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Managing threats to floodplain biodiversity and cultural values on Kakadu National Park

Part I: Risks from sea level rise due to climate change

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Important disclaimer

Shortened forms

ArcMap	ESRI GIS software
ARR	Alligator Rivers Region
BestFit	Palisade distribution fitting software
BoM	Bureau of Meteorology
BoM	In Part II Kakadu Board of Management
BMT WBM	Engineering & environmental consulting firm
CSIRO	Commonwealth Scientific Industrial Research Organisation
EAR	East Alligator River
HCVAE99	High Conservation Value Aquatic Ecosystems at the 99th percentile
IPCC	International Panel Climate Change
IPCC4	IPCCs' 4th Assessment
Kakadu	Kakadu National Park
KNP	Kakadu National Park
LiDAR	Light Detection and Ranging (remote sensing method)
NERP	National Environmental Research Program
NT	Northern Territory
QERA	Quantitative Ecological Risk Assessment
QuickBird	High resolution satellite data capture
SAR	South Alligator River
SLR	Sea Level Rise
SWI	Saltwater inundation
TO	Traditional Owner
TRaCK	Tropical Rivers and Coastal Knowledge (CERF Hub)
WV2	WorldView2 (high resolution satellite data capture)
WR	Western Rivers

Contents

Figures

Tables

Acknowledgments

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We are very grateful to the Traditional Owners of Kakadu National Park and parks staff for their continuous support, participation and enthusiasm throughout the project. In particular we thank Peter Christophersen, Sandra McGregor, Violet Lawson and Victor Cooper (Kakadu Traditional Owners), and Anne O’Dea, Steve Winderlich and Gabrielle O'Loughlin (parks staff). Lastly we thank NERP scientists from a range of institutions who worked on Kakadu and contributed many ideas and encouragement throughout, too many to name here.

Executive summary (Parts I & II)

1. Kakadu National Park is a World Heritage icon famous for its natural and cultural values, particularly its coastal floodplains encompassing Ramsar-listed freshwater wetlands. These floodplains are highly vulnerable to climate change induced sea level rise (SLR) because they are low-lying, a risk that will exacerbate with increases in extreme weather events such as storm surges and flooding.
2. The overall aim of this component of the NERP Floodplains study is to contribute new knowledge to support the management of risks to natural and cultural values from future saltwater intrusion due to climate change-induced sea level rise.
3. Part I of this report assesses the potential biodiversity impacts of three future climate change-SLR scenarios (2030 0.14m; 2070 0.70m; & 2100 1.1m) on a selection of key plant and animal indicator species, in particular the iconic Magpie Goose and their seasonal habitats. These species are important bush tucker for local Indigenous people and so have high cultural value.
4. Part II of this report undertakes an integrated assessment of socio-ecological and cultural aspects of potential SLR impacts, and draws on the outcomes of a series of participatory workshops and interviews with both Traditional Owner and park staff to elicit floodplain values and management options such as adaptation responses. Yellow Water is used as a case study because its location beyond the tidal reach in the South Alligator River system suggests that its wetlands will likely be the main freshwater refuge from the future effects of saltwater inundation, as confirmed in Part I of this study.

Technical summary (Part I)

Modelling SLR and saltwater inundation

1. A hydrodynamic model was developed to map the frequency and extent of saltwater inundation (SWI) in the Alligator Rivers Region (ARR) for the following three climate change induced Sea Level Rise (SLR) scenarios: Present-day (2013); 0.14m (2030); 0.70m (2070) and 1.1m (2100). These represent scenarios 17y, 57y and 87y in the future, respectively.
2. The model is essentially a “Bath Tub” type SLR model driven dynamically by dry season October tides and projected increases in mean SLR. Model outputs were derived for a high resolution 60m grid across all floodplains in the ARR, and comprised mean water depth (m), mean and maximum extent and frequency of SWI (%F) over the tidal range. Outputs were used in all consultations with stakeholders to visualise and communicate SLR risks and used in all assessments reported here.
3. A more complex hydrodynamic model was also developed that couples a rainfall-runoff sub-model to a tidal sub-model for the Present-day and 2070 SLR scenarios only, allowing the effects of a wet season storm surge and heavy rainfall event to be simulated. Model outputs were derived for the same 60m grid across the ARR floodplains and included both dry (October 2012) and wet (March 2013) season simulations. Outputs included a range of parameters for salinity (ppt), water depth (m), and the extent and frequency of SWI. The storm surge model is currently under internal review and results are not reported here. This work was commissioned by CSIRO in a non-NERP project but is complimentary to the results reported here. Hence, all outputs will be made publically available subject to journal publication.

Proportion of floodplains lost to SLR

4. Assessments of potential SLR impacts on floodplains and associated biodiversity indicators were undertaken at a park-wide scale and for the following three case study areas given the expected differential impact across the park dependent on tidal influence and topography: Boggy Plain and Yellow Water wetland in the middle and upper reaches of the South Alligator River, respectively; and Magela Creek floodplain, a tributary of the East Alligator River.
5. The predicted proportion of floodplain lost to SLR on Kakadu between the Present-day and 2030 scenarios is imperceptible at 3%; hence, no detailed assessments are made for 2030. In contrast, a threshold apparently exists between 2030 and 2070 when the predicted proportion of floodplains lost to SWI substantially increases. The SLR rise model predicts that by 2070 60% of freshwater floodplains on the park will be lost to SWI, and that for 2100 78%. Base on this rate of loss (using IPCC4 climate change projections) all freshwater floodplains on Kakadu will be inundated by saltwater by 2132, 117y from now. This prediction timeframe could be accelerated if future SLR projections show acceleration due to ice global sheets melting.
6. The predicted proportion of floodplain lost to SWI varied by site related to the degree of tidal influence, with Boggy Plain, Magela Creek floodplain and Yellow Water wetland losing 77%, 26% and 23% respectively by 2070, and 84%, 55% and 42% respectively by 2100.

SLR impacts on floodplain biodiversity & bush tucker values

7. The distribution and abundance (numbers/km^2) of all Magpie Goose aerial survey observations in the ARR in the dry season (1981-2003), and that for their nests in the wet season (1984-2000), were mapped to identify “Hotspots” or “Density Clusters” of habitat use on the Park that encompassed decadal-scale variations in environmental conditions.

8. The distribution of Magpie Goose dry season Hotspots over 22 y co-occurred with the combined distribution of *Eleocharis sphacelata and E. dulcis*, two tall sedge species that geese depend on for both nesting material and food, respectively.
9. The frequency and extent of tidal SWI in the dry season for the Present-day (2013, 0m) and 2030 (0.14m) SLR scenarios showed little difference between the two (+3% increase) and, hence, the 2030 SLR scenario was not considered further in assessments.
10. The predicted proportions of Magpie Goose seasonal Hotspots lost to SWI in the 2070 SLR scenario were substantial (57% & 75% for dry & wet season, respectively). The upstream areas that were not inundated with saltwater are identified as potential refuge areas for nesting and dry season feeding/roosting at the 2070 time frame.
11. In contrast, most seasonal Hotspots were lost to SWI at the 2100 SLR scenario (90% & 97% for dry and wet seasons, respectively). The small numbers of upstream areas that showed no SWI are identified as refuge areas for nesting and dry season feeding/roosting at the 2100 time frame.
12. Similarly results were obtained for floodplain vegetation classes mapped in 1990. For example, 75% and 85% of *E. sphacelata* and *E. dulcis* are predicted to be lost to SWI in 2100, respectively. And that for Wild Rice and all Water Lilies combined, 81% and 89% respectively.
13. The presence-absence distributions of Long-necked Turtles (*Chelodina rugosa*), Pig-nose Turtles (*Carettochelys insculpta*) and Black Bream (*Hephaestus fuliginosus*) on Kakadu sub-catchments reflecting suitable habitat were mapped to assess the degree of overlap with SWI at the 2070 and 2100 SLR scenarios and, similarly for High Conservation Value Aquatic Ecosystems (HCVAE99). The predicted proportion of all these freshwater bush tucker and biodiversity assets lost to SWI was small, ranging between 0.3% and 5.0% across both SLR scenarios, reflecting the fact that they are not confined to floodplain habitats.

Salinity tolerances of floodplain plants

14. Freshwater plants are absent in areas where the mean frequency of SWI in the dry season is ~22% or greater (using Stage 1 model). In contrast, the mean frequency of SWI where saline habitats occur is ~22% or less, possibly marking the approximate boundary between saline and freshwater habitats.
15. A literature review was undertaken of the salinity tolerances of plants that occur on Kakadu floodplains and an ecotoxicological effects model fitted to the range of data (i.e. a Species Sensitivity Distribution-SSD) for more detailed risk assessment given predicted salinity exposures in case study areas for different SLR scenarios. The SSD data to salt toxicity is best characterised by a Log Logistic model. Literature values ranged between 0.0009ppt (*Alysicarpus vaginalis*) to 37.25ppt (*Cressa cretica*), with most freshwater aquatic and riparian plants having values in the range 0-2.0ppt.
16. The linear relationship between mean salinity derived by independent hydrodynamic modeling of Magela Creek floodplain and the frequency of SWI (%P) derived by Stage 1 hydrodynamic modeling was statistically significant (R^2=42%, n=434, P<0.0001) across a high spatial resolution grid (50m). The regression equation predicts that when the frequency of SWI (%P) is zero in the dry season salinity is ~ 2ppt, approximating the salinity tolerance for freshwater plants found in our literature review and the boundary between the presence and absence of saline habitats.
17. Vegetation on Magela Creek floodplain exhibited similar gradient relationships between water depth and salinity as that found for wetlands around Darwin Harbour by Cowie (2003). Emergent macrophytes preferred deep water and salinities < 1ppt apart from *Eleocharis dulcis,* which also preferred deep water but with higher salinity (~2.8ppt). A similar water depth-salinity relationship was found for plants on Boggy Plain but not for Yellow Water that currently only

experiences infrequent saltwater flushes from King High tides. Regression Tree (or Random Forest) models will be used with Stage 2 SLR model salinity outputs for the 2070 SLR scenario across a 60m grid to predict what type of floodplain vegetation is likely to occur there.

18. The salinity profile of Boggy Plain during a King High tide in November 2012 was compared to the salinity profile for a 0.7m SLR (2070 scenario) that was estimated using the local calibration method developed by Dutra et al. (2013). The saltwater flush from a King High tide extended to the boundary of possibly the largest stand of water chestnut (*Eleocharis dulcis*) in the NT and a major feeding ground of Magpie Geese in the dry late dry season (home to 70- 80% of the NT population). The bulbs of *E. dulcis* are a preferred dry season food for geese and the western boundary of this stand marks the transition between saline flats and freshwater swamp, with a sudden 1m increase in water depth (Bayliss pers. obs.).
19. The Species Sensitivity Distribution (SSD) function of wetland plants on Boggy Plain to salinity concentration (effects) were combined with the predicted salinity exposures for 2012 and 2070 to undertake a Quantitative Ecological Risk Assessment (ERA) for SLR. The 2070 salinity exposure curve completely overtops the salinity effects curve giving an overall risk probability of 1.0 (or 100%). Therefore, just using the proportion of Boggy Plain inundated by saltwater in 2070 (84%) underestimates the risk from SLR because it does not account for the proportion of saline habitats and associated plants with higher salt tolerances.

Integrated assessment of multiple risks over different time frames

20. Large areas of Magpie Goose nesting habitat (Hotspot-colonies) on the Wildman River floodplain, the west bank of the South Alligator River floodplain, and the northern section of Magela Creek floodplain, are currently all relatively free from the risk of pig damage. In contrast, large areas of dry season feeding habitat comprising extensive stands of *E. dulcis* are at high risk from pig damage, an unsurprising result given that they also consume large quantities *E. dulcis* bulbs in the late dry season as water levels recede.
21. All Magpie Goose dry season feeding/roosting habitats (Hotspots) are not at immediate risk from Para Grass, particularly on the South Alligator River floodplain. Similarly, there is little interaction between goose nesting Hotspots in the western rivers and along the South Alligator River floodplain corridor. In contrast, goose nesting Hotspots on the Magela floodplain are at very high risk from Para Grass.
22. The intersections between saltwater inundation and both goose seasonal Hotspots are extensive, with small remnant refuge areas identified in the upper reaches of all floodplains. These visual assessments highlight areas where reversible invasive species management actions can be implemented for net conservation benefit (i.e. not a "sunk cost due to SLR), although they may currently be considered too costly in present day terms because SLR impacts have not manifest.
23. The integrated assessment indicates also that intensive pig control is required in the few remnant areas of goose dry season sites, and that for nesting sites the extensive patch of Para Grass on the central Magela floodplain should now be seriously considered for active controlled and perhaps rehabilitation through re-vegetation of native wetland plants. Without considering the future impact of SLR, the cost of controlling this weed patch in present day terms may be viewed as cost prohibitive.
24. However, in terms of avoiding sunk costs, the 2100 SLR scenario needs to be considered also as most floodplains on Kakadu are predicted to be lost to SWI. Nevertheless, a mitigating factor in considering this worst case scenario is that we could not model and hence predict the creation of new freshwater floodplain habitat as the sea pushes further inland over time. The high resolution LiDAR DEM is constrained in that it hugs the current floodplain boundary. We

therefore recommend that this additional terrain modeling be undertaken as a high priority to better evaluate future mitigation and adaptive management options.

Recommendations

1. That the package of Decision Support Tools developed for the SLR component of the project be continually updated and improved with new knowledge and data in order to enhance risk assessments and reduce uncertainties. Specifically these are: (i) the Stage 2 saltwater inundation model; and (ii) the Google Earth software tool used to visualize and communicate risks during consultations.
2. The integrated assessment framework developed as a proof on concept model on selected threats and biodiversity assets should be extended to encompass all multiple risks to multiple floodplain assets and incorporated into a Bayesian Belief Network (BBN) to capture uncertainties and interactions. This BBN should also include key social and cultural aspects of decision making (see Part II).
3. In relation to 1 above, that a network of inexpensive tidal gauge/water depth recorders be established on all major rivers and floodplains across the park, and should include inexpensive data loggers that continuously record salinity and other water quality variables. ERISS has the expertise and capacity to implement and manage this network.
4. That dedicated systematic monitoring programs of floodplain threats and assets be developed and implemented to replace the *ad hoc* opportunistic nature of previous surveys. For example: helicopter weed surveys (including native vegetation); fixed wing aerial surveys for waterbirds and feral animals; and use of satellite remote sensing captures to monitor fire scars, vegetation and hydrological conditions on floodplains. Other biodiversity and cultural indicator species also need to be identified for future monitoring purposes. These programs should be managed jointly with Kakadu Traditional Owners and will require targeted training programs.
5. That additional terrain modeling is undertaken as a high priority to better evaluate future mitigation and adaptive management options. There is currently no high resolution LiDAR DEM coverage of adjacent non-floodplain areas across the park, needed to model and predict the creation of new freshwater wetlands as the sea pushes further inland over time. This is a major gap in knowledge that constrains all the assessments presented here to adopt a worst case scenario outlook. Given the costs this additional coverage should only focus in areas identified as having high management priority.
6. That detailed ecotoxicological studies of the salt toxicities of a range of freshwater plants that occur on Kakadu wetlands be initiated, including laboratory, mesocosm and field studies. ERISS has the expertise and capacity to undertake this research. Nearly all of the laboratory and field studies on the salt toxicity of wetland plants were undertaken for species in temperate environments in Southern Australia, or overseas.

Part I Risk from sea level rise due to climate change

1 Introduction

Climate change induced sea level rise (SLR) is recognized as a major threat to low-lying coastal areas worldwide because of the concentration of populations and their assets along the coasts (Nichols 2011; Nicholls and Cazenave 2010; Nicholls et al. 2007a). Additionally, the effects of an increasing mean SLR will be exacerbated by increases in extreme weather events and associated storm surges and flooding. Nicholls (2007b) estimated that about 20 million people globally live below mean high tide levels, with over 200 million people vulnerable to flooding during extreme storm events. Nationally, southern Australia has the concentration of people and infrastructure most at risk from SLR and, in contrast, remote and relatively undeveloped northern Australia has high value natural and cultural assets at high risk (Bayliss et al. 2013). For example, Kakadu National Park is a World Heritage site with internationally significant Ramsar-listed wetlands and is an Australian icon famous for its natural and cultural values (Press et al. 1995), particularly its low-lying freshwater floodplains that are highly vulnerable to SLR and concomitant saltwater inundation (CSIRO & BoM 2007; Bartolo et al. 2008, 2012; Boustead 2009; Director of Parks 2010; BMT WBM 2010b; Bayliss et al. 2011, 2012), which will be exacerbated by changes in the intensity of extreme weather events such storm surges and flooding associated with cyclones (IPCC 2012; BMT WBM 2009; BoM 2013; CSIRO 2013).

