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Hydrodynamic Modelling of Tidal Inundation from Sea Level Rise in Kakadu National Park

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Executive summary

Sea level rise threatens to detrimentally impact the low-lying floodplains of Kakadu National Park through:

1. the saline inundation of freshwater areas
2. the loss of native vegetation and
3. the loss of wildlife habitat for endemic species.

As Kakadu National Park is world renowned for its cultural heritage and ecological significance there are many conservation drivers for protecting areas of the low-lying floodplain including a world heritage listing by UNESCO and wetlands listing under the Ramsar Convention.

There are four tidal rivers within Kakadu National Park, the South Alligator, East Alligator, West Alligator and Wildmann Rivers. To inform the decision making and sustainable management of these rivers and coastal systems we used hydrodynamic modelling to predict the changes in intertidal zone for four sea level rise scenarios. These are a 0.00m rise for current day, a 0.14 m rise for 2030, a 0.70 m rise for 2070 and a 1.10 m rise for 2100.

The modelling approach used a finite volume inundation method based on the Shallow Water equations. Simulations were performed at a spatial resolution of 60 m^2 for each of the river systems. For all simulations a Digital Elevation Model constructed from Lidar point cloud data was used to resolve the coastal and river system terrains. Lidar data offers the high level of vertical accuracy, 0.10 m, necessary for analysing sea level rise effects, such as the sea level rise of 0.14 m predicted for the year 2030. In comparing the four scenarios we give predicted maximum inundation extents, average inundation depth and frequency of inundation. We also show why using a bathtub fill method is not suitable for modelling in the low-lying floodplains.

Our results predict that for 2030, there will be an increase of 14 % in the intertidal zone and by 2070, 89 % as compared with current day. For 2100, we predict almost 90 % of the floodplain to be saline inundated. For case sites of interest, Boggy Plain and Magela Creek, we predict saline inundation to occur for a sea level rise between +0.14 m and + 0.70 m. The estimated timescale of risk for these freshwater areas is therefore between 2030 and 2070.

Through this research we demonstrate the need and advantage to using hydrodynamic modelling opposed to bathtub fills to predict changes in tidal inundation from sea level rise. Acknowledged constraints on the accuracy of the modelling are lack of gauge data in tidal and river systems.

Part I Stage 1 Technical Report

1 Introduction

1.1 Background

Kakadu National Park (KNP) is located within the Northern Territory, Australia, approximately 180 km East of Darwin. There are of four tidal river systems that form the main ecological arterials of the KNP; the South Alligator, East Alligator, West Alligator and the Wildmann Rivers, Figure 1. The floodplains for these river systems stretch over 2,960 km^2 within extended Alligator Rivers Region (Finlayson et al., 2006) and are of elevations between 0.2 – 1.2 m above Mean High Water Level (Eliot et al., 1999). These low-lying floodplains are vulnerable to sea level rise impacts including; changes in the intertidal zone, saline intrusion of freshwater areas, loss of native vegetation and loss of wildlife habitat for endemic species to KNP (Bayliss et al., 1997, Bartolo et al., 2008).

Figure 1 The four river systems of Kakadu National Park and the associated floodplains. The boundaries of Kakadu National Park and the extended Alligator Rivers Region are as marked.

Conservation drivers for the preservation of low-lying floodplains and the more general Kakadu region include its world-renowned biodiversity and cultural heritage. Formal protections for KNP's biodiversity include a World Heritage Listing. This listing acknowledges the park to include over one third of Australia's bird species, one quarter of Australia's land mammals and an exceptionally high numbers of reptile, frog and fish species (World Heritage Convention UNESCO, 2014).The world heritage listing and protection is also jointly awarded for the cultural significance of KNP. The Bininj and Mungguy peoples, the traditional owners of the land (Land Rights Act 1976), have a history of habitation in the area extending over 50,000 years. Physical record of this habitation is recorded in the landscape through cultural sites, rock art and archaeological evidence dating back thousands of years (World Heritage Convention UNESCO, 2014). Moreover, the land has a spiritual significance to the traditional owners through the belief that the people and land are linked. Other protections include the listing of KNP under the National Parks and Wildlife Conservation Act 1975 and the listing of the KNP wetlands under the Ramsar Convention (Bayliss et al., 2012).

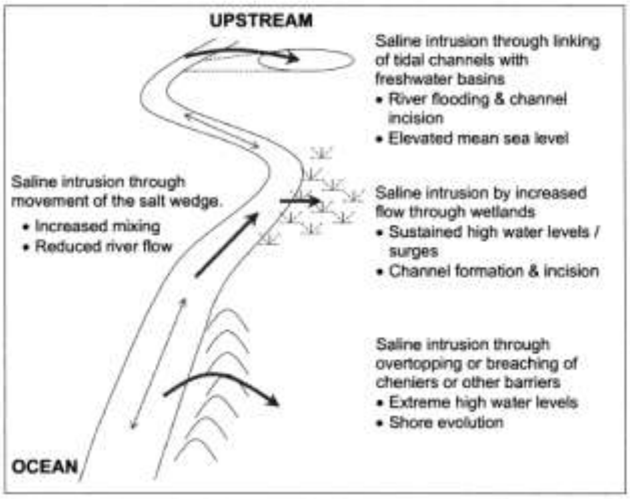

Figure 6. Potential mechanisms of saltwater intrusion. Variation in the expected form of saline water intrusion with distance upstream from the river mouth.

Figure 2 Potential mechanisms of saltwater intrusion in tidal river systems based on distance from the river mouth, adopted from (Winn et al., 2006).

For the tidal river systems of KNP, the mechanisms of saltwater intrusion will vary depending upon the location within the tidal stream, see Figure 2 (Winn et al., 2006). The impact of saline intrusion is also dependent upon where in the river mixing between fresh water catchment flows and tide is occurring. During the wet season heavy rainfall results in mixing occurring further 20 – 40 km from the mouth, lessening of saline impacts upstream (Woodroffe et al., 1989). In contrast, during the dry season the tidal influence is dominant and becomes saline the full tidal reach, thereby providing conditions conducive to saltwater ingress (Woodroffe et al., 1989). Storm surge also provides a means for saltwater ingress through elevated sea levels and flood inundation (Winn et al., 2006). The process of saline intrusion is therefore affected by the intensity of meteorological factors of seasonality, tide, rainfall and storm surge. (Bayliss et al., 1997, Cobb et al., 2000). The rate and extent of saline intrusion is also dependent upon geomorphology, sedimentation and groundwater hydrology (Cobb et al., 2000, Bayliss et al., 1997). Other influencing factors include sea level fluctuations and of particular interest to this study sea level rises (Winn et al., 2006).

Sea level rise and the resulting saltwater inundation of freshwater areas have been highlighted as a concern in a series of collaborative vulnerability assessments of Kakadu National Park and the extended Alligator Rivers Region (Bayliss et al., 1997, Cobb et al., 2000, Bartolo et al., 2008). Bayliss et al. (1997) used a bathtub approach, referred to as terrain contours, to identify areas of the KNP floodplain vulnerable to a 0.3 m sea level rise by 2030. The elevation of the bathtub fill is assumed to be the highest astronomical tide in the Van Diemans Gulf, 3 m AHD, plus the predicted rise of 0.3 m. Hare (2005) predicts that for a 1 – 2 degree temperature increase, 50 % of the Kakadu wetlands will be vulnerable to sea level rise, with the vulnerability extending to the entire floodplain for a 2 – 3 degree temperature increase. However we note that estimate is not on a regional scale and does not cite the method of inundation prediction. Bartolo et al. (2008) predicted 66 % of coastal wetland vulnerable for 2030 from a figure of 175 587 ha, estimated by Bayliss (1997). This figure is revised to 72 % for freshwater floodplain when saline coastal habitats are excluded (Bartolo et al., 2008).

Within the literature there is great variability between both predicted changes in sea level rise and the time scale at which these changes will occur, Table 1 (Dutra and Bayliss, 2013). Sea level rise predictions are also variable on a regional versus global scale. Accurate estimates of the extent of freshwater floodplain vulnerable to sea level rise and the timescale at which changes will occur is therefore subject uncertainty. This speaks to the variability of results reported within the current literature.

