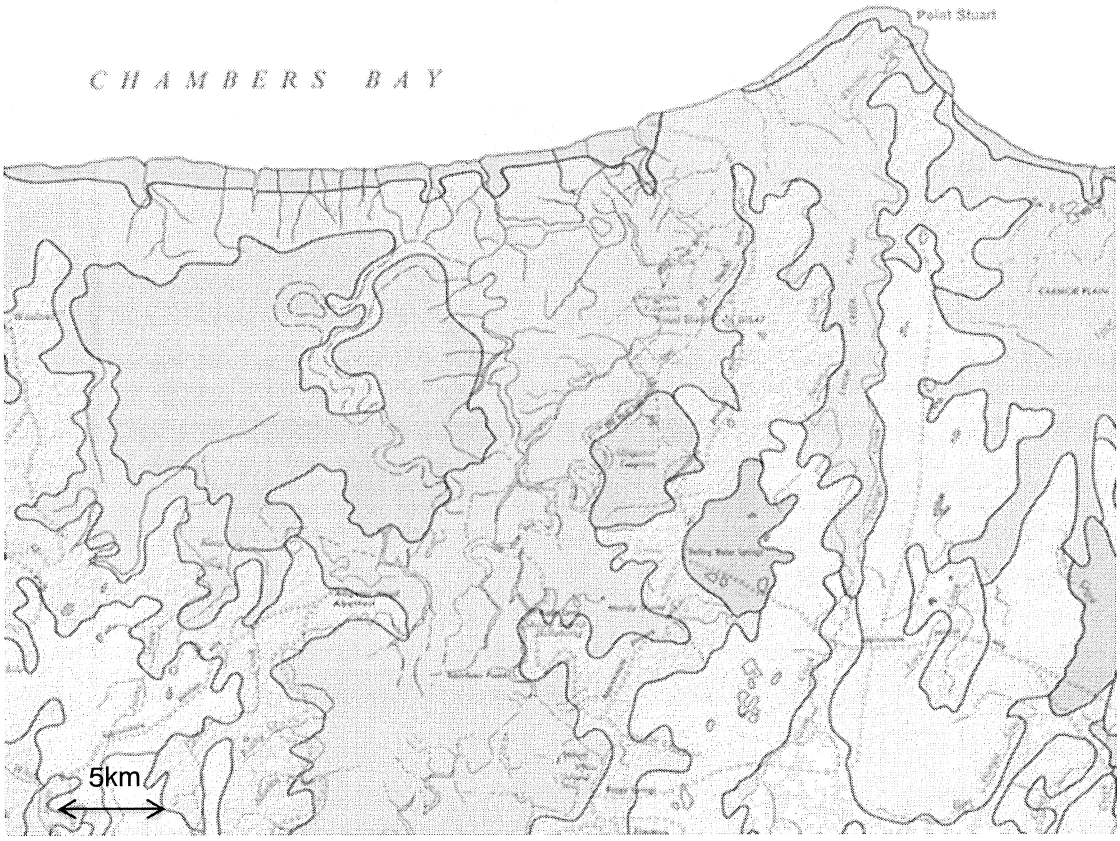


Figure 7. 1969: Blue area signifies saline vegetation, Orange area signifies sedgeland and herbaceous swamp vegetation, Purple area signifies Melaleuca swamp (Story, 1969).

When comparing the vegetation maps from the Land Research Series report no.25 (CSIRO, 1969) to present day saline areas, it is evident that there has been approximately 263km^2 of saltwater intrusion over the last 40 years (**Figure 9**). The change in wetland vegetation has been extensive. Most areas were directly affected by the hypersaline conditions around Sampan and Tommycut Creeks. The melaleuca areas would have been exposed to saline water from 1950 onwards (Knighton et al., 1992), although these areas held melaleuca communities in 1969 (Story et al., 1969). This is due to the saline tolerance of the dominant species *Melaleuca cajuputi* and *Melaleuca viridiflora*. Most of the dieback would then have occurred in the 1970's as the areas became heavily exposed to salt water and held less fresh water due to the increased drainage network. Similar processes of melaleuca dieback were occurring in the Point Farewell region to the East with 45% of Melaleuca forest area lost between 1950 and 1975 (Winn, 2001).

1.8. Causes

Many factors contributed to the initiation and rapid spread of saltwater intrusion. The most dominant of these are large buffalo populations, cyclones, and sea level rise.

1.8.1. Buffalo

Buffalo have been present in heavy populations since the 1930's rising to a peak in the 1980s of over 400,000 head. In the years leading up to the time of channel extension Buffalo hide production increased from 6000 in the mid-1920s, to 16,000 in 1936/37 in the Mary River region. Hunting then declined leaving populations to flourish (Woodroffe and Mulrennan, 1993). Buffalo activity has certainly increased and may have initiated channel development in the lower Mary River. The buffalo contribute to salt water intrusion by heavy grazing and trampling of channel banks and the formation of buffalo pads and subsequent swim channels in wet season flows (Fogarty, 1982).

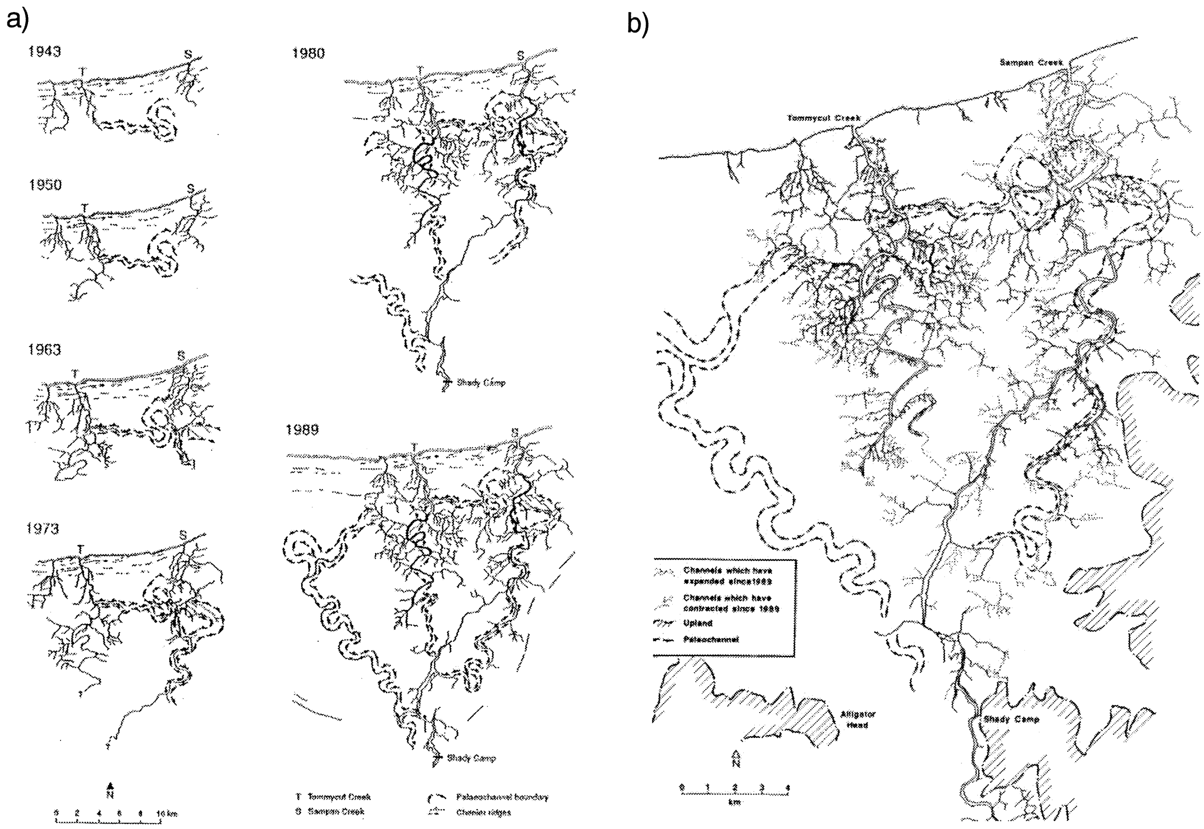


Figure 8. a) Expansion of Sampan and Tommycut Creeks, 1943-1989 (Knighton et al., 1992) **b**) The tidal network mapped from 1991 aerial photography, and comparison with the network mapped from 1989 aerial photography (Woodroffe and Mulrennan, 1993).

1.8.2. Cyclones

Cyclones have a great potential for triggering the rapid change seen in the Mary River. Storm surges combined with the larger than normal waves associated with cyclones have enough erosive power to cause breaches in the Chenier ridges fringing the fresh/brackish vegetation. In the mid 1960's - 5 cyclones in 4.5yrs, followed by Tracy 5.5yrs later, passed the Mary River, their 'eyes' within 50km of Point Stewart. Considering that over the century only 11 cyclones passed within 50km of Point Stuart it is significant that 6 of these happened in one decade.

Previous to this, in 1937, the slow moving Tropical Cyclone (Unnamed number 5) stalled for three days in the western flank of Van Diemen Gulf (**Figure 10**). With a central pressure on the 10th of March recorded at 955 hPa. Generally, cyclones of 955 hPa produce wind speeds of approximately 200kph, which would have been aimed directly at the Mary River coastline. A new moon was on the 12th of March meaning that tides would have been close to mean high water spring (MHWS), so a large storm surge would have occurred and eroded the Chenier ridges protecting the freshwater wetlands to some extent (Bureau of Meteorology, 2013).

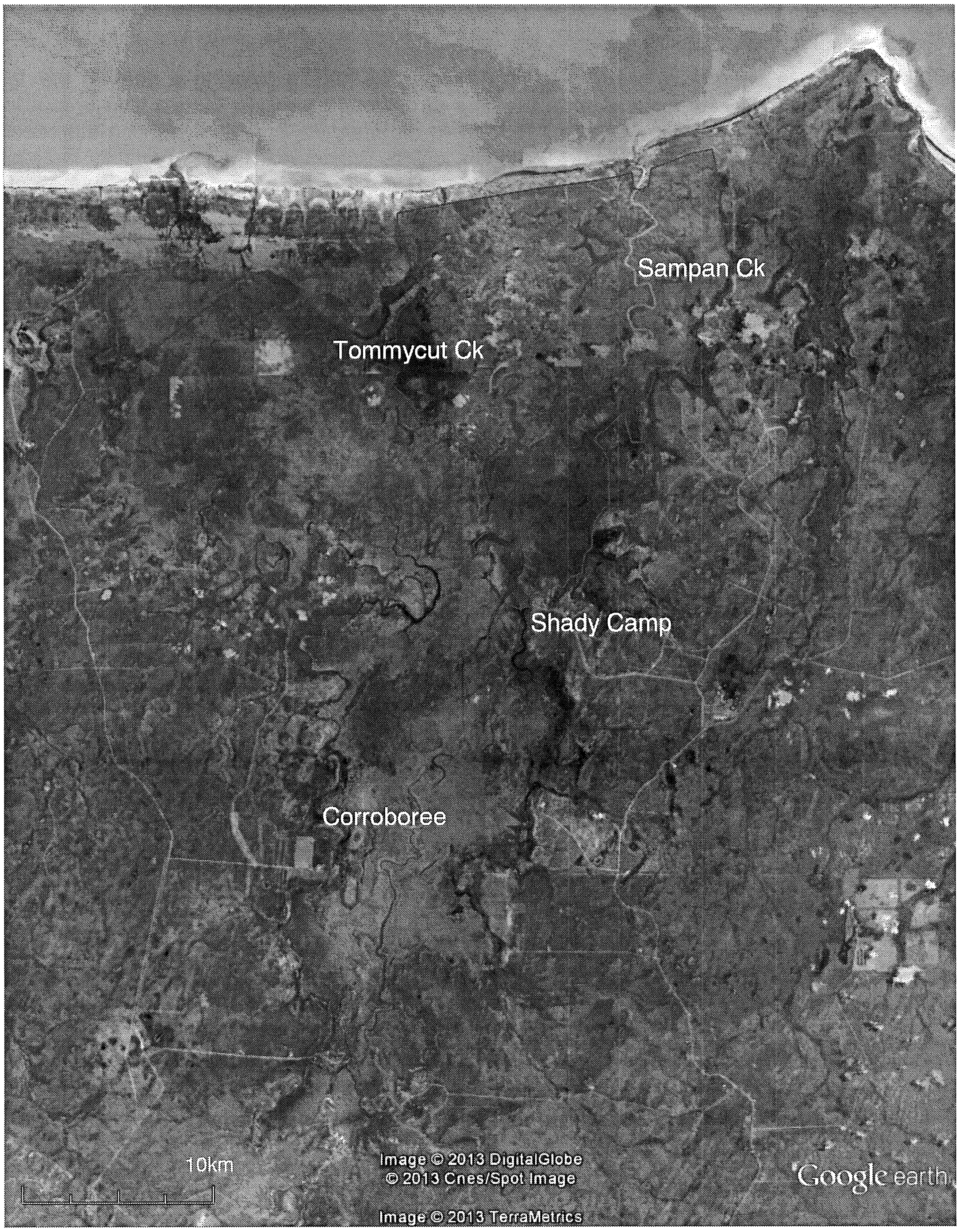


Figure 9. Present day Google Earth Image of the Lower Mary River Plains with an outline of the 263km^2 area affected by saltwater intrusion since the 1940s.

1.8.3. Sea level rise

Not only was SLR significant in the last 30 years, oceans in the early 20th century also experienced a rapid rise (Jevrejeva et al., 2006). Analysis by the Permanent Service for Mean Sea Level (PSMSL) has revealed that over the last 100 years the rate of rise of 2.5 ± 1.0 mm/yr occurred between 1920 and 1945, resulting in a mean global sea level rise of 48mm (**Figure 11**). Comparable to the 1993 to 2003 global rate of 3.1 ± 0.7 mm/yr, if it was magnified in the same way as in the Timor Sea it could have initiated the coastal erosion required to trigger network expansion in the lower Mary wetlands.

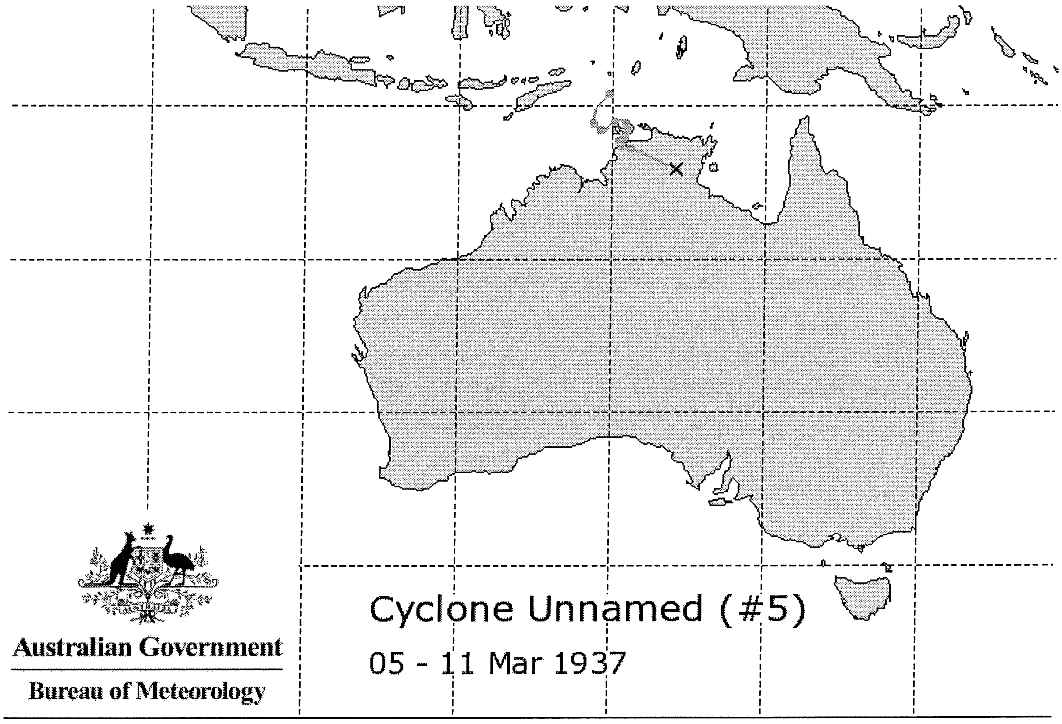


Figure 10. The path of Cyclone Unnamed #5. Blue dots that are close together in the western flank of Van Diemen Gulf signify stalling (BOM).

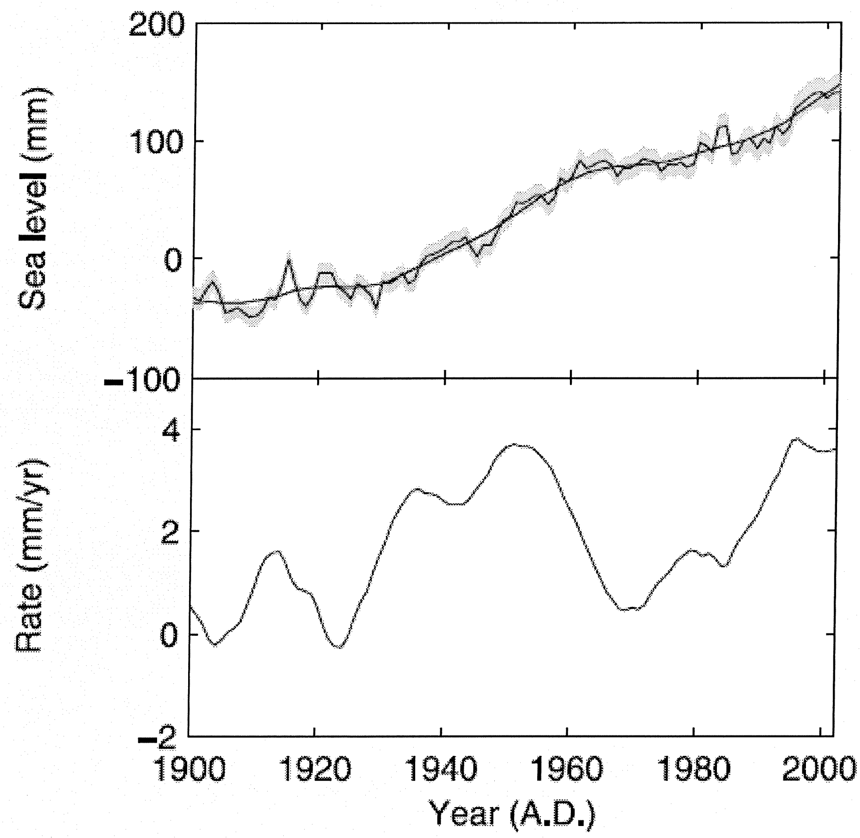


Figure 11. SLR (top), rate of SLR (bottom). Rate is over 2mm/yr. between 1930 and 1960 (Jevrejeva et al., 2008).

1.9. History of intervention

Buffalo, being one of the contributors to the erosion of creeks, were culled from 1982 to the early 1990s. Although the cull was aimed at eradicating tuberculosis it had a land management effect that reduced the future impacts of buffalo. The first active 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 expansion.

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.

1.10. Past reports and consulting

The most relevant technical reports on the Mary River coastal wetlands are summarised in point form below.

Australian Marine and Offshore Group, Mary River Wetlands, Report no 1, 2000 (AMOG, 2000)

- Desktop study of reports and previous work.

Recommended actions:

- Shady Camp to Alligator Head barrage
- Small weirs and overland flow controls downstream of Shady Camp
- New management practices

Claims/unknowns to solve with the model:

- Both creeks need partial closure. Barra creek: "will direct flow between TC and Sampan"

*Evidence on the LiDAR DEM shows this is no longer a hydraulic connection.

- "A rise of sea level as small as 100mm would have a considerable impact on the Mary River. Tidal penetration via Tommycut and Sampan and all the minor creeks entering van Diemen Gulf would be increased greatly. Tidal range increase. Tidal storage on the coastal plain would increase. Exacerbate erosion and headward advance of Tommycut and Sampan and their tributaries. Coastal erosion, reduction of the width of fringing mangroves, loss of seaward Chenier and growth of tidal creeks cutting the seaward Cheniers"

*Almost 100mm had occurred in the 10yrs before this study and again in the 10 years since. Some of this may have occurred at differing degrees but not all

- "A 200-250mm rise will result in coastal erosion, recession of the coastline and dramatically increased salt water penetration throughout the coastal and estuarine plains. It is likely there will be a transgressive phase with the sea extending over most of the coastal plain and a sequence of stages similar to those described by Woodroffe and Mulrennan for the evolution of the present plain, extending over a time period of centuries"

*Some of this this may occur with 400-500mm of SLR and the last statement at 1000mm.

Delft report Oct 2000 (van der Wegen and Verhagen, 2000)

- Review of AMOG report and recommendations

Recommended actions:

- Rejection of the barrages in the mouth due to diversion of flow causing new problems.
- Placement of submerged weirs at Dead Fish Billabong and Roonees Lagoon
- Recommendations from Delft and AMOG are to "Provision of a system of barrages and levies on coastal and tributary creeks to the west of the Western paleo channel"

*With sea level rise this is not necessarily beneficial. These low lying areas may best be left to return to the mangrove swamp conditions of 5000 yrs. ago.

Claims/unknowns to solve with the model:

- state that tidal action was the driver behind continual erosion of the tidal creeks.
- Partial closure at the mouth of both creeks is rejected by Delft due to restriction of wet season floods.
- Reduction of velocities in the mouth of both creeks would effectively decrease or halt the widening processes.
- WEIR CREST HEIGHT
- A high crest (+1mAHD) will force water flows to divert. High currents will occur at the embankments eroding them and even leading to overturning of the weir in a later stage.
- Create weirs at 0m AHD, these weirs will result in a tidal difference decrease of 50 % upstream.
- Model study should determine whether the submerged weirs form a serious obstacle in discharging the fresh water floods to sea via Tommycut and Sampan Creeks. Suggest that submerged weirs are placed upstream to reduce this effect.

*compare models of weirs upstream and at the mouth for floodplain inundation and velocities.

- When closure takes place in one creek only, the effects will be overtaken by the tide entering the system from the other creek.

AMOG Mary River Wetlands, Report no 2 2001

- Review of options and Delft report

Recommended actions:

- Shady Camp to Alligator Head closure
- Continue minor control structures

Claims/unknowns to solve with the model

- "The headward growth of creeks would increase substantially if tidal barriers were introduced, as the tidally driven salt water flows search for new channels through which to penetrate inland."
- "TC and Sampan were smaller and headward expansion is occurring near the tidal limits of these minor creeks where the tidal range is further restricted. Despite this, the minor creeks have proliferated and extended and are still doing so"
- "The half tide weirs on Tommycut and Sampan Creeks recommended in the Delft memo cannot function without substantial works extending across the width of the wetlands and hence are not recommended".