Nevertheless, the major current threats to Kakadu floodplains are invasive species, particularly feral pigs (*Sus scrofa;* Bayliss & Walden 2004) and aquatic weeds (Setterfield et al. 2014, McMaster et al. 2014) such as the woody mimosa shrub (*Mimosa pigra*), floating salvinia fern (*Salvinia molesta*), para grass (*Urochloa mutica*) and olive hymenachne (*Hymenachne amplexicaulis*). Floodplain habitats support much of Kakadu's biodiversity and tourism values (Boustead 2009; Tremblay 2006) and provide significant bush tucker food and other cultural resources for resident Indigenous communities, and these all at risk from the current impacts of invasive species and future saltwater inundation (SWI) from SLR (Tremblay 2010; Bayliss et al. 2012).

The NERP 3.2 Kakadu Floodplains project encompasses four linked but discrete sub-projects.

1. Indigenous values of floodplains
2. Invasive aquatic grass management
3. Risks from sea level rise due to climate change
4. Assessment of management options for multiple threats

The main aim of sub-projects 1-3 is to contribute new knowledge to support the management of threats to natural and cultural values of floodplains from saltwater intrusion and aquatic weeds (sub-projects 2 & 3, respectively). The key question of sub-project 3 is "what are the potential impacts of climate change induced SLR on floodplain biodiversity and Indigenous cultural resources (bush tucker)?" Part I of this report addresses biodiversity through a selection of key plant and animal indicator species such as the iconic Magpie Goose (*Anseranus semipalmata*) and their seasonal wetland habitats. However, our indicator species for biodiversity also provide high value bush tucker for local Indigenous people. Part II of this report assesses socio-ecological and cultural aspects of the impacts of SLR, and summarises outcomes of the participatory workshops and interviews used to elicit the small range of management options, in particular adaptation responses.

2 Methods

2.1 Modelling Sea Level Rise (SLR)

There are three broad landscapes that characterise World Heritage Kakadu National park: Floodplains; Lowlands; and Sandstone Escarpment (Fig. 1a). Of these the low-lying coastal floodplains are most at risk from future climate change because of projected Sea Level Rise (SLR) and the concomitant saltwater inundation (SWI) of extensive areas of high conservation value freshwater wetlands (Bartolo et al. 2008; Department of Climate Change 2009; Director of Parks 2010; BMT WBM 2010a&b; Traill 2010; Bayliss et al. 2011, 2012). Bartolo et al. (2008) used coarse GIS analysis to estimate that at least 60% of Kakadu's wetlands could be lost over the next 50 years given IPCC4 (2007) projections. The hydrodynamic modelling study by BMT WBM (2010a) into the vulnerability of the South Alligator River floodplains to projected SLR by 2030 and 2070 (IPCC 2007) also indicated similar levels of high risk to low-lying coastal wetlands. Nevertheless, both studies were constrained by lack of a sub-meter high resolution Digital Elevation Model (DEM). The Shuttle Radar Topography Mission (SRTM) dataset (flown in 2000), enhanced by Geoscience Australia and used by BMT WBM (2010a), had a vertical accuracy of $\pm$ 3 - 5m although levels were given in interpolated increments of 1m. The SRTM DEM was assessed by BMT WBM as being unsuitable for SLR modelling in the ARR given that most of its floodplain have levels that fall 1-2m in a 100km or more. Since then, however, high spatial and vertical resolution LiDAR coverage has been obtained over all ARR floodplains (Kakadu LiDAR Project 2011) and this data underpins our risk modelling of SWI.

Whilst Kakadu is a well-researched park with respect to biophysical values and processes, particularly Magela Creek floodplain downstream of Ranger Uranium Mine (see Bayliss et al. 2012), there remain key knowledge and data gaps for much of its floodplains. Hence, our assessment adopts the following two scales in order to utilise historical data on some wetlands and limited data on others: (i) Whole of Kakadu National Park (& itself nested within the broader Alligator Rivers Region (ARR)); and (ii) for three case study areas that have existing data on floodplain vegetation and waterbird use, particularly for the iconic Magpie Goose (*Anseranas semipalmata*). These are: Boggy Plain; Yellow Water; and Magela Creek floodplain (Fig. 1b). These wetlands are listed as Ramsar sites in their own right and all lie on a north-south salinity gradient dependent on tidal influence or roughly distance from the coast. The ARR encompasses the Wildman (WR) and West Alligator (WAR) rivers to the west, and the South Alligator (SAR) and East Alligator (EAR) rivers to the east with the EAR including the Magela Creek system. Whist the eastern boundary of KNP follows the EAR and artificially dissects its floodplain, they are included in our SLR impact assessments given that our key ecological indictor is the highly mobile Magpie Goose (Frith & Davies 1961; Franklin 2008; Whitehead et al. 1992; Traill et al. 2010).

A literature review of climate change scenarios for the Kakadu project was undertaken by Dutra and Bayliss (2013) at the start of the project (drawing on Church 2008, Church & White 2011, Church et al. 2011), and SLR projections for the Present (2012 & 2013 baselines), 2030, 2070 and 2100 are summarised in Table 1. A conceptual model of climatic and hydrodynamic processes showing key links and interactions between tides, rainfall and runoff-stream flow is provide by Dutra et al. (2013), Saunders et al. (2014) and Hilton et al. (2014).

Table 1. Summary of climate change induced Sea Level Rise (SLR) scenarios and projections used in all saltwater inundation modelling (see Dutra & Bayliss 2013; Table 1 in Dutra et al. 2013).

Scenario	Present (2013)	2030	2070	2100
Years from 2013	0	17	57	87
SLR (m)	0	0.14	0.70	1.1
Rainfall	Current	No change	No change	No change

Of necessity the SLR hydrodynamic modelling was staged in two sequential parts in order to produce first pass Salt Water Inundation (SWI) maps so that engagement with Parks staff and Kakadu Traditional Owners (TOs) could commence on potential impacts and management responses/options over different scenario time frames. These were:

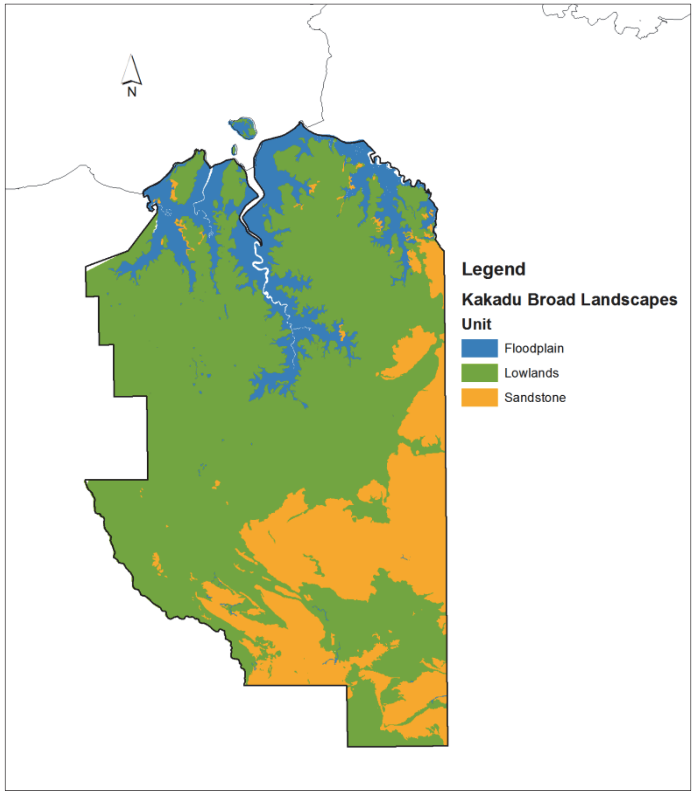
1. *Stage 1:* A dry season "Bath Tub" model driven dynamically by tides and projected increases in mean sea level for each scenario (see Saunders et al. 2014 for details). Model outputs for each 60m grid cell on floodplains in the ARR are mean water depth (m), maximum extent and the frequency of SWI using October 2013 tides as the representative dry season tide (Table 2, Saunders et al. 2014).
2. *Stage 2:* A more complex hydrodynamic model that couples a rainfall-runoff sub-model to a tidal sub-model for the Present and 2070 SLR scenarios only (Stage 1 results show no major difference between the Present and 2030 scenarios). Model outputs for each 60m grid cell on floodplains in the ARR are for the dry (October) and wet (March) seasons, and for the wet season are with and without a storm surge (Table 2, Hilton et al. 2014). This was a non-NERP project funded internally by CSIRO and results will be made available to NERP researchers when appropriately reviewed.

Both stages of SLR modelling needed significantly more resourcing by CSIRO above our NERP co-investment, requiring the coastal modelling team to re-schedule other work flow over a longer time period to accommodate the extra load. The Stage1 modelling phase has strong links with NERP Project 3.4 (Hydrodynamic, sediment transport & water quality models in estuarine & coastal environments of the ARR: assessing climate change impacts) and involved one cross-project workshop in Darwin in the early stages (Appendix C, Table 7) to develop a conceptual model for the ARR, and a series of following meetings to share calibration data. Current plans are to publish SLR modelling results jointly.

An example of Stage 1 SWI model outputs is illustrated in Figure 2, which compares the Present day (Oct, 2013) maximum extent of SWI on Kakadu with that for a projected 0.7m SLR in 2070 (Saunders et al. 2014). The results of Stage 2 SWI outputs are currently under internal review and will be made publically available on completion of both the internal review process and a review process for journal publication (anticipated in late May).

Dutra and Bayliss (2013) developed an empirical (as c.f. process) SWI model to derive water depth and salinity values for each SLR scenario using local calibration data. This rapid and potentially cost-effective assessment method was applied to 60m grids in the Boggy Plain and Yellow Water case study areas (see section 3.3).

(a)



(b)

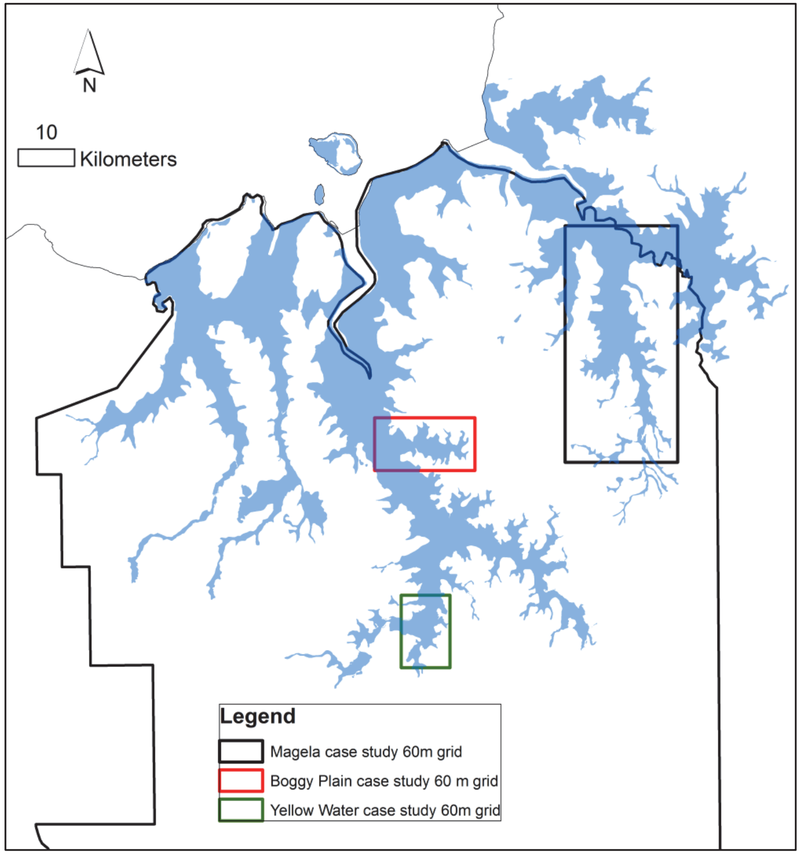


Figure 1a&b. (a) Broad landscapes on Kakadu National Park (Floodplains, Lowland woodland & sandstone escarpment; Parks GIS data). (b) Three case study areas on Kakadu for more detailed assessments (see text).

Table 2. Summary of Stage 1 and 2 Salt Water Inundation modelling outputs produced by the CSIRO coastal modelling team (Saunders et al. 2014 & Hilton et al. 2014).

Stage	Season	Month	Simulation variable	Scenario Year			
				Present	2030	2070	2100
Stage 1	Dry	Oct. 2013	Maximum extent	X	X	X	X
	Dry	Oct. 2013	Inundation frequency (%)	X	X	X	X
	Dry	Oct. 2013	Mean water depth (m)	X	X	X	X
Stage 2	Dry	Oct. 2012	Maximum extent	X		X	
			Inundation frequency (%)	X		X	
			Mean water depth (m)	X		X	
			Mean salinity (ppt)	X		X	
			Median salinity (ppt)	X		X	
			Minimum salinity (ppt)	X		X	
			Maximum salinity (ppt)	X		X	
			Frequency of inundation > 2pp salinity	x		X	
Stage 2	Wet*	Mar 2013	Maximum extent with & without a storm surge	X		X	
			Inundation frequency (%) with & with a storm surge	X		X	
			Mean water depth (m) with & without a storm surge	X		X	
			Minimum salinity (ppt) with & without a storm surge	X		X	
			Maximum salinity (ppt) with & without a storm surge	X		X	
			Mean salinity (ppt) with & without a storm surge	X		X	
			Median salinity (ppt) with & without a storm surge	X		X	
			Freq of inundation>2pp salinity (with & without SS)	X		X	

* All wet season combinations of SWI frequencies were simulated with three water depth floors to aid visualisation of salinity maps (1mm, 1cm & 10cm; Hilton et al. 2014).

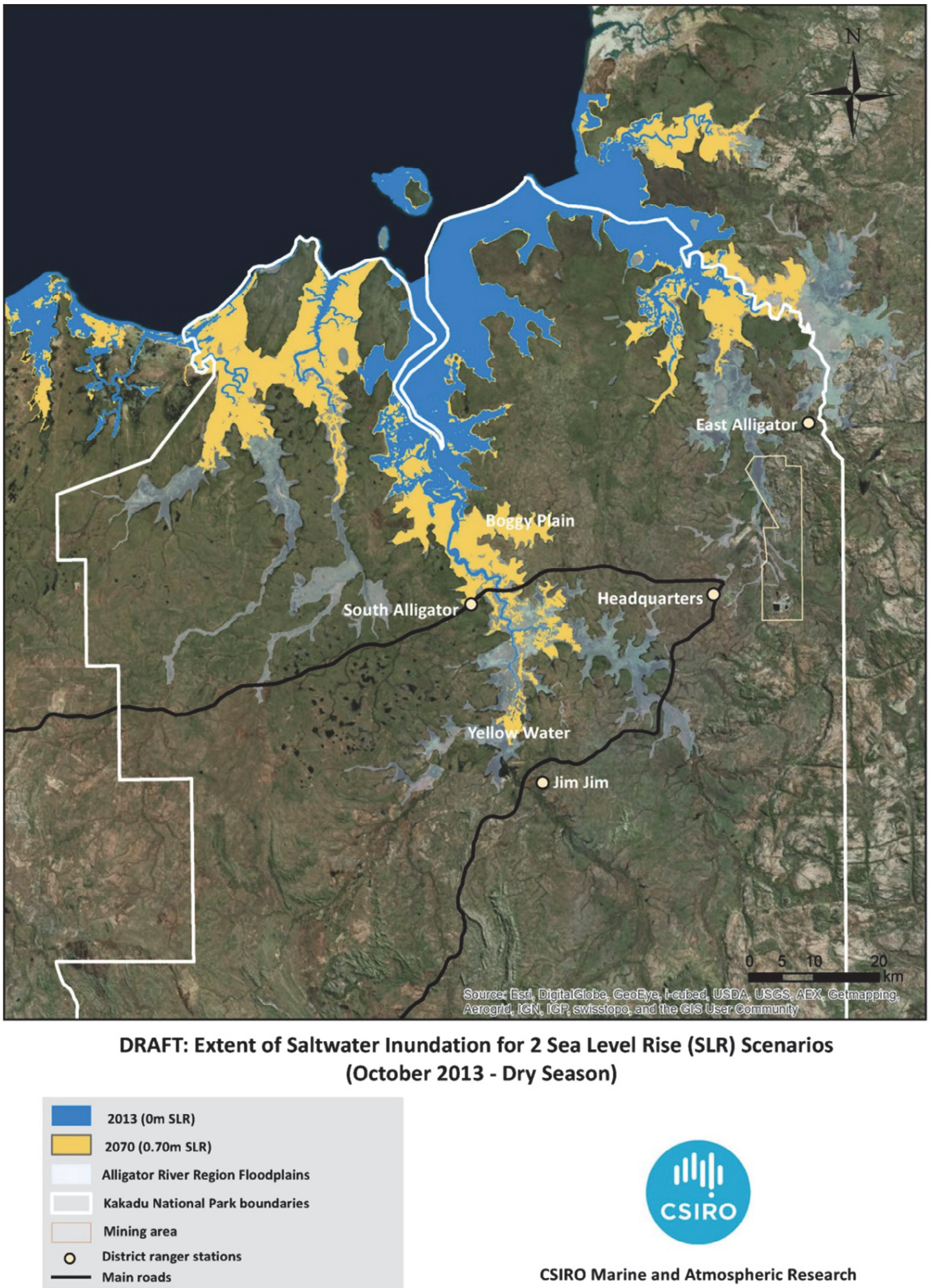


Figure 2. Comparison of the Present day (Oct. 2013) extent of saltwater Inundation on Kakadu National park with a projected 0.7m Sea Level Rise (Scenario in 2070) using the Stage 1 model (Saunders et al. 2014).