Table 1 Literature survey of sea level rise predictions adopted from internal CSIRO collaborator report. For listed references please refer directly to report. (Dutra and Bayliss, 2013)

Time Scale	Predicted or observed changes	Spatial Scale	References
2030	+0.17m	Kakadu National Park	(Hyder Consulting Pty Ltd, 2008) (Bayliss et al., 1997); (Church et al., 2008)
2030	+0.143m	Kakadu National Park	(BMT WBM, 2011)
2030	0.03m – 0.17m	Global	(CSIRO, 2007)
2070	+0.50m – 0.70m	Kakadu National Park	(Hyder Consulting Pty Ltd, 2008) (Bayliss et al., 1997);(BMT WBM, 2011)
2070	+0.07m – 0.49m	Global	(CSIRO, 2007)
2100	+ 0.6m (±0.59m) – 1.6m (±1.8m)	Global	(Jevrejeva et al., 2010)
2100	0.5m-1.4m	Global	(Rahmstorf, 2007a, b)
2100	0.75m-1.9m	Global	(Vermeer and Rahmstorf, 2009)
2100	0.8m-2m	Global	(Pfeffer et al., 2008)
2090-2099	+0.59m	Global	(IPCC, 2007)
2100 (B1)	0.18m – 0.38m; central estimate 0.28m + 0.1 – 0.2 from ice sheets	Global	(CSIRO, 2007)
2100 (A1T)	0.20m - 0.45m; central estimate 0.33m + 0.1 – 0.2 from ice sheets	Global	(CSIRO, 2007)
2100 (B2)	0.20m - 0.43m; central estimate 0.32m + 0.1 – 0.2 from ice sheets	Global	(CSIRO, 2007)
2100 (A1B)	0.21m - 0.48m; central estimate 0.35m + 0.1 – 0.2 from ice sheets	Global	(CSIRO, 2007)
2100 (A2)	0.23m - 0.51m; central estimate 0.37m + 0.1 – 0.2 from ice sheets	Global	(CSIRO, 2007)
2100	0.26m - 0.59m; central estimate 0.43m + 0.1 –	Global	(CSIRO, 2007)

(A1FI)	0.2 from ice sheets		

When assessing floodplain vulnerability to changes in sea level rise a graphical imaging system (GIS) approach or 1D bathtub fill method can provide an initial frame of reference; however hydrodynamic modelling provides a more accurate tool for prediction. In particular within the Kakadu region hydrodynamic modelling is necessary, as it can better capture the influence of topography and tide. Model sensitivity to vertical changes in tidal elevation is paramount as the flood plains are low-lying and the spring tidal range in the Van Diemen Gulf is 6 m (Woodroffe et al., 1989). Bathtub models are likely to overestimate inundation extent over such flat terrain, whereas hydrodynamic models can better capture the establishment of channel connectivity and the ebbing and flow of tide. The extent of tidal influence in the region is also 105 km upstream in the South Alligator River (Woodroffe et al., 1989). Bathtub fill models are not equipped to deal with this type of tidal reach and are therefore unable to capture the mechanisms of saline intrusion occurring upstream, see Figure 2.

Within the literature there are limited investigations into the use of hydrodynamic modelling for predicting sea level rise inundation effects in the Kakadu region. Previous to 2011, when a LiDAR survey was undertaken (Furgo Spatial Solutions Pty Ltd, 2012), a Digital Elevation Model (DEM) of sufficient vertical sensitivity did not exist in order to accurately perform hydrodynamic modelling in the Kakadu region. BMT WBM (2010) was unable to undertake hydrodynamic modelling for an impact assessment of saline intrusion into the freshwater billabongs off the South Alligator River due to the insufficient elevation data. Instead, the study used proximity and anecdotal evidence to make qualitative assessments. Other challenges to performing hydrodynamic modelling in the region have been the insufficient tidal gauge and river gauge data. In general, the hydrodynamic and hydrologic processes within the Van Diemans Gulf region and KNP are relatively poorly understood (Bayliss et al., 1997, Bartolo et al., 2008).

1.2 Computational design and modelling approach

The purpose of this study is to use hydrodynamic modelling to identify changes in the intertidal zone due to sea level rise and identify freshwater areas at risk of saline intrusion. These results can be used to assess the severity of risk to an area and provide a timescale for mitigation strategies. Through this modelling we also demonstrate why a bathtub approach is not suitable for accurate inundation predictions in the Kakadu Region. Other added advantages to using a hydrodynamic model opposed to a bathtub fill are we can utilise the temporal and spatial dimensions of the modelling to provide measures of tidal inundation frequency and average depth.

The modelling will consider four sea level rise scenarios from current day to 2100;

Current Day Scenario: No sea level rise, + 0.00 m

2030 Scenario: A sea level rise of +0.14 m

2070 Scenario: A sea level rise of +0.70 m and

2100 Scenario: A sea level rise of +1.10 m.

The scenarios of 2030 and 2070 are chosen to be in keeping with the most recent vulnerability assessments (BMT WBM, 2011). The 2100 scenario rise of +1.1m is chosen as it is an estimate in the upper to mid range of global predictions for 2100 (Table 1). For base comparison and validation, the current day scenario of +0.00 m must also be modelled. From these scenarios, the risk will be assessed at three case sites of interest identified in discussions with traditional owners and stakeholders; Boggy Plain, Yellow Water and the Magela Creek Floodplain.

1.3 Sites of interest

Magela Creek floodplain is located on the Eastern arm of the East Alligator River. The floodplain belongs to the wetland within KNP protected under the Ramsar Convention and is also a site of cultural importance. Given the proximity of Magela Creek floodplain to a Uranium mine, the site has been in focus of many ecological risk assessments (Eliot et al., 1999). The site has also been identified as vulnerable to saline inundation due to sea level rise (Bayliss et al., 2012).

Yellow Water area is one of the main tourist drawcards to the region. Located at the end the South Alligator River's tidal reach, the northern end of Yellow Water forms the boundary between freshwater habitat and tidally inundated wetland (Petty et al., 2005). Impacts of saline intrusion are already present within the area as a result of buffalo tracks and tourist driven boating widening and deepening the river system. Mitigation against saline intrusion has included the addition of levee banks, removal of introduced buffalo species and prohibition of boating (Petty et al., 2005).

Boggy Plain is a freshwater habitat located to the West of the South Alligator River. Anecdotal evidence suggests saline intrusion into the area occurs on some king tides, with the extent of intrusion minimal and restricted to the first third of the area. Boggy Plain is also the habitat to populations of Magpie Geese, birds of significance to the traditional owners. Bayliss et al. (1997) states 60 – 70 % of the Northern Territories Magpie Geese population retreat to Boggy Plain and the Noulangie floodplain during dry season.

2 Methodology

The computational method used to model the current day scenario and the predicted seas level rise scenarios for 2030, 2070 and 2100 is a conservative finite volume method that uses the shallow water equations,

$$\frac{\partial h}{\partial t} + (\nabla \cdot \boldsymbol{q})h = 0$$

$$\frac{\partial \boldsymbol{q}}{\partial t} + (\nabla \cdot \boldsymbol{u})\boldsymbol{q} + \frac{g}{2}\nabla h^2 - \boldsymbol{s} = 0$$

$$\boldsymbol{s} = gh\,\nabla b + g n_m^2 h^{\frac{-1}{3}} \boldsymbol{q}|\boldsymbol{q}|$$

where *h* is height of the water, $\boldsymbol{q}$ is the unit discharge from a given cell, $\boldsymbol{u}$ is the vector of the horizontal velocities in x and y directions, g is gravity and $\boldsymbol{s}$ combines the drag terms. These equations are simplified to two-dimensions under the assumption that the height of the water is much less than the width and length of the computational domain, and under the assumption that the vertical velocity can be depth averaged. These assumptions hold as the tidal height is small in relation to the expanse of computational domain. Equation three describes the two frictional terms, one proportional to the slope of the base terrain and the other a terrain friction defined using a constant Manning's Drag Coefficient, n_m. For our simulations we use a Manning's drag of 0.025 for moderate land usage. In future work, there is scope to vary the Manning's drag coefficient according to the land use and vegetation. The main inputs required for shallow water model are a base digital elevation model (DEM), the elevation of mean sea level and a tidal boundary forcing. Optional inputs include; rainfall and soil infiltration introduced respectively through source and sink map inputs.

3 Simulation Inputs

3.1 Digital Elevation Models

Arguably the most important input into the hydrodynamic model is the Digital Elevation Model (DEM) of the Kakadu National Park topography and bathymetry. Three DEMs were combined to create a single base DEM for input into the computational model. A 1 m resolution topography map generated from a LiDAR survey was used for the morphology of the four river systems (Furgo Spatial Solutions Pty Ltd, 2012). LiDAR data provides a sufficient spatial resolution to capture the fine topographical details such as the small tributaries and creeks. The projection system of this DEM is GDA94 MGA Zone 53 and the vertical datum is Australian Height Datum (AHD). The parks topographical domain was completed using a DEM generated from the Shuttle Radar Topographic Mission (STRM) at a 1 arc second resolution (~ 30 m) (Geoscience Australia et al., 2011). The projection system of this DEM is WSG84 with a vertical datum of EGM96. A bathymetric DEM for the coastal and adjacent sea areas in Van Dieman's Gulf at a 1 arc minute (~ 250 m) was used to complete the full computational domain (Geoscience Australia, 2009). The combined DEM for input was converted to a projection system of GDA94 MGA Zone 53 and vertical datum of AHD. The vertical datum of AHD ensures that the mean sea level within the computational domain is 0 m in elevation relative to the time of collection.