*not substantiated by any modelling or analysis, speculation, assumption.

Woodroffe, Geomorphology of the Lower Mary River Plains. 1993

- Comprehensive report on geography, geology and hydrography

Tommycut Creek Closure (Wyllie et al., 1997)

- Modelling of Lower Mary River Channels with barrage in place at Dead Fish Billabong
- Found that flow is diverted through connecting channels between Tommycut and Sampan

*Could only test Tommycut creek closure as Sampan was not well defined in the geometry

Claims/unknowns to solve with the model:

- Closure of Tommycut (By how much?) will lead to an increase in flood elevations over the floodplain of 0.3m.
- Additional flows carried by Sampan Creek

Past models

- Tommycut Creek Closure. Weir in of Tommycut Creek and hydrodynamic implications
- Current project - Mary River Salt Water Intrusion Project.

1.11. Brief

Methods used

- Modelling with MIKE21 FM (Flexible Mesh) produced by DHI (Danish Hydraulics Institute) (2011)
- Surveying with LiDAR commissioned by FUGRO
- Bathymetric surveying with depth sounder (CDU)
- Hydrographic data supplied by NRETAS (inflow and ocean data)

Aims

- Examine the effectiveness of barrages and submerged weirs in mitigating and reducing saltwater intrusion on the Mary River coastal floodplains.
- Use hydrodynamic modelling to improve our understanding the present hydraulics of the system
- Simulate scenarios of predicted SLR over the next 100 years (0.3m 2050 and 0.8m 2100) and incorporate submerged weirs to determine their effect on salinity levels and floodplain inundation within the estuarine zone.
- Determine their effect on erosion rates due to a reduction in velocity head.

2. METHODS

2.1. Project Design

2.1.1. Area of interest

The area of interest was selected to cover the salt intruded areas and capture the most important hydraulic interactions of the lower Mary River. Areas west towards the Adelaide River system were not included due to their relatively stable state compared to the Tommycut Sampan area. The eastern boundary was defined with land elevations above 5m AHD. The northern boundary was tidally driven with recorded data offshore and designed to minimise boundary affects at the mouth of both creeks. The southern boundary was defined by the Shady Camp Barrage (upstream) hydrograph.

2.1.2. Modelling

MIKE 21 FM (Flexible Mesh) HD (hydrodynamics) surface water numerical modelling package for coastal, estuarine and floodplain environments was used. 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).

2.1.3. Surveying

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.

Datums used in capture were:

Horizontal Datum GDA94

Vertical Datum AHD as defined by AUSGeoid09BETA7

Map Projection MGA Zone52 South

The total captured area covering 371km^2, within the Geographic Bounding Box:

BOUNDING	Coordinate
West longitude	131° 37' 34" E
North latitude	12° 15' 07" S
East longitude	131° 49' 45" E
South latitude	12° 30' 04" S

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 datums to the LiDAR survey. Areas surveyed were:

- Sampan Creek 1km upstream of barrage and barrage to mouth
- Tommycut Creek upper tributaries to mouth.
- Two long-sections per channel
- Over 100 cross-sections

2.1.4. Data processing

LiDAR data was thinned from a 10m key-point digital elevation model (DEM) to a 10m gridded DEM for processing efficiency. Bathymetry was integrated into the LiDAR dataset at specific bank sections using the height difference between the bank and the water level. From the LiDAR, bank heights are known relative to AHD so water depths were processed to AHD for incorporation into the mesh using the formula:

$$D_T\ (AHD) = b_e - (d_m + b_h)$$

Where D_T = total depth relative to AHD, b_e = elevation of bank in AHD, d_m = depth measured, b_h = bank height.

Bathymetry between cross-sections was derived with a combination of measured data from either one or two mid-channel long-sections to gauge depth and by linearly interpolating between the cross-sections along the channel banks to best define the channel.

The resolution of the LiDAR data on the floodplain was high enough so that mesh elevations could be calculated with more efficient linear interpolation techniques, while the natural neighbour interpolation technique was employed in for the channel bathymetry.

2.1.5. LiDAR returns

The captured area used for mesh building has a mean elevation of 1.86m above AHD, which is below MHWS relative to the tidal levels at the mouth (**Figure 12**). Once processed, the returns produce a highly detailed DEM of the terrain (**Figure 13**).

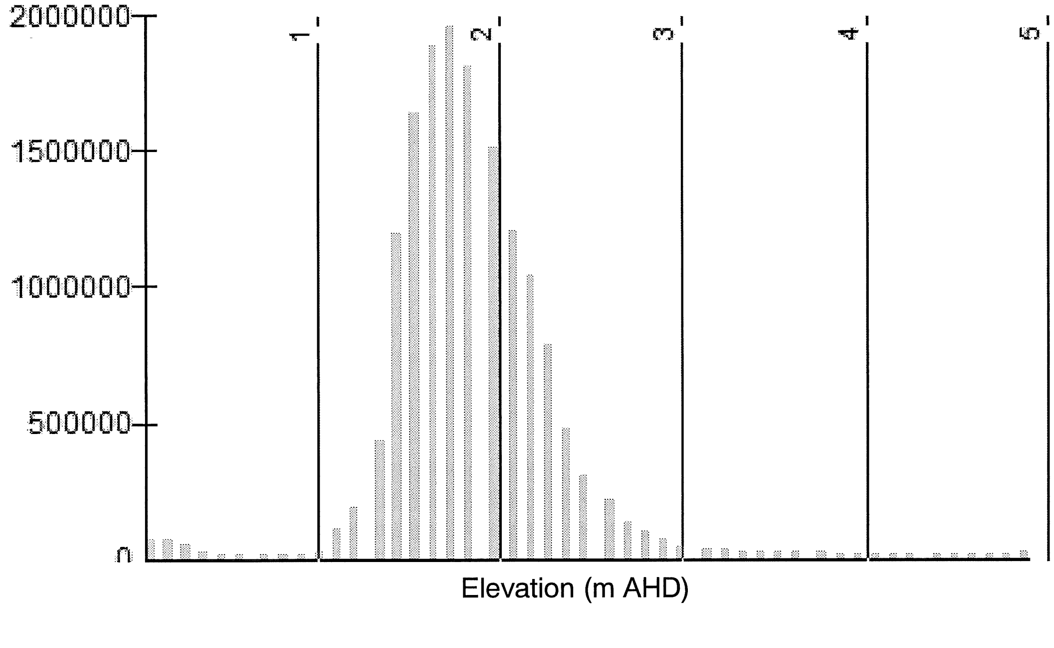


Figure 12. Elevation distribution of the lower Mary River from Shady Camp to the coastline within the area of interest. Mean = 1.86m, Standard Deviation = 0.53m.

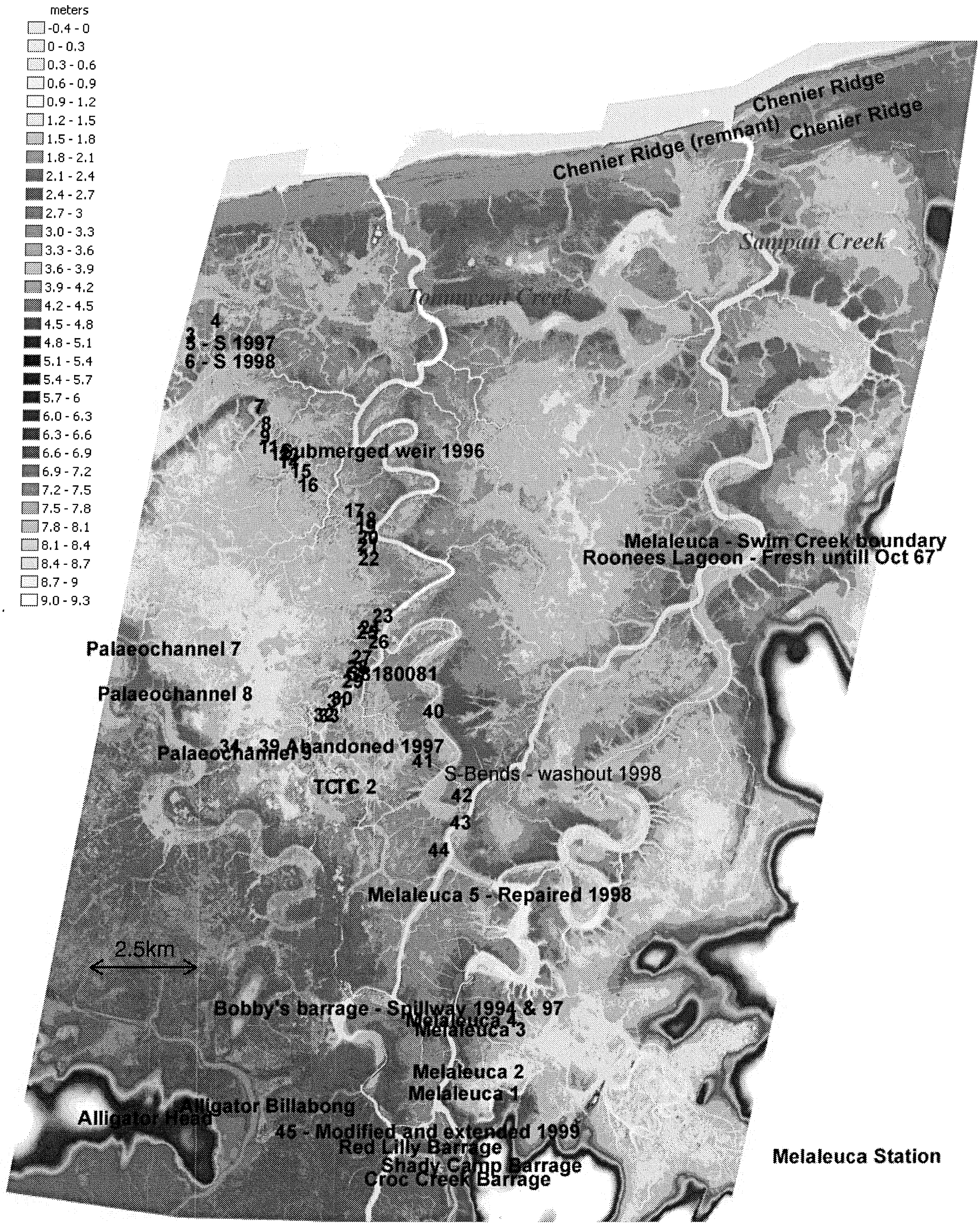


Figure 13. LiDAR derived DEM of the area of interest. With labels of significant geographical units and barrages constructed during the Northern Territory Government salt water intrusion control programme.

2.2. Model Characteristics

2.2.1. Mesh building

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 14** with the fine scale "Cutting" developed to represent the subtle interaction between Tommycut and Sampan Creeks (**Figure 15**).

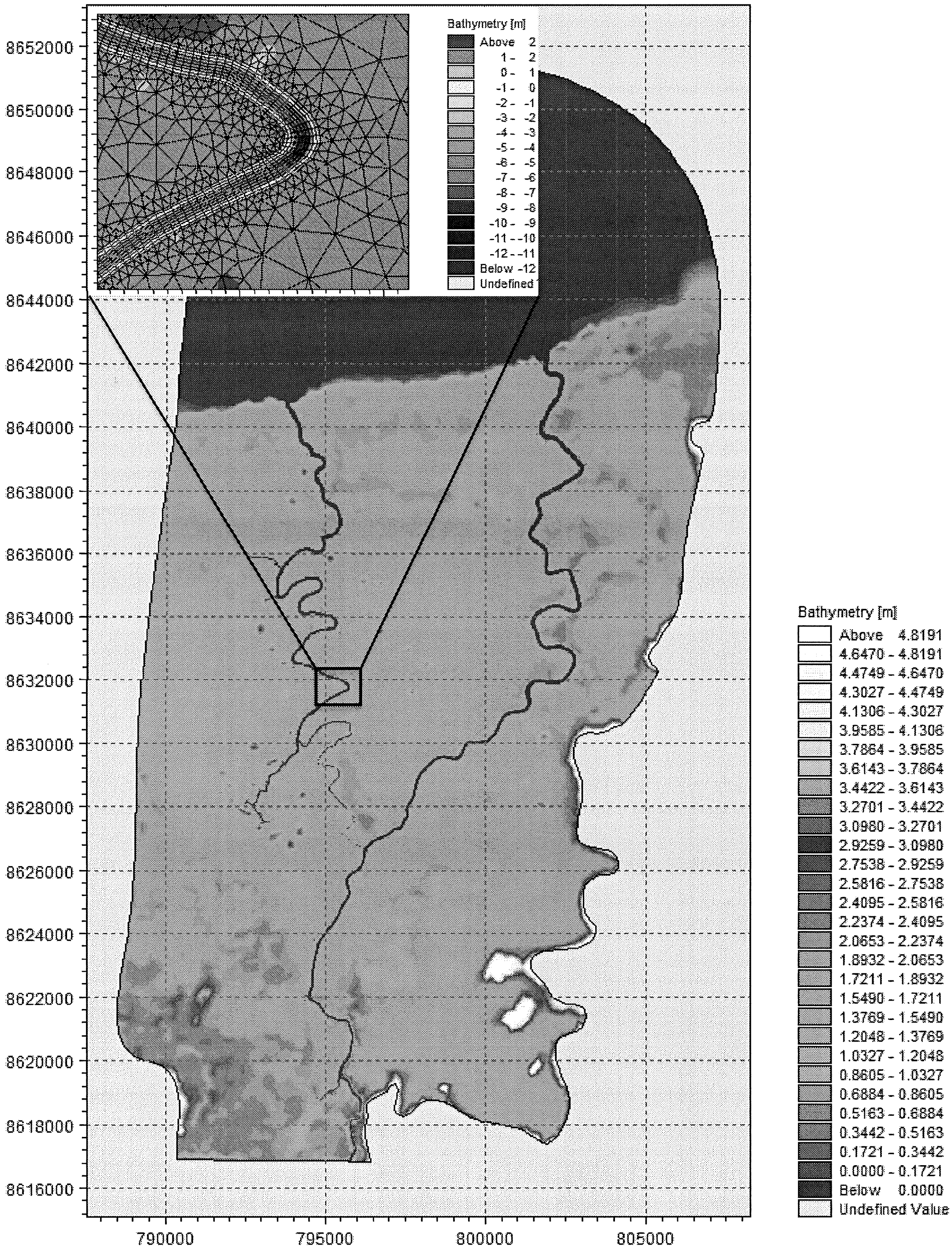


Figure 14. Terrain data from the whole mesh. Bounded by the Van Diemen Gulf to the north and Shady Camp Billabong to the south. Insert shows the general triangular-quadrilateral mesh structure used to define the system.

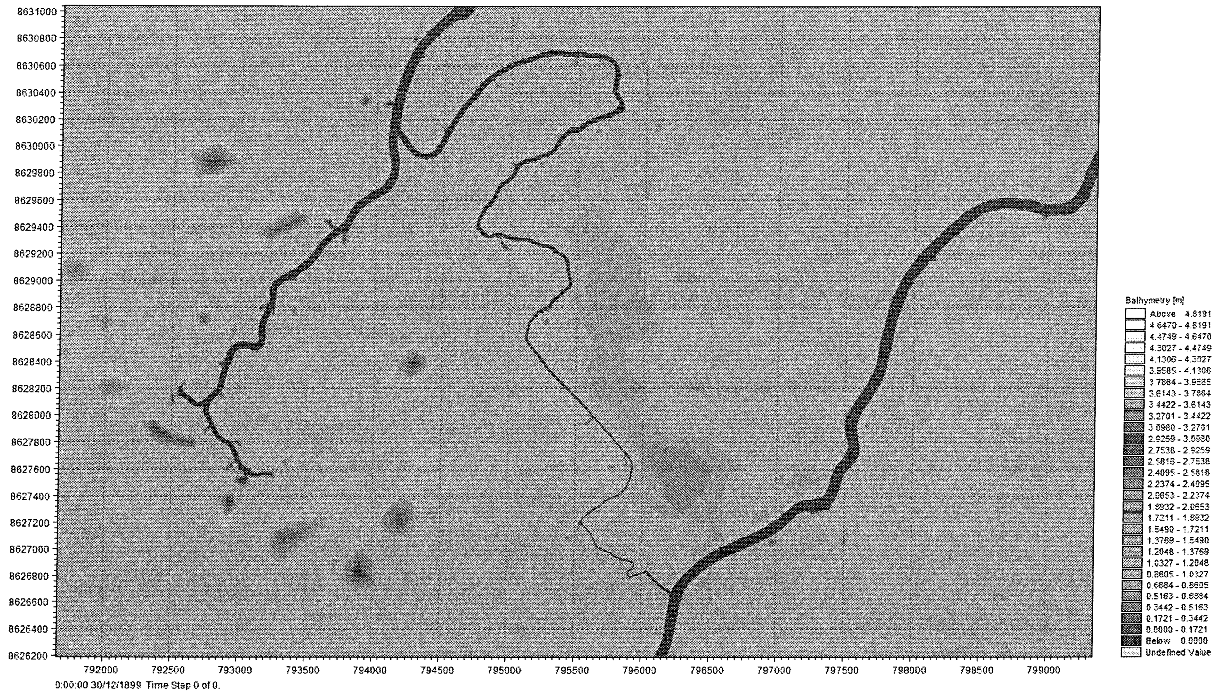


Figure 15. Mesh derived geometry of the channels and floodplains near "The Cutting".

2.2.2. Parameters

MIKE 21 modelling software configuration employed in model runs:

Boundary parameters

- Inflow was kept constant at $5m^3s^{-1}$ to simulate an end of dry season hydrodynamic and inundation conditions.
- Chambers Bay tide was driven by tidal data collected from 4/6/1993 to 16/9/1993 this period coincided with a 7.5m tide recorded in Darwin Harbour which is 93% of the 2008 highest astronomical tide of 8.1m. So it is evident that the Chambers Bay gauging captured a significant spring tide and is appropriate for this study.

Three sea level conditions were tested:

- +0.0m AHD
- +0.3m AHD
- +0.8m AHD

Tidal pattern was not altered although an increase in SL could affect tidal harmonics within Van Diemen Gulf; this was deemed negligible for the purposes of this study.

Chambers Bay tidal records were captured in 1993, in the year of the installation of the Darwin SEAFRAME tide gauge. Since 1993 the SEAFRAME tide gauge recorded 185mm of relative sea level rise in Darwin. To compensate this 150mm was added to the tidal graph to create present day conditions.

Flow data from G8180059 was incorporated in the model for the upstream inflow hydrograph for the full 2008/2009 water year (**Figure 16**). This was tested without weirs to access the stability of the simulation. Following the successful run of current conditions all three SLR scenarios were tested both with and without submerged weirs.

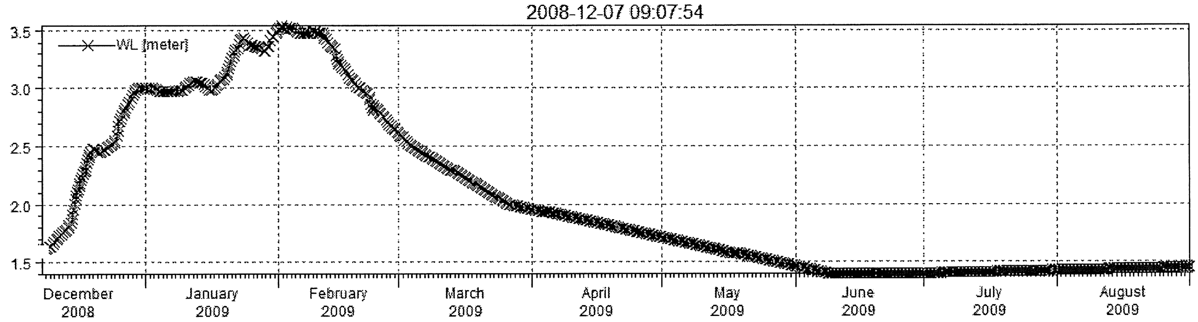


Figure 16. Hydrograph recorded upstream of Shady Camp Barrage. It represents a year of high flooding.

Flooding and drying of the floodplain activated

This allows smooth calculation of moving boundaries (flooding and drying fronts) in floodplain areas due to tidal changes and wet season flow.

- Drying value - 0.005 (element is removed from the simulation)
- Flooding value - 0.05 (element is re-entered into the calculation)
- Wetting value - 0.1 (below this value, momentum fluxes are set to zero and only mass fluxes are considered)

Salinity module configuration

Initial conditions are provided by a salinity map that varies linearly from 32 PSU at Chambers Bay to fresh water at Shady Camp barrage (**Figure 17**). This allows for rapid start-up of salinity modelling as salinity levels modelled are equal to the given boundaries. Horizontal dispersion is calculated with a scaled eddy viscosity formulation, scaling factor = $0.1m^2s^{-1}$.

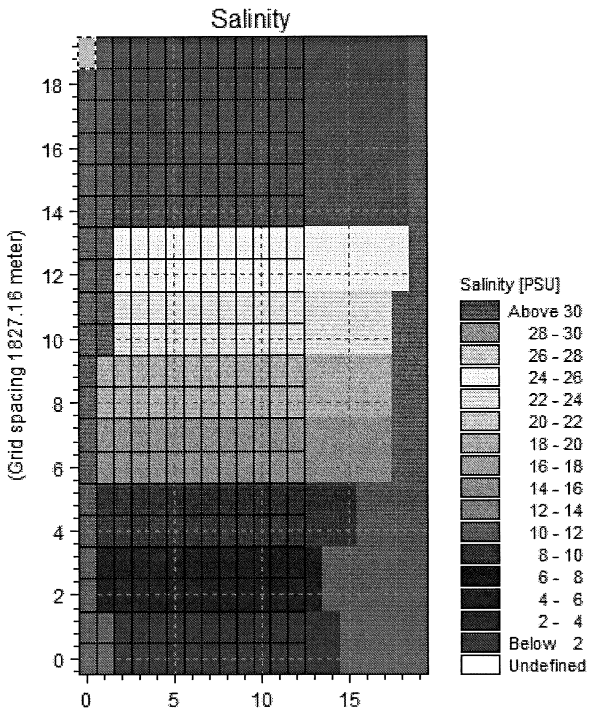


Figure 17. Salinity map for initial conditions. Grid values are superimposed onto the corresponding wet area of the model for the first time step.

Smagorinsky formulation for eddy viscosity calculations (variable)

Eddy coefficient = $0.28m^2s^{-1}$ (Default)

Bed roughness

Friction is constant in the domain between $32m^{1/3}s^{-2}$ – $60m^{1/3}s^{-2}$. This is the main calibration parameter, awaiting calibration data: This could include, channel water level, velocity, salinity and discharge data at various locations in Tommycut and Sampan Creeks. In later test runs, a friction parameter map controls the basic channel/floodplain bed friction **Figure 18**. Varies from Manning's 'M' = 20 (Manning's 'n' = 0.05) over the floodplain and Manning's 'M' = 50 (Manning's 'n' = 0.02) within the channel.