2.2 Seasonal distribution and abundance of Magpie Geese

Long-term aerial survey data (1981 to 2003)

The seasonal distribution and abundance of Magpie Geese and their nests in the ARR were derived from long-term historical data sets (1981-2003; n=22y) where observations were made systematically on fixed aerial survey transects allowing data to be mapped on a spatial grid (see Appendix A; Morton et al. 1990a, 1991; Bayliss & Yeomans 1990a; Saalfeld 1990; Chatto 2006; for further data summaries see also Colley 1999, Boyden et al. 2008 & Boyden 2010). The earlier (since 1956) CSIRO annual aerial surveys of Magpie Goose nesting colonies (Tulloch & McKean 1983, Tulloch 1985, Tulloch et al. 1988) could not be used in our spatial assessments because data were not collected on systematic grids using standardised survey variables. The Magpie Goose aerial survey grid across the western 'Top End' of the NT is illustrated in Figure 3a, and a close up for the ARR in Figure 3b. All observed counts (of geese or nests) were adjusted for differences in transect counting width/observer (100m c.f. 200m) and number of observers, and then corrected for seasonal visibility bias after Bayliss (1990a). Data per 2.7km grid cell are corrected absolute density estimates (numbers/km^2).

Mapping seasonal "hotspots" of Magpie Geese habitat use

The historical time series of Magpie Goose surveys across the NT encompassing the ARR shows marked seasonal, annual and decadal variations in distribution and abundance, reflecting significant temporal and spatial variation in habitat suitability and use. Variation in wet season rainfall and, hence, floodplain habitat condition is a major driver of Magpie Goose population dynamics (Bayliss 1989) and nesting ecology (Whitehead & Tschirner 1990). It would be challenging to simply choose a "representative" wet and dry season pattern of site-specific habitat use on Kakadu floodplains to undertake SLR impact assessments spanning decades into the future. A similar argument would also apply to developing seasonal Habitat Suitability Models (HSMs) for Magpie Geese based on a small subset of environmental conditions. The appropriate time scale for our SLR impact assessments would encompass all historical survey data spanning the greatest range of habitat conditions and decadal changes in rainfall and river flow-floodplain inundation (Bayliss et al. 2011; Erskine et al. 2011).

The mean long-term density of Magpie Geese and their nests in grid cells would reflect long-term habitat use but would require the simultaneous use of some metric of long-term variance, such as the Standard Deviation, to interpret correctly. Instead we use a simple form of spatial cluster analysis that derives a single metric and that comes with a statistical significance test. These "clusters" or "hotspots" were calculated in ArcMap™ 10.2 (Mitchell 2005) using the Getis-Ord Gi* test statistic (% z-score; see Getis & Ord 1992) and resulting polygons greater than 95% significance level were smoothed. Statistical analyses outside the GIS were undertaken with Statistica™ software (Statsoft Inc. 2011) and imported back into the GIS.

2.3 Freshwater floodplain vegetation

Broad floodplain vegetation types vary between different river systems in the Northern Territory (Frith & Davies 1961; Finlayson et al. 1988, 1989; Whitehead et al. 1990), most likely because of variations in the geomorphologic structure of the floodplains and past and current land use practices. However, vegetation composition on floodplains show marked variation with changes in micro-topography, principally through its effects on hydrology (Bowman & Wilson 1986). Distinct vegetation types are often associated with geomorphic features on the floodplains such as high and low-lying depressions, palaeochannels and drainage depressions (Story et al. 1976). Salinity is an important factor that influences the composition of floodplain vegetation communities, as most floristic groups are associated with distinct salinity and water depth regimes (Cowie 2003). In general, diversity is low at wet and saline sites and highest in the drier sites (Wilson et al. 1991). The most common community type found on floodplains across the NT is wild rice (*Oryza spp*) grasslands, followed by the native grass *Ischaemum australe* and the tall sedges *Eleocharis dulcis* and *E. sphacelata*. These sedges are important nesting and dry season habitat components of Magpie Geese. For example, they prefer *E. sphacelata* to build stages and nests (Frith & Davies 1961) and, in contrast, the bulbs of *E. dulcis* are a key dry season food. Wild Rice (*Oryza* spp) is a key food source for emergent goslings and adult birds (Frith & Davies 1961, Whitehead & Saalfeld 2000). Marked annual and seasonal variations in floodplain vegetation composition and abundance occur also due to the alternating wetting and drying cycle between seasons (Finlayson et al. 1990). Hence, floristic changes are also strongly associated with variations in annual rainfall and flow (Finlayson et al. 1993). Although exotic weed species make up a small proportion (<0.5 %) of the total number of species encountered on floodplains they pose serious threats to conservation values (Finlayson et al. 2006, Bayliss et al. 2008), particularly on conservation lands such as Kakadu (Setterfield et al. 2014).

1990 aerial survey of floodplain vegetation in the ARR

Wilson et al. (1991) mapped the percentage cover of floodplain vegetation classes across the western “Top End” of the NT from March-May 1990 using the Magpie Goose aerial survey grid (2.7km cell size). Although this data set is 25 years old we use it in our SLR assessments because 1990 is close to the midpoint (1992) of the historical run of Magpie Goose surveys (1981-2003) used to determine spatio-temporal clusters of seasonal habitat use or suitability. This approach uses all available data encompassing decadal-scale changes in environmental conditions. Additionally, whilst coarse, the Wilson et al. (1991) floodplain vegetation map for the ARR is at a higher level of genera and species resolution for aquatic macrophytes than the park-wide Schodde et al. (1987) vegetation map. Para grass on Magela floodplain has not been included as a vegetation class in this data set as no extensive stands were recorded during survey. Bayliss et al. (2012) suggest that it did not rapidly spread across the Magela floodplain until exceptional wet season conditions experienced after 1990.

High resolution vegetation maps from satellite data

High resolution floodplain vegetation maps have been produce for the three case study areas but not for the whole park due to costs of satellite data acquisition and associated field costs for calibration and validation. The following high resolution floodplain vegetation maps are available: a WorldView2 (WV2) map of Magela Creek floodplain (Whiteside & Bartolo 2014); a QuickBird^{TM} map of Boggy Plain (Boyden et al. 2003); WV2 maps of Boggy Plain in 2010 and 2012 (Anstee et al. 2014); WV2 maps of Yellow Water and parts of Magela in 2010 and 2012 (Anstee et al. 2014). These maps were used to examine in greater detail potential impacts of SWI on different floodplain vegetation classes. Although very high resolution (sub-meter black & white & 2m colour pixels), vegetation classification data were re-sampled to 60m grid cells being the minimum cell size for Stage 1 and 2 SWI model outputs. A medium resolution vegetation map of parts of Kakadu floodplains has been produced also using ALOS 2010 satellite data (Anstee et al. 2014), and the distribution of lilies and open water as a cover class was used in our SLR assessments.

2.4 HCVAEs and other bush tucker animals (turtles & fish)

Freshwater aquatic ecosystems in northern Australian encompass a unique and diverse range of water-dependent plants and animals across a wide range of environmental settings and, in general, are considered to be of high conservation value (Pusey & Kennard 2009, Kennard 2010). Kennard (2010) developed a systematic approach to the identification of High Conservation Value Aquatic Ecosystems (HCVAE) using the classification framework and criteria proposed by the Commonwealth Aquatic Ecosystem Task Group (e.g. species diversity, distinctiveness & vital habitat, representativeness). Sub-catchments that met four or more criteria based on raw input data were concentrated in the northern "Top End" of the Northern Territory and the tip of Cape York Peninsula. Based on a strict 99th percentile threshold he identified subsets of sub-catchments potentially containing HCVAEs (HCVAE99) for the whole of Northern Australia and for each Australian Water Council (AWC) drainage basin. Bayliss et al. (2011) examined their HCVAE99 biodiversity metric for the South Alligator River catchment on Kakadu in relation to the combined threats of current water resource development (non-existent) and future SLR at 2100 (a projected 1.1m increase in mean sea level), and his methodology was extended to all sub-catchments on the park to undertake a similar risk analysis but with a far greater horizontal and vertical resolution DEM using the LiDAR data.

In contrast to the availability of population-level data for Magpie Geese (e.g. nest density) there is a paucity of such data for other wildlife species on Kakadu. Hence, in addition to the above biodiversity index for freshwater aquatic ecosystems, we used the predictive (presence/absence) models of species distributions (HSMs) developed by Kennard et al. (2010) for two freshwater turtle species (Long-necked turtle, *Chelodina rugosa*; Pig-nose Turtle, *Carettochelys insculpta*) and one species of fish (Black Bream, *Hephaestus fuliginosus*) to assess potential SLR impacts on these three key bush tucker and biodiversity species on Kakadu. The presence-absence species HSM models, whilst appropriate over Northern Australia and drainage basin scales, may not be suitably predictive for local or sub-catchment scales. Nevertheless, they are the best we have and can serve as a "place holder" until increased knowledge of the distribution and abundance for greater suite of species is obtained.

2.5 Saline habitats

Saline habitats on Kakadu comprise: mangroves; saltflats (or saltpans); samphire dominated saltflats; and free standing water (likely salty due to frequent exposure to tides) and bare ground (terrestrial). A GIS layer of saline habitats (D. Ward pers. comm.) was used to examine broad patterns between the frequency and extent of SWI predicted by Stage 1 modelling for the Present-day SLR scenario (0m SLR, 2013 dry season using October tides; see Saunders et al. 2014). The statistical characteristics of the frequency of SWI across the park and for each saline habitat were profiled with Probability Distribution Functions (PDF) and their associated Cumulative Frequency Distribution Functions (CFD) using BestFit^{TM} software (Palisade 2002). Similarly, the statistical characteristics of the frequency of SWI for a selection of key floodplain plants using the data from Wilson et al (1991) were also described. The distribution of saline habitats was examined also in relation to the distribution of a selection of key floodplain plants mapped by Wilson et al. (1991) and identified Magpie Goose seasonal "Hotspots".

2.6 Salinity tolerance of floodplain plants

Hart et al. (1991) reviewed lethal and sub-lethal effects of salinity on microbes (mainly bacteria), macrophytes and micro-algae, riparian vegetation, invertebrates, fish, amphibians, reptiles, mammals and birds, and concluded that direct adverse biological effects are likely to occur in Australian rivers, streams and wetlands if salinity is increased to around 1000 mg/L or 1 ppt. They highlighted also that there is a general lack of data on the sensitivity of freshwater plants and animals to increased salinity. Given the range of salinity tolerances of freshwater plant species reported in the literature, and the species-specific knowledge gap for floodplain plant species found on Kakadu, we undertook a comprehensive review and analysis of published data (Appendix B). We then used standard eco-toxicological models to characterise the likely effects on the full range of plant species of exposure to increasing salt concentrations, which effectively is the Species Sensitivity Distribution (SSD) modelling approach (see Bayliss et al. 2012 for a similar approach to minesite pollutants on Kakadu). There was a range of assessment end-points reported in the literature (e.g. growth, survival) and a combination of lethal and sub-lethal effects and duration times. Nevertheless, where provided, we used mortality (death of an individual) over the longest duration. A quantitative Ecological Risk Assessment can then be undertaken for different wetlands on Kakadu where exposure salinities can be measured or modelled (see below).

2.7 Salinity risk profiles of case study areas

2.7.1 MAGELA CREEK FLOODPLAIN (EAR)

Relationship between salinity & the frequency of SWI (Stage 1 Present-day Oct. 2013)

Stage 1 and 2 SWI modelling used the same hydrodynamic shallow-water equations and modelling procedures except that for Stage 2 a wet season component was added to allow simulation of a storm surge-extreme rainfall flood event (see Hilton et al. 2014). Stage 1 SWI model outputs (frequency of inundation & maximum extent) were therefore cross-referenced to outputs for Magela Creek floodplain from an independently derived SWI hydrodynamic model used to derive salinity concentration (ppt) and water depth (m) (Project 3.4, D. Williams pers. comm.). Stage 1 outputs (%P or frequency of SWI) on a 60m grid were re-sampled to the same 50m grid as that used by project 3.4 in order to examine the broad correlation between %P and Present-day dry season salinity concentration on Magela floodplain (at the 80th percentile, D. Williams pers. comm.).

Relationship between salinity, water depth & the occurrence of floodplain plants (a HSM)

Cowie (2003) found a strong relationship between water depth (m) and salinity (ppt) for different wetland plants around Darwin Harbour (see Fig. 21a from Cowie 2003). The wetland plant classes on Magela floodplain mapped by Whiteside and Bartolo (2014) were paired to the mean salinity (ppt) and water depth (m) model values described above across a 50m grid. The overall mean values of both inundation variables were then derived for each plant class and examined for relationships similar to that found by Cowie (2003).

2.7.2 BOGGY PLAIN (SAR)

Boyden et al. (2004) used a high resolution Quickbird™ satellite image of Boggy Plain in May 2003 (early dry season) to map floodplain vegetation classes. The relationship between water depth (m) and salinity (ppt) for their wetland plant classes were examined. Early dry season salinity and water depth values were derived using the local calibration method of Dutra et al. (2013) on a 50m grid, and vegetation was re-sampled to the same grid. The potential exposure effects of salinity resulting from a King high tide in November 2012 and from a predicted 0.7m SLR scenario in 2070 was examined also. Salinity measurements on the floodplain during the King high tide were obtained by Kakadu TOs Peter Christophersen and Sandra McGregor (pers. comm.)

2.8 Other landscape threats to floodplains

Bayliss et al. (2012) highlighted other current and more immediate landscape-scale threats to Kakadu floodplains besides projected SLR and associated SWI 55y and 85y into the future (2070 & 2100 climate change scenarios, respectively) such as aquatic weeds (Setterfield et al. 2014), feral pigs (Bayliss & Walden 2003, Woodward et al. 2011, Jambrecina 2011) and unmanaged fire (see

Atkins & Winderlich 2010) as opposed to floodplains managed carefully by Indigenous burning regimes (McGregor et al. 2010).

Component 3 of the NERP Floodplains project (Management of wetland weeds) deals specifically with the threat from aquatic weds to floodplain values and is reported separately. The largest core infestation of para grass occurs on the Magela Creek floodplain (Setterfield et al. 2014), with high levels of infestation also found on the Wildman River floodplain and with smaller patches occurring on the West and South Alligator floodplain margins (McMaster et al. 2014).