The input DEM for simulation must have a high level of vertical accuracy to model inundation from predicted sea level rises. For this reason the high resolution DEM from LiDAR was necessary as the vertical accuracy of elevations is within 0.1 m. The DEM from satellite over the entire park in contrast has a low level of vertical accuracy, in the order of metres, making it unsuitable for hydrodynamic modelling of the low-lying coastal areas and floodplains.

It is important to note that the combined DEM used was not without its data limitations. Artificial and inaccurate striping of river elevations was present within the LiDAR generated DEM and required manual editing. Sounding data within the region is also limited, particularly within the river mouths and the coastal areas. The available bathymetric DEM therefore provided a coarse and discrete contoured representation of bathymetric areas. It therefore must be acknowledged that the accuracy of the inundation modelling is only as accurate as the available input data.

The spatial resolution of the DEM for input was down-scaled to a resolution of 60 m^2. At this resolution 4, 800,000 cells were needed to divide the entire computational domain of the floodplain. At a resolution of 60 m^2 some of the fine-scale connectivity detail will be lost, however there is a computational trade-off between efficiency and accuracy. Simulations run at a 60 m^2 resolution allow for longer simulated time-scale. Longer timescales also provide a better holistic representation of tidal behaviour, as opposed to simulating only a few tidal cycles at a higher resolution. It is also essential to consider longer temporal scales to assess changes in tidal inundation, particularly as the upstream river behaviour will take time to establish over subsequent tides.

3.2 Tidal Boundary Forcing

There is a lack of available tidal gauge data in the Van Diemans Gulf region. This limitation has been acknowledged in other research, including saline intrusion, with studies forced to use the Darwin tidal gauge for mean sea level fluctuations and tidal information (Eliot et al., 1999, Winn et al., 2006). Given the insufficient period of record and the lack of historical measurement in the Van

Dieman's Gulf, the Darwin Gauge is the only historical record with sufficient data to make longer term vulnerability assessments on the changes in tidal inundation from sea level rise. We use the Darwin tidal gauge recording from October 2013 to simulate tidal behaviour in the South and the East Alligator Rivers (Bureau Of Meteorology, 2013). However the tidal range for Darwin is too great to simulate tide in the region of the West Alligator and Wildmann Rivers. Simulations of this region with the Darwin gauge result in an over prediction of tidal inundation extent. There are limited recordings of tidal data at a gauge near the mouth of West Alligator River for 1998. From these recordings we use predictions made for 2007 from the 1998 data to simulate tide in the West Alligator and Wildmann Rivers. As we must use two different tidal inputs, we have selected a comparable time length and tidal pattern from both gauges to use as input,
Figure 3.

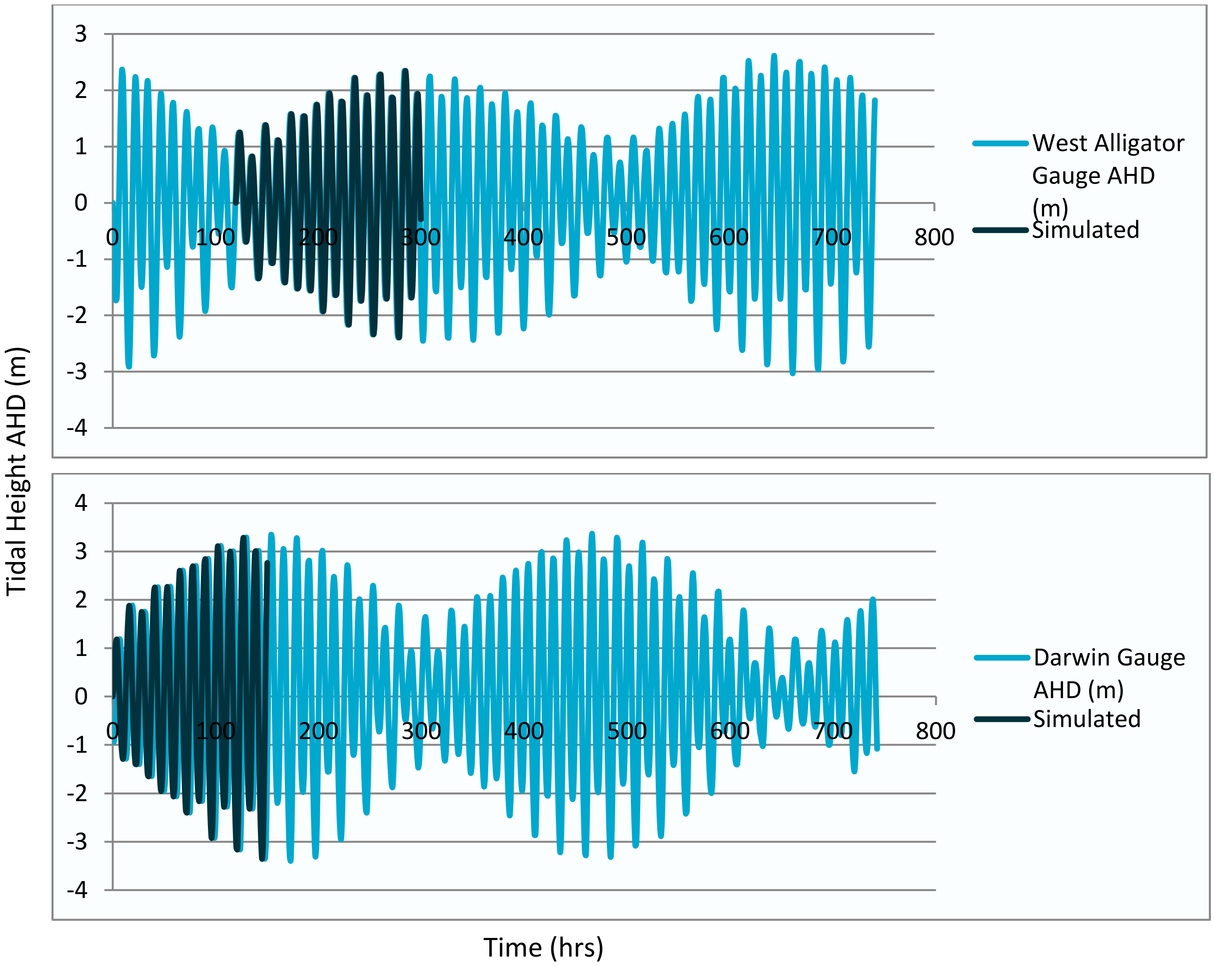

Figure 3 Hourly tidal heights in AHD for the month of October at the West Alligator Gauge 2007 and the Darwin Gauge 2013. The tidal cycles highlighted in navy are those used to generate the results.

Both tidal boundary forcings are taken from the month of October. October is the end of the six month dry season beginning in May. Mid October also serves as the transition between Gurrung, the Hot Dry Weather Season, and Gunumeleng, the Pre-Monsoonal Storm Season according to the six season calendar observed by the traditional owners (Finlayson et al., 2006). During the dry months May to October, the mean rainfall at Jabiru Airport was 66.6 mm, within the East Alligator catchment, and at Aurora Kakadu Resort, 52.2 mm, within the South Alligator catchment(Bureau of Meteorology, 2013). A tidal forcing from October will therefore allow for more accurate assessment of changes in tidal ingress as there is minimal freshwater influence during the preceding months.

4 Validation

Validation tests of the shallow water model were performed to ensure the accuracy of inundation prediction. Historically, this validation has included the benchmarking of the shallow water solver for general wave run up behaviour and maximum inundation extents using the NOAA laboratory benchmarks (Synolakis et al., 2008). For this particular study we recreate the large scale rainfall event associated with Cyclone George over the dates of the 27th to 5th of February. In the selection of this event we are able to compare the spatial component of the modelling, the inundation extent, to available landsat data of inundated floodplains (Ward, 2013). We can also compare temporal changes in river elevations using the available gauge data, G8200041 and G8210028 (Department of Land Resource Management, 2013). This serves as an indicator that the discharge rates are correct. Little rainfall occurred across the catchment in the days prior to the selected event prior meaning clear comparison to gauges can be made as upstream rainfall flows were negligible. Thiessen polygons were used in the simulation as a source maps to recreate the rainfall event. These polygons were created using the historical records of rainfall at the gauges; 014042, 014198, 014208, 014252, 014263, 014275 and 014281 (Bureau of Meteorology, 2013).