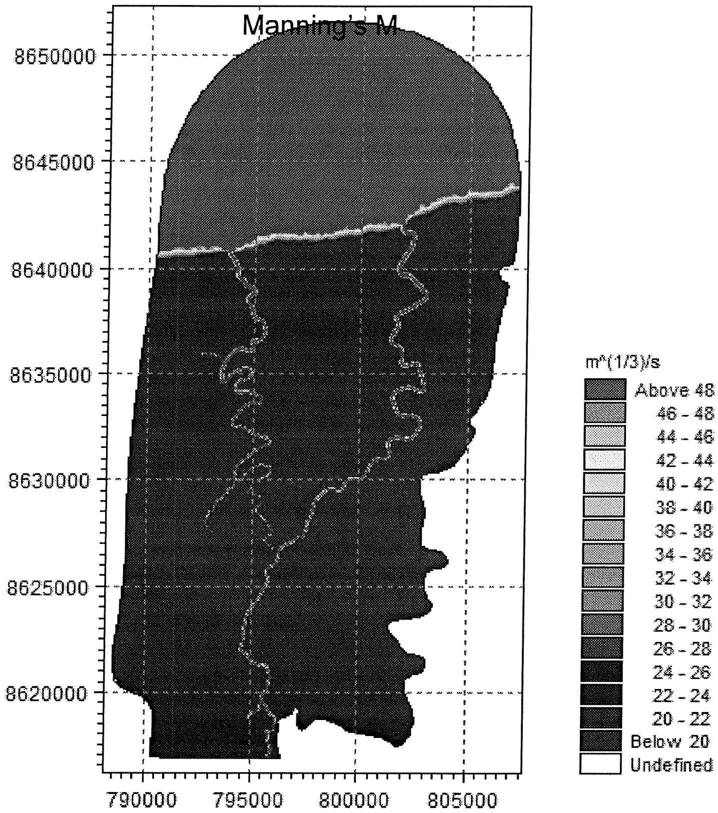


Figure 18. Bed resistance map in Manning's 'M' units.

2.2.3. Structures

Weirs located at the mouth of Sampan and Tommycut (**Figure 19**)

Weir Data

Sampan mouth

Width: 161m

Crest level: 1m, 0m

Coord no.	Easting	Northing
1	801900	8640560
2	802050	8640500

Tommycut mouth

Width: 136

Crest level: 1m, 0m

Coord no.	Easting	Northing
1	794106	8639924
2	794243	8639940

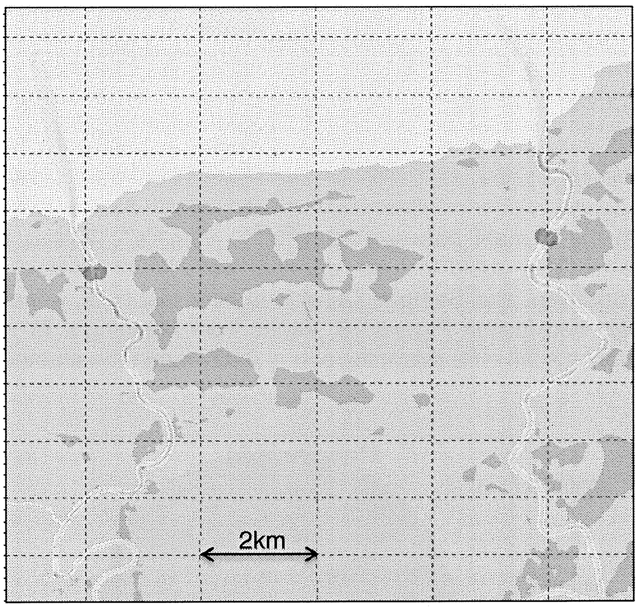


Figure 19. Red marks show the location of submerged weirs in Sampan Creek (right) and Tommycut Creek (left).

Weirs upstream at Dead Fish Billabong in Tommycut Creek and Roonees Lagoon in Sampan Creek **(Figure 20)**.

Weir data: Dead Fish Billabong

Width: 58m

Crest level: 1m

Coord no.	Easting	Northing
1	795024	8631395
2	795075	8631324

Weir data: Roonees Lagoon

Width: 128m

Crest level: 1m

Coord no.	Easting	Northing
1	801517	8633489
2	801634	8633542

Shady Camp Barrage

Weir data: Shady Camp Barrage

Width: 69m

Crest level: 1.72m (From LiDAR DEM)

Coord no.	Easting	Northing
1	796052	8618341
2	796121	8618341

Evaporation

Specified at a constant 5mm per day.

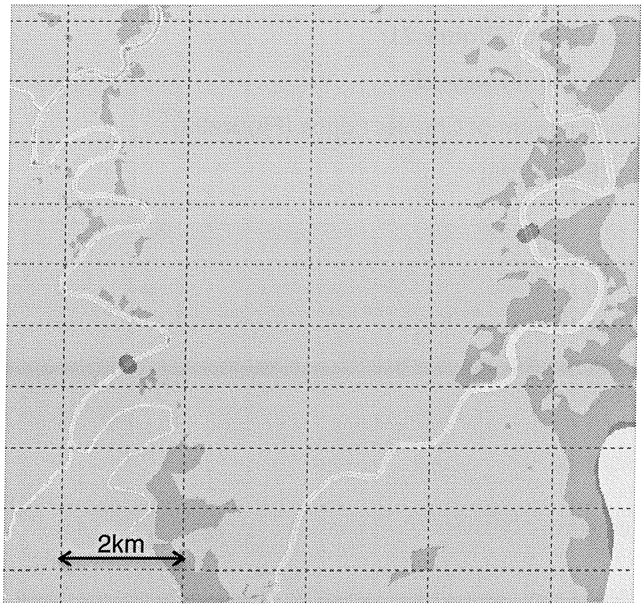


Figure 20. Red marks show location of submerged weirs tested in Roonees Lagoon (right) and Dead Fish Billabong (left)

2.2.4. Data summary

Data used to run the simulations are as follows:

- Inflow hydrograph (water level)
- Chambers Bay tidal data (water level)
- LiDAR data approximately 30 million points covering 370km^2
- Bathymetric data of approximately 20,000 data points including two long-sections and over 100 cross-sections
- Evaporation data from Woodroffe and Mulrennan (1993)
- Friction coefficients used were based on the values used in AWACS modelling of Tommycut Creek (1997). A Manning's 'n' of 0.05 over the floodplain and 0.02 within the channel.

2.2.5. Data output specifications

Whole area output – extracting items including

- Surface elevation
- Water depth
- U Velocity
- V Velocity
- P flux
- Q flux
- Density
- Salinity
- Current speed
- Current direction

Discharge outputs

- Tommycut Creek Mouth (**Figure 21**)
- Sampan Creek Mouth (**Figure 22**)
- Entire coastline upstream of Chenier ridges (**Figure23**)
- Sampan Inflow (**Figure 24**)

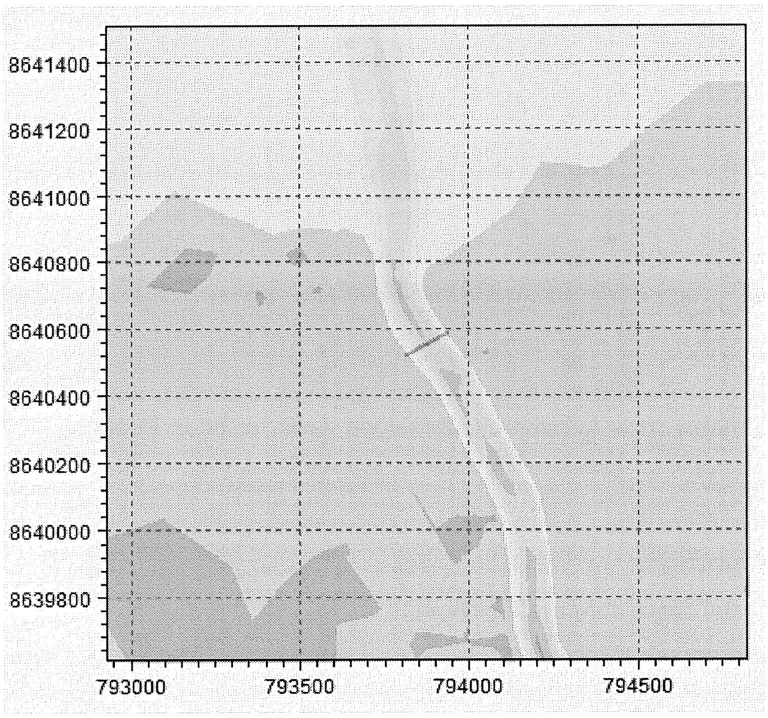


Figure 21. Tommycut Creek mouth, discharge cross-section line in red.

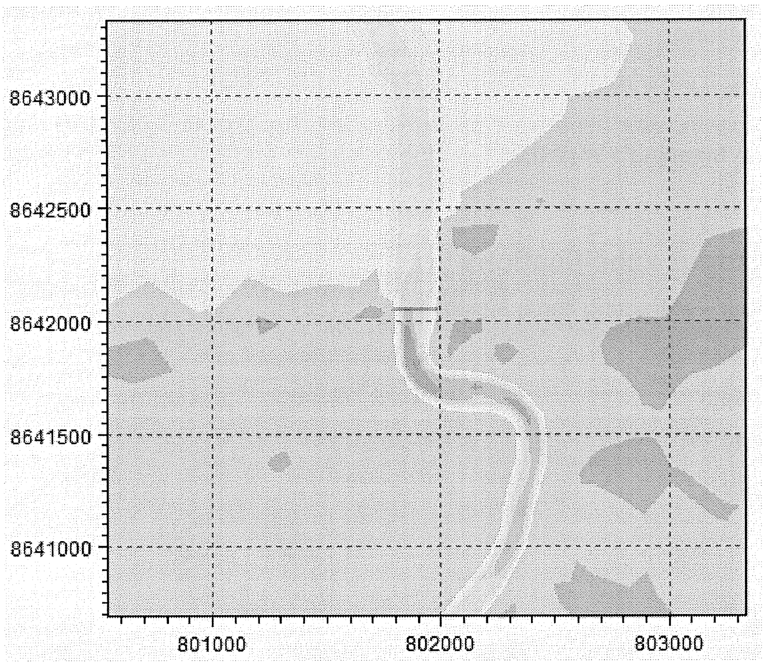


Figure 22. Sampan Creek mouth, discharge cross-section line in red.

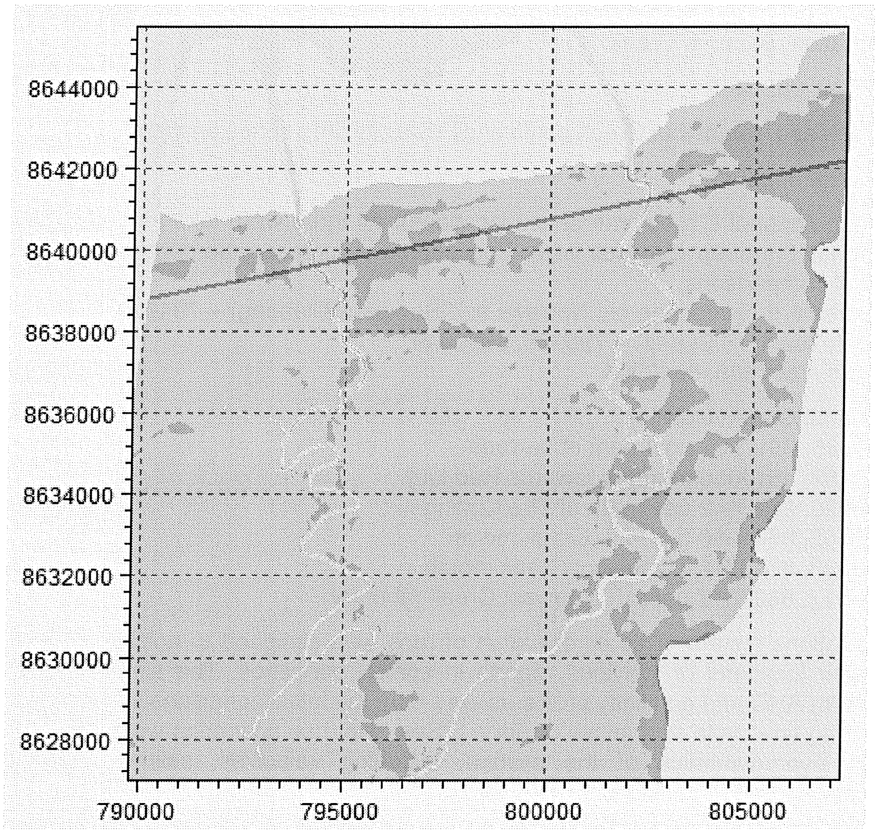


Figure 23. The whole coast (floodplain and both creeks), discharge line.

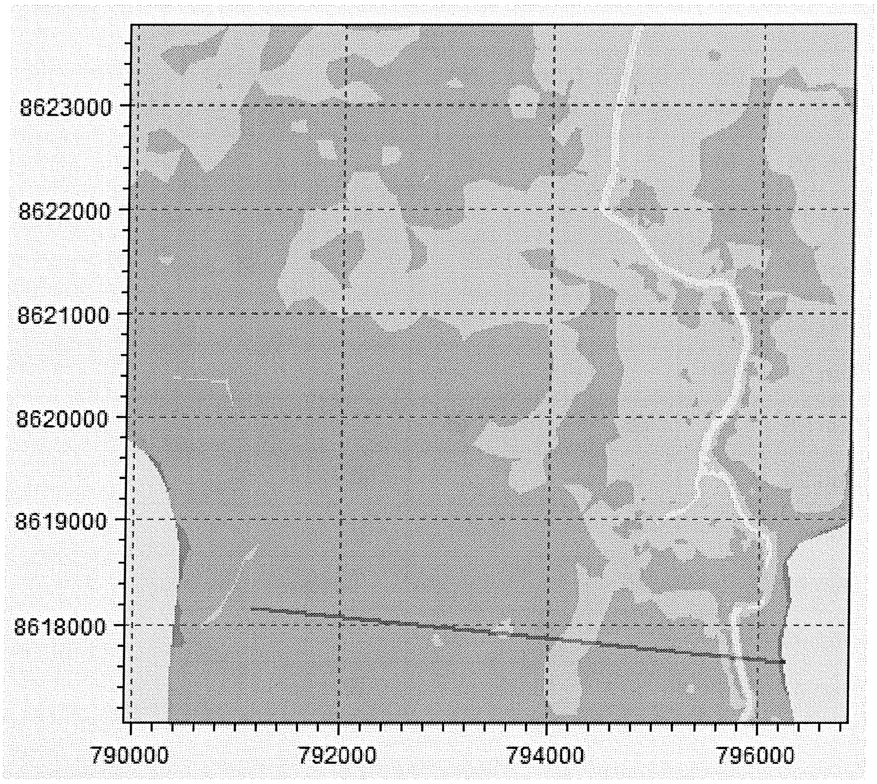


Figure 24. Sampan inflow discharge line. Extends across floodplain to capture wet season flow.

Time series outputs

Upstream location, Sampan Creek:

- 795800, 8620400

Sampan Creek and Tommycut Creek confluence (Salinity time series analysis):

- 796230, 8626525

Sampan along channel (Three time series locations): All three were taken from locations where the channel is approximately 8m deep (Bankfull flow). This served to increase the control measure of the data, allowing better velocity comparisons.

- Upstream (between the old Narrows and Sampan Billabong) – 794739, 8623501
- Middle reach (S Bends) – 799978, 8630049
- Mouth – 801885, 8642204

Dry season analysis of velocities:

- 795785, 8617987 upstream of barrage
- 795167, 8619055 tributary towards Red Lilly
- 796220, 8626442 upstream of The Cutting
- 801865, 8641956 Sampan Creek mouth
- 793808, 8640718 Tommycut Creek mouth
- 793017, 8627617 upper Tommycut Creek tributary

Weir combinations tested: This combination of runs was designed to quickly evaluate the effectiveness of proposed weir locations of previous reports in control scenarios. The simulations start with water in the system at 0.0m AHD and a salinity profile derived from the initial conditions salinity map. It is then run through a typical spring tide cycle and inflow of $5m^3s^{-1}$. Sea level rise scenarios were used to simulate the potential changes in hydrodynamics of the system, including velocities, salinity, inundation areas and weir effectiveness (**Table 1**).

Table 1. Runs tested to assess dry season conditions. TCM = Tommycut Creek mouth, SCM = Sampan Creek mouth, TCUP = Tommycut Creek at Dead Fish Billabong, SCUP = Sampan Creek at Roonees Lagoon.

	0m SLR	0.3m SLR	0.8m SLR	No Weir	Weir TCM	Weir TC Upstream	Weir TCM+SCM	Weir TCUP+SCUP
Run 30	☑			☑				
Run 31	☑				☑			
Run 32	☑					☑		
Run 33	☑						☑	
Run 34	☑							☑
Run 38		☑		☑				
Run 39		☑			☑			
Run 41		☑					☑	
Run 42		☑						☑
Run 46			☑	☑				
Run 47			☑		☑			
Run 49			☑				☑	
Run 50			☑					☑

'Water year' simulations

Simulations of the water year from the beginning of the wet season to the end of the dry season to evaluate the hydrodynamics associated with erosive conditions (**Table 2**). The effect of submerged weirs on wet season flood attenuation is also assessed along with the effect of sea level rise on salt accumulation in the estuary/floodplain system.

Table 2. Full water year configurations tested.

	0m SLR	0.3m SLR	0.8m SLR	No weir	Weir TCM+SCM 1m crests	Weir TCM+SCM 0.0m crests
Run070	☑				☑	
Run071	☑			☑		
Run072		☑			☑	
Run073		☑		☑		
Run074			☑		☑	
Run075			☑	☑		
Run082	☑					☑

Calibration

Data for calibration are limited. Water level at the mouth of each creek was used to calibrate with offshore data (Chambers Bay). Previous velocity measurements from (Woodroffe and Mulrennan, 1993) were used to check model outputs. As they are historic data, both calibration datasets represent a slightly different system to what was modelled in this study. For this reason the model is described as 'indicative' of real scenarios.

3. RESULTS

3.1. Calibration

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) (**Figure 25**). The dampening visible below 0m AHD is a result of shoaling just offshore of the mouth. 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.

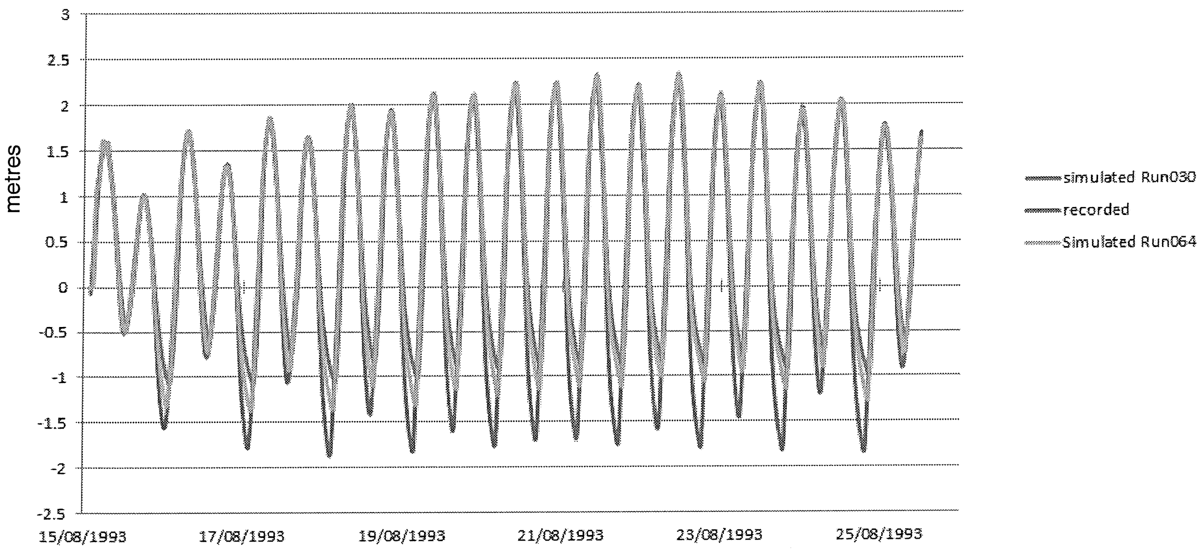


Figure 25. Sampan Creek mouth simulated and recorded water levels. Run030 original test (R^2 = 0.9), Run064 after reducing the bed friction to 'M' = 60 (R^2 = 0.964).

Tommycut creek data were initially much less consistent following the pattern at an R^2 value of 0.88 (**Figure 26**). The difference in magnitudes between recorded and simulated data is most likely due to an AHD reduction error in the recorded data, which appears to be approximately -0.9m AHD. With the reduction error accounted for and bed friction reduced to 'M'= 60, Tommycut mouth water level was simulated at an R^2 value of 0.976 (**Figure 27**).

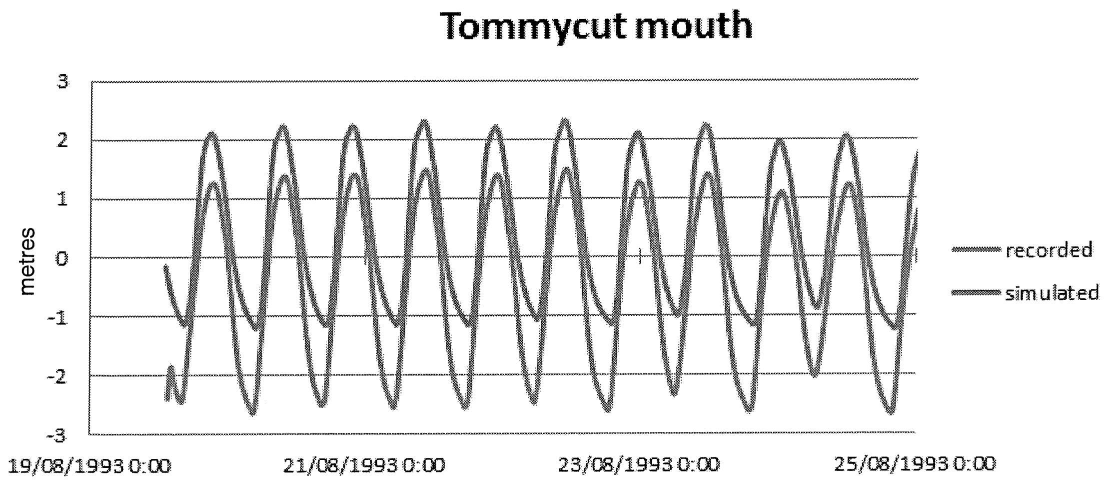


Figure 26. Tommycut Creek mouth simulated and recorded water levels. Note the unaccounted for negative shift in the recorded data.