The percentage of ground disturbance damage (%PD) caused by feral pigs was recorded during dry season aerial surveys of feral animals on Kakadu in November 2001 and 2003 (Bayliss & Saalfeld unpubl. data as reported by Boyden et al. 2008), and the distribution and extent of this damage is reported here to provide further context for the need to address multiple cumulative risks through integrated assessments and management. Integrated management of invasive species on Kakadu is part of park policy and operational management procedures (Director of Parks 2007).

Part II of this report (Participatory Methods and integrated assessments; Dutra et al. 2015) attempts to address other landscape-scale risks at more immediate time frames than SWI due to climate change, and within a socio-ecological context with respect to developing and evaluating potential management options.

(a)

(b)

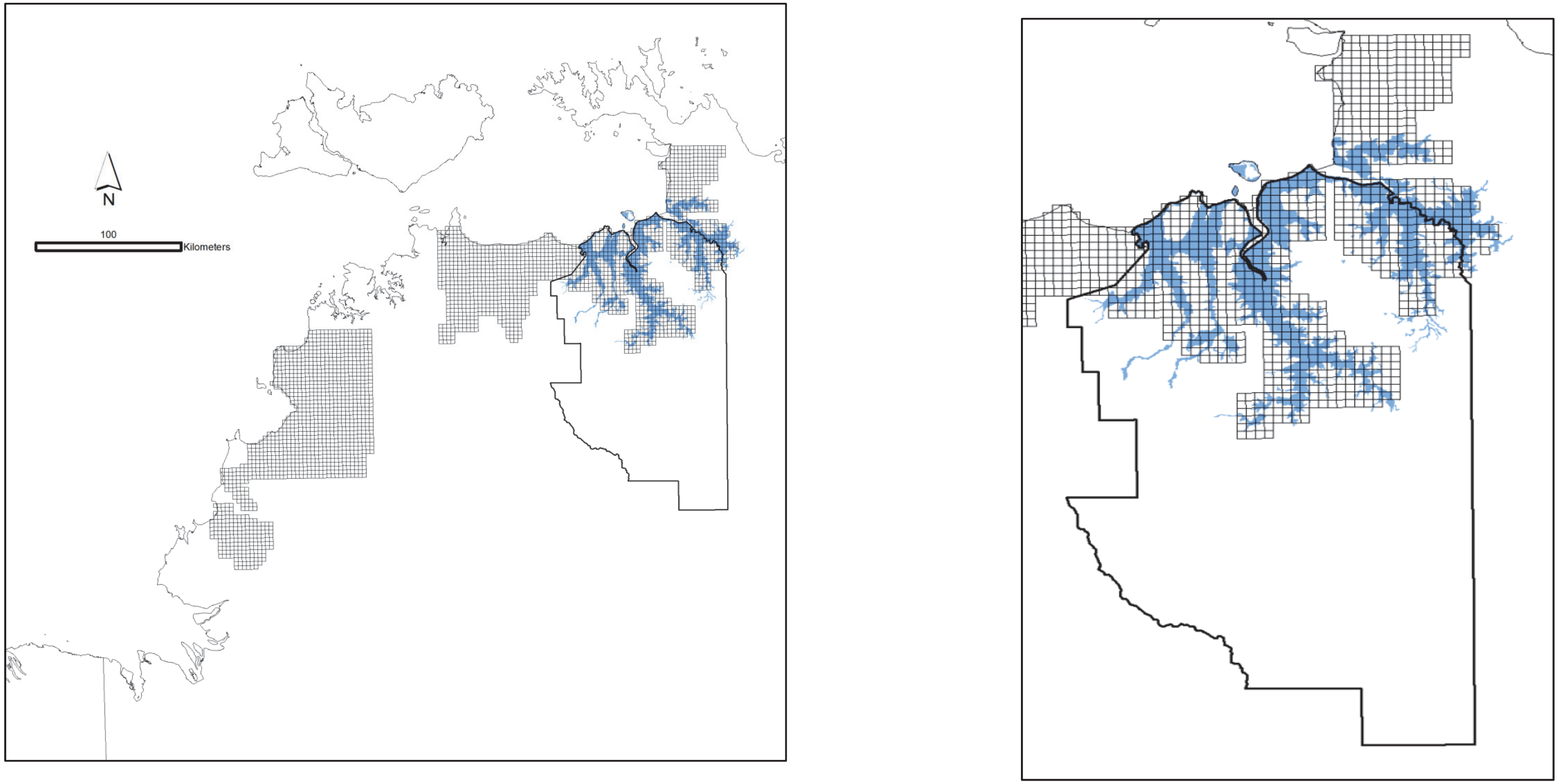


Figure 3a&b. (a) Magpie Geese aerial survey grid (2.7 km x 2.7 km) in the "Top End" of the Northern Territory (1990-2003). From 1983 to 1989 a 5.4km grid was used. (b) The same survey grid in the Alligator Rivers Region encompassing Kakadu National Park.

3 Results

3.1 Sea Level Rise projections and Saltwater Inundation (SWI)

The linear relationship between projected SLR and Scenario Year between 2030 and 2100 is illustrated in Figure 4a, and the concomitant linear trend in the percentage or proportion of Kakadu floodplains lost to SWI in Figure 4b (regression equations shown). Base on this rate of loss all freshwater floodplains on Kakadu will be inundated by salt water by 2132, 117y from now. The rate of floodplain lost to SLR is almost imperceptible between 2013 and 2030 (3% increase, Table 3). In contrast, the proportion of floodplain lost significantly increases in linear fashion past a threshold value somewhere between 2030 and 2070 (Fig. 4c, Table 3). Figure 4c shows the same data in Figure 4b but broken down by case study area. Magela Creek floodplain shows a similar threshold effect as that for the whole park, most likely reflecting the fact that it's a much larger proportion of all Kakadu floodplains. Boggy plain on the SAR is situated closer to the coastline and results show a strong threshold effect in 2070 where most of its floodplain will be inundated by salt water in 2070 (84%, Table 4). There is only a small effect of SWI due to tides before 2070 (Table 4). In contrast, Yellow Water, situated far upstream on the SAR, has the least proportion of floodplain lost to SLR (Table 4) and therefore has the potential to be a key refuge area from the effects of SWI over these timeframes. Unfortunately the LiDAR capture closely hugged the borders of all wetlands in the ARR due to costs and, hence, there is no fine-scale DEM in surrounding terrestrial areas to model the creation of new freshwater wetlands as sea water pushes in over time. This is a major gap in knowledge and constrains the assessments presented here to adopt a worst case scenario outlook. We emphasise that our estimated proportions of floodplains lost to SWI are due to the influence of dry season tides only.

(a) (b)

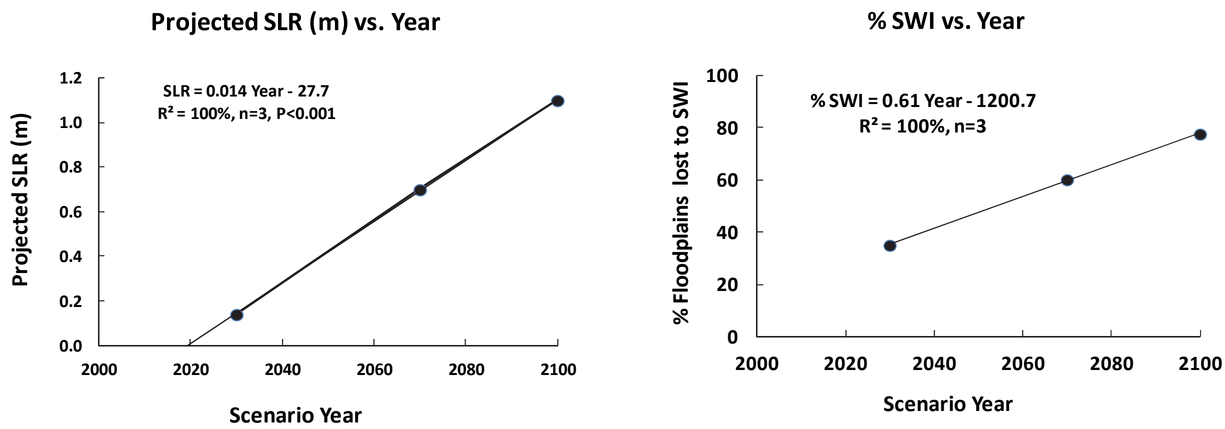


Figure 4a-c. (a) The linear relationship between projected Seal Level Rise and Scenario Year. (b) Linear regression equation predicting percentage of freshwater floodplains lost (%) to tidal saltwater inundation in the dry season (Oct. 2013 baseline) by year. (c) Comparison of predicted percentage (%) loss of freshwater floodplains by Scenario Year for Kakadu, Boggy Plain, Magela Creek floodplain and Yellow Water wetlands.

(c)

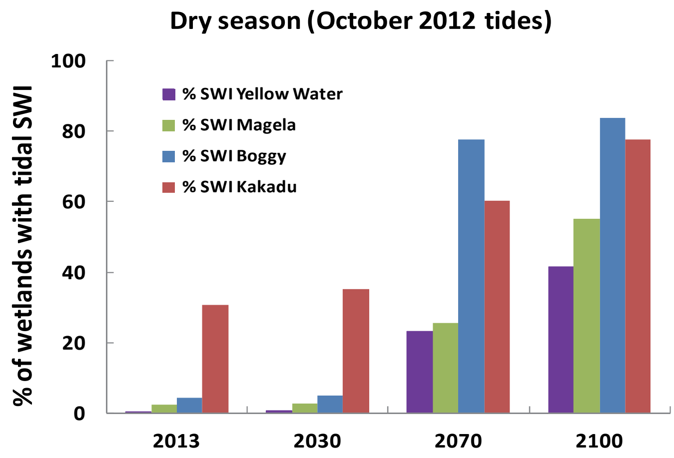


Figure 4c cont.

Table 3. Summary of the extent (%) of floodplain lost to SWI (Stage 1 SLR model) for each of the Scenario Years for Kakadu as a whole and the three case study areas (see Figure 4c).

Scenario Year	Kakadu NP	Magela Creek	Boggy Plain	Yellow Water
2013	31	2	4	0
2030	34	3	5	2
2070	60	26	77	23
2100	78	55	84	42

3.2 Sea Level Rise (SLR) impacts on floodplain biodiversity assets

3.2.1 MAGPIE GEESE & THEIR SEASONAL HABITATS & SLR

The distribution and abundance (numbers/km^2) of Magpie Goose aerial survey observations in the ARR in the dry season (1981-2003), and that for their nests in the wet season (1984-2000), are illustrated in Figure 5. Figure 6a maps the distribution and long-term mean density of Magpie Geese (1991-2003) in the ARR in the dry season across a 2.7km grid and, similarly, in Figure 6b for their nests in the wet season (1984-2000).

Areas of high abundance of Tall Spike Rush (*Eleocharis sphacelata*) and Water Chestnut (*Eleocharis dulcis*) sedges in the ARR ascertained in the late 1989/1990 wet season by Wilson and Whitehead (1991) in the ARR are shown in Figures 7a and b, respectively . Figure 8a maps both *Eleocharis* species combined, and that for Wild Rice (*Oryza spp*.) in Figure 8b.

The distribution of Magpie Goose “Hotspot” or “Density Clusters” in the ARR in the dry season and their nests in the wet season over 22 years of surveys (1981-2003) are illustrated in Figure 9a. The distribution of dry season Hotspots in relation to the co-occurrence of both *Eleocharis* species combined (Total) is illustrated in Figure 9b.

The separation between the occurrence of Magpie Goose seasonal Hotspots and saline habitats is illustrated in Figure 10a. Similarly the frequency and extent of tidal SWI in the dry season is illustrated in Figure 10b showing little to no overlap with saline environments.

The frequency and extent of tidal SWI in the dry season for the Present day (2013, 0m) and 2030 (0.14m) SLR scenarios is illustrated in Figure 11a and shows little difference between the two (Table 4). However, in contrast, the intersection between Magpie Goose seasonal Hotspots and the 2070 SLR scenarios illustrated in Figure 11b shows substantial overlap in the dry (57%) and wet (75%) seasons (Table 4). The upstream areas that do not intersect are identified in this analysis as potential refuge areas for nesting and dry season feeding/roosting at the 2070 time frame.

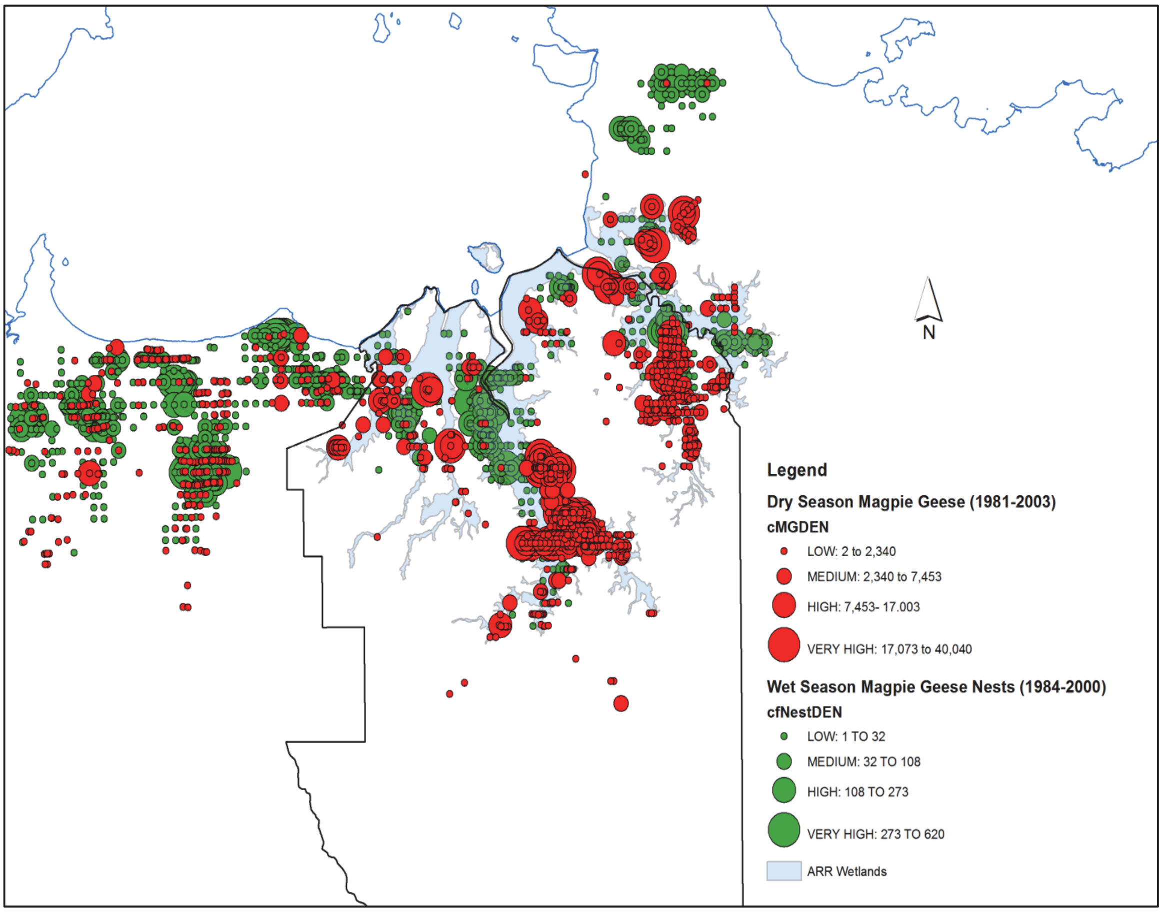


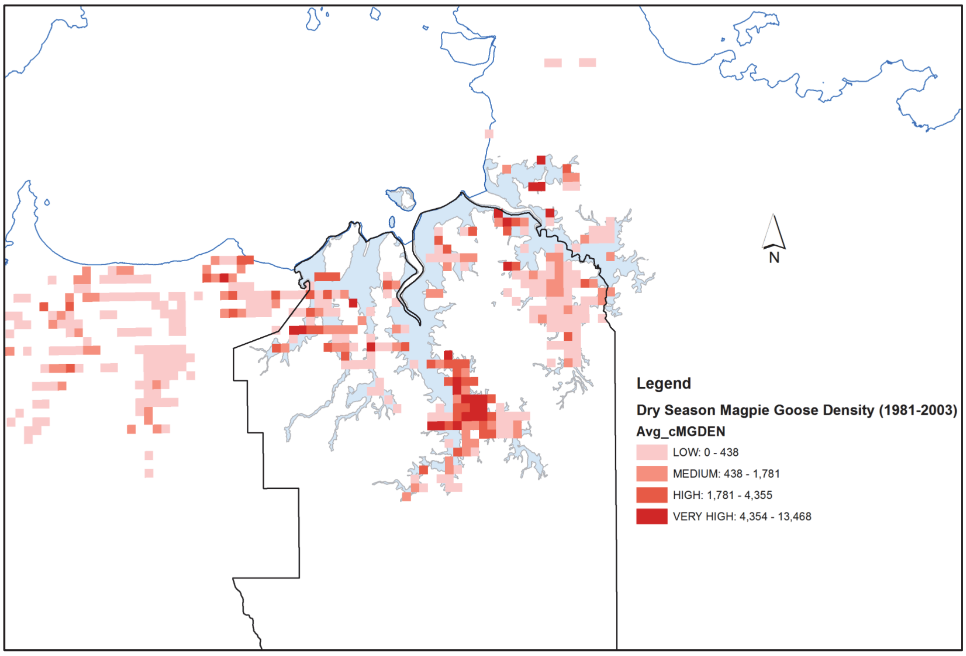
Figure 5. The distribution and abundance of Magpie Goose aerial survey observations in the Alligator Rivers Region (ARR) in the dry season (red circles, 1981-2003) and wet season (green circles nests, 1984-2000).