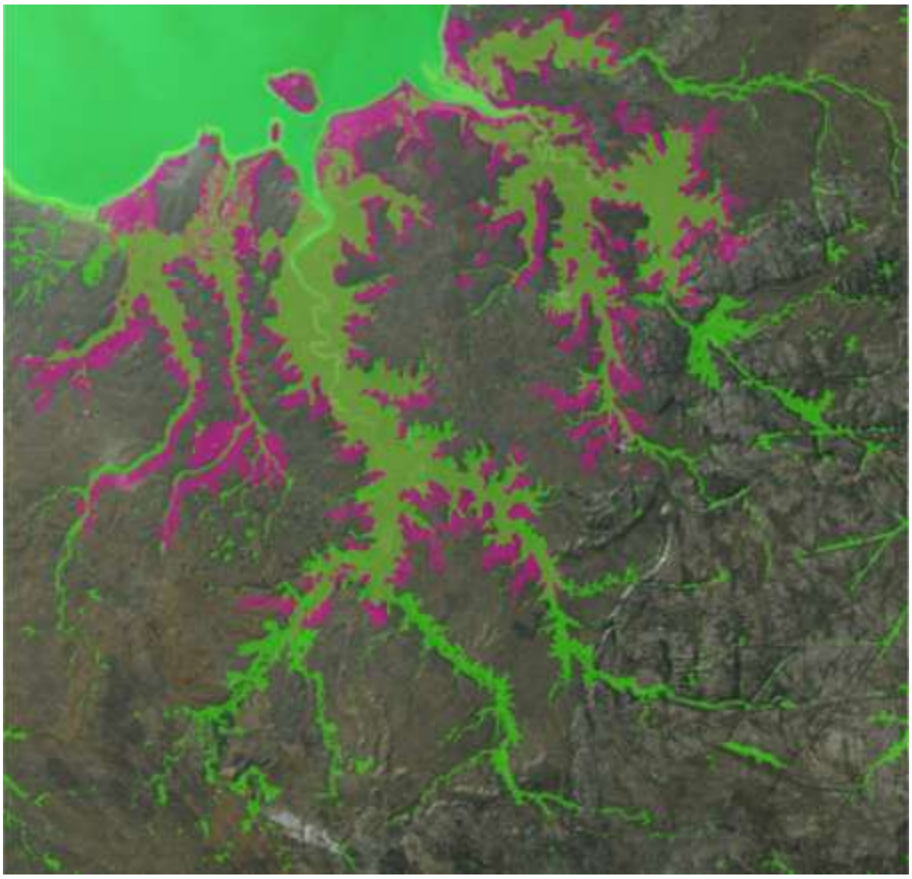

Figure 4 Simulated flood extent (green) as compared with cumulative landsat data of the inundated floodplains captured during a series of wet seasons (pink).

For the spatial inundation we achieve good agreement to the available landsat data of the inundated floodplains. Upstream we notice a greater inundation extent. On subsequent days this water will flow downstream hence why it does not appear in the satellite capture. Also in this particular simulation we consider rainfall contribution only. Disagreement along the coastal areas can therefore be attributed to missing tidal influences.

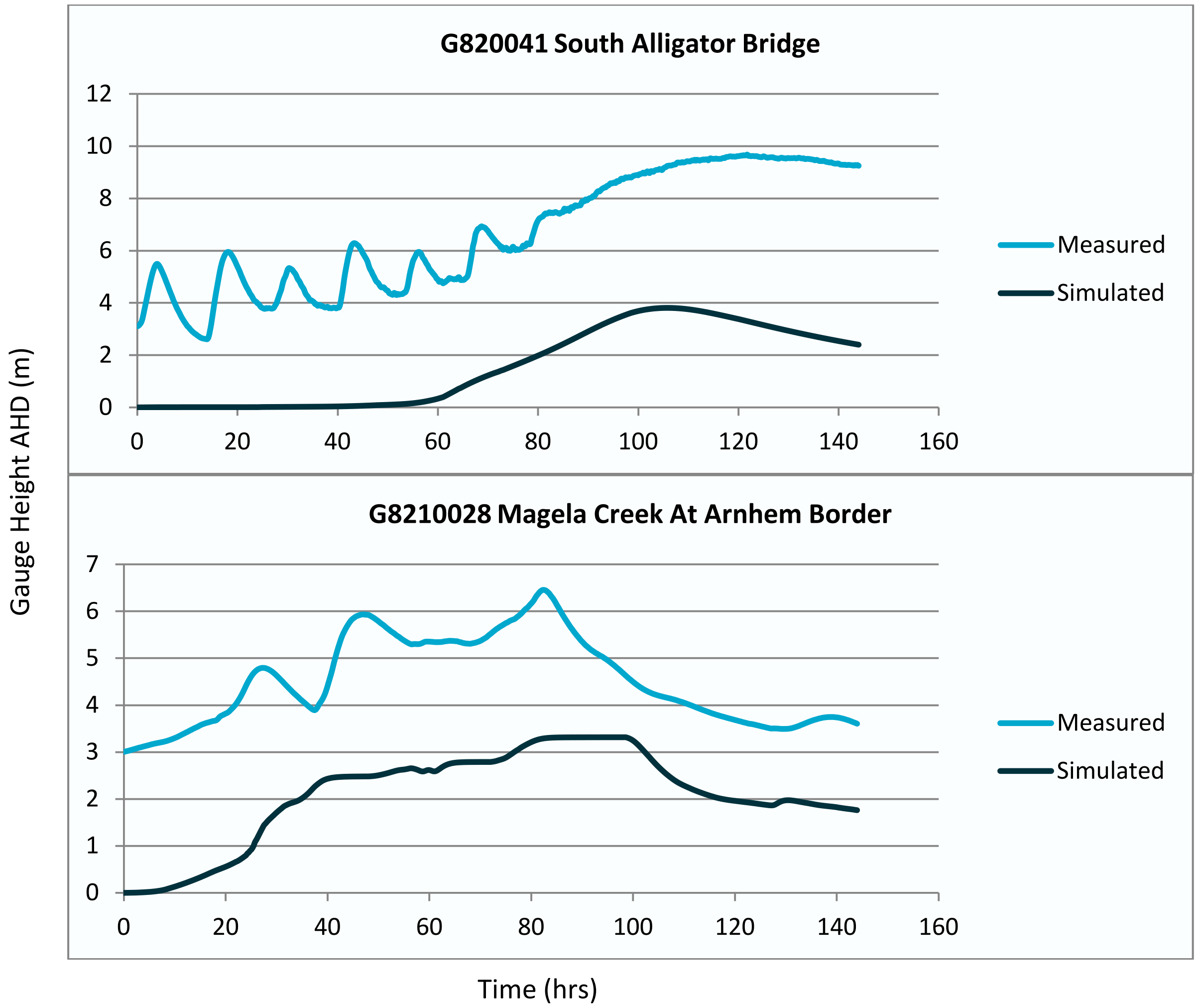

Figure 5 Simulated and measured results for G8200041 the South Alligator Bridge Gauge and G8210028 for Magela Creek at Jabiru.

Figure 5 shows the comparison of two gauge results. It should be noted there much uncertainty with the gauge datum's relative to AHD. As such it is very difficult to compare the two sets of results accurately. The initial river fill for this simulation was AHD, so this also means a translation between the two sets of results depending on the real height of water in the river initially which could not be accurately estimated.

We note the unit of measurement for the rainfall input data was daily. Therefore the simulated gauge results are of this sensitivity. However, the actual river gauges have a highly sampling frequency of an hour. This why there are peaks and troughs presents in the measured G8210028 data occurring over a time period less than 24 hours. What is to be understood however from these graphs is that the average flow height within the river is comparable to that simulated. For gauge G8200041 tidal influences were present in the measured but are not included in the simulated results. Again the average shape and rate of change of water height in the river is used for comparison and bears good agreement.

5 Inundation Predictions from Sea Level Rise

5.1 Boggy Plain and Bathtub Modelling Limitations

Bathtub modelling has traditionally been used to assess sea level rise impacts in KNP; however its application is not suitable in all areas. To convey why the modelling is not suitable we consider the case study site of Boggy Plain. Boggy Plain is a freshwater billabong extending a distance 15.4 km from the South Alligator River. A bathtub fill of the area for two different elevations, 3.2 m and 3.3 m AHD, is presented in Figure 6.