The flood tide is stronger than the ebb tide (**Figure 28**), as is expected in systems with high amounts of floodplain drainage. The flood/ebb tide outputs correspond to the data collected by (Woodroffe and Mulrennan, 1993) (**Figure 29a**) although there is much less attenuation of the tide upstream compared to 1992 data, owing to the greater channel density due to erosion over the last 20 years. The shapes of the curves show good correspondence, further supporting the model.

Recorded and simulated water level and flow rate patterns give a qualitative indication that the model provides a good representation of the system. The final bed roughness parameters in a fully calibrated model would be based on present water level and velocity data at multiple locations along both Tommycut and Sampan Creeks and a physical assessment of the surfaces.

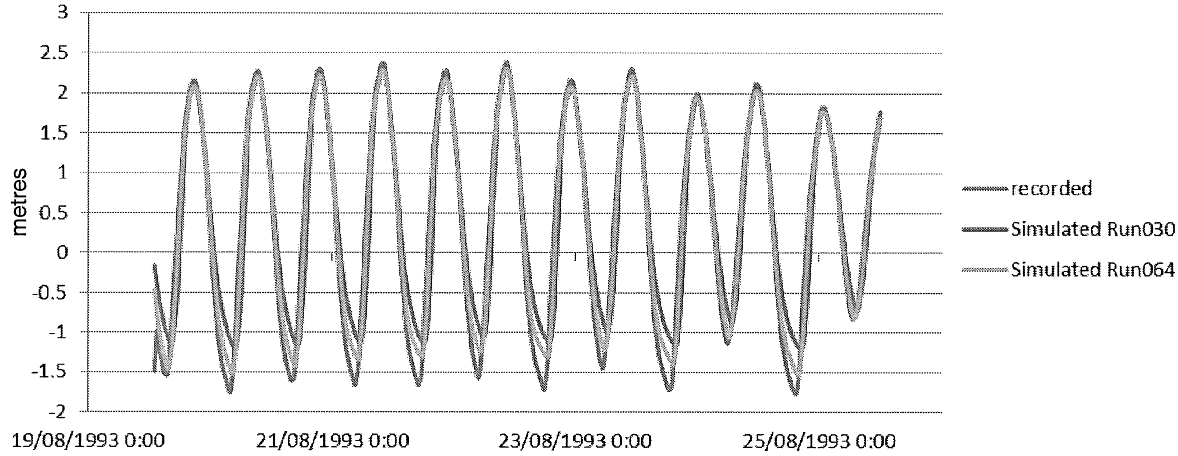


Figure 27. Tommycut Creek mouth simulated and recorded water levels. Run030 original test (R^2 = 0.88), Run064 after reducing the bed friction to 'M' = 60 (R^2 = 0.976).

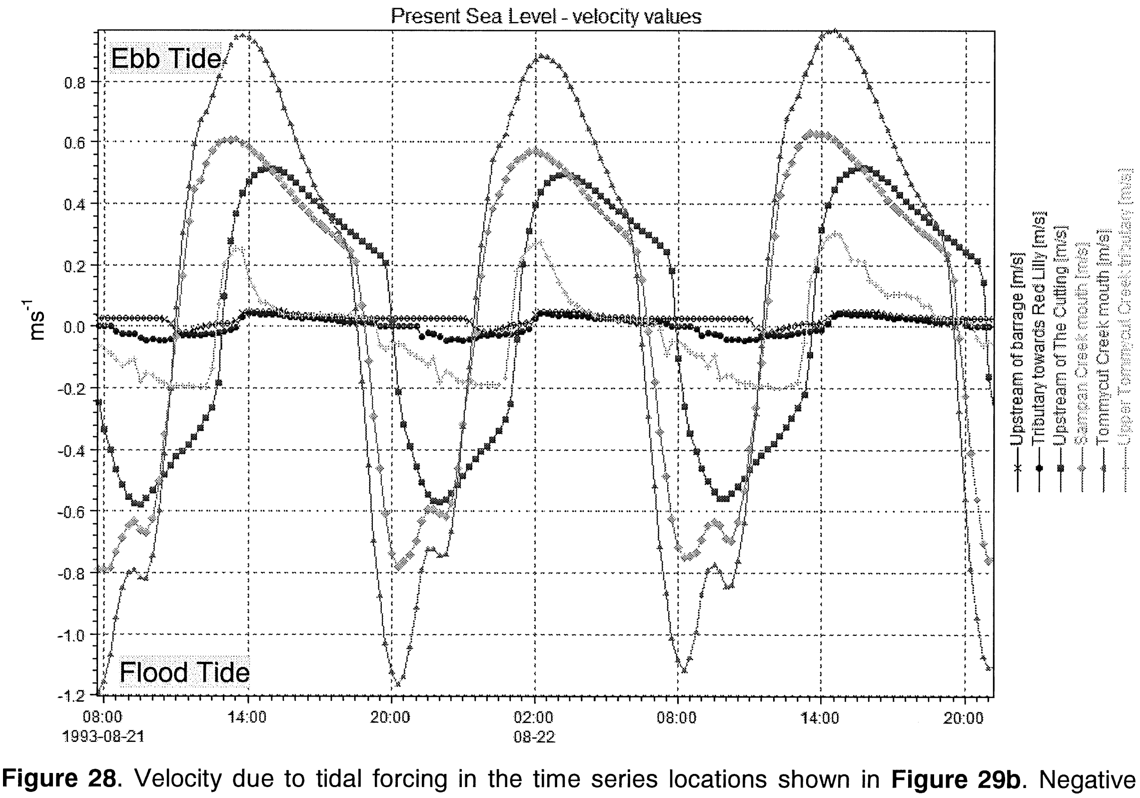


Figure 28. Velocity due to tidal forcing in the time series locations shown in **Figure 29b**. Negative values correspond to flood tides and positive values correspond to ebb tides.

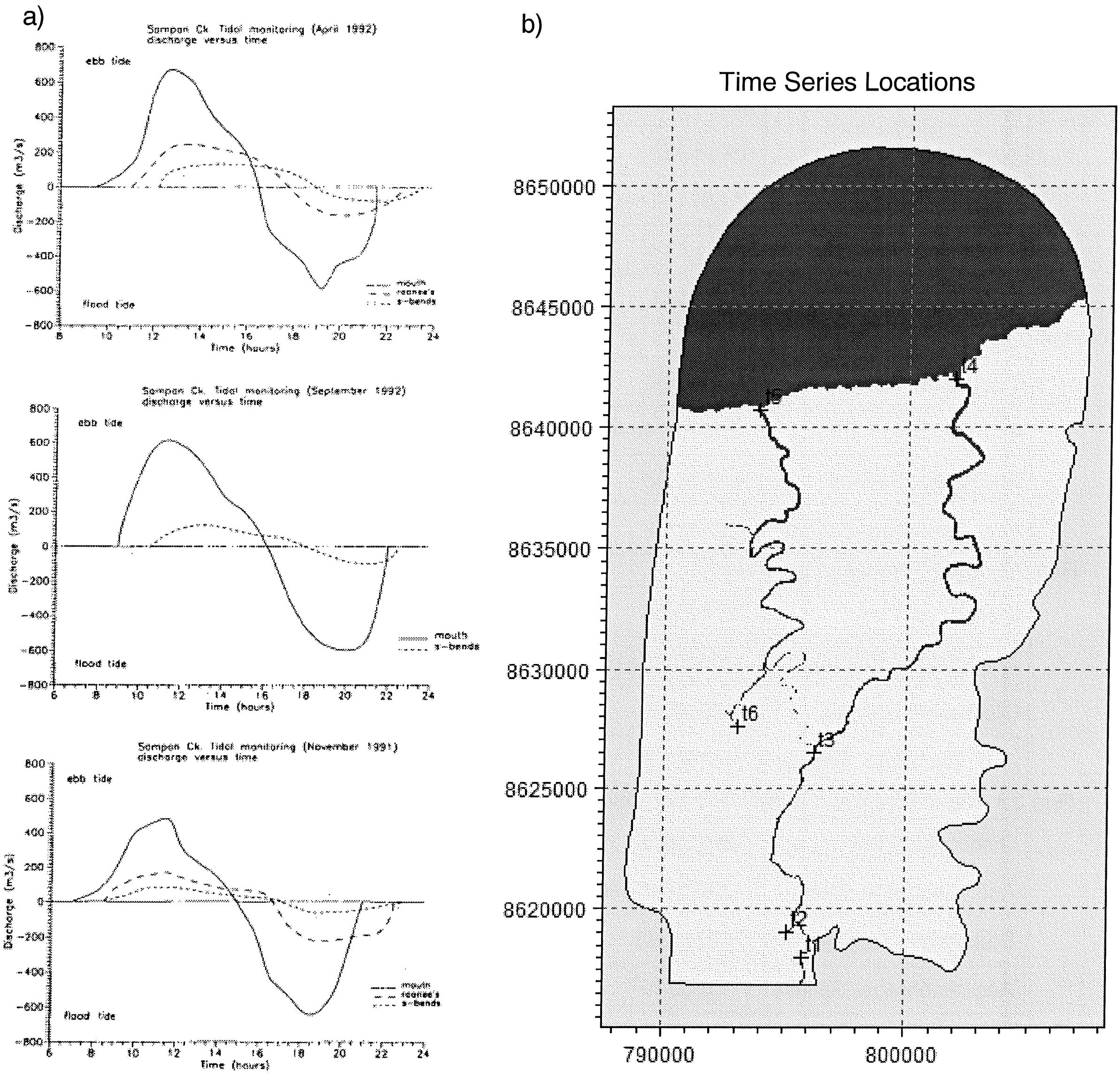


Figure 29. a) discharge data recorded by (Woodroffe and Mulrennan, 1993). b) Time series locations used to compare trends in flow rates along channel (t1 – t6).

3.2. Submerged weir locations

To investigate the most effective submerged weir locations the sequence of control runs produced in **Table 1** was used to assess changes in discharge and cumulative discharge across the coastline discharge line (**Figure 23**). It was found that weirs located in the mouth are much more effective than in upstream locations.

Discharge analysis

Comparing Run031 and Run032 to current conditions (Run030) shows a decrease in discharge into the estuary with a weir located at Tommycut mouth and an increase in discharge if the weir is placed at Dead Fish Billabong (**Table 3**). Partial blockage of both Sampan and Tommycut Creeks at their mouths leads to significant ebb tide dampening (70%) and reduction in flood tide flows by up to 25%. In contrast, partially blocking Tommycut Creek and Sampan Creek in upstream locations has little effect on maximum discharges but increases the mean to produce a higher cumulative discharge (Run034). The 'zero' results from Run033 mean that no net salt has left the estuary, owing to the significantly reduced ebb tide.

Table 3. Results of the weir location analysis, present day sea level, 10 day spring tide cycle and 4 weir combinations.

Run 030 - current conditions

Item	Min	Max	Mean	SD
Discharge, Flow	-2769.433	1255.929	-33.48506	910.8054
Acc. discharge, Flow	-4.337141e+007	5209391	-1.474908e+007	1.267421e+007
Discharge, Salinity	-90213.14	40696.5	-1127.575	28740.1
Acc. discharge, Salinity	-1430680	129270.5	-496446	418133

Run 031 - Weir Tommycut

Discharge, Flow	-2471.054	835.6533	-29.99927	621.9359
Acc. discharge, Flow	-3.792714e+007	1856421	-1.425811e+007	1.08848e+007
Discharge, Salinity	-80426.36	26974.31	-1015.764	19578.55
Acc. discharge, Salinity	-1256150	45826.25	-476344	364948.6

Run 32 - Weir Tommycut upstream

Discharge, Flow	-2741.666	1309.359	-34.87795	861.9341
Acc. discharge, Flow	-4.578023e+007	4551082	-1.580315e+007	1.351442e+007
Discharge, Salinity	-89050.13	42358.4	-1188.956	27037.7
Acc. discharge, Salinity	-1513963	113438.1	-531799.4	449122.7

Run 33 - Weir Tommycut mouth and Sampan mouth

Discharge, Flow	-2070.872	380.6131	-28.54611	335.2776
Acc. discharge, Flow	-3.577545e+007	0	-1.651866e+007	1.057532e+007
Discharge, Salinity	-68713.83	12442.63	-925.4016	11003.39
Acc. discharge, Salinity	-1165320	0	-529503.8	348164.5

Run 034 - Weir Tommycut upstream and Sampan upstream

Discharge, Flow	-2672.684	1352.895	-38.26975	765.0854
Acc. discharge, Flow	-5.070258e+007	2108212	-1.942952e+007	1.482797e+007
Discharge, Salinity	-87483.28	44190.85	-1251.03	24682.4
Acc. discharge, Salinity	-1653090	52905.75	-630128.6	485398.5

Inundation analysis

Both Run031 and Run033 scenarios indicate reduced inundation (**Figure 30 b & d**). Run 033 simulated weirs installed in both creek mouths at 1m AHD, while Run 031 has one weir at Tommycut mouth choking flow. Submerged weirs located at upstream locations did not have a desired effect on inundation or salinity levels. Salt concentration within the model is similar between Runs030-032 (current conditions, TCM and TCUP) with most of the fresh water directed through Sampan Creek (**Figure 30 a – c**). Runs 033 and 034 have submerged weirs located in Sampan Creek, slowing the offshore flow and directing the freshwater flow into Tommycut through "The Cutting" (**Figure 30 d & e**). The submerged weirs have a marked effect on salinity levels in the main channels but their control over salinity levels on the floodplains is not as effective (**Figure**

30 a – e). It suggests that Chenier Ridge restoration and reinforcement may be a good intervention method used in conjunction with weirs. To confirm this wet season analysis will be required. The fresh water flushing of the floodplains may be enough with backwater effects from weirs to reduce salinity levels to that of the main channel.

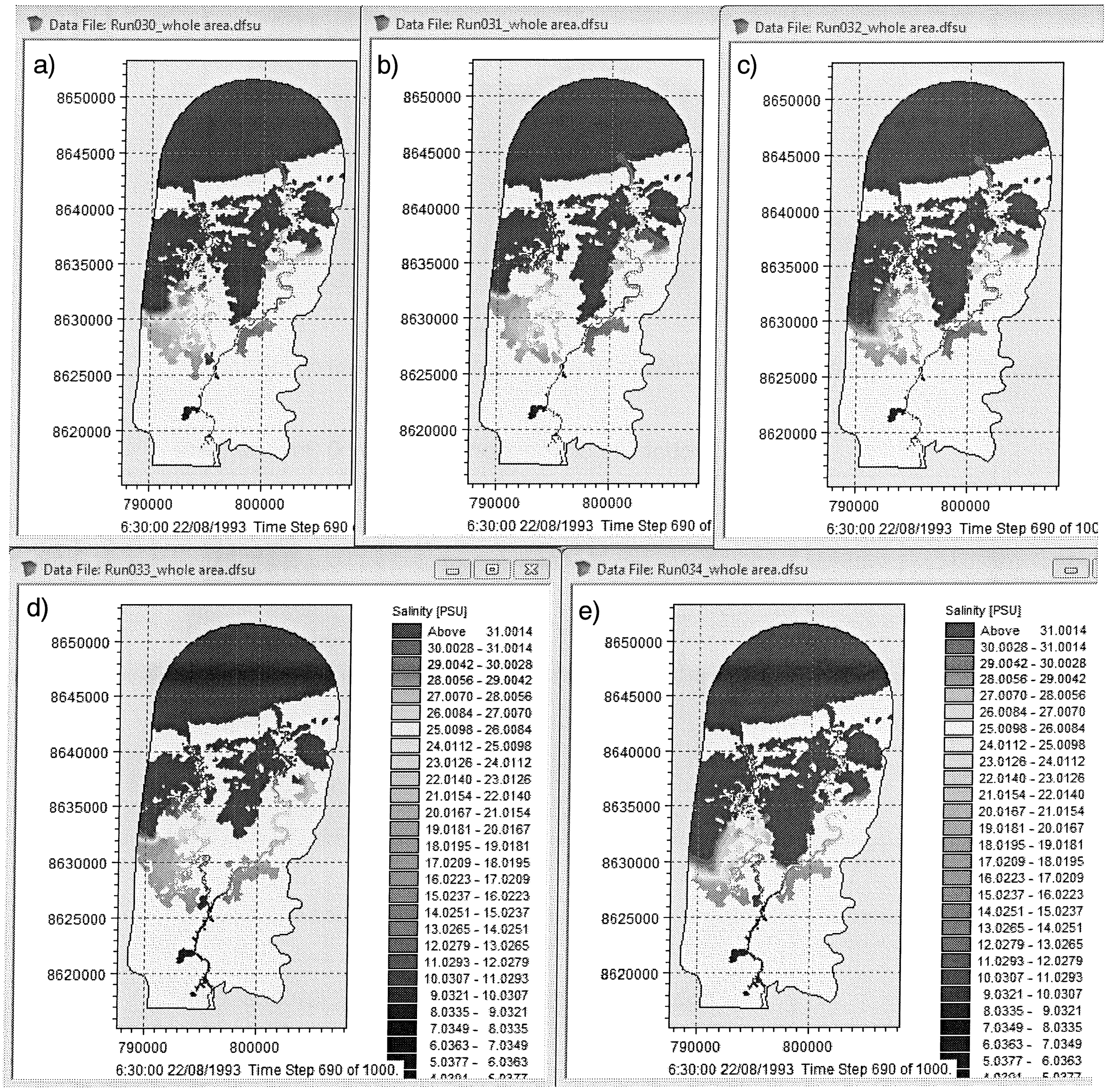


Figure 30. Inundation and salinity concentration maps of the 5 weir combinations (including no weirs) used to assess location effectiveness. a) No weirs b) weir Tommycut mouth c) weir Tommycut upstream d) weir Tommycut mouth and Sampan mouth e) weir Tommycut upstream and Sampan upstream.

3.3. Increase of temporal inundation with sea level rise.

Occurrence probability of tidal elevations were analysed for a better understanding of the temporal extent of inundation. Present day tides exceed 2 metres AHD for only 4.2% of a three month tide cycle (**Figure 31**). After a sea level rise of 0.3m, tidal levels will exceed 2 metres 14% of the time and 2.5m 0.5% of the time (**Figure 32**). With a sea level rise of 0.8m, tidal levels will exceed 2 metres 30% of the time, 2.5m 14% of the time and 3m 0.5% of the time (**Figure 33**). This equates to inundation of areas previously untouched by tidal flow for 25% of a three month period after a sea level rise of 0.8m.

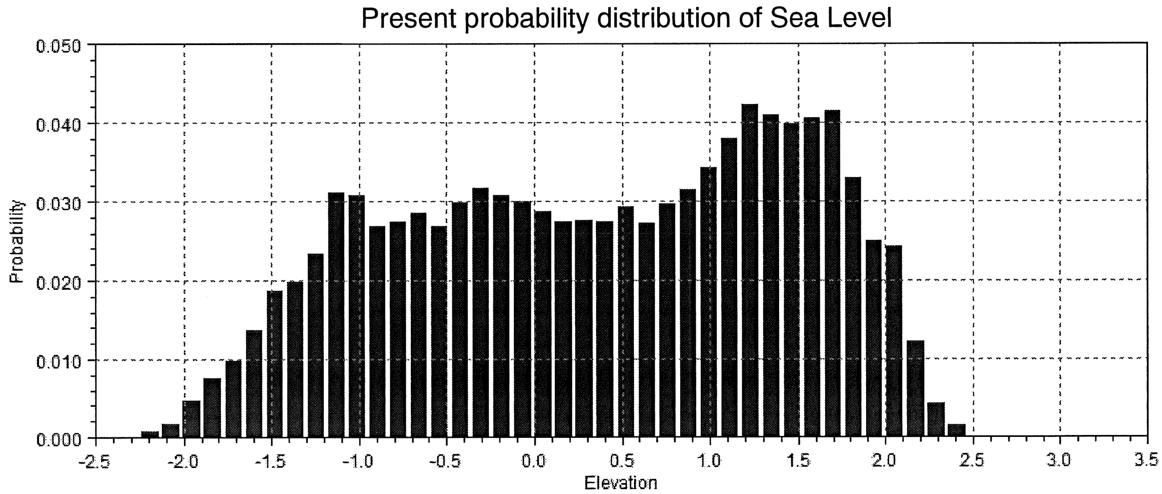


Figure 31. Occurrence probability of tidal elevation in present sea level conditions.

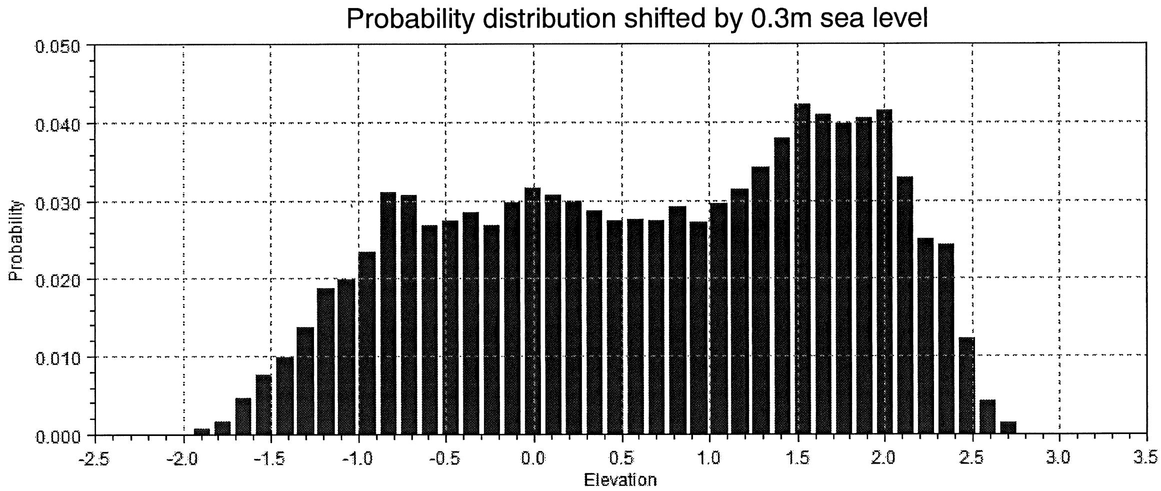


Figure 32. Occurrence probability of tidal elevation after a sea level rise of 0.3m.