Table 4. Summary of the extent (%) of Magpie Goose seasonal Hotspots, key floodplain plant classes (1990) and HCVAE99 values potentially lost to SWI (Stage 1 SLR model) for the 2070 and 2100 scenarios only (see Figure 4c).

Key Ecological Attribute	2070	2100
Magpie Goose dry season Hotspots	57	90
Magpie Geese wet season Nest Hotspots	76	97
Spike Rush (*Eleocharis sphacelata*)	45	75
Water Chestnut (*Eleocharis dulcis*)	59	84
Wild Rice (*Oryza spp*)	51	81
Hymenachne (*Hymenachne acutigluma*)	29	68
Red, Blue & White/Yellow Lilies	65	89
Long-necked Turtle	10	13
Pig-nose Turtle	0.3	1.7
Black Bream	2	4
HCVAE99	3	5

The intersection between Magpie Goose seasonal Hotspots and the frequency and extent of the 2100 SLR scenario is illustrated in Figure 11c and shows an almost complete overlap (90% & 97% for dry & wet seasons, respectively; Table 4). The small numbers of upstream areas that do not intersect are identified as refuge areas for nesting and dry season feeding/roosting at these time frames. Similar results were obtained for *E. sphecelata* and *E. dulcis* (for 2100 75% & 84%, respectively; see Fig. 11d for both species combined & Table 4), comprising floodplain plants that Magpie Geese heavily depend on for nesting and feeding. The non-overlapping areas identify the very small number of potential refuge areas for both plant species.

(a) Dry season Magpie Goose densities



(b) Wet season Magpie Goose nest densities

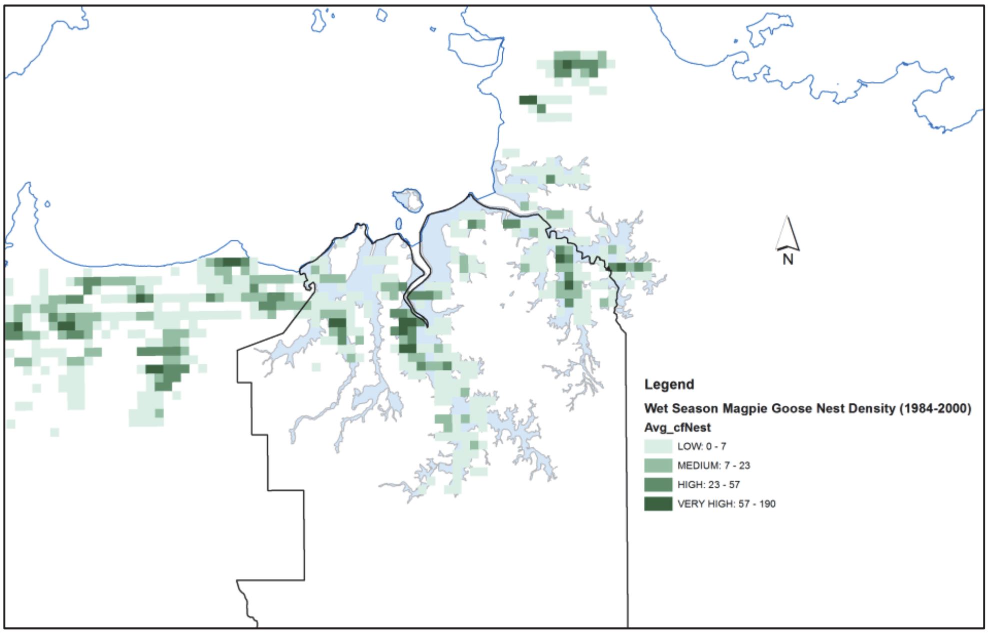
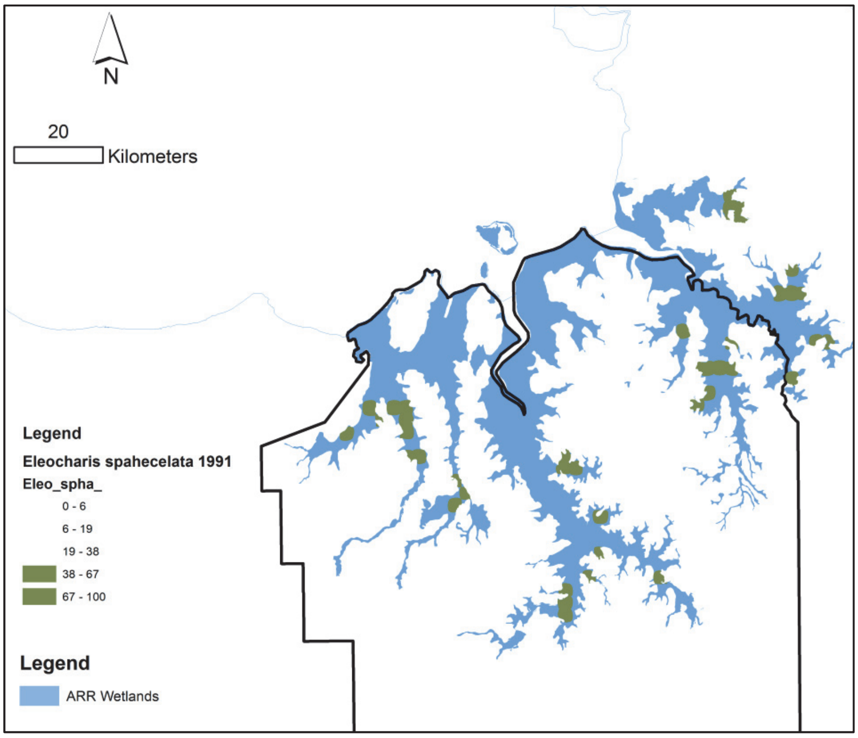


Figure 6a&b. (a) The distribution and long-term mean abundance (numbers/km^2) of Magpie Geese (1991-2003) in the ARR in the dry season, and (b) that for their nests in the wet season (1984-2000), across the 2.7km survey grid.

(a) Tall Spike Rush (*Eleocharis sphacelata*)



(b) Water Chestnut (*Eleocharis dulcis)*

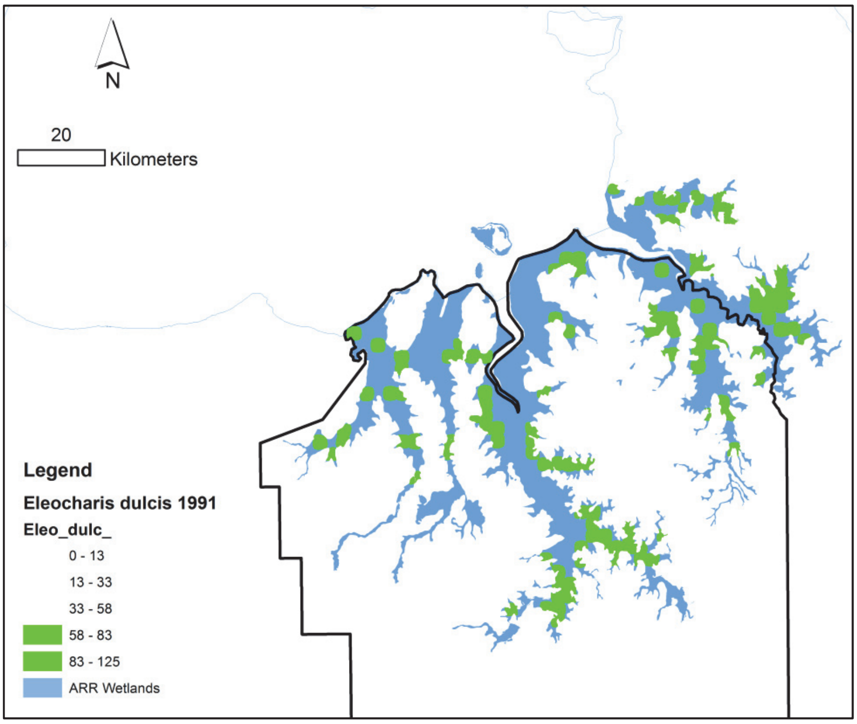
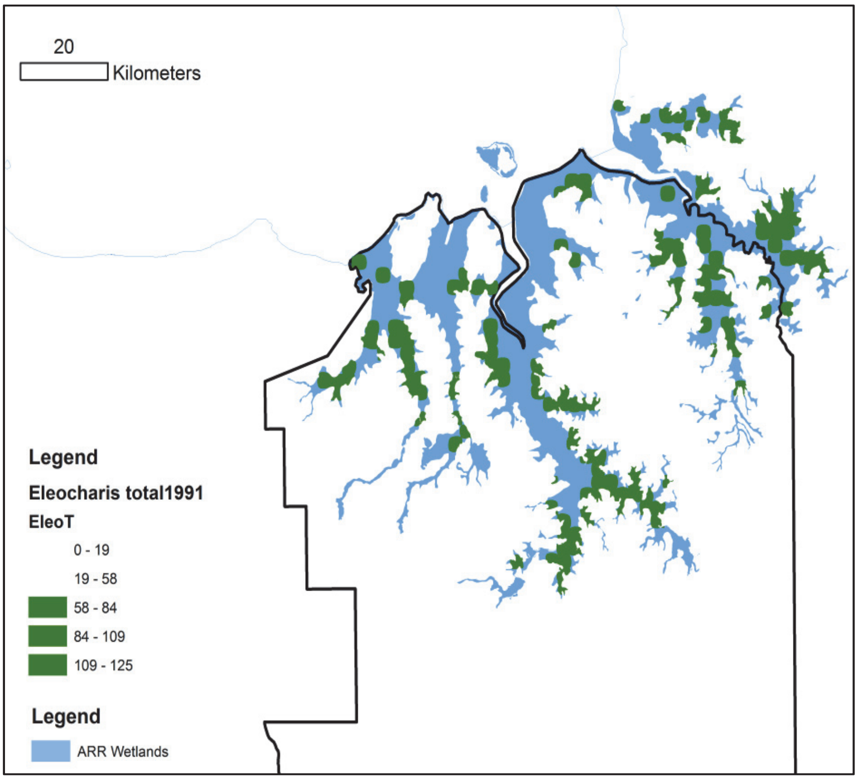


Figure 7a&b. Distribution of high abundance areas of (a) tall Spike Rush (*Eleocharis sphacelata*) and (b) Water Chestnut (*E. dulcis*) in the ARR in 1990 (Wilson et al. (1991).

(c) Total *Eleocharis* (both species combined)



(d) Wild Rice (*Oryza spp*.)

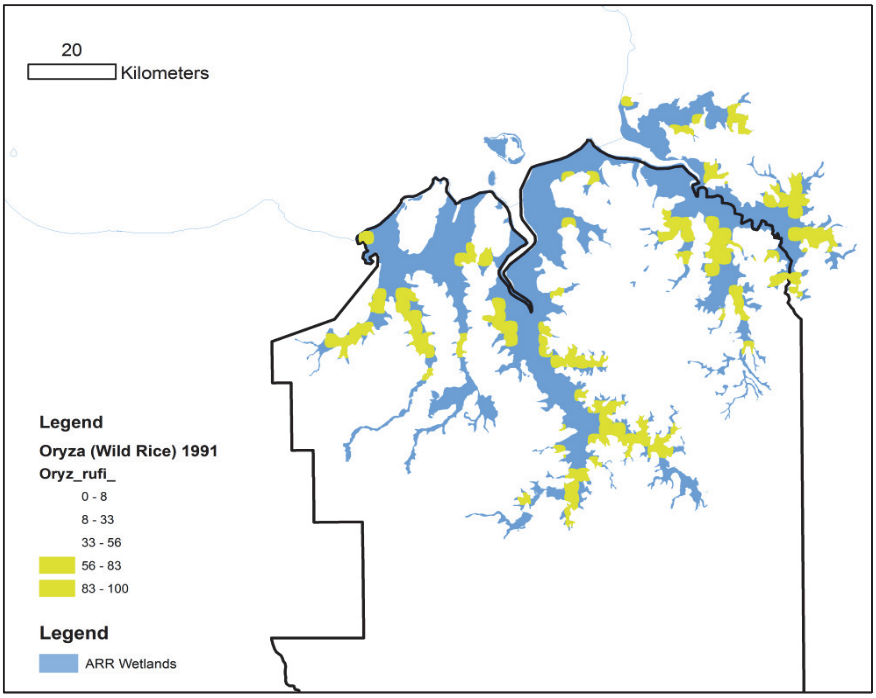
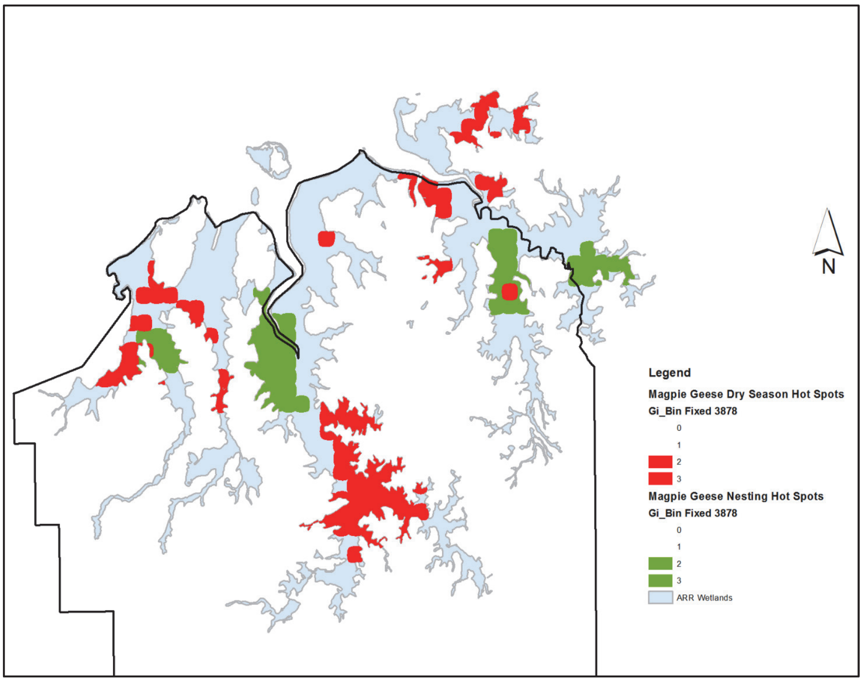


Figure 8a&b. Distribution of high abundance areas of (a) both tall *Eleocharis* sedge species combined and (b) Wild Rice (*Oryza spp*) in the ARR in 1990 (Wilson et al. (1991).

(a) Magpie Goose dry season and wet season nesting Hotspot sites.