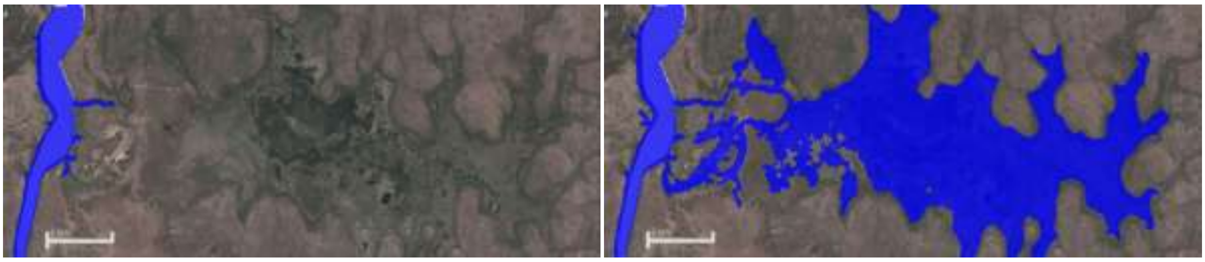

Figure 6 Bathtub fills of the South Alligator River and Boggy Plain for elevations of 3.2 m (left) and 3.3 m (right) AHD.

A bathtub fill at an elevation of 3.3 m suggests that saline inundation will occur for the full extent of Boggy Plain. Whereas, a bathtub fill at an elevation of 3.2 m predicts no inundation in the area. For Boggy Plain to be predicted as saline inundated by a bathtub fill the vertical sensitivity is only 0.1 m. This is the borderline within the accuracy of the DEM. There is therefore a danger is to over predict inundation extent given the vertical sensitivity and the low-lying terrain extending kilometres. To accurately assess risk to the area, tidal flow behaviours need to be included.

Consider the application of hydrodynamic modelling to predicting saline inundation in Boggy Plain. Of the limited gauge data available, there is a gauge located at the South Alligator River Bridge. This gauge is approximately 12 km upstream to Boggy Plain. The gauge, G8200041 (Department of Land Resource Management, 2013), now decommissioned, recorded tidal influences and river heights from 1969 to 2011. For simulation, hydrostatic boundary conditions were used, with a boundary forcing corresponding to the tidal recordings at the gauge from February 1st to 5th in 2007 (Figure 7). For the scenario, the mean river level was estimated at 0.84 m AHD from the 2007 gauge measurements. This was assuming a gauge datum of -2.961 m. There is some uncertainty related to the gauge datum due the use of more than one benchmarking system and past physical sinking of the gauge.

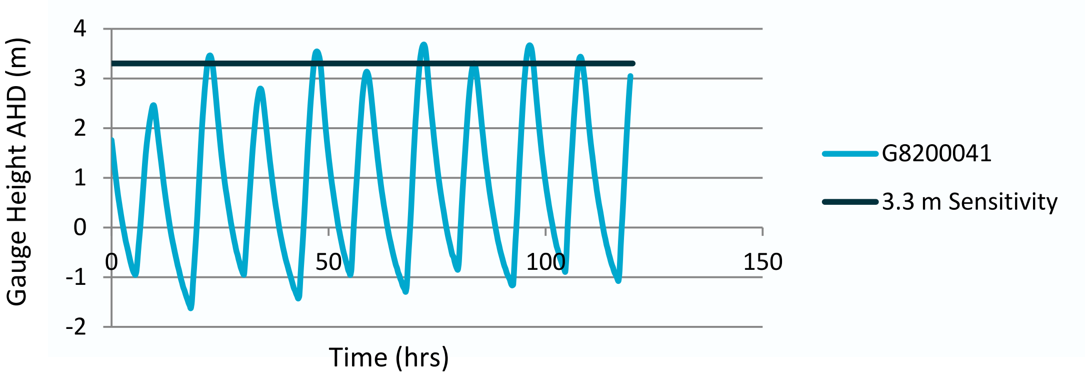

Figure 7 Measurements of river height AHD at the South Alligator River bridge gauge, G8200041, from the 1st to the 5th of February. The dark blue line is the threshold for inundation to occur into Boggy Plain.

The simulated inundation extents for the four highest tides are shown in Figure 8. We observe the building of the flow and establishing of connectivity down the smaller tributaries over subsequent days. We also observe for the given tidal input that saline intrusion only occurs in the first part of Boggy Plain.

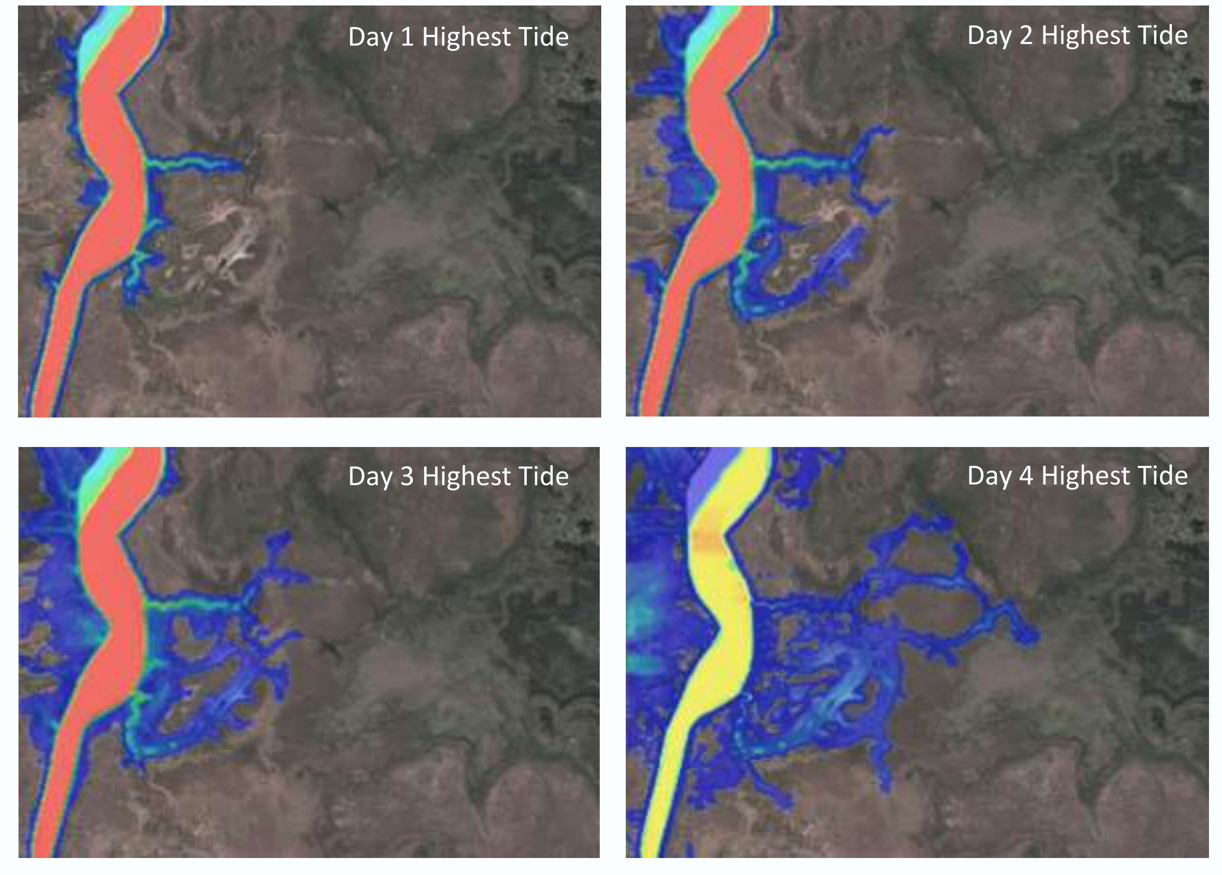

Figure 8 Tidal extents at the four highest tides during the 1st to 5th of February.

From the flow development observed in Figure 8, it is clear that only under a sustained river elevation of 3.3 m and on subsequent tides will saline inundation occur in Boggy Plain. However, a bathtub fill at an elevation of 3.3 m suggests that saline inundation will occur for the full extent of Boggy Plain. Bathtub models do not take into account flow behaviours, such as tidal effects or the time taken for flow connectivity to become established. A bathtub fill approach is therefore not suited for accurate inundation predictions in these low-lying areas of intricate connectivity.

5.2 Maximum Inundation Extents

The maximum extents simulated for the four sea level rise scenarios are shown in Figure 9. Each scenario result is composited from a pair of simulations, one for the South and East Alligator Rivers, simulated using Darwin tidal data and one for the West Alligator and Wildmann Rivers, simulated using West Alligator tidal data. In general we find the extent of inundation increases upstream from 2013 to 2100. The depth of inundation to also increases.