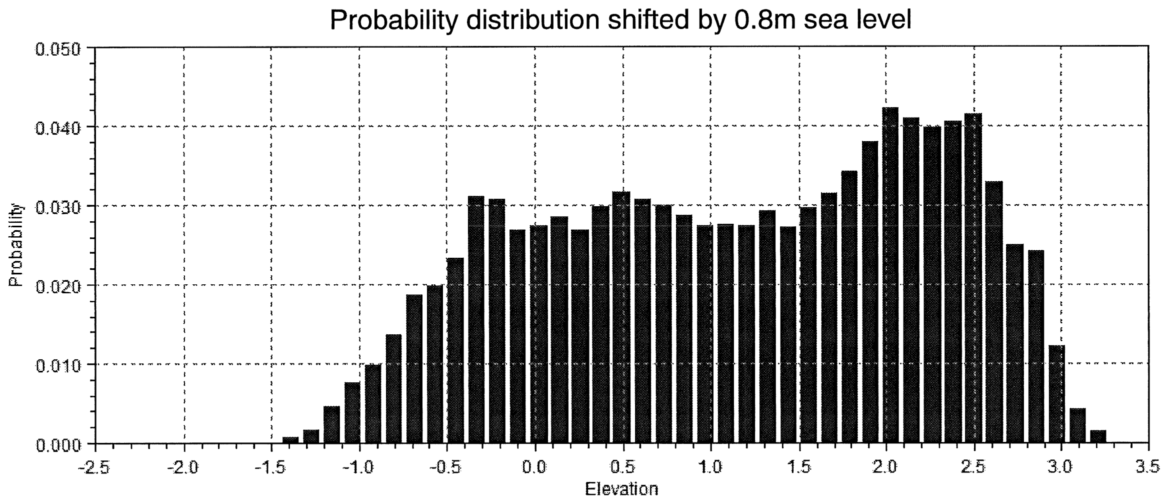


Figure 33. Occurrence probability of tidal elevation after a sea level rise of 0.8m.

3.4. Structures

3.4.1. Tidal amplitudes

Water levels were extracted from full water year outputs in upstream locations to gauge the effectiveness of submerged weirs in reducing tidal amplitude. In the present state, tidal amplitude just downstream of Shady Camp Barrage is 3.2m (**Figure 34**). This is reduced by 45% with weirs in the mouth installed (amplitude down to 1.7m) (**Figure 35**). Weirs installed at 1m AHD results in a 72% reduction in tidal amplitude (0.9m) (**Figure 36**). The reduction is focused on ebb tide flow and tidal/flood peak elevations remain the same.

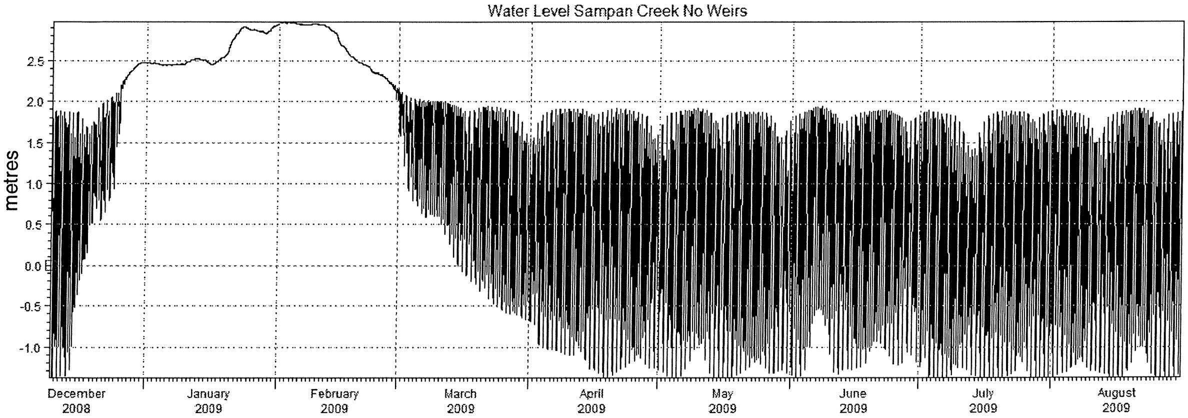


Figure 34. Time series extracted 2km downstream of Shady Camp Barrage (795800, 8620400). Present state, no submerged weirs.

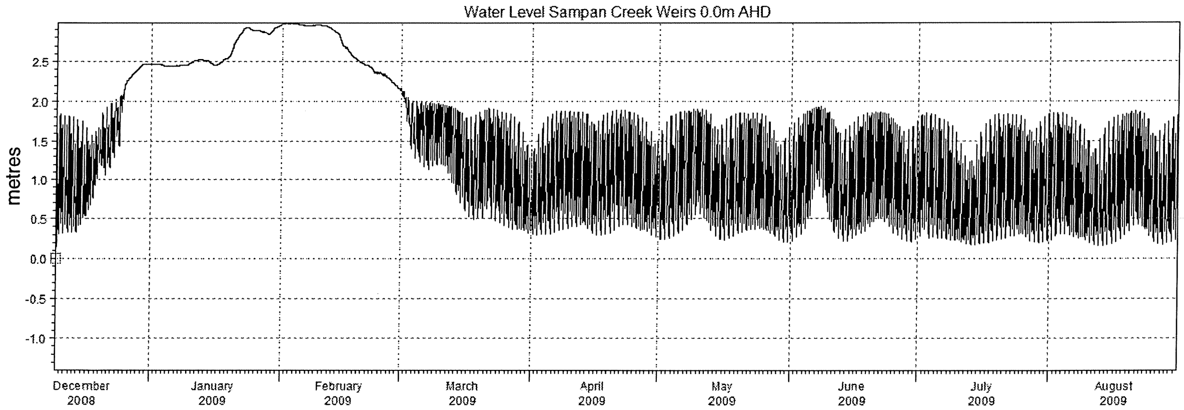


Figure 35. Tidal amplitude with submerged weirs at TCM and SCM at 0.0m AHD (795800, 8620400).

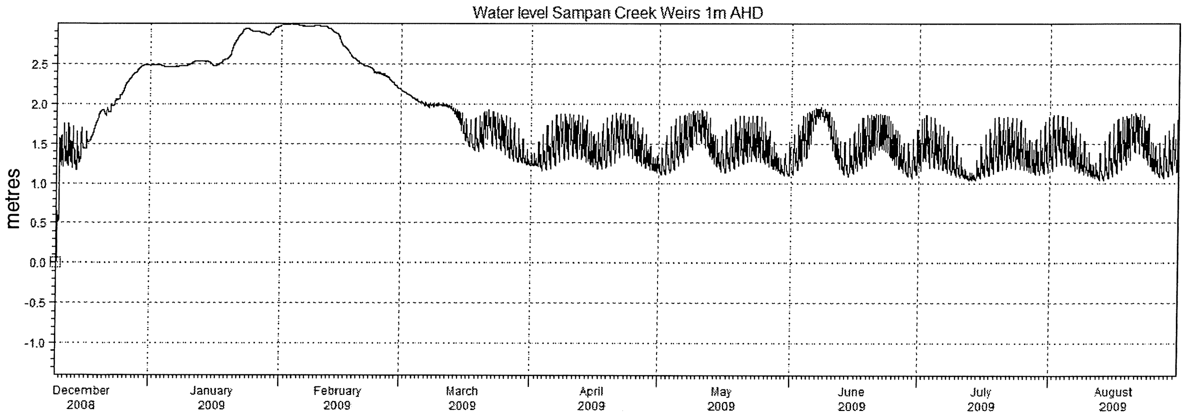


Figure 36. Tidal amplitude with submerged weirs at TCM and SCM at 1.0m AHD (795800, 8620400).

Van der Wegen and Verhagen, (2000) predictions of 50% reduction in tidal amplitude upstream with 0.0m AHD weirs were close to simulated outputs of tidal reduction (Figure 35). Although there is increased tidal attenuation in the Tommycut and Sampan estuaries it is not enough to cancel the upstream benefits of submerged weirs.

3.4.2. 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.

Throughout the water year max velocities of $1.5ms^{-1}$ occur during flood inception when flow is at bankfull height (**Figure 37**). 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 (**Table 4** – current max row). 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.

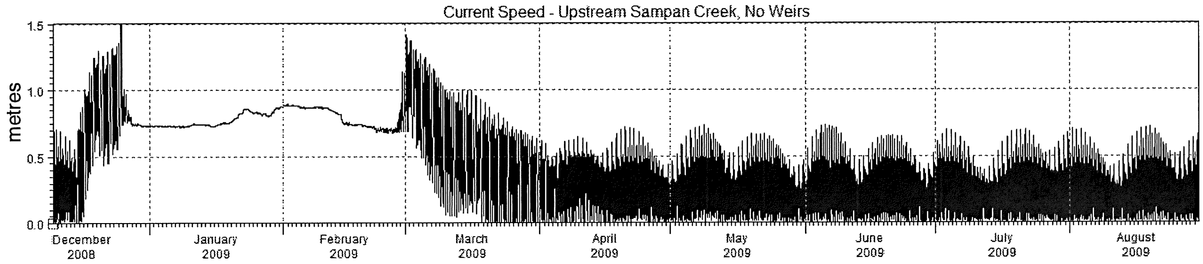


Figure 37. Current speed time series extracted 2km downstream of Shady Camp Barrage (795800, 8620400). Present state.

Table 4. The important variables that contribute to velocity; Inflow, flow efficiency, velocity head and tide.

WL to current velocity, no weirs												
overbank												
current min	current max	change	change %	WL max	inflow WL	Head	WL min	Inflow WL	Head	Date WL min	Low Tide	Time
0.517353	1.26869	0.751337	145%	2.05014	2.5	0.44986	1.12678	2.51	1.38322	24/12 2:40am	-0.789	23/12 11:10pm
0.590485	1.33288	0.742395	126%	1.98399	2.51	0.52601	0.935879	2.52	1.584121	24/12 3:20pm	-1.959	11:10am
0.554233	1.3582	0.803967	145%	2.09722	2.54	0.44278	1.44444	2.55	1.10556	25/12 3:30am	-0.842	24/12 11:50pm
0.656258	1.50508	0.848822	129%	2.10037	2.57	0.46963	1.59939	2.63	1.03061	25/12 3:50pm	-2.032	11:50am
0.738564	1.00558	0.267016	36%	2.1991	2.7	0.5009	2.16119	2.73	0.56881	26/12 4:10am	-1.009	12:30am
0.765245	0.973113	0.207868	27%	2.25176	2.75	0.49824	2.2075	2.77	0.5625	26/12 5:00pm	-2.059	12:30pm
return to channel												
current min	current max	change	change %	WL max	inflow WL	Head	WL min	Inflow WL	Head	Date WL min	Low Tide	Time
0.692135	1.1376	0.445465	64%	2.18991	2.65	0.46009	2.02781	2.63	0.60219	28/2 8:50am	-1.659	4:10am
0.687399	1.12801	0.440611	64%	2.16411	2.62	0.45589	2.00916	2.62	0.61084	28/2 8:50pm	-0.345	4:50pm
0.697388	1.41265	0.715262	103%	2.14274	2.6	0.45726	1.58074	2.59	1.00926	01/3 9:40am	-1.369	5:30am
0.691943	1.28476	0.592817	86%	2.11381	2.58	0.46619	1.67408	2.58	0.90592	01/3 10:10pm	-0.169	6:30pm
0.876109	1.37482	0.498711	57%	1.98568	2.57	0.58432	1.22173	2.58	1.35827	02/3 10:50am	-1.159	7:00am
0.639575	1.30608	0.666505	104%	2.07523	2.54	0.46477	1.3711	2.53	1.1589	02/3 11:50pm	-0.276	8:10pm

Properties of the upstream system

- Tides have the greatest effect on in-channel flows
- Increasing flow volumes lead to increasing velocities at low tide (water level minimum)
- Bankfull flows are most efficient at transporting large inflows while still influenced by tidal flow, causing peaks in velocities (**Figure 38** + **39**)

- Once inflows are great enough for overbank flows, velocities drop due to greater flow volumes on the floodplain. The inefficient channel and floodplain flow dampens the tidal influence from downstream leading to a lower velocity head and stabilization of velocities (**Figure 37 –** January and February).
- The inefficiency brought about by overbank flow is due to resistance at the channel/floodplain boundary (Knight and Brown, 2001).
- The combination of bankfull flows (2.6m inflow water level) and any low tide (neap or spring) creates the highest velocities (**Figure 38**).
- If inflow increases greatly to bankfull levels as the tide is in ebb phase then the velocity potential is greater as overbank dampening is delayed. Therefore the flood inception stage has the most erosive potential (**Figure 38 –** last peak was a result of this effect).
- Once the flow is overbank, even powerful tides of -2m lose their effect on the velocity head. As such, velocities remain below $0.9ms^{-1}$ throughout overbank flood conditions.

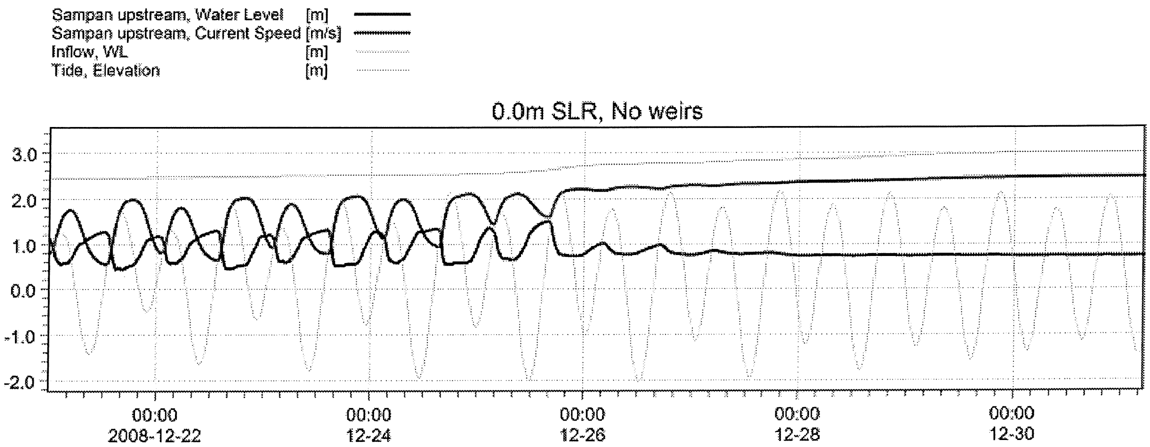


Figure 38. Time series of the critical factors affecting velocity from **Table 4,** (location 795800, 8620400).

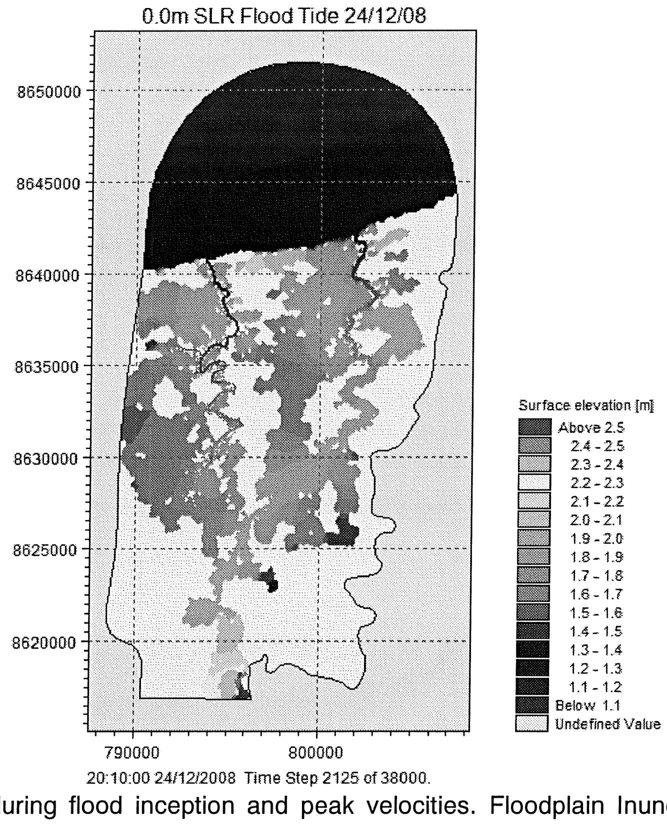


Figure 39. Inundation during flood inception and peak velocities. Floodplain Inundation is still minor and channels are still clearly defined in the coastal areas.

Maximum velocities are reduced to 1ms^{-1} at the beginning of flood in December as the river breaks its banks and again in March during the runoff as the flow returns to bankfull flows (**Figure 40**). Although the discharge is the same, weirs reduce the ebb tide and resulting velocity head to only 88mm so that velocities are restricted to a 30% increase. The area 2km downstream experiences little to no upstream flow until 20/3/09 when flow over Shady Camp Barrage is not sufficient to hold back the incoming tide.

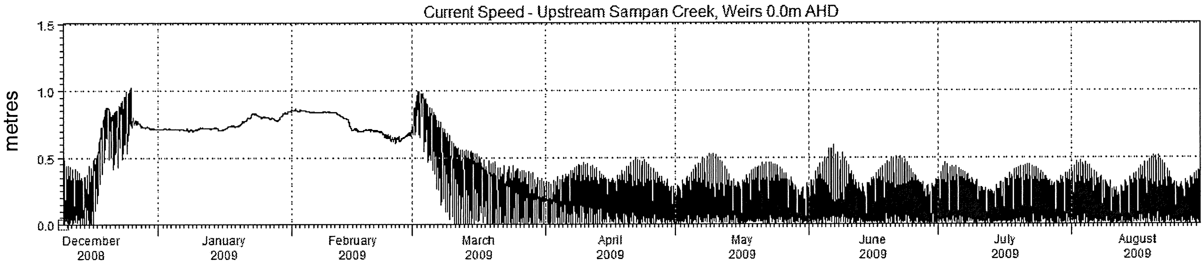


Figure 40. Time series of current speed extracted 2km downstream of Shady Camp Barrage (795800, 8620400). Present sea level, weirs at 0.0m AHD in the mouths of Tommycut and Sampan Creeks.

- Slower velocities in the channel overall, causes a delay in tide by 2hrs at Shady Camp Barrage.
- Delayed runoff velocities due to attenuation on the floodplain and dampening of the low tide.
- Peak velocities are not reached until flow is well within the bank due to reduction in velocity head caused by floodplain attenuation.
- Weirs cause floodplain attenuation, dampening of the low tide and result in a reduction in velocity head.
- Dampening due to floodplain runoff diminishes as water levels drop below 2.52m (**Table 5**).

Table 5. Inflow, flow efficiency, velocity head and tide. Present sea level weirs at TCM and SCM at 0.0m AHD.

WL to current velocity, 0.0m weirs												
overbank												
current min	current max	change	change %	WL max	inflow WL	Head	WL min	Inflow WL	Head	Date WL min	Low Tide	Time
0.488723	0.956777	0.468054	96%	2.02064	2.5	0.47936	1.55694	2.51	0.95306	24/12 4:00am	-0.789	23/12 11:10pm
0.600297	0.991611	0.391314	65%	1.92195	2.51	0.58805	1.44518	2.52	1.07482	24/12 4:10pm	-1.959	11:10am
0.532834	0.987964	0.45513	85%	2.076	2.54	0.464	1.86253	2.56	0.69747	25/12 4:50am	-0.842	24/12 11:50pm
0.674619	1.02103	0.346411	51%	2.08382	2.58	0.49618	2.02771	2.63	0.60229	25/12 3:00pm	-2.032	11:50am
0.724143	0.798637	0.074494	10%	2.19131	2.7	0.50869	2.21104	2.73	0.51896	26/12 2:30am	-1.009	12:30am
return to channel												
current min	current max	change	change %	WL max	inflow WL	Head	WL min	Inflow WL	Head	Date WL min	Low Tide	Time
0.67564	0.873197	0.197557	29%	2.14458	2.6	0.45542	2.05576	2.58	0.52424	01/3 11:50am	-1.369	5:30am
0.674483	0.962392	0.287909	43%	2.1174	2.58	0.4626	1.98788	2.58	0.59212	01/3 11:50pm	-0.169	6:30pm
0.817561	0.996832	0.179271	22%	2.04402	2.57	0.52598	1.75173	2.54	0.78827	02/3 12:50pm	-1.159	7:00am
0.653027	0.980395	0.327368	50%	2.04729	2.54	0.49271	1.69158	2.53	0.83842	03/3 1:50am	-0.276	8:10pm
0.81128	0.97537	0.16409	20%	1.79255	2.52	0.72745	1.40503	2.51	1.10497	03/3 1:30pm	-1.149	8:30am

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 41**).

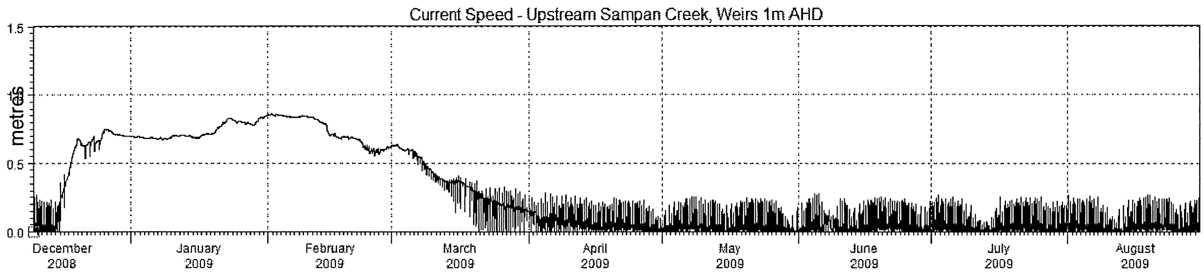


Figure 41. Time series extracted 2km downstream of Shady Camp Barrage (795800 8620400). Present sea level, weirs at 1.0m AHD in the mouths of Tommycut and Sampan Creeks.

3.5. Sea Level Rise

Modelling sea level rise of 0.3m and analysing the bankfull flow event revealed very interesting results (**Figure 42**). The combination of high inflow and efficient 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 (**Figure 43**). 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, although results are still processing for Run075 (0.8m SLR and no weirs).

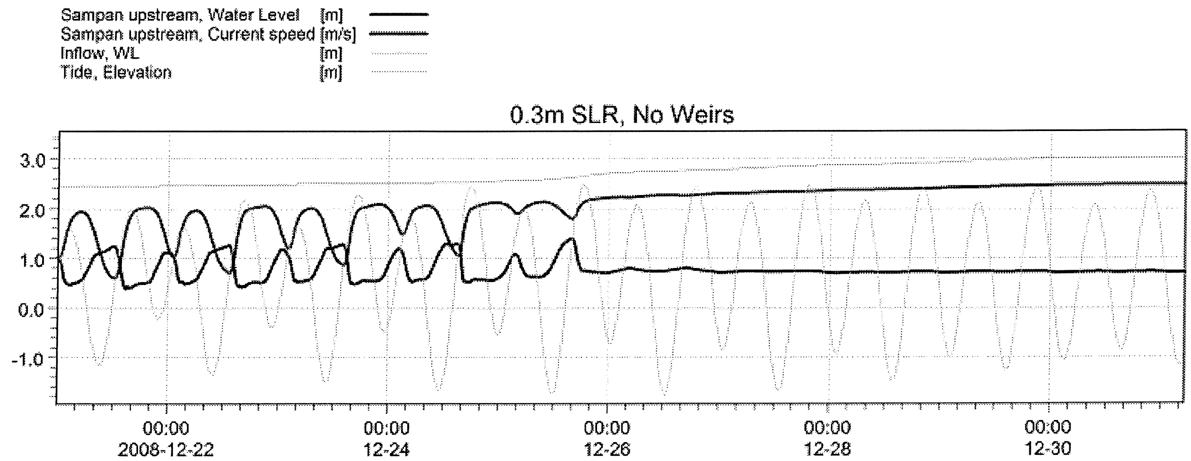


Figure 42. Time series extract of the critical factors affecting velocity after a 0.3m SLR.