(b) Magpie Goose dry season Hotspots and the co- occurrence of *Eleocharis* (Total)

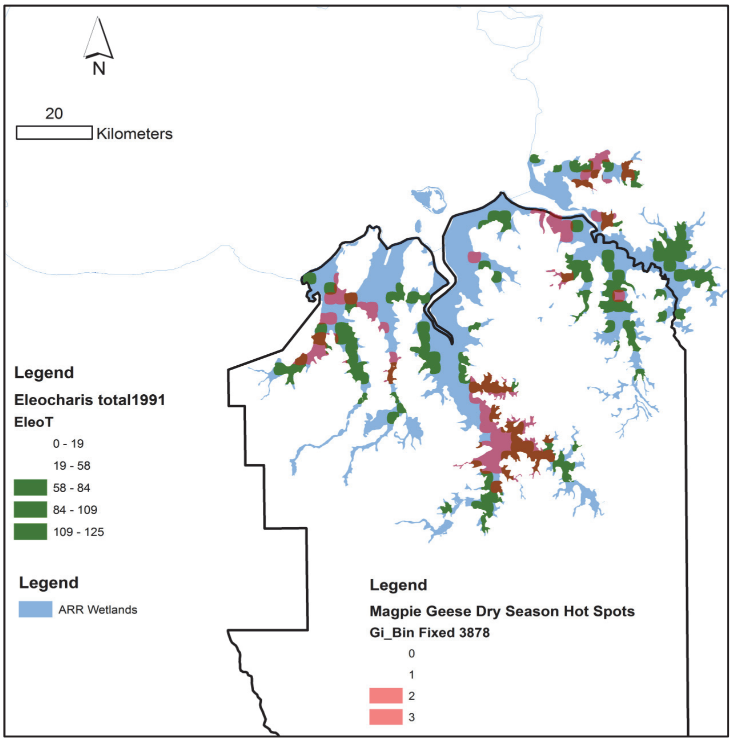
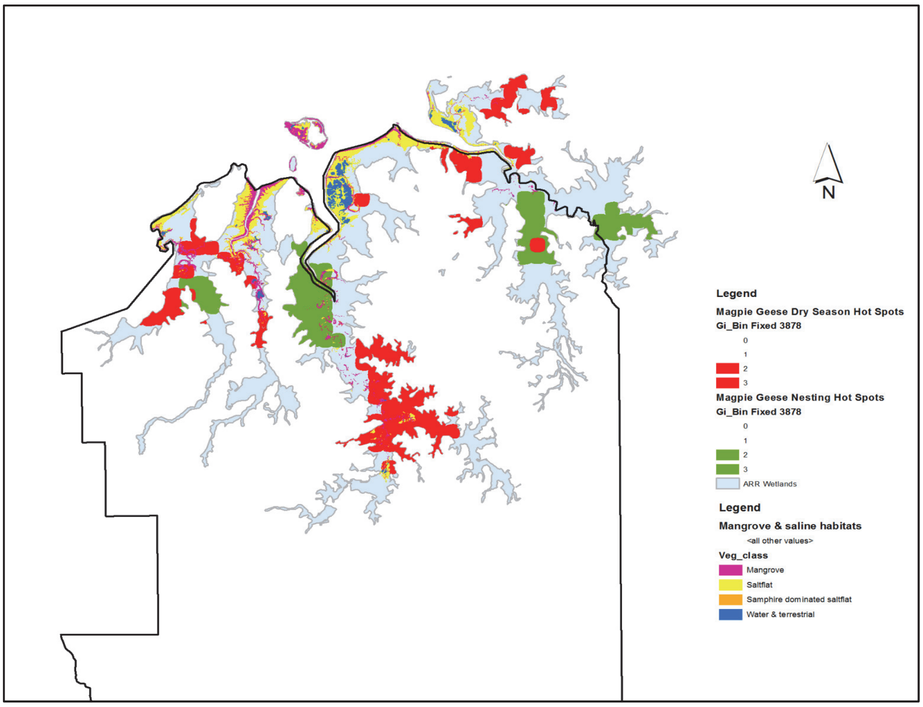


Figure 9a&b. Distribution of long-term (1981-2003, n=22y) "Hotspot" or "Density Cluster" areas of Magpie Geese in the ARR in the (a) dry season (red) and wet (green) season as indexed by nest density). (b) Location of Magpie Geese dry season Hotspots in relation to both tall *Eleocharis* sedge species combined (Total).

(a) Seasonal Hotspots of Magpie Geese in relation to saline habitats.



(b) Seasonal Hotspots of Magpie Geese in relation to the frequency of SWI in the dry season.

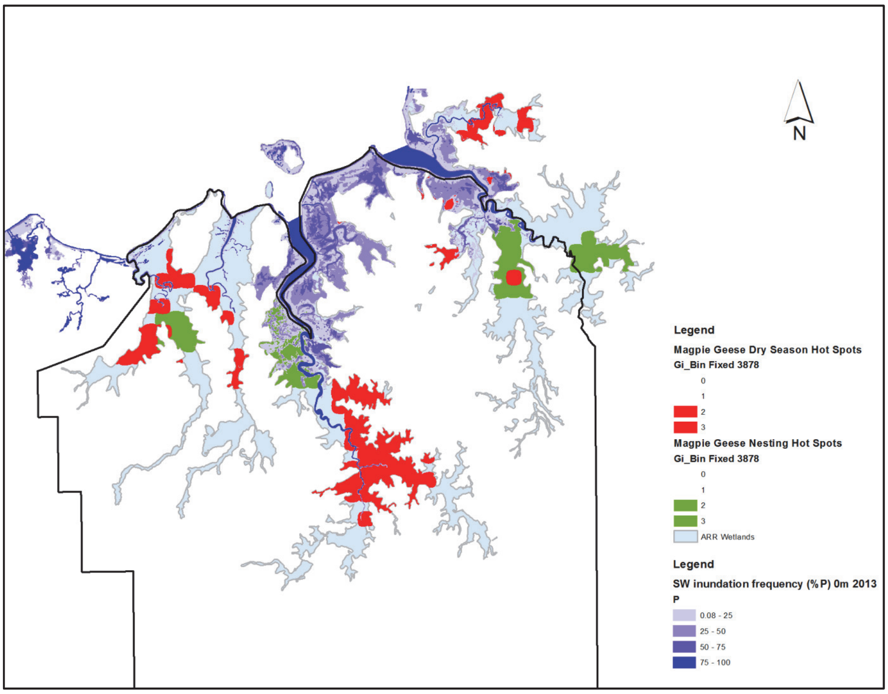
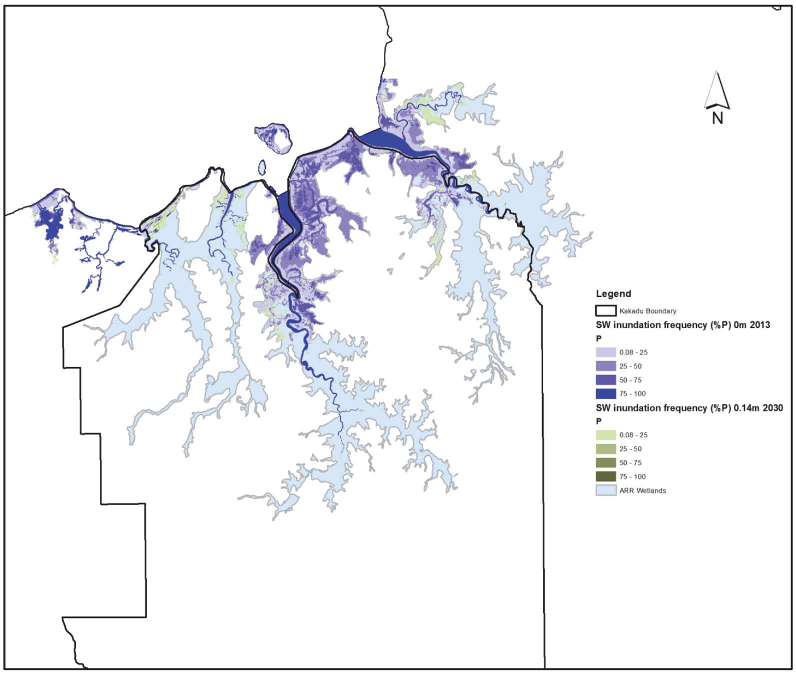


Figure 10a&b. (a) The occurrence of Magpie Goose seasonal Hotspots in relation to saline habitats showing their separation and, similarly, for the (b) frequency and extent of tidal SWI in the dry season (October 2013 tides) showing little to no overlap with saline environments.

(a) Comparison of the frequency and extent of SWI for the 2013 & 2030 SLR scenarios.



(b) Intersection between Magpie Goose seasonal Hotspots & the 2070 SLR scenario.

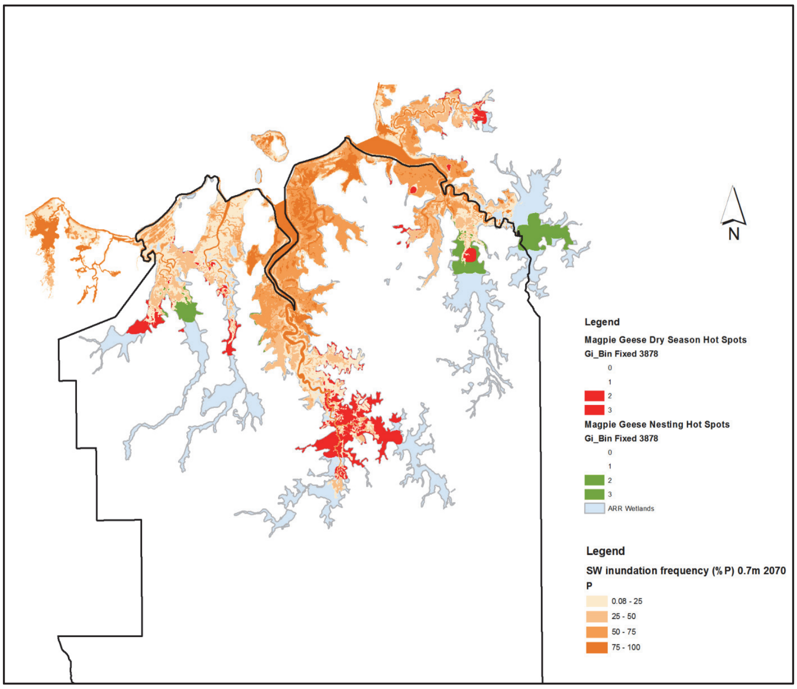
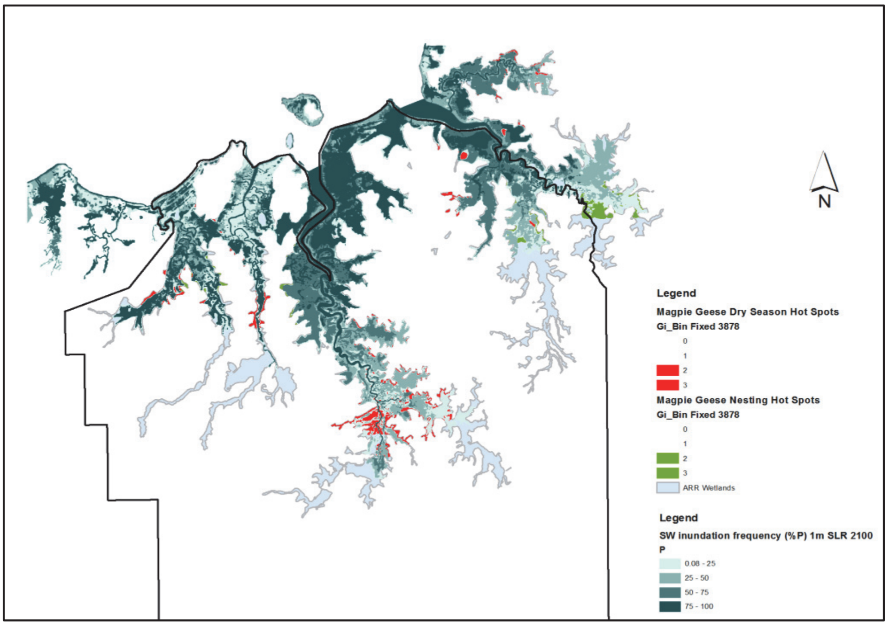


Figure 11a-d. (a) Frequency and extent of SWI in the dry season (October 2013) for the Present-day (2013, 0m) and 2070 (0.14m) SLR scenarios showing little difference. (b) The intersection between Magpie Goose seasonal Hotspots and the 2070 SLR scenario showing substantial overlap. The upstream (red & green) areas that do not intersect are identified as potential refuge areas for nesting and dry season feeding/roosting at the 2070 time frame.

(c) Intersection between Magpie Goose seasonal Hotspots & the 2100 SLR scenario



(d) Intersection between Total *Eleocharis* mapped in 1990 & the 2100 SLR scenario.

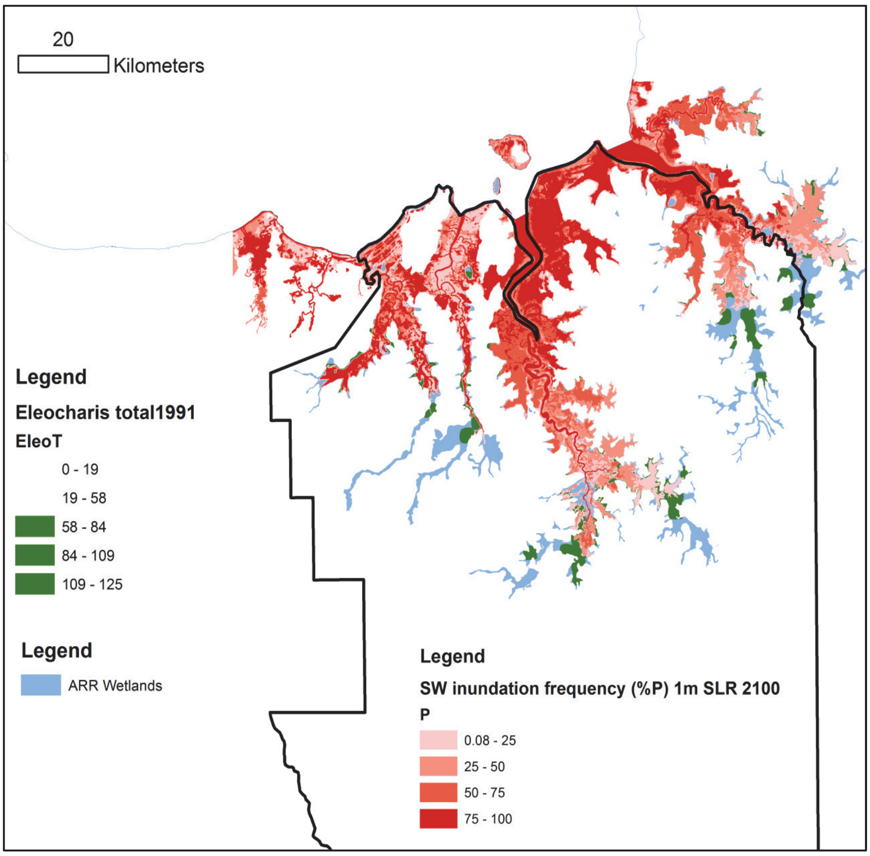


Figure 11c&d cont. (c) The intersection between Magpie Goose seasonal Hotspots and the frequency and extent of the 2100 SLR scenario showing an almost complete overlap. The small numbers of upstream areas that don't intersect are identified as potential refuge areas for nesting and dry season feeding/roosting at the 2100 time frame. Similarly for (b) both tall *Eleocharis* sedge species combined (Total).

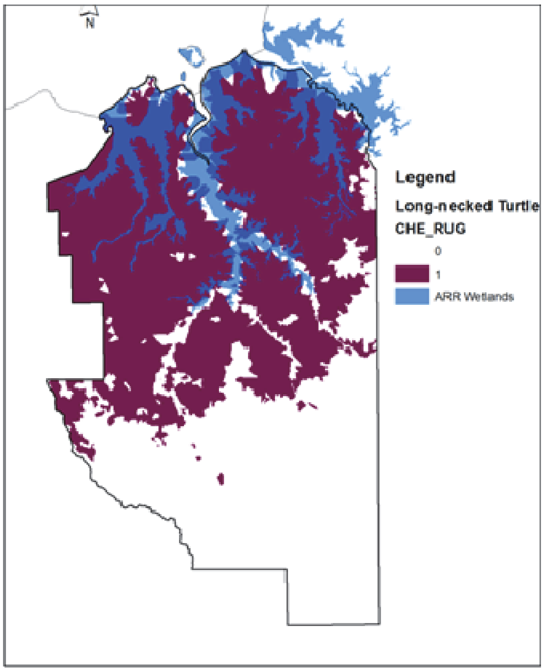
3.2.2 HIGH CONSERVATION VALUE AQUATIC ECOSYSTEMS (HCVAE) AND OTHER BUSH TUCKER ANIMALS (TURTLES & FISH)

The presence-absence distribution of Long-necked Turtles (*Chelodina rugosa*), Pig-nose Turtles (*Carettochelys insculpta*), Black Bream (*Hephaestus fuliginosus*) and High Conservation Value Aquatic Ecosystems (HCVAE99 sum of all criteria met at the 99^{th} percentile, Kennard 2010) on Kakadu sub-catchments are illustrated in Figures 12a-d, respectively. The first three distributions were determined by Habitat Suitability Models (HSM; Kennard 2010a) and the latter by modelling conservation criteria of HCVAEs (Kennard et al. 2010).