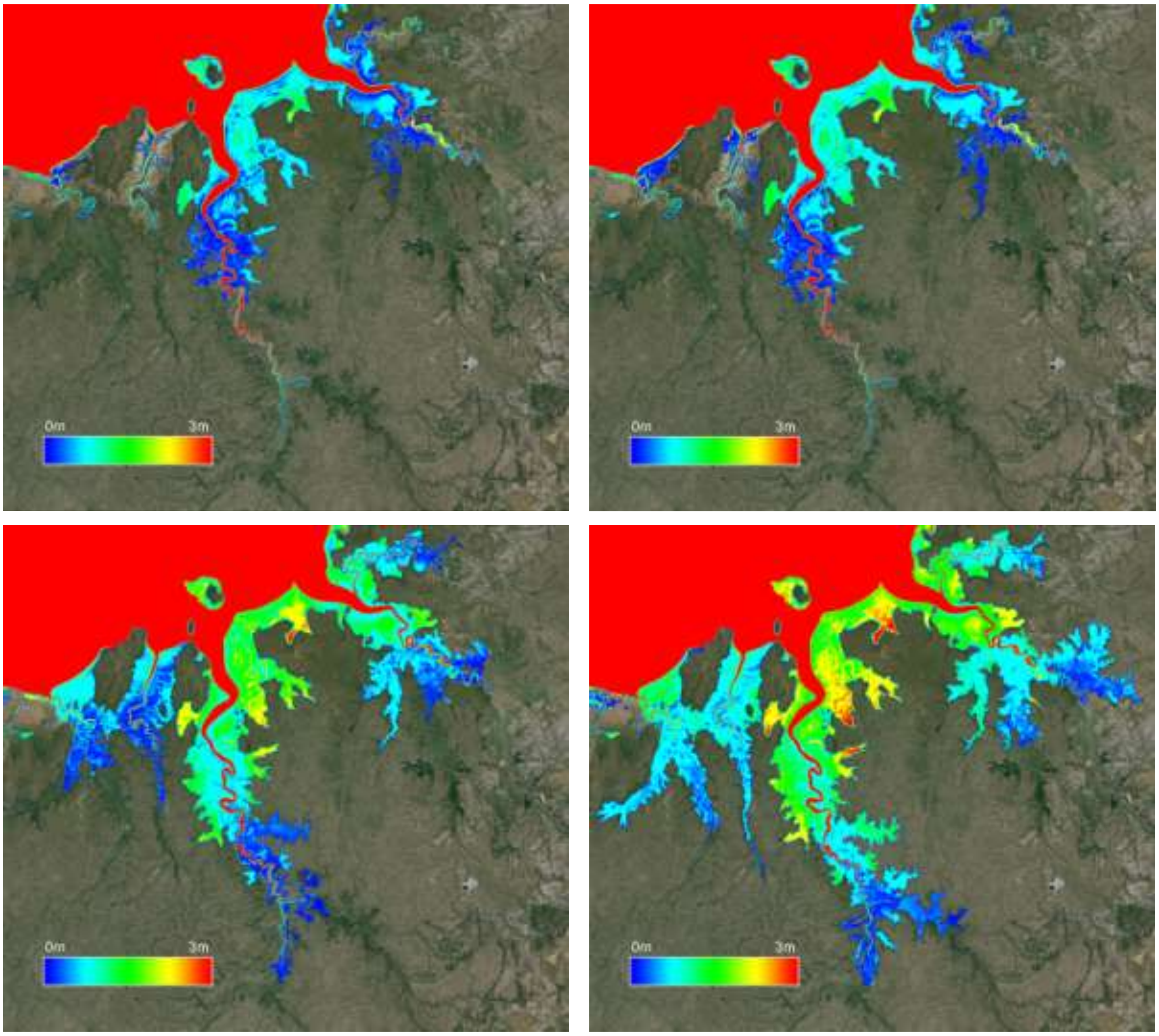

Figure 9 The maximum simulated tidal extents for the scenarios of current day, 2030, 2070 and 2100. The water is shaded by depth with red of depth 5m or greater and dark blue at depth 0 m.

From the results in Figure 9, the timescale that case study areas will become vulnerable to sea level rise was determined. Boggy Plain is at risk of saline inundation for a sea level rise of between 0.14 m and 0.70 m. Rises of 0.70 m and above see classification of the entire area as vulnerable. Magela Creek floodplain is similar, experiencing vulnerability to saline inundation for a sea level rise between 0.14 m and 0.70 m. A rise of between 0.70 m and 1.10 m sees the entire Magela floodplain becoming saline inundated. The tidal reach of the South Alligator River noticeably extends inland for a rise 0.70 m effecting Yellow Water. For the 1.10 m sea level rise prediction, the South Alligator Rivers tidal reach also widens at the inland tip.

The area and percentage of floodplain tidally inundated for all four scenarios is given in Table 2. A figure of 2960 km^2 was used for the total area of the Kakadu floodplain (Finlayson et al., 2006). We also estimate this figure for the floodplain from land elevations of the input DEM between of 0 m and 4.5 m AHD. For 2030, the percentage of the floodplain predicted as inundated is 41%; an increase of 14 % in the intertidal zone as compared with the current day scenario. For 2070, the percentage of inundated floodplain increases to 68%. By 2100 and a sea level rise of 1.10 m, almost the entire floodplain is predicted as vulnerable, with a percentage of 87%.

Table 2 The area and percentage of the floodplain predicted as tidally inundated for current day, 2030, 2070 and 2100.

Floodplain	Floodplain (km^2)	Current Day (0.00 m)	2030 (+0.14 m)	2070 (+0.70 m)	2100 (+1.10 m)
Whole Park (hx 60m Darwin)	2960	1059	1209	2013	2576
% Floodplain Inundation		36%	41%	68%	87%
% Increase on 0.00 m			14%	89%	142%

It is suspected that the extent of coastal inundation is a slight overestimate for the South and East Alligator Rivers. This can be inferred from vegetation growth as seen in satellite imagery for the current day scenario. The cause is suspected differences in the range of the Darwin tidal gauge as compared with the actual tidal range in the South and East Alligator Rivers. Due to insufficient tidal data however the Darwin gauge was the only suitable tidal information available for these areas. We have more confidence in the upstream measurements as they appear to be in closer agreement to the range measured at the South Alligator River gauge, G8200041. The disparity between overestimation of inundation in the coast, versus accurate inundation upstream suggests that closer analysis of the flow behaviours in the river is needed. This type of analysis would only be possible with more data recordings in the river system.

5.3 Inundation Frequency and Average Inundation Extents

It is customary to present maximum extent maps when considering inundation; however measures of inundation frequency and average inundation help provide a more holistic picture. Through the use of the hydrodynamic modelling, opposed to a bathtub method, these measures are also accessible. Figure 10 depicts the inundation frequency for the four scenarios considered.