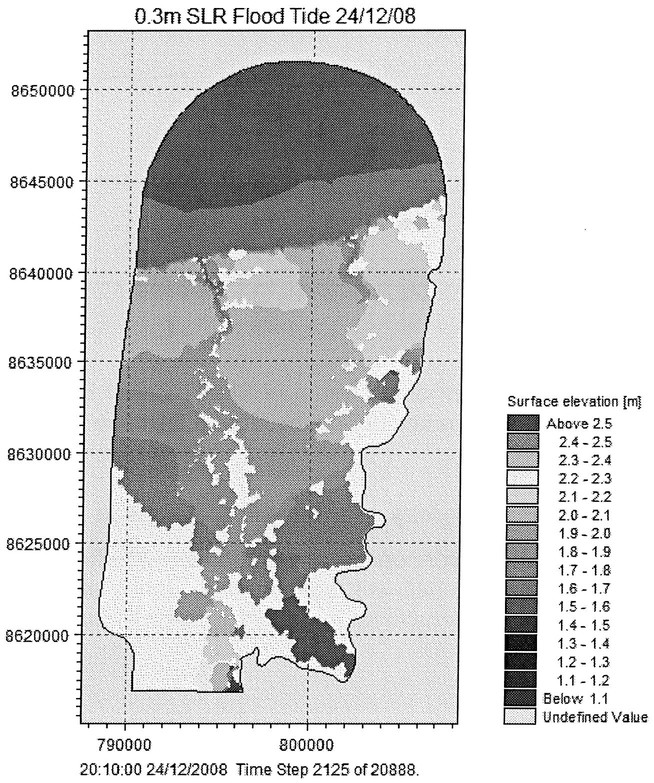


Figure 43. Inundation during flood inception and peak velocities. Large increase in floodplain inundation compared to Figure 39. Channels are barely defined at the coast.

3.5.1. Sea Level Rise and Submerged Weirs

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 (**Figure 44**). With further SLR (0.8m) the tidal flow is high enough to induce a reduction in velocity head. Most of the flow is over the floodplain in this scenario so tidal attenuation is dominant causing peaks in the water level with the flood tide and a resultant drop in velocity (**Figure 45**).

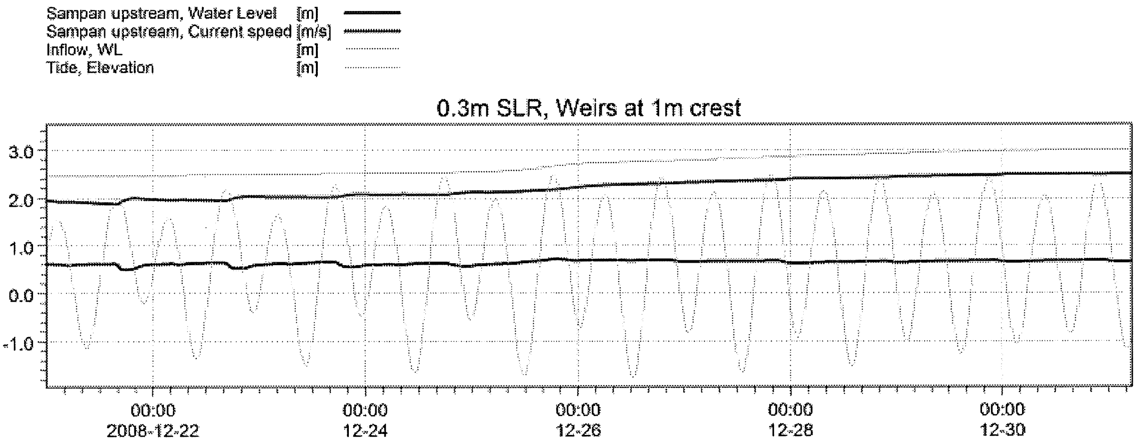


Figure 44. Time series extracted 2km downstream of Shady Camp Barrage (795800, 8620400) 0.3m sea level rise, weirs at 1.0m AHD in the mouths of Tommycut and Sampan Creeks.

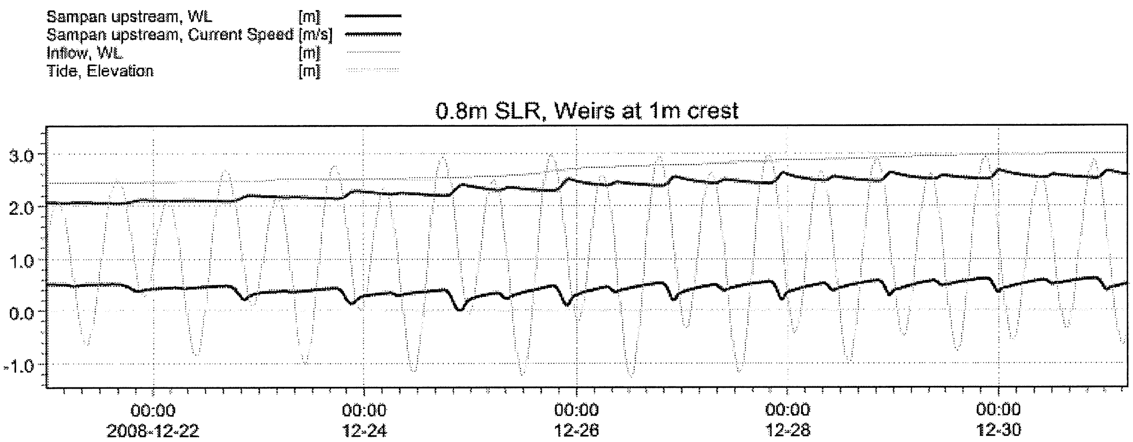


Figure 45. Time series extracted 2km downstream of Shady Camp Barrage (795800, 8620400). 0.8m sea level rise, weirs at 1.0m AHD in the mouths of Tommycut and Sampan Creeks.

Comparison of sea level rises with weirs over the full Wet season

The attenuation effect is extremely pronounced and combines with the flood tide to create reverse peaks in all conditions except neap tides and high wet season flow. Spring tides serve to drop the current speeds down to zero even before water levels have returned to the channel during the runoff (**Figure 46**).

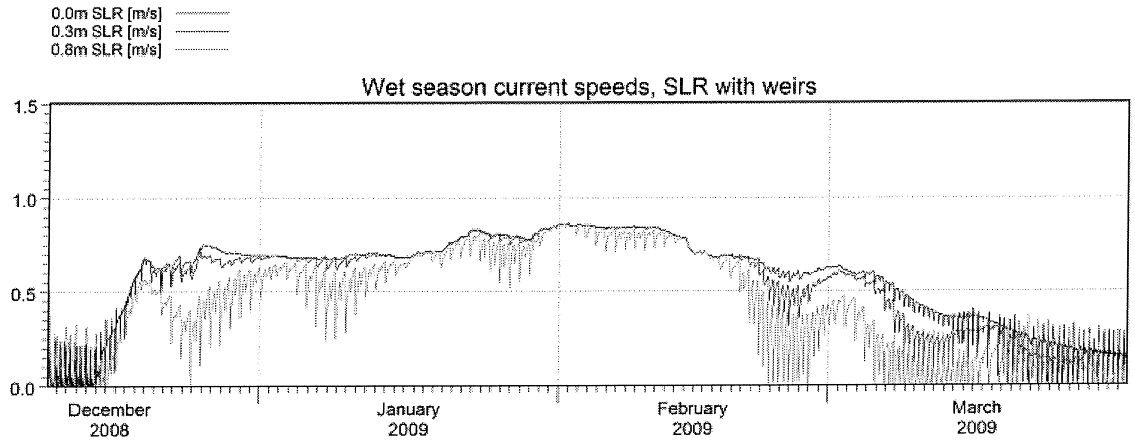


Figure 46. Full wet season outputs for all three sea level rise scenarios with submerged weirs at 1.0m AHD.

3.6. Sampan along channel processes

3.6.1. Without weirs

To help understand the relative interactions in downstream locations, the three time series points in **Figure 47** were used.

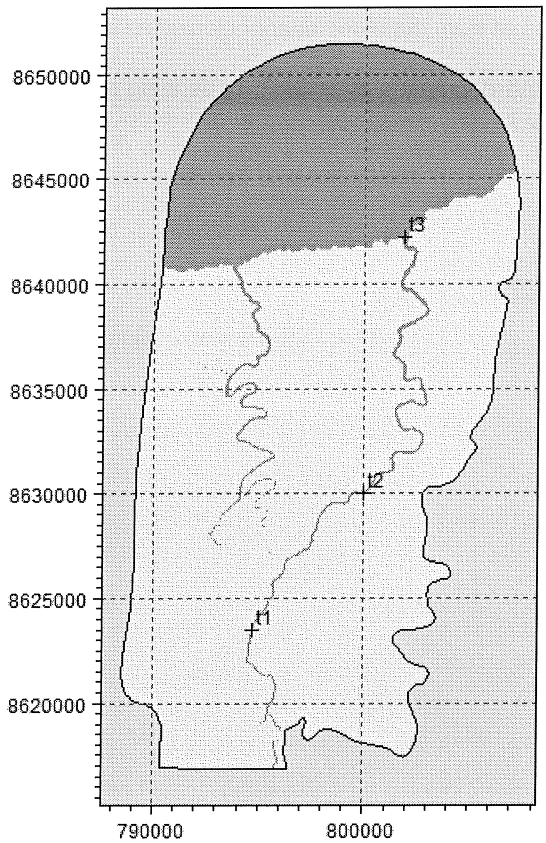


Figure 47. Sampan current speed time series locations

Velocities are greater where flow is closer to peak efficiency (I.e. bankfull flow). The initial low speeds at the mouth are due to an inflow that is not large enough to create a significant velocity head in such a high volume channel. Peak flows at the mouth are experienced in the height of the Wet season when inflow is large enough to produce near bankfull conditions during low tide. As time series locations move from upstream to downstream, they undergo a progressively later peak before flow exceeds the bank, at which stage dampening of the ebb tide will occur (**Figure 48**). The mouth will not dampen the velocity head as its banks will not flood like those upstream.

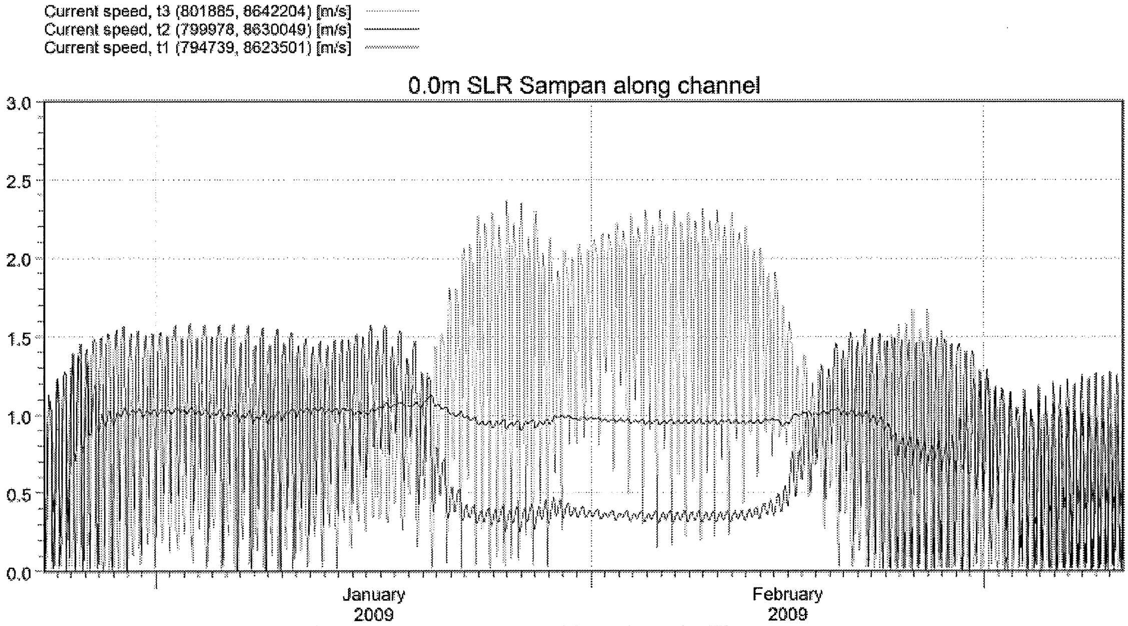


Figure 48. Time series output from the along channel locations in **Figure 47**.

Velocity both increases and decreases after SLR, depending on location. At the mouth, current velocity is stronger than before by up to 23%, which will lead to erosion of the channel and hence a wider mouth. While further upstream the velocities either stay the same or drop due to increased attenuation on the floodplain **(Figure 49)**. As before attenuation delays the ebb tide after SLR and results in a smaller velocity head and reduced velocities.

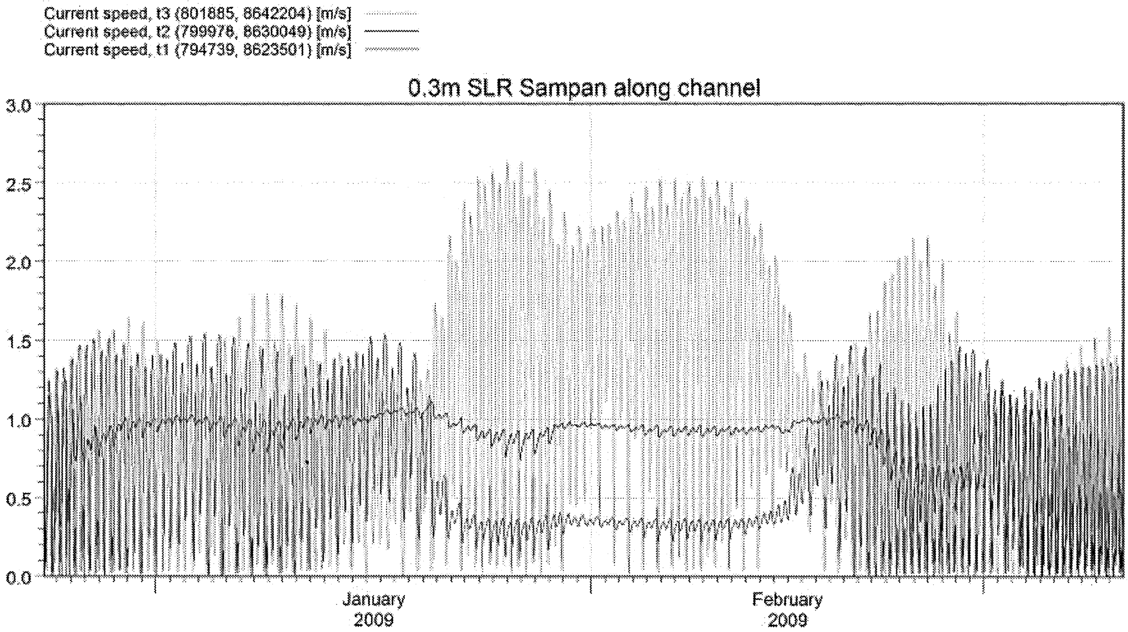


Figure 49. Along channel time series locations, extraction of the the 0.3m SLR output.

3.6.2. With Weirs

Velocities drop in all locations. In this scenario the middle reaches drop in velocity significantly (blue line, t2). This is due to overbank flooding of the plain just upstream of this area and in the western floodplain. This combined with the weir induced dampening of the ebb tide keeps velocity head to a minimum. Further upstream (black line, t1), velocities increase due to the inflow discharge, although they are still much lower than the same location without weirs. Velocities do not exceed $0.9ms^{-1}$ and do not contain peaks as there is no ebb tide induced velocity head **(Figure 50)**.

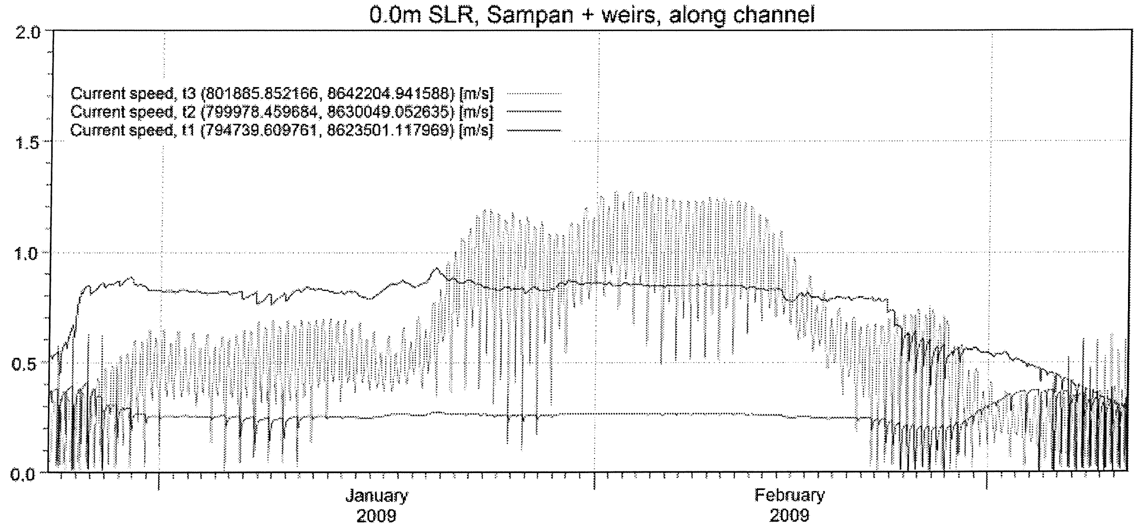


Figure 50. Along channel time series locations, extraction of the 0.0m SLR output. Weirs at 1m AHD installed in the mouths of both creeks.

Similar to velocity forcing without weirs, a 0.3m SLR causes velocities to increase slightly at the mouth and decrease in locations upstream of the weirs. Downstream of the weirs, ebb tides are not reduced and produce a significant velocity head. Upstream of the weirs there is little ebb flow and enough flood tide flow to produce a backwater effect seen in the down-dip current speed sections (**Figure 51**).

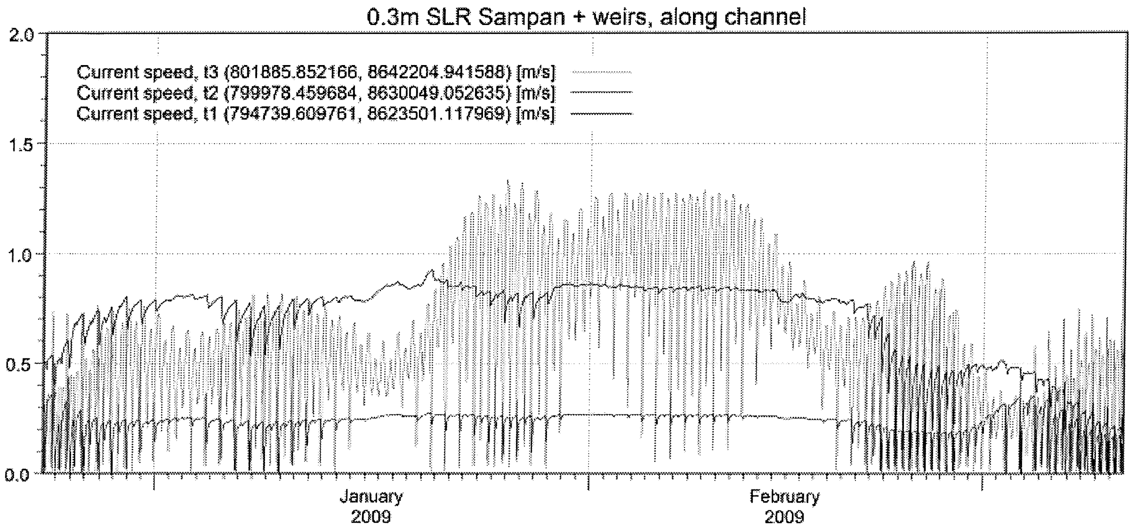


Figure 51. Along channel time series locations, extraction of the 0.3m SLR output. Weirs at 1m AHD installed in the mouths of both creeks.

Velocities increase further at the mouth, with peak velocities increasing by 39% to 1.8ms^{-1}, but upstream velocities drop after 0.8m of sea level rise. There is no ebb tide action in upstream locations; the current profile is created from inflow and flood tide flow alone. This continues into the dry season, where ebb flow only slightly affects currents in the middle reach, this decreases to insignificant values upstream (**Figure 52**).

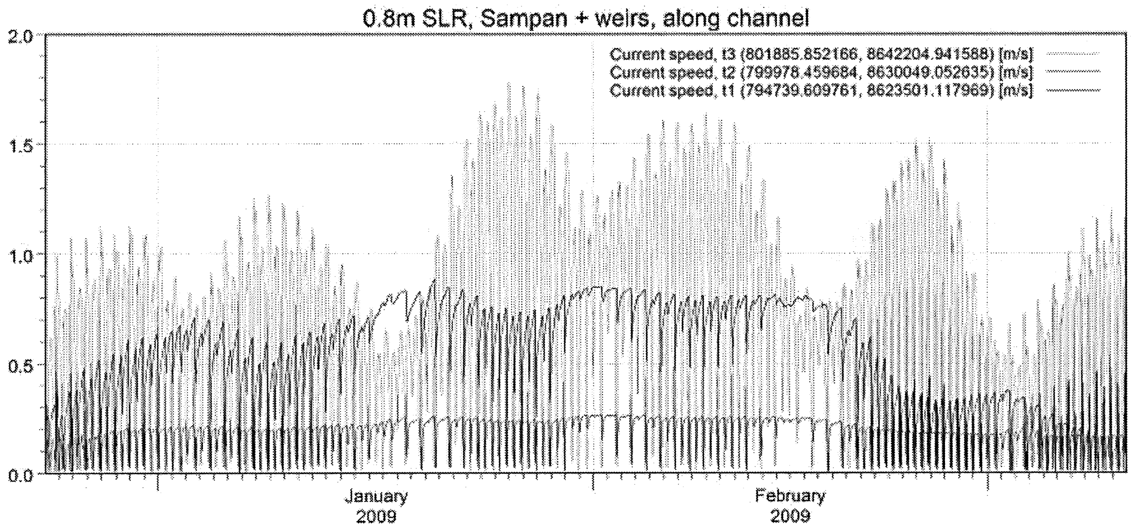


Figure 52. Along channel time series locations, extraction of the 0.8m SLR output. Weirs at 1m AHD installed in the mouths of both creeks.