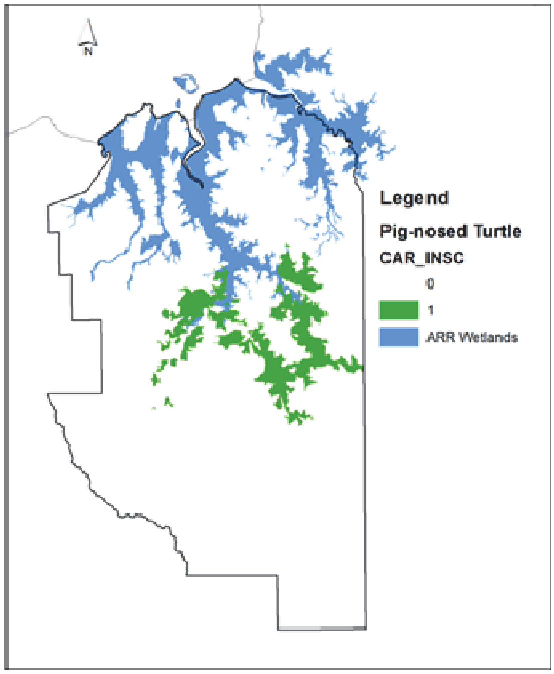
The intersection between the frequency and extent of SWI for the 2070 SLR scenario and modelled presence-absence distributions of Long-necked Turtles, Pig-nose Turtles and Black Bream, and HCVAE 99^{th} percentile values for Kakadu sub-catchments, are illustrated in Figures 13a-c, respectively (& see Table 4).

The extent of tidal SWI in the dry season for the 2070 SLR scenario for the three case study areas (Boggy Plain, Magela Creek floodplain & Yellow Water wetlands) are illustrated in Figure 13d, respectively (& see Table 3 for % loss). The upper floodplains of Magela Creek and Yellow Water suffer less extensive SWI compared to coastal areas and floodplains in the middle of river reaches within tidal range.

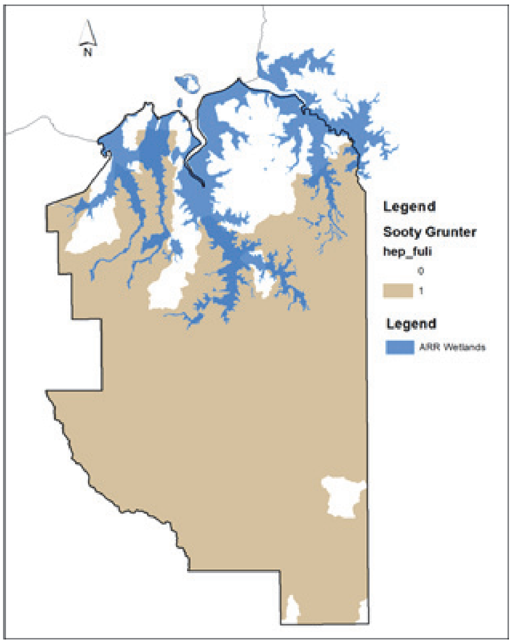
(a) Long-necked Turtle



(b) Pig-nose Turtle



(c) Black Bream (Sooty Grunter)



(d) HCVAE (99th percentile)

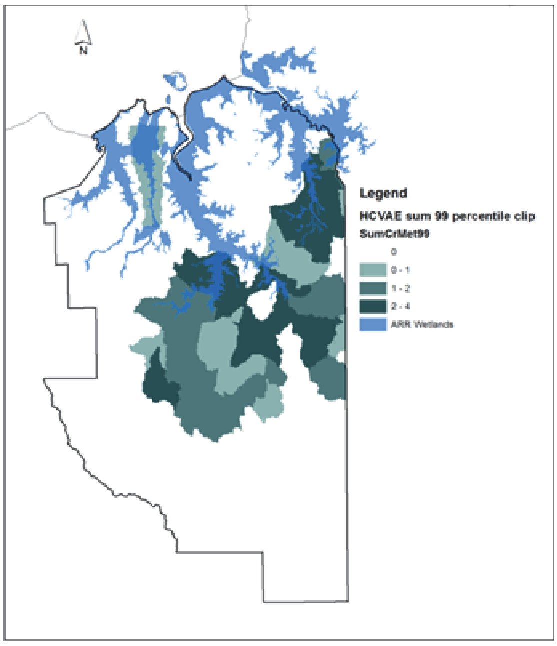
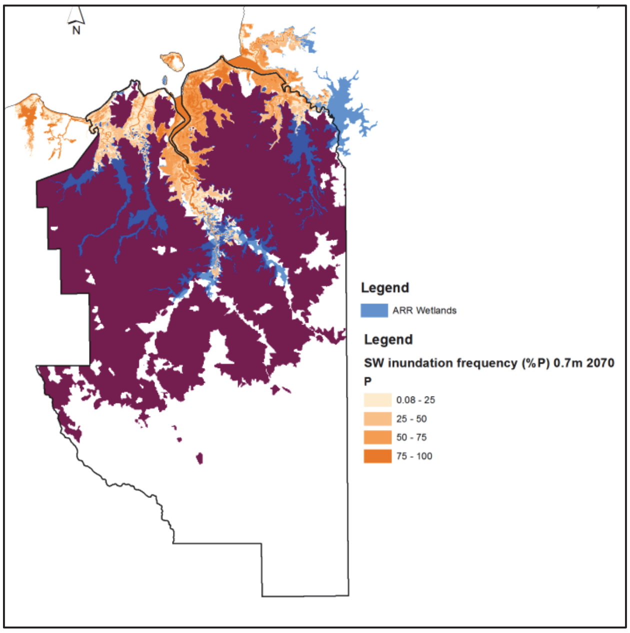
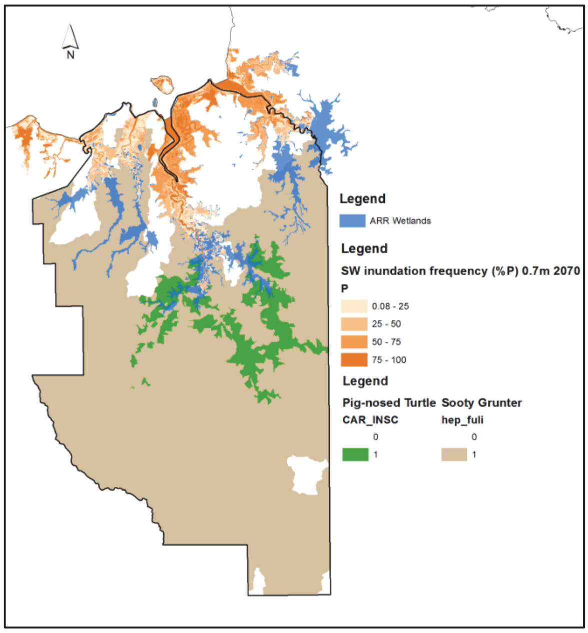


Figure 12a-d. The presence-absence distribution of (a) Long-necked Turtles (*Chelodina rugosa*), (b) Pig-nose Turtles (*Carettochelys insculpta*) and (c) Black Bream (*Hephaestus fuliginosus*) based on habitat suitability and species records (Kennard 2010a). (d) High Conservation Value Aquatic Ecosystems (HCVAE99 sum of all criteria met at the 99th percentile) on Kakadu sub-catchments (Kennard et al. 2010).

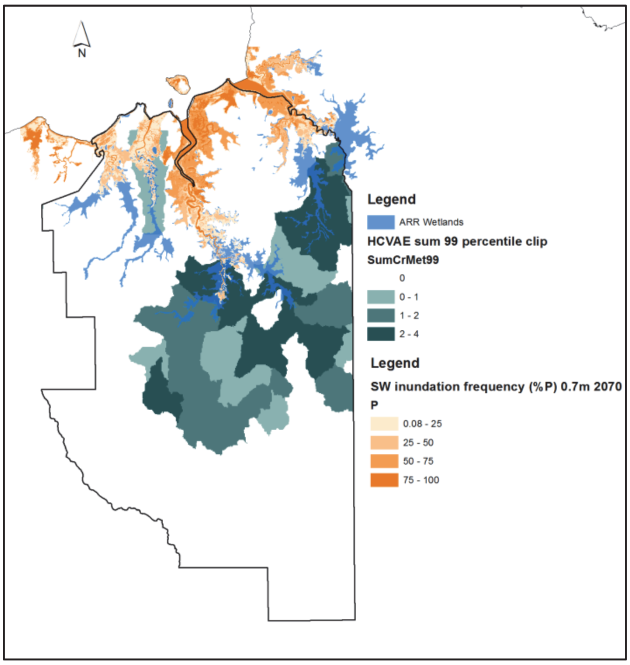
(a) Long-necked Turtle & 2070 SLR



(b) Pig-nosed Turtle & Black Bream 2070 SLR



(c) HCVAE99 & 2070 SLR



(d) Case study areas & 2070 SLR

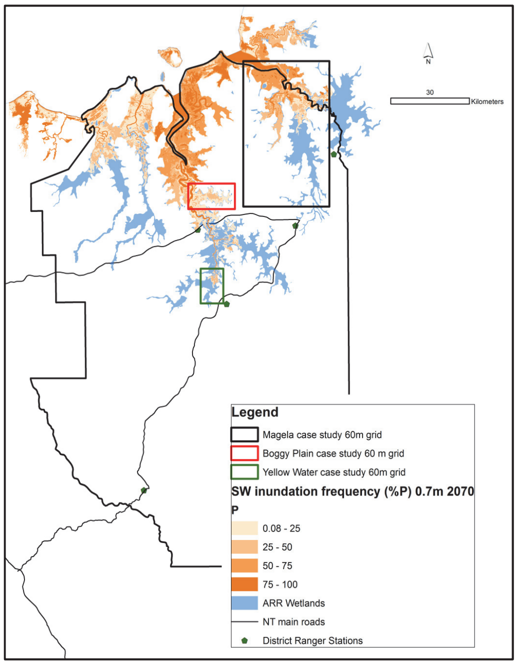


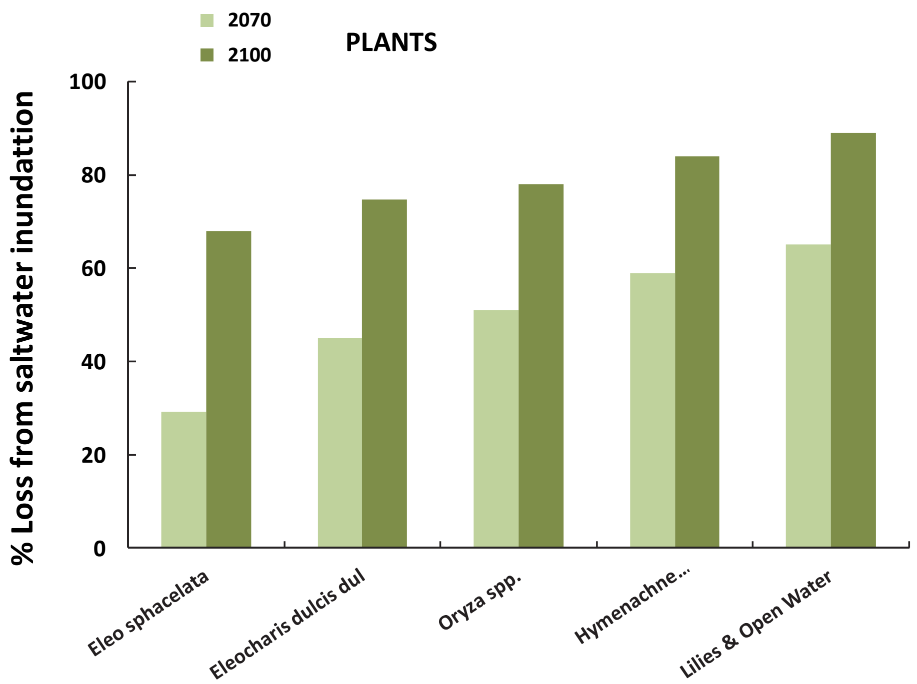
Figure 13a-d. The intersection between the frequency and extent of SWI for the 2070 SLR scenario and modelled presence-absence distributions of (a) Long-necked Turtles, (b) Pig-nose Turtles and Black Bream, and (c) HCVAE 99th percentile values for Kakadu sub-catchments. (d) The frequency and extent of tidal SWI in the dry season for the 2070 SLR scenario for the three case study areas (Boggy Plain, Magela Creek floodplain & Yellow Water wetland).

3.2.3 SUMMARY OF PREDICTED SLR IMPACTS

The predicted loss (%) to SWI of floodplain plant classes mapped by Wilson and Whitehead (1991) in 1990 on Kakadu for the 2070 and 2100 SLR scenarios is graphed in Figure 14a and, similarly, for selected bush tucker animal species and the HCVAE99 biodiversity metric in Figure 14b. Both *Eleocharis* species are key seasonal resources for the Magpie Goose, which is a high value bush tucker species in itself. Lilies in open water habitats are also important bush tucker species and include red, blue and yellow/white lilies combined (*Nelumbo nucifera, Nymphaea violacea* & *Nymphoides indica*, respectively).

The increasing trend between the predicted losses (%) of 1990 floodplain plant classes (Wilson & Whitehead 1991) and projected SLR (m) is illustrated in Figure 15a. Similarly, the slight increasing trend between the predicted losses (%) of selected bush tucker animal species and the HCVAE99 biodiversity metric are illustrated in Figure 15b. Because Magpie Geese and these freshwater floodplain plants are entirely dependent on freshwater floodplain habitats they lose out the most with respect to SLR. In contrast, the selected bush tucker animal species that have substantial non-floodplain distributions across the park lose out the least and, similarly, for the HCVAE99 conservation metric. Whilst they all occur in freshwater aquatic habitats they are not restricted to freshwater floodplains.