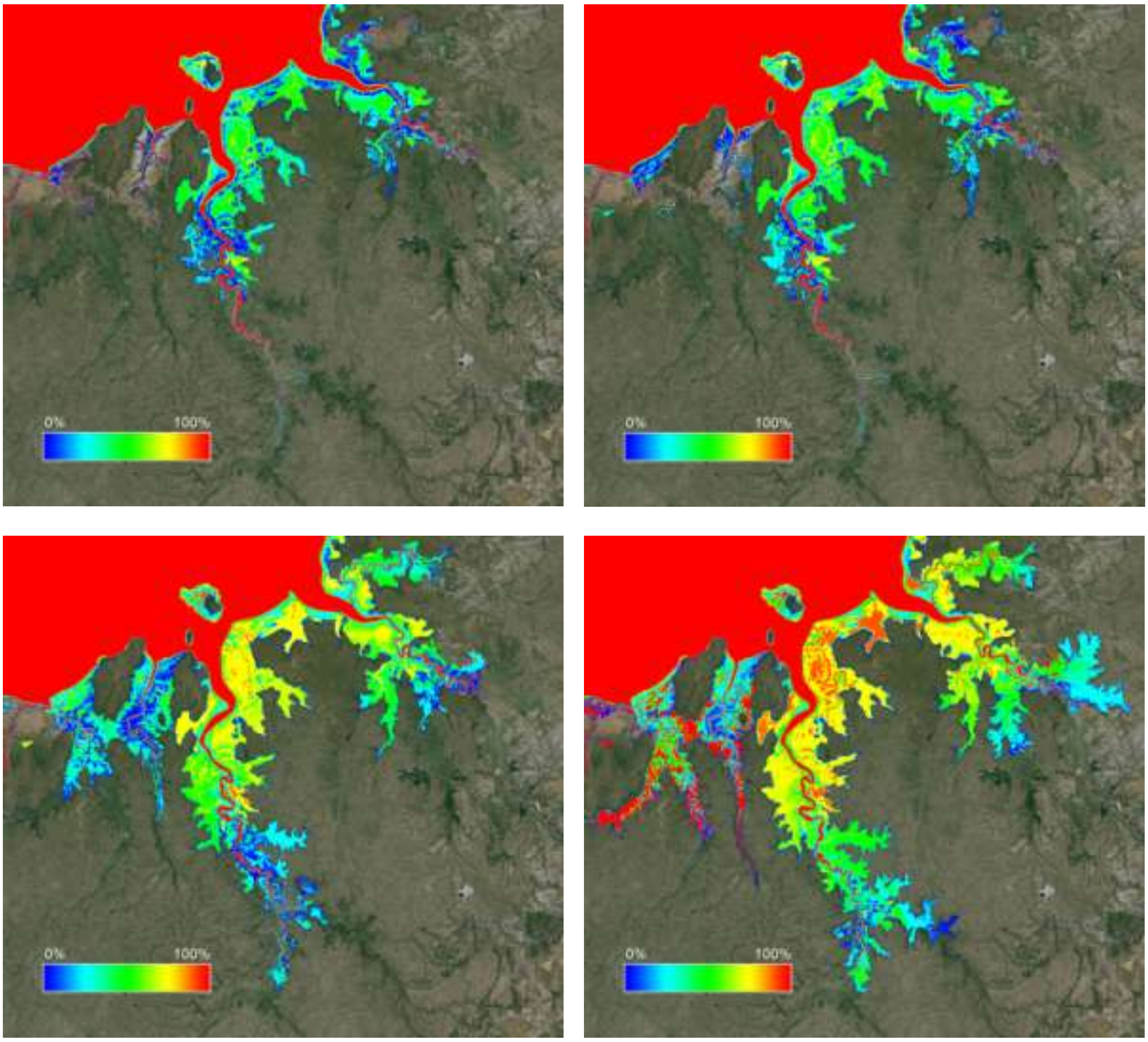

Figure 10 The frequency of inundation for the scenarios of current day, 2030, 2070 and 2100. The water is shaded as a percentage with red of depth 100% inundated or and dark blue 0% inundated.

The frequency of inundation in coastal areas changes from ~ 40 % in 2013, to ~70 % in 2070 and ~90% in 2100. We also see a change in the frequency of inundation experienced upstream. From Figure 10 it is also possible to identify the main flow channels and smaller tributaries. This is particularly apparent in the 2100 map given the greater variation in the colour scale. Areas of water pooling in the floodplain can also be seen. These may be areas where the later addition of evaporation influences may be needed. Also apparent is that there is a bank either side of the rivers which flow must overtop to enter the floodplain.

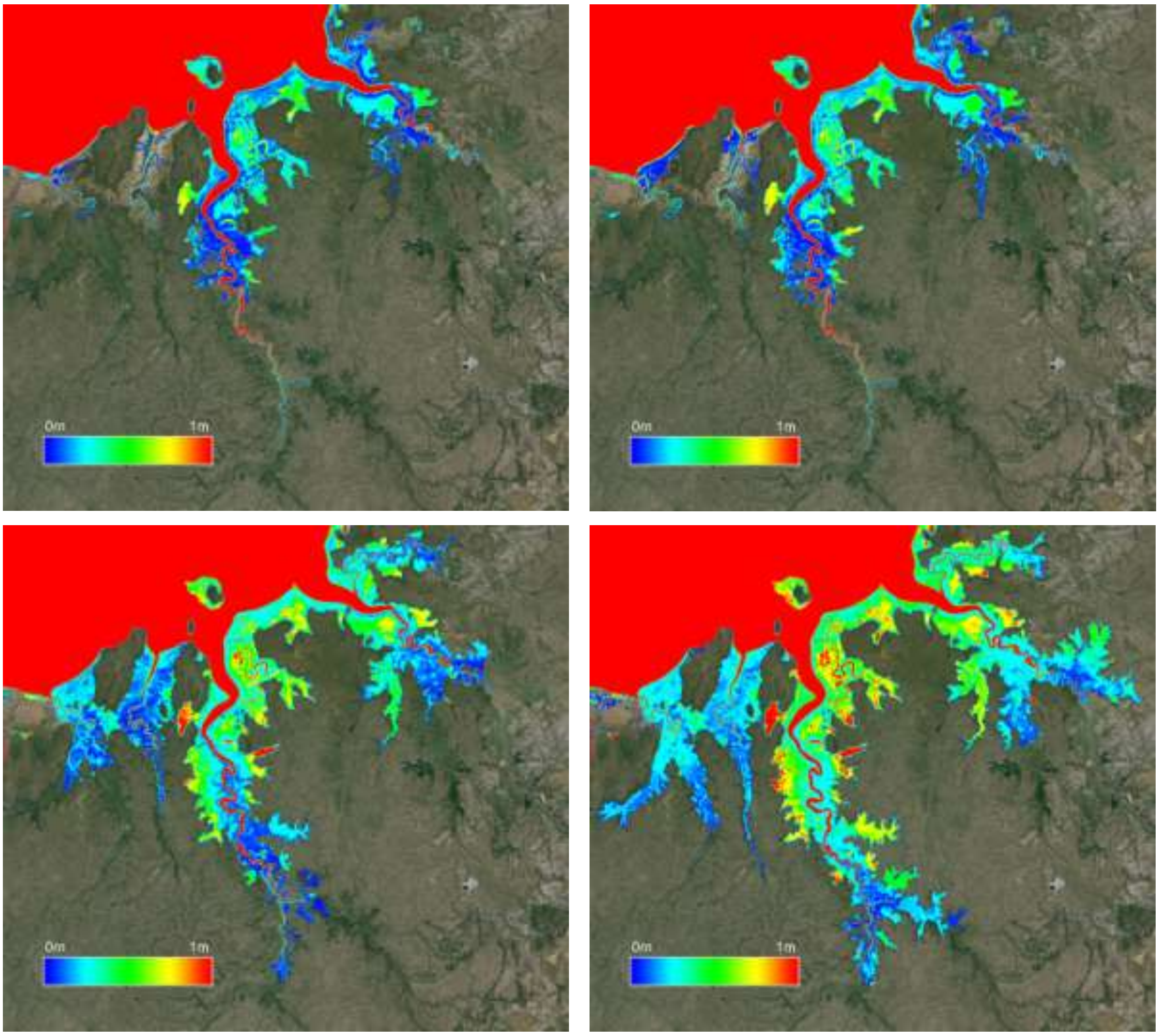

Figure 11 The average depth of inundation for the scenarios of current day, 2030, 2070 and 2100. The water is shaded by depth with red of depth 1m or greater and dark blue at depth 0 m.

When assessing an area vulnerable to saline inundation, for instance when vegetation is at risk of dieback, important aspects are depth and the period that saline water is present. The depths of average inundation portray a very different picture to those of maximum inundation. The colour scale used to present the Figure 11 average maps is from 0 – 1 m, whereas for the maximum maps in Figure 9 the scale is 0 – 3 m. In particular for 2013 we see that the average depth of inundation in the coastal areas is low, less than 0.40 cm. Maximum inundation extents therefore provide only part of the picture.

We note that the average and temporal maps also provide extra information about connectivity. For instance, there are areas that experience frequent inundation counter intuitively to the level of average inundation. The area of Boggy Plain for the 2070 scenario is one such example. Inundation is occurring only on some tides, but due to the one way connectivity of the area when the tide enters into Boggy Plain it cannot leave again. Therefore it must stay inundated during the simulation, hence why a high frequency and but low average inundation.

6 Discussion

Mangrove growth, which provides an indicator for area saline inundated by tide, provides a basis for evaluating frequently inundated tidal areas. The current day extent of mangrove growth has been recorded using stereo aerial photography (Mitchell et al., 2007). From these results we can state good agreement with our current day inundation predictions for East Field Island, West Alligator and Wildmann Rivers. We also note that despite over prediction in the South and East Alligator Rivers due to the use of a Darwin tide, areas experiencing a high frequency of inundation (Figure 10) share good agreement to the locations of mangrove vegetation.