3.7. Flood tide dominance

Without weirs

The cumulative flood tide increases with SLR of 0.3m by over 100% during spring tides (**Figure 53** – 04-22). At the end of the month, cumulative discharge into the estuary was simulated at 1.6E+7 (0.0m SLR) and 2.5E+7 (0.3m SLR). Awaiting data output for 0.8m SLR, no weirs. It is expected that flood tide dominance would increase logarithmically with respect to SLR at a rate similar to the simulations with weirs, below (**Figure 54**).

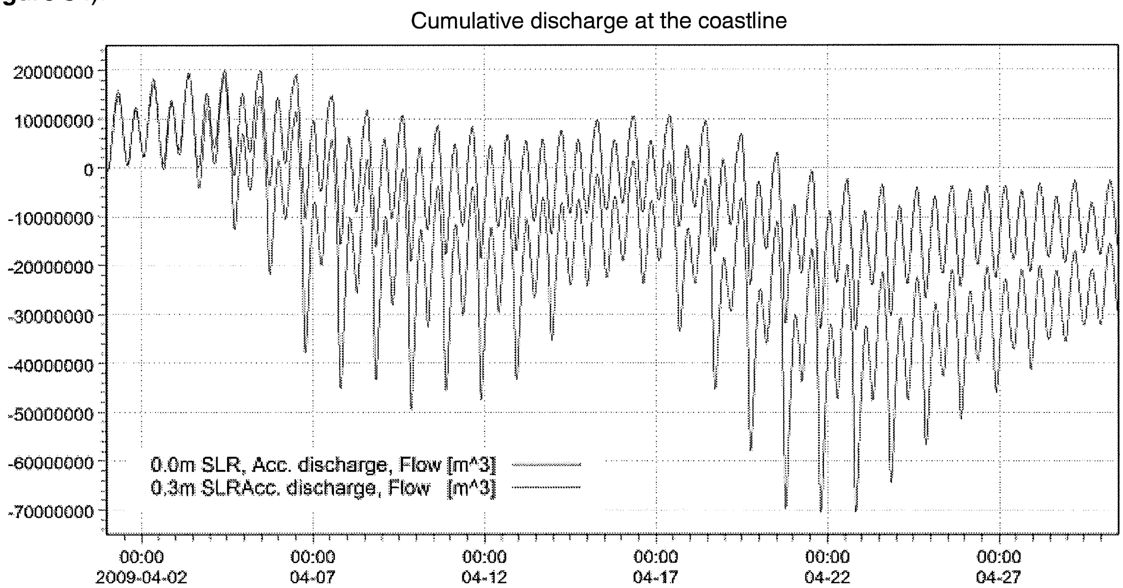


Figure 53. Extraction of cumulative discharge across the whole coastline (including Tommycut and Sampan Creek mouths) in 0.0m SLR and 0.3m SLR conditions without weirs, following the end of wet season flow in April.

With weirs

Discharge is dampened by the weirs but the cumulative discharge rate is still very similar to conditions without weirs. In the month of April, the flood tide (into the estuary) resulted in a cumulative discharge of 2E+7m^3 in the 0.0m SLR scenario and 6E+7m^3 in the 0.3m SLR scenario. Cumulative flood tide discharge was 1.23E+8m^3 from April to September (0.0m SLR), 2.96E+8m^3 (0.3m SLR) and 1.14E+9m^3 (0.8m SLR); which equates to 2.4 times the present day flood discharge after 0.3m SLR and 9.25 times the present day flood discharge after 0.8m SLR (**Figure 54**).

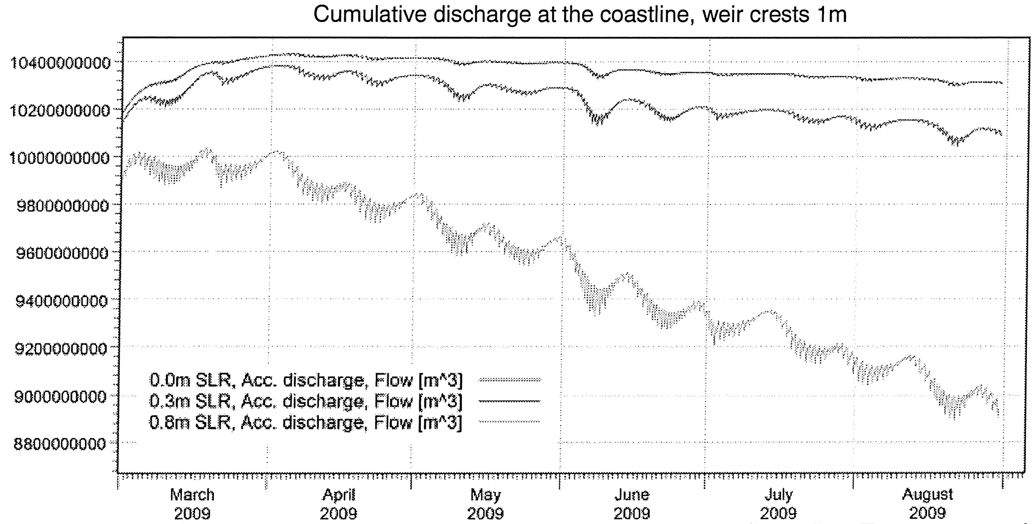


Figure 54. Extraction of cumulative discharge across the whole coastline (including Tommycut and Sampan mouths) in 0.0m SLR, 0.3m SLR and 0.8m SLR scenarios with weirs at TCM and SCM.

3.8. Salinity

3.8.1. Salinity volumes

The coastline discharge output also enables salinity volumes into the estuary to be calculated. Weirs only slightly affect the estuarine salt content as they not only dampen the ebb tide, but also the flood tide. Sea level rise has a major effect, producing a logarithmic increase in volume similar to cumulative discharge (**Figure 55**). The critical factors in SLR impact are not only how much salt water, but where will it inundate and how far will it intrude to. Control runs outlined in **Table 1** were again used to find the subtle differences for scenarios with and without weirs.

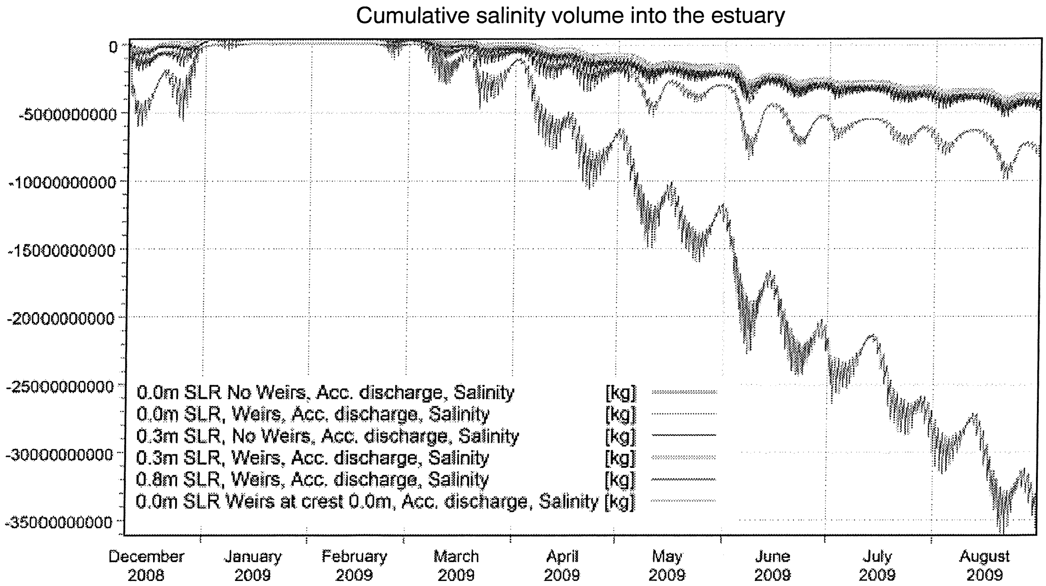


Figure 55. Cumulative discharge of salt in kilograms across the coastline.

3.8.2. Inundation and salinity concentrations

Modelled salinity concentrations represent the salinity pattern of the physical system well. The relatively restricted hydraulic connection between Tommycut Creek and flood flows is captured in the model. Simulated moderate wet season flows ($300m^3s^{-1}$) show Sampan creek flow is fresh beyond its mouth, whereas Tommycut Creek retains its highly saline flow (**Figure 56**). The effect can be seen in satellite images taken during wet season conditions in March. Light brown saline water is visible in Tommycut Creek and its tributaries while Sampan Creek and the majority of its surrounding floodplains have the dark brown colour of fresh water runoff (**Figure 57**). The close match between the modelled and physical system gives confidence to the analysis on sea level rise and submerged weirs below.

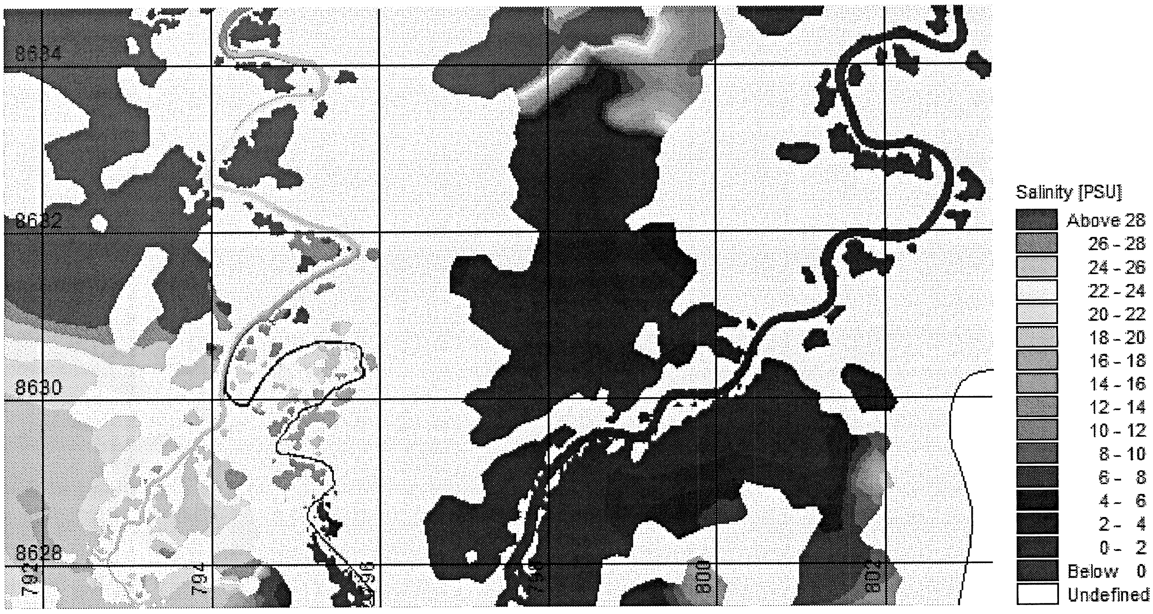


Figure 56. Inundation and salinity output from downstream of the Tommycut/Sampan confluence to Roonees Lagoon (inflow of $300m^3s^{-1}$).

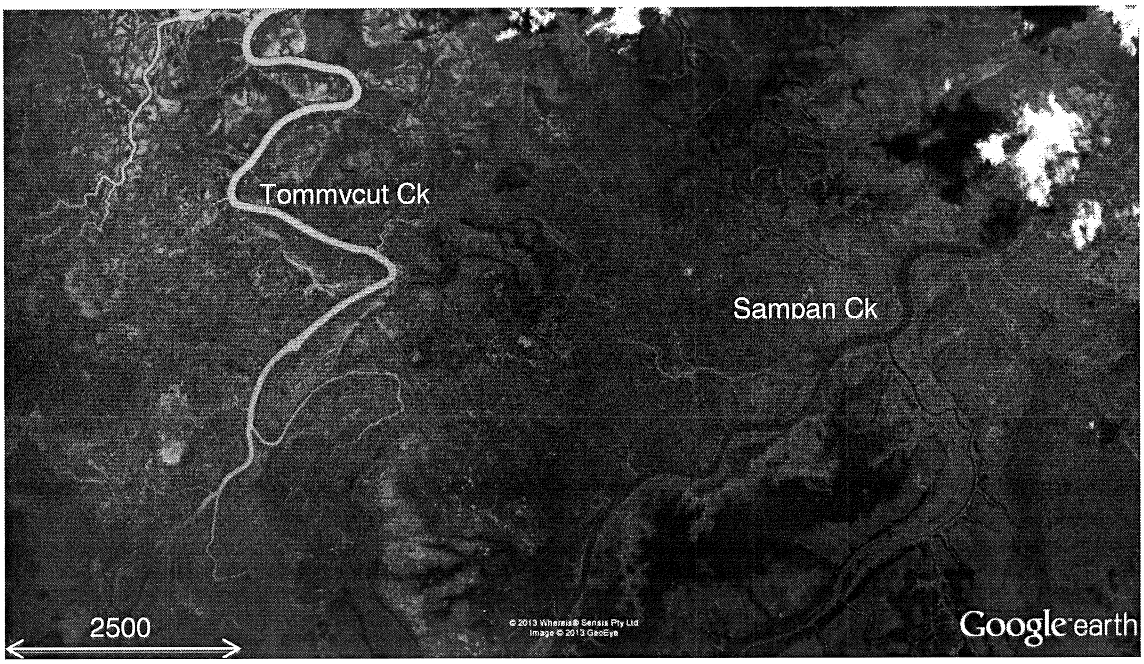


Figure 57. Satellite image of the area from Figure 56 during wet season floods, the colour difference between the two creeks clearly showing the bias in runoff to Sampan Creek.

Sea level rise and weir installation

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

0.0m sea level rise

The scenario for spring tide in present conditions tide has inundated the floodplain in expected areas and salinity levels are in equilibrium with the forcing conditions at each boundary (**Figure 58**). At these low flows, the fresh water is flushed through Sampan Creek effectively while Tommycut increases in salinity, an indication that the model is representative of hydraulic conditions. Installing weirs in this scenario reduces the inundation extent but also serves to increase the salinity of the system. As before, 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 59**).

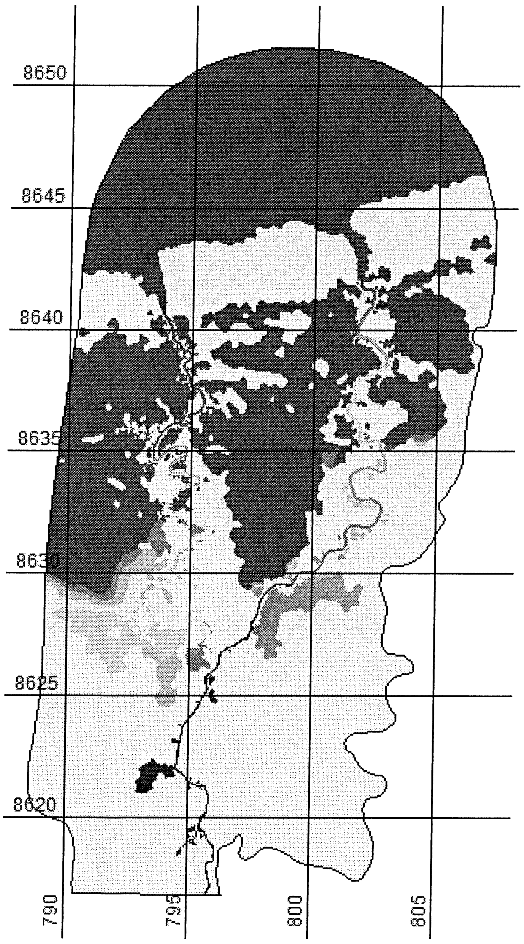


Figure 58. Run030 (0.0m SLR, No Weirs), whole area output of salinity after 7 days of tidal flow.

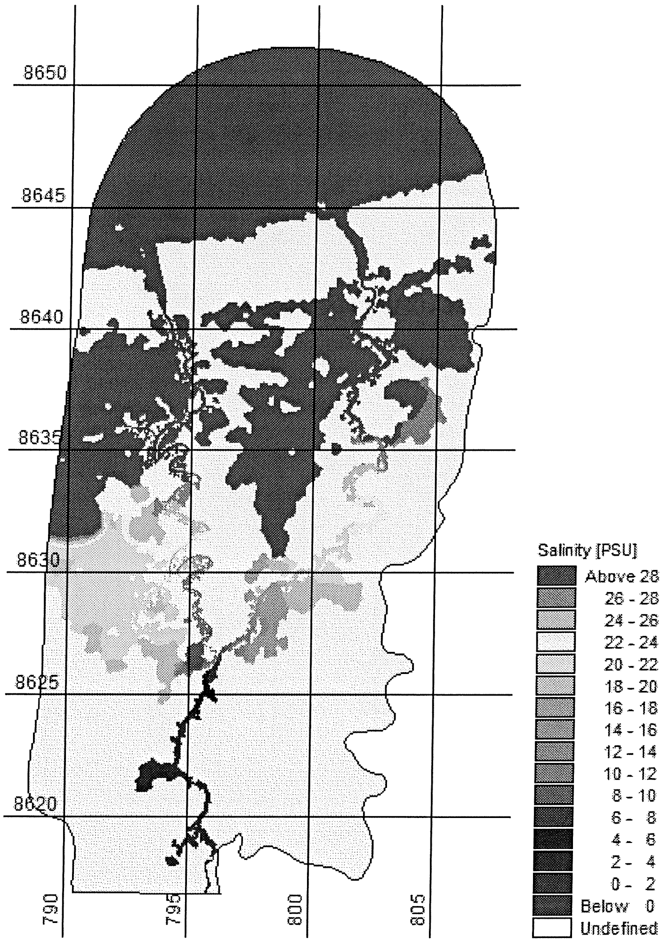


Figure 59. Run033 (0.0m SLR, Weirs at TCM and SCM), whole area output of salinity after 7 days of tidal flow.

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 flows, which can reduce to zero. The buffer zone from salt to fresh is very narrow (**Figure 60**). Adding weirs slows down the ebb flow and the back water 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 61**).

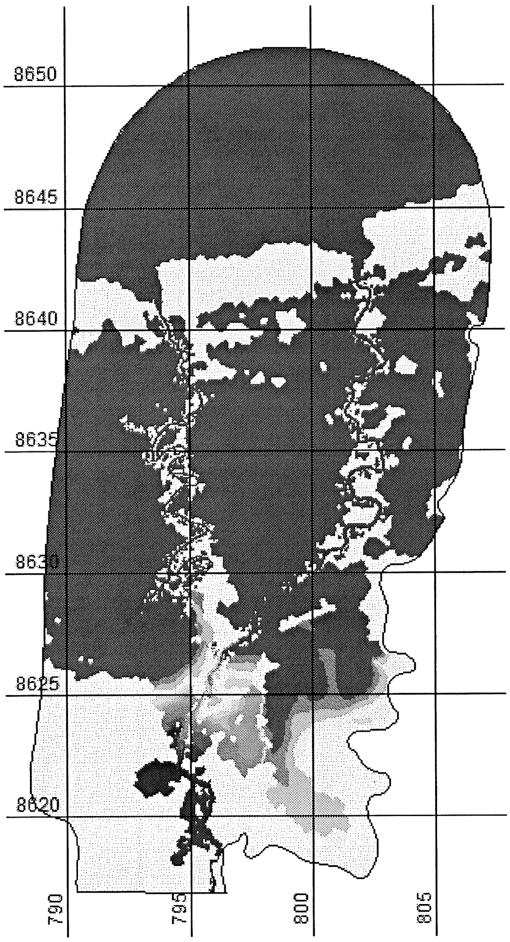


Figure 60. Run038 (0.3m SLR, No Weirs).

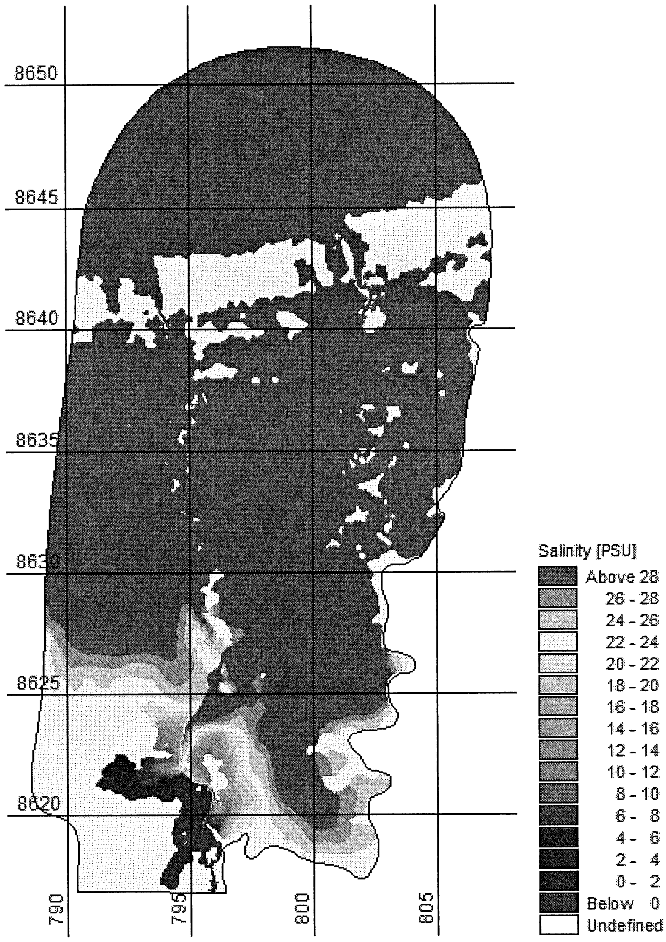


Figure 61. Run041 (0.3m SLR, Weirs at TCM and SCM).

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 62**). 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 63**).

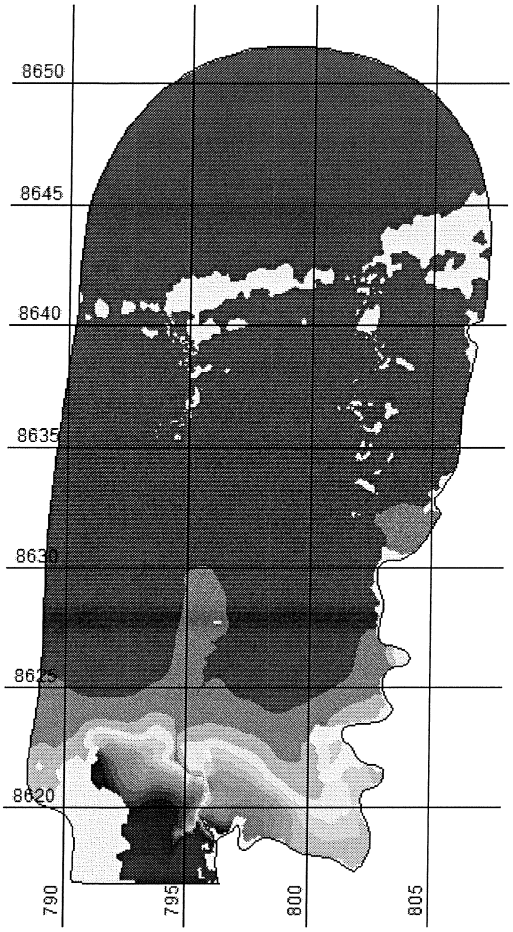


Figure 62. Run046 (0.8m SLR, No Weirs).