It is difficult to compare the predicted floodplain inundation percentage with the other predictions reported in the literature. For 2030 and a sea level rise of +0.14 m, we predict 41% of the total floodplain to be inundated. By 2070 we predict a 68% loss of floodplain for a 0.70 m rise. In contrast, Bartolo et al. (2008) reports the figures 66% for coastal wetlands and 72% for freshwater areas, for a + 0.30 m rise on the same timescale. For the dry season by 2030 the forecasted temperature rise is predicted as 1 – 2 degrees (Bartolo et al., 2008). This makes our 2030 floodplain estimate comparable to a prediction of 50% for a 1 – 2 degree rise (Hare, 2005). By 2070 the temperature is expected to rise between 1 – 5.5 degrees (Bartolo et al., 2008). Our prediction that floodplain inundation risk is 87% by 2100 appears consistent with the prediction that the entire floodplain would be lost for a 2-3 degree rise (Hare, 2005). However total area figures for coastal wetland are inconsistent, the figure reported from Bayliss et al. (1997) is 1756 km^2 and from Bartolo et al. (2008), 2655 km^2. Finlayson et al. (2006) reports a figure of 2960 km^2 for the total floodplain whereas Eliot et al. (1999) reports 1950 km^2. As such, to accurately compare estimated percentages the method of inundation prediction, the land type and the area estimate of the land type need to be consistent. Regardless however, the predictions in sea level rise literature for both rise and timescale are inconsistent.

The freshwater billabongs in the South Alligator River identified as at risk of saline inundation (Figure 9) are in partial agreement to the results reported based on proximity to the river (BMT WBM, 2010), see Figure 4-6). For the freshwater areas at the far reach of the South Alligator we identify the timescale of saline risk between 2070 and 2100, suggesting a lower risk. However, (BMT WBM, 2010) suggests these areas are at high risk. In reality due to tidal creek expansion, these areas area at a higher risk, however there is not the scope to include geomorphologic changes in the modelling at present. The results agree that areas upstream from Yellow Water and at the far end of the Noulangie floodplain are of low risk to no risk. Boggy Plain is an area we predict as of saline risk between 2030 and 2070. From these results we would suggest this is a mid risk area, opposed to a low risk. Areas closer to the coast are subject to predictions of high risk in our modelling. This can be attributed to the tidal input from Darwin being of a higher tidal range causing an over prediction in these areas. Predictions of risk for the midstream after Boggy Plain share good agreement.

7 Model Limitations

7.1 Data Limitations

One of the biggest limitations to accurately modelling inundation from sea level rise is the scarcity of tidal and river gauges in the Kakadu region for model validation. This scarcity of gauge data can be partially attributed to the fact the population drivers behind water allocation planning and flood forecasting are not significant in the region. Also given the vast expanse of the park, gauge maintenance is difficult, expensive in terms of manual hours and requires transport to remote regions. For the available gauges, historical record is often over different years and of poor data provenance, presenting another obstacle to model validation. The limitations of existing data for modelling in the region have been long acknowledged in the literature; Eliot (2000) acknowledges insufficient tidal data in the Van Diemans Gulf, Bartolo et al. (2008) the inadequate existing hydrodynamic and hydrologic data and BMT WBM (2010) insufficient vertical accuracy of digital elevation data.

7.2 Model Exclusions

At some point, geomorphologic changes including sediment transfer will need to be coupled to the hydrodynamic modelling to accurately assess future inundation extents. However, study into geomorphology is a research area unto itself (Cobb et al., 2000, Winn et al., 2006). Accurate future prediction of geomorphologic changes; including rate of change, extent of change and sediment transfer, is extremely difficult. The problem is compounded by the regions data limitations. Inclusion of geomorphologic changes is therefore not within the scope of this research.

Groundwater hydrology will also need included with the hydrodynamic modelling at some stage in the future. Again this is a discipline unto itself and is difficulty given the lack of data in the region. However, the source of the rivers is tidal as opposed from upstream in the mountains or from an underground aquifer. This minimises the need for this component of the modelling.

Specific aspects that are yet to be included are soil infiltration and evaporation. At present the simulated timescale is not long enough to warrant these inclusions. However, these factors would be vitally important to water pooling on the floodplains when simulating yearlong timescales. We have scope to include soil infiltration through the introduction of a time controlled, negative sink map. Rates of evaporation too could be included. However, whilst both of these processes are conceivable to implement, insufficient data will make the process difficult.

7.3 Resolution Constraints

The balance between computational efficiency and resolution is a limiting factor to the simulations. A 1 m DEM of the Kakadu region is available; however the pre-processing, running the simulation and post-processing would be too computationally intensive and computationally expensive at this resolution. As this is a preliminary study into the hydrodynamics of the Kakadu region and the aim was to capture a series of subsequent tides, a 60 m DEM is sufficient. However, given the intricacy of connections between the small tidal creeks, there are drivers for a higher resolution than 60 m. Future work should consider a nested or discretised approach to the modelling in order to improve the accuracy in the areas needed, river and floodplain, and reduce the accuracy in areas of Van Diemen's Gulf and upper escarpment. However, to accurately model sub-areas at a high resolution sufficient hydrodynamic data for boundary enforcing would be required.

8 Future Directions

8.1 Field Studies

Moving forward with this project one of the essential aspects will be to conduct a field survey to improve model validation. The primary aim of the field survey will be to establish a sensor network to collect tidal, river height and river discharge measurements in regions of interest. The network should include three tidal sensors to capture tidal behaviour in the mouths of the South Alligator, East Alligator and West Alligator Rivers. Sensors should also be placed in close proximity to Boggy Plain, Magela Creek floodplain and Yellow Water in order to have the capacity to perform high resolution modelling in these areas. At present the data for these areas is not available or is of poor data provenance, such as the uncertainty of the gauge datum for G8200041 relative to AHD.

This sensor network might also include discretizing the South and East Alligator Rivers into stages, and sampling the terrain elevation, river elevation and discharge rate at these stages. The validation of model can then be improved by modelling the stages of the river before considering the whole system. At present, not being able to validate tidal behaviours in each of the main segments of the river is a barrier to achieving accurate inundation predictions.

8.2 Coupling Salinity and Hydrodynamic Modelling

One of the primary concerns due to an increase in sea level is the loss of vegetation through saline intrusion. A species already being monitored is the Melaleuca forest (paperbark forest). From a series of aerial photographs, Winn et al. (2006) reports a 64 % loss of the native Melaleca Forest due to an increase in floodplain extent and saline intrusion in the Point Farewell region. It follows that the future directions of this research include coupling a salinity model to the hydrodynamics to assess when the salinity will cause dieback of vegetation. The inclusion of salinity is also necessary to assess sea level rise impacts during the wet season, when freshwater from rainfall and saltwater from tide will alter the mechanism of saline ingress (Figure 2).

8.3 Incorporating Uncertainty

In this research we have aimed to better frame the discussion around how to present and interpret results of sea level rise inundation. We achieved this by moving the discussion from bathtub fill to a hydrodynamic model and by presenting the inundation maps not just in terms of maximum extent, but also average inundation and inundation frequency. However more can be done to incorporate the inherent uncertainty and natural variability of sea level rise predictions.

At present each of the modelled scenarios is a snapshot created using a set of deterministic inputs. However, natural variation occurs within the model inputs; including sea level fluctuations, tidal variability and rainfall variability. Future climate forecasts also predict; changes in rainfall intensity and increase in the intensity of tropical cyclones, potentially effecting the intensity of storm surges

(Bartolo et al., 2008). Therefore ideally to capture the true vulnerability of areas in KNP, multiple different scenarios should be simulated. An automatic measure of saline inundation risk should be created by combining the information of inundation frequency and average inundation. This measure can then be converted into a probability of inundation over all scenarios simulated. In this manner the vulnerability of an area can be expressed as probability thereby truly encapsulating the uncertainty and variability inherent within sea level rise modelling.

9 Conclusion

Hydrodynamic modelling was used to assess which areas of the Kakadu floodplain would be vulnerable to saline inundation from to sea level rise. Four scenarios were considered, no rise, 0.00m for current day, 0.14 m rise for 2030, 0.70 m rise for 2070 and 1.10 m rise for 2100. Good agreement was achieved for the current day scenario in areas of West Alligator River, Wildmann River and upstream in the South and East Alligator. Due to lack of sufficient gauge data, coastal inundation near the mouths of the South and East Alligator is a small over prediction.

From the results we find case site areas of Boggy Plain and Magela Creek vulnerable to a rise between 0.14 m and 0.70 m. We also find for a 1.10 m sea level rise approximately 90% of the floodplain is vulnerable.

Historically, assessment of floodplain vulnerability to sea level rise has been done using a bathtub fill. We show bathtub fills are inappropriate for inundation predictions in these low-lying floodplains. In using hydrodynamic modelling we also obtained outputs of average inundation and temporal inundation, opposed to just considering maximum extents.

In future work, it is desired to combine the average inundation and temporal inundation to create one measure of risk. This is necessary to provide a probabilistic estimate of vulnerability over multiple scenarios and will assist in representing the results relative to the inherent uncertainty within sea level rise processes. Other necessary future work is the coupling of salinity to the hydrodynamics to model wet season saline inundation vulnerability.

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