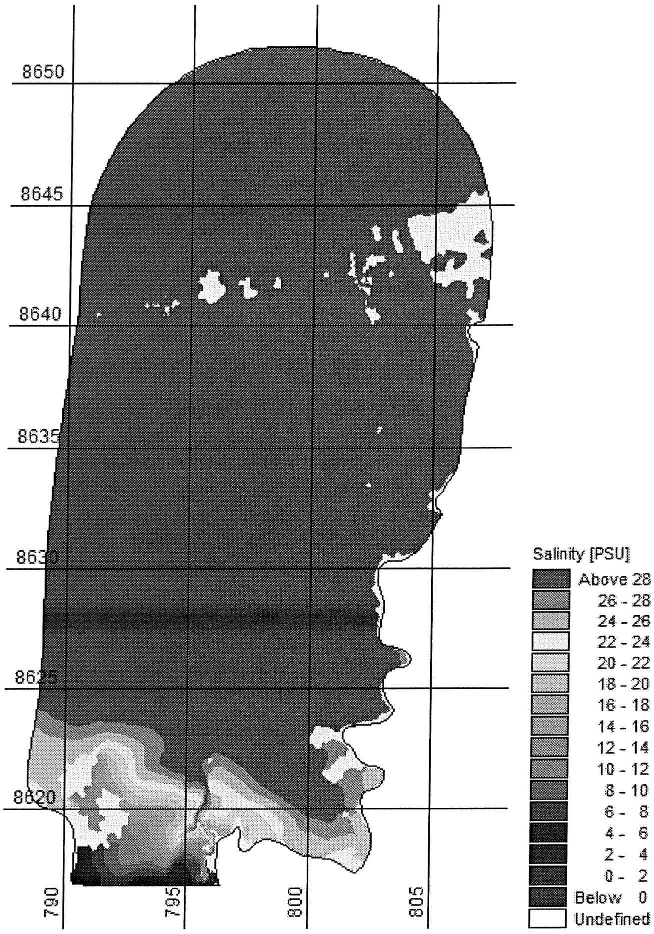


Figure 63. Run049 (0.8m SLR, Weirs at TCM and SCM).

Time series salinity concentrations

To better define the change in salinity concentrations with SLR and weir installation, a time series extraction point was chosen at the Tommycut Creek/Sampan Creek confluence to illustrate the change in salinity concentrations with SLR and weir installation. Weirs do not have a negative effect in present sea level conditions as the flood tide is not too dominant. As the sea level increases by a 0.3m rise, the ebb dampening effect from weirs is very noticeable. Not allowing the significant flood tides to ebb effectively back out to sea, salt concentrations climb quickly to sea water concentrations and do not recover. By 0.8m SLR the main section of flow is over the floodplains, so although the ebb tide is reduced with weirs, concentrations are very similar with and without weirs (**Figure 64**).

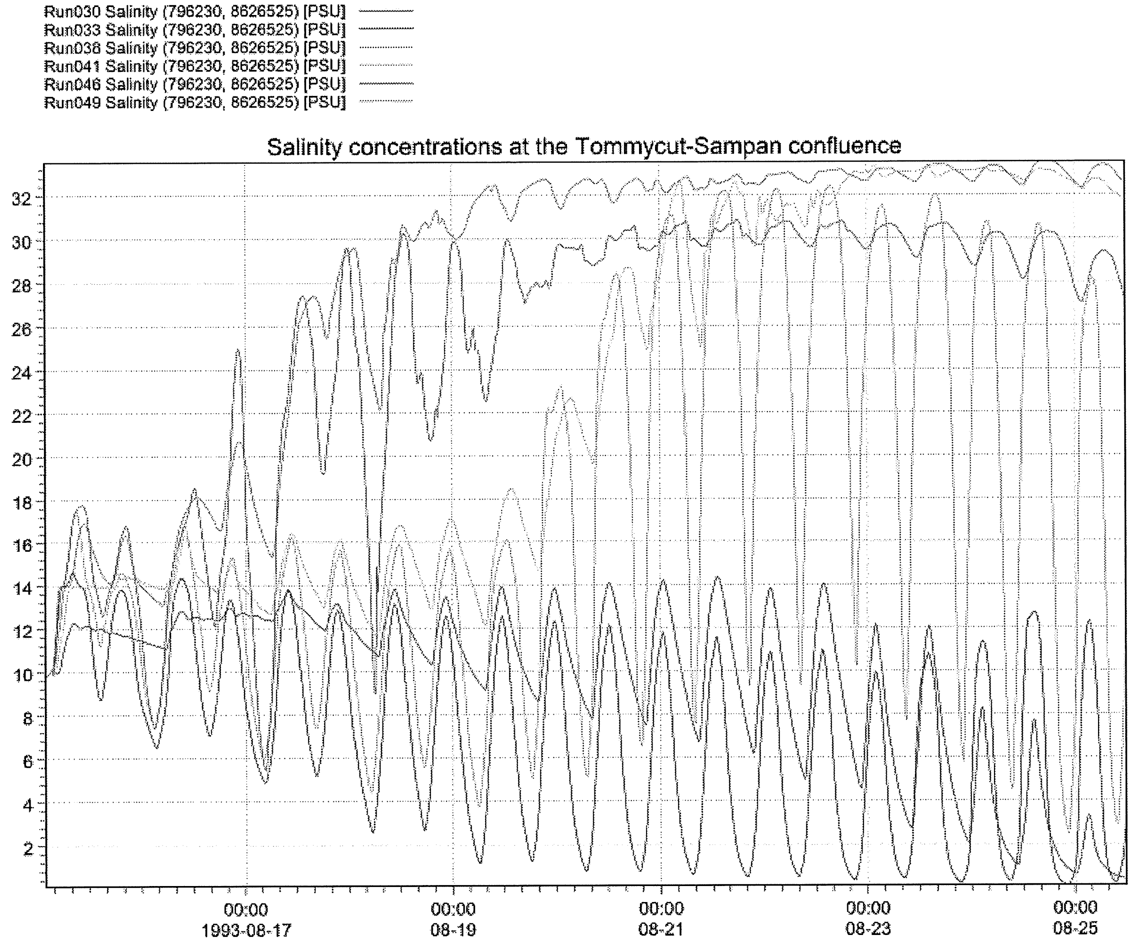


Figure 64. Time series extractions from the centre of channel at the confluence of Tommycut and Sampan Creeks.

3.9. Floodplain water levels and salinity

Analysis of the full 'water year' simulations for floodplain water retention with and without weirs shows an increase in water depth of 10-20cm during flood conditions and similar water depths during the runoff with a delay of two days. After the runoff and throughout the dry season, water depths on the floodplain remain similar (**Figure 65**).

Weirs only delay salinity levels by 15 days and the effect diminishes at the beginning of April when salinity reaches 20 PSU. Conditions remain hypersaline on the floodplain throughout the dry season and weirs only serve to keep the concentrations up above 45 PSU for longer periods (**Figure 66**).

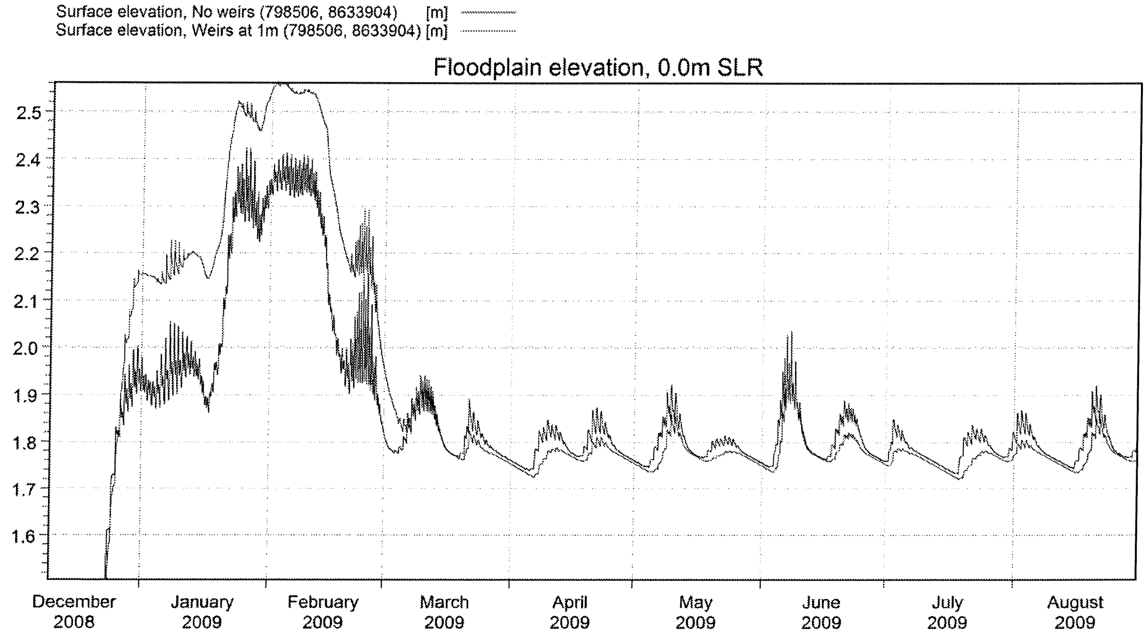


Figure 65. Floodplain water levels in the floodplain between Tommycut and Sampan.

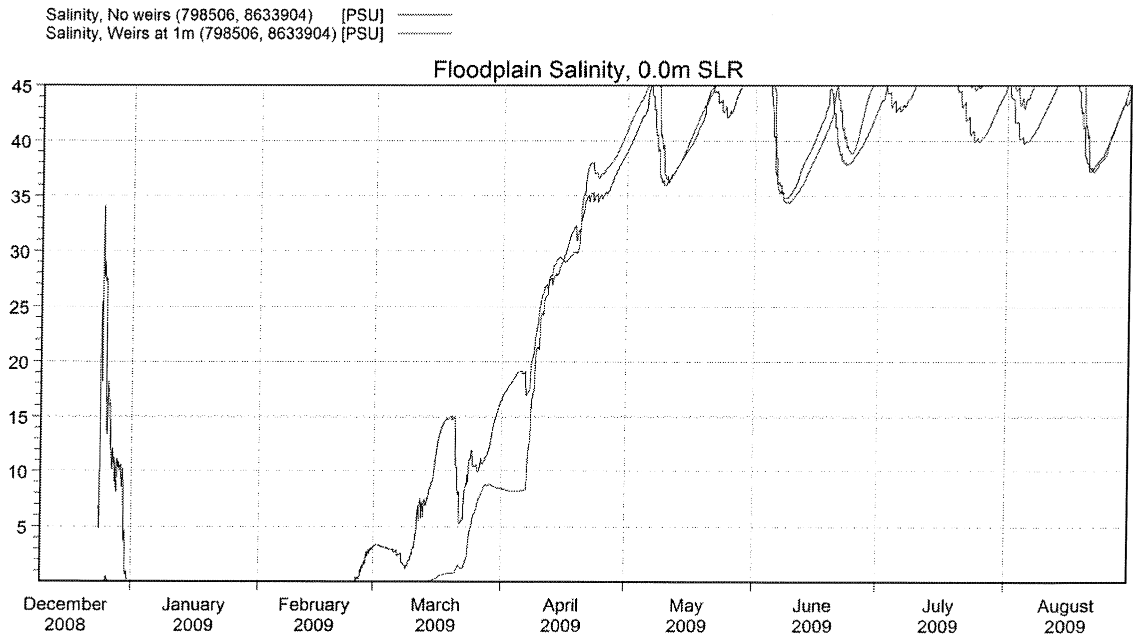


Figure 66. Floodplain salinity levels in the floodplain between Tommycut and Sampan.

4. DISCUSSION

4.1. Sea level rise

Tides over 2m AHD are critical for the characteristics of the system as they lead to extensive inundation of low lying areas. The rate of SLR, and the type of wetland present, will determine the effectiveness of floodplain aggradation. It is known that mangrove wetlands are the most effective sediment accumulators in coastal areas (McKee et al., 2007, Comeaux et al., 2012, Rogers et al., 2012) and because of this, they may be able to produce a stable environment in the event of 0.8m SLR when tides are over 2m 30% of the time. But, encouragingly, the formation of dense channels and mangroves between Tommycut and Sampan is a step towards the "big swamp" phase in Mary River estuarine plain history where mangrove forests covered the entire area (Mulrennan and Woodroffe, 1998, Woodroffe et al., 1985, Wolanski and Chappell, 1996). It should be considered a viable option to promote mangrove formation in areas of saltwater intrusion as this may provide the best form of SLR mitigation.

4.2. Erosion

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. Although 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 46** shows, as sea level increases, velocity drops further due to greater inundation and attenuation on the floodplains.

4.3. Inundation

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 60**). 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 62** will lead to dramatic changes to the morphology and biodiversity. Due to the greater flow velocities at the mouth (**Figure 49**), channel widening will be likely to occur. The increased flood tide action (**Figure 53**) with reduction in current velocities upstream of the mouth will promote sediment accumulation via marine sediments 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 in the channel.

4.4. Flood tide sediment accumulation

One of the most important processes of the macro-tidal estuarine floodplains of the Northern Territory is the flood tide dominance of such estuary types. The flood tide deposits marine sediment on inundated areas of the floodplain which in the past has allowed these areas to accumulate substrate at the same rate as rising sea levels (Wolanski and Chappell, 1996). The flood tide dominance is not lost with weirs installed. Although the flood tide is reduced significantly, the ebb tide experiences a greater reduction and the cumulative discharge ratio between flood and ebb tide remains the same (**Figure 54**). Therefore, weirs will not hinder the significant advantage of flood tide dominance in the event of SLR.

4.5. Salinity

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). At 0.3m SLR concentration reaches 32 PSU quickly and remains very high, whereas it is cyclic without weirs (**Figure 64**). Negative effects only increase when the backwater effect of weirs combines with 0.8m of SLR. 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 63**). 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.

4.6. Limitations

The model has improved the potential for decision making dramatically but its limitations should be considered during the decision making process. 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 (i.e. high velocities in the mouth leading to channel widening) but there are others that may be unforseen due to the complex processes in a rapidly evolving system like the Mary River.

5. RECOMMENDATIONS

- Prepare stakeholders for extensive salt water intrusion of the floodplains downstream of Shady Camp Barrage.
- Promote mangrove community establishment in the downstream area as freshwater/brackish ecosystems are lost to salt water intrusion. 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. The low erosion resistance and low bed roughness of hypersaline mudflats lowers coastal resilience to sea level rise and if they become widespread, could lead to increased salt water intrusion upstream.
- Weirs 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. Short term erosion will be reduced but floodplain water retention is not dramatically improved and salinity still reaches sea water concentrations quickly after the runoff. Difficulty of weir construction in the area is also a concern. Past reports have estimated a construction cost in the order of 2 million dollars per weir. There is a high potential for damage around the weir due to high velocities so maintenance and emergency repairs should be accounted for.
- Natural processes of land adaption are much more effective at mitigating sea level rise. The reduction in velocities upstream of the mouth, together with higher land elevations upstream of Shady Camp will result in the slowing of headwater extension. The "big swamp" state of 5000-6000ya is a likely result of future coastal inundation and will provide excellent habitat to many species of flora and fauna.
- If weirs were implemented to achieve a near-term reduction in erosion it is recommended that modelling continues with calibration and validation as well as rigorous weir position and crest height testing to increase the timespan of their value and to balance negative effects.
- Upstream, Corroboree will undergo similar changes to that which occurred to billabongs downstream of Shady Camp (Red Lilly, Sampan Billabong, Alligator Lagoon, Dead Fish Billabong and Roonees Lagoon). It is unlikely that weirs could prevent this in the event of sea level rise. There is an 8km length of semi-incised channel between Shady Camp and Corroboree so minimal erosion is required for channel formation.
- Extensive land survey or further LiDAR survey should be undertaken in areas not already covered by surveying in this project. The western plains are still fresh water habitats and elevations will give a clear indication of the fate of those areas. The estuarine plain upstream of Shady Camp Billabong to Corroboree is also a critical area for extensive elevation surveying, which will help determine the vulnerability of its freshwater habitat.

6. CONCLUSION

The model has led to a detailed understanding of the hydrodynamics of the Mary River downstream of Shady Camp and has shed light on the effects of any future sea level rise on the lower wetlands. Overall, it will contribute to informed decisions on future management of the system, whether through intervention or preparation for likely environmental changes. It has solved many previous unknowns, such as the dominant forces behind headwater extension and the benefits, limitations and drawbacks of submerged weir construction. The model can easily be optimised to help finalise detailed intervention, mitigation or adaption actions through appropriate calibration and validation.

7. 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.

ALTAMIMI, Z., SILLARD, P. & BOUCHER, C. 2002. ITRF2000: A new release of the International Terrestrial Reference Frame for earth science applications. Journal of Geophysical Research, 107.

APPLEGATE, R. 1999. Saltwater Intrusion and the Mary River Wetlands of the Northern Territory. In: W.J., S. (ed.) An International Perspective on Wetland Rehabilitation. Dordrecht, The Netherlands: Kluwer Academic Publishers.

AUSTRALIAN MARINE AND OFFSHORE GROUP. 2000. Mary River Wetlands Report No. 1: Mary River Wetlands Salt Intrusion.

BALLUA, V., BOUIN, M.-N., SIMÉONI, P., CRAWFORD, W. C., CALMANT, S., BORÉ, J.-M., KANAS, T. & PELLETIER, B. 2011. Comparing the role of absolute sea-level rise and vertical tectonic motions in coastal flooding, Torres Islands (Vanuatu). PNAS.

BAYLISS, B., BRENNAN, K., ELIOT, I., FINLAYSON, M., HALL, R., HOUSE, T., PIDGEON, B., WALDEN, D. & WATERMAN, P. 1997. Vulnerability assessment of predicted climate change and sea level rise in the Alligator Rivers Region, Northern Territory Australia. In: SCIENTIST, S. (ed.) Supervising Scientist Report 123. Canberra.

BISHOP, K. & FORBES, M. 1991. The freshwater fishes of northern Australia. In: HAYNES, C., RIDPATH, M. & WILLIAMS, M. (eds.) Monsoonal Australia: Landscape, ecology and man in the northern lowlands. Balkema, Rotterdam.

BOM 2011. Annual sea level data summary report. The Australian Baseline Sea Level Monitoring Project.

BOM, cyclone history, http://www.bom.gov.au/cyclone/history/index.shtml. accessed 15/01/2013.

BROCKLEHURST, P. & KERCKHOF, D. V. 2002. Melaleuca Forests of the Northern Territory.

COBB, S., SAYNOR, M., ELIOT, M., ELIOT, I. & HALL, R. 2007. Saltwater intrusion and mangrove encroachment of coastal wetlands in the Alligator Rivers Region, Northern Territory, Australia. In: SCIENTIST, S. (ed.) Supervising Scientist Report.

COMEAUX, R. S., ALLISON, M. A. & BIANCHI, T. S. 2012. Mangrove expansion in the Gulf of Mexico with climate change: Implications for wetland health and resistance to rising sea levels. Estuarine, Coastal and Shelf Science, 96, 81-95.

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

HARRISON, L., MCGUIRE, L., WARD, S., FISHER, A., PAVEY, C., FEGAN, M. & LYNCH, B. 2009. An inventory of sites of international and national significance for biodiversity values in the Northern Territory. Department of Natural Resources, Environment, The Arts and Sport. Darwin, NT.

JEVREJEVA, S., GRINSTED, A., MOORE, J. C. & HOLGATE, S. 2006. Nonlinear trends and multiyear cycles in sea level records. Journal of Geophysical Research, 111.

JEVREJEVA, S., MOORE, J. C., GRINSTED, A. & WOODWORTH, P. L. 2008. Recent global sea level acceleration started over 200 years ago? Geophysical Research Letters, 35.

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.

JONAUSKAS, P. & APPLEGATE, R. 2002. Recommendations: Saltwater Intrusion, Yellow Waters, Kakadu National Park. NRETAS.

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., MILLS, K. & WOODROFFE, C. D. 1991. Tidal-creek extension and saltwater intrusion in northern Australia. Geology, 19, 831-834.

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. In: ENVIRONMENT, S. C. O. T. (ed.). Darwin, NT: Legislative Assembly of the Northern Territory.

MCKEE, K. L., CAHOON, D. R. & FELLER, I. C. 2007. Caribbean mangroves adjust to rising sea level through biotic controls on change in soil elevation. Global Ecology and Biogeography.

MULRENNAN, M. E. & WOODROFFE, C. D. 1998. Holocene development of the lower Mary River plains, Northern Territory, Australia. The Holocene, 8, 565-579.

NEUBAUER, S. 2011. Ecosystem Responses of a Tidal Freshwater Marsh Experiencing Saltwater Intrusion and Altered Hydrology. Estuaries and Coasts, 1-17.

ROGERS, K., SAINTILAN, N. & COPELAND, C. 2012. Modelling wetland surface elevation dynamics and its application to forecasting the effects of sea-level rise on estuarine wetlands. Ecological Modelling, 244, 148-157.

STORY, R. 1969. Vegetation and Pasture Lands. Commonwealth Scientific and Industrial Research Organisation - Division of Land Research.

STORY, R., WILLIAMS, M. A. J., HOOPER, A. D. L., O'FARRALL, R. E. & MCALPINE, J. R. 1969. Lands of the Adelaide-Alligator Area, Northern Territory. Land Research Series. Commonweath Scientific and Industrial Research Organisation.

VAN DER WEGEN, M. & VERHAGEN, H. J. 2000. Salt Intrusion in the Mary River Wetlands: Review of Consultancy Recommendations. International Institute for Infrastructural, Hydraulic and Environmental Engineering.

VICTORIAN GOVERNMENT DEPARTMENT OF SUSTAINABILITY AND ENVIRONMENT (2006) Wetlands, Biodiversity and Salt.

WINN, K. 2001. Saltwater intrusion and morphological change at Point Farewell, Alligator Rivers Region. In: SCIENTIST, S. (ed.) Internal Report.

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.

WOODROFFE, C. D., THOM, B. G. & CHAPPELL, J. 1985. Development of widespread mangrove swamps in mid-Holocene times in northern Australia. Nature, 317, 711-713.

WYLLIE, S., ROIZENBLIT, A. & COURIEL, E. 1997. Investigations into the closure of Tommycut Creek on the flooding characteristics of the Lower Mary River. Australian Water and Coastal Studies PTY LTD.