(a)



(b)

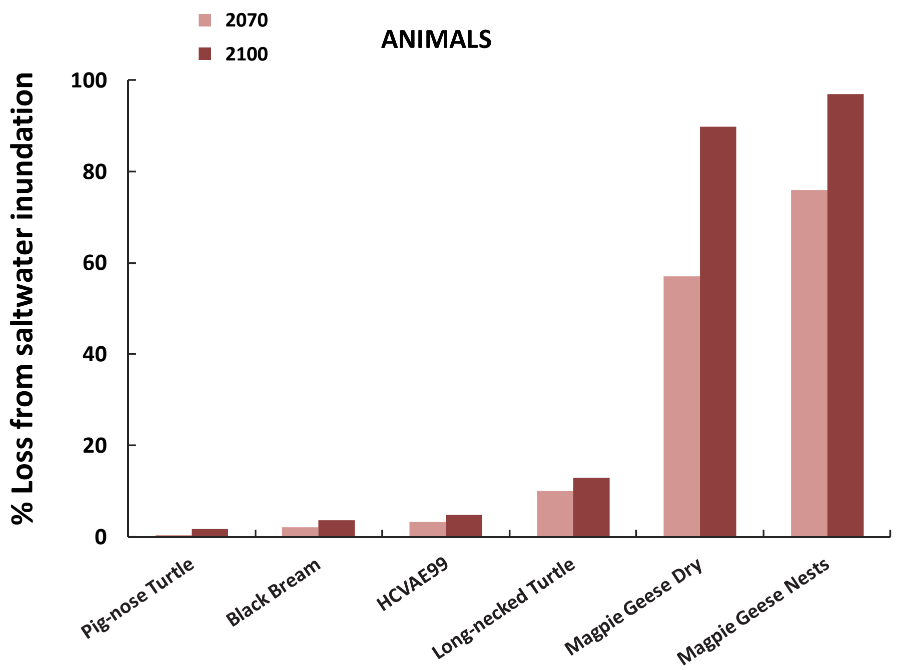
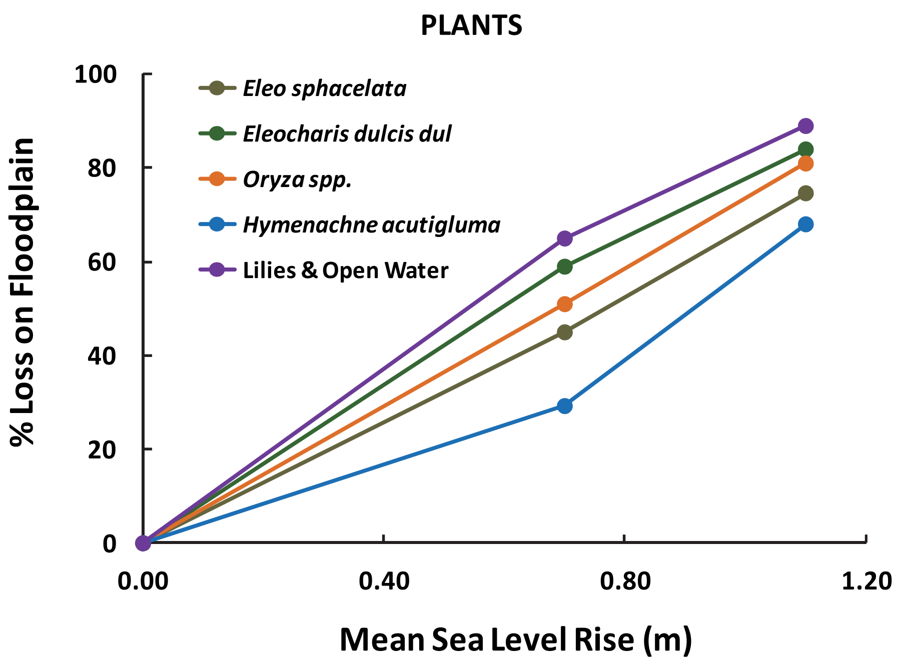


Figure 14a&b. (a) Predicted loss (%) of 1990 floodplain plant classes (Wilson & Whitehead 1991) to SWI for the 2070 and 2100 SLR scenarios. And similarly for (b) selected bush tucker animal species and the HCVAE99 biodiversity metric.

(a)



(b)

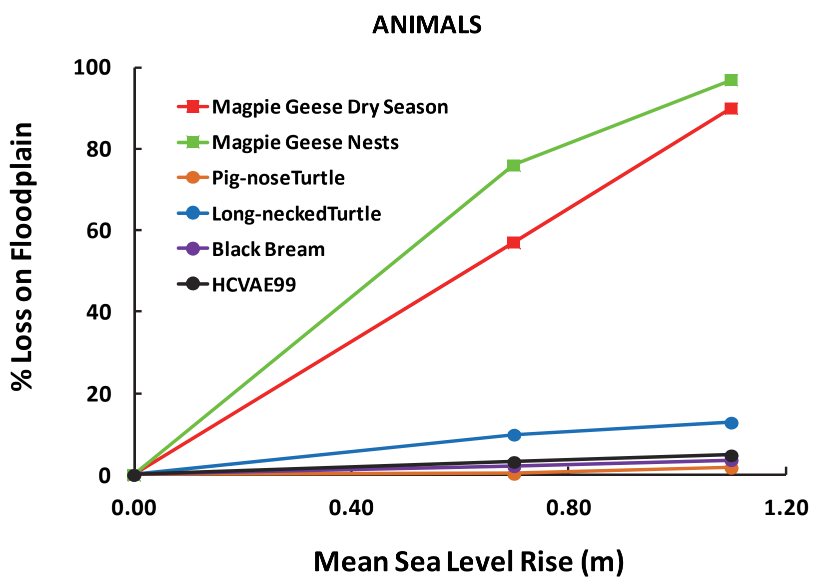


Figure 15a&b. (a) The increasing trend between predicted losses (%) to SWI of 1990 floodplain plant classes (Wilson & Whitehead (1991) and projected mean SLR (m). (b) Similarly for the slightly increasing trend for selected bush tucker animal species and the HCVAE99 biodiversity metric.

3.3 Detailed characterisation of salinity risk profiles

3.3.1 SALINITY TOLERANCES OF FLOODPLAIN PLANTS

The statistical characterisation of the frequency of SWI (%P) in the 2013 dry season for the ARR (Stage 1 SLR model outputs, Saunders et al. 2014) is illustrated in Figure 16a&b. The frequency distribution (PDF) signature of %P values is bimodal most likely reflecting the occurrence of high and low tides. Similar statistical characterisations were obtained for the following saline habitats: mangrove (Fig. 16c&d); saltpans (Fig. 16e&f); saltpans dominated by samphire vegetation (Fig. 16g&h); and water/terrestrial environments (Fig. 16i&j). In general, the Cumulative Frequency Distribution (CFD) curves of the frequency of SWI (%P) for all four saline habitats are similar, albeit with mangroves occurring in places with a greater range of SWI (Fig. 16k). The latter result may reflect the fact that most mangrove species are able to tolerate a wide range of salinities and are found growing in gradients from seawater to freshwater (Ball & Pidsley 1995).

On average at least two spring and neap tide periods occur each month. The SLR simulations in Stage 1 modelling encompassed one neap and one spring tide period in the first half on October 2013, and the proportions of spring and neap tides periods would remain the same for the entire month. Floodplains inundated at 100% frequency (%P) in October would experience ~ 31 spring and 31 neap tides, or about 16 spring high and 16 neap high tides (~ 8 days or 180h of exposure duration to tidal waters). A 1%, 30% and 50% frequency of SWI would experience exposure durations to tidal waters of ~2h, 54h and 90h per month, respectively.

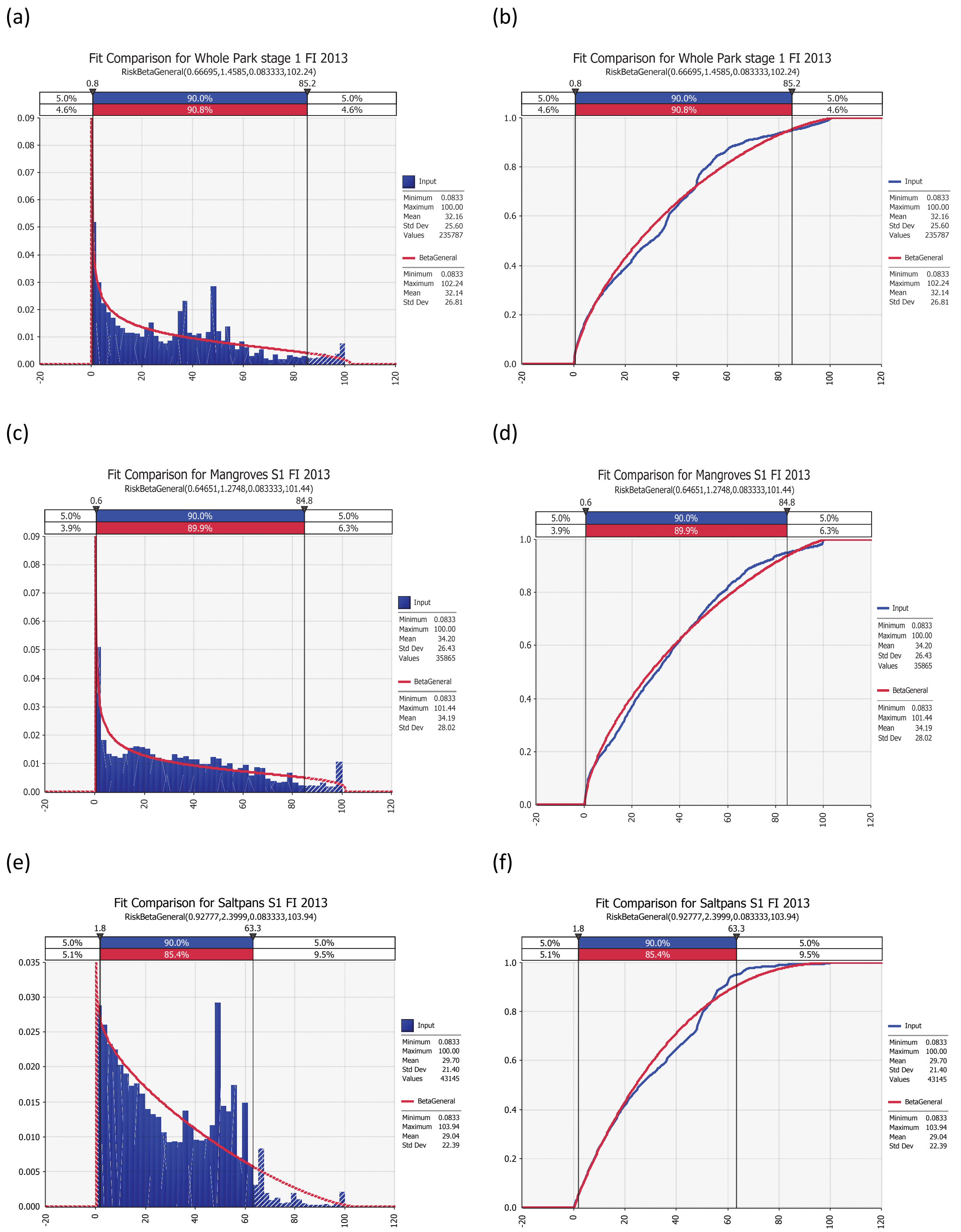


Figure 16a-f. (a&b) Statistical characterisation (Probability Distribution Function PDF & Cumulative Frequency Distribution Function CFD, respectively) of the frequency of SWI in the 2013 dry season using October tides and Stage 1 SLR model outputs for the whole park (Saunders et al. 2014). Similarly for the following saline habitats: (c&d) mangroves; (e&f) saltpans; (g&h) saltpans dominated by samphire vegetation; and (i&j) water & terrestrial environments. (k) CFD profiles for all four saline habitats combined.

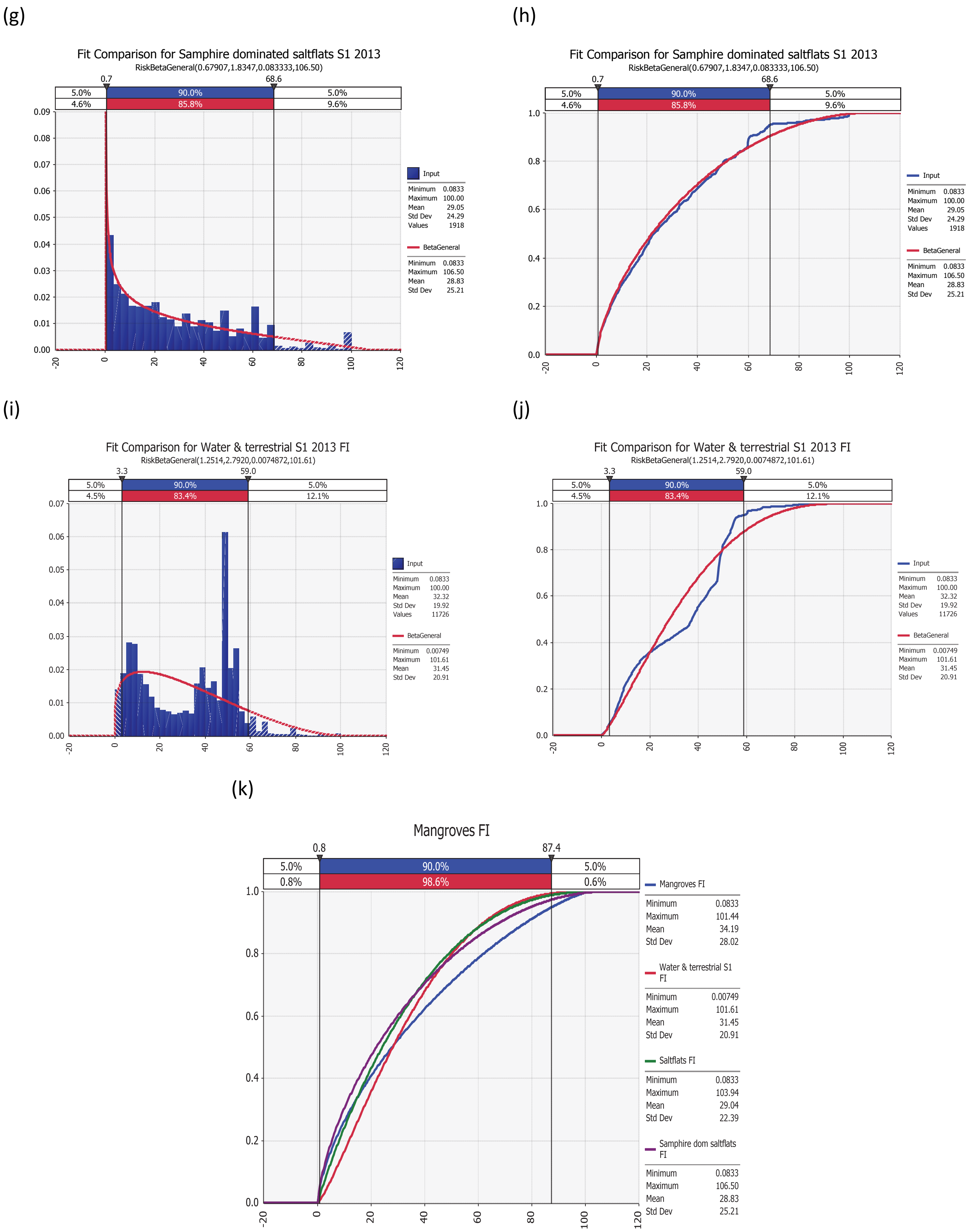


Figure 16g-f cont.

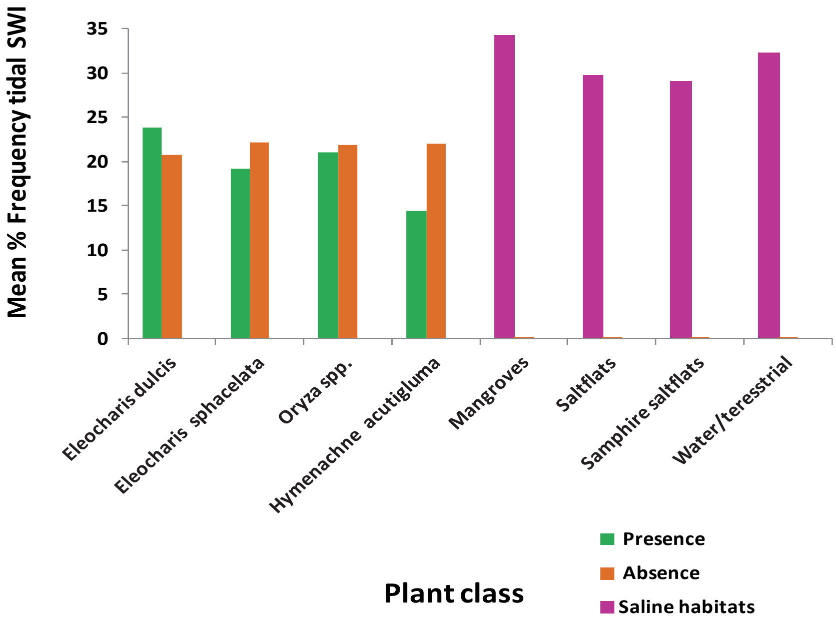


Figure 17. The mean percentage (%P) frequency of tidal SWI in the dry season (October 2013, Stage 1 SLR model outputs) for the presence and absence of freshwater plant classes mapped by Wilson & Whitehead (1991) in 1990, and that for saline habitats (D. Ward, Griffith University). The %P values for the absence of saline habitats are < 2%, approximating the boundary between saline and fresh water habitats.

The mean percentage frequency (%P) of SWI in the dry season (October 2013, Stage 1 SLR model) for freshwater plant classes in the ARR mapped in 1990 by Wilson and Whitehead (1991) is illustrated in Figure 17 and, similarly, for present day saline habitats (D. Ward pers. comm.). Freshwater plants occur in areas with mean %P values ranging between 14-24%, with *Eleocharis dulcis* having the maximum mean value of 24% and *Hymenachne acutigluma* having the minimum mean value of 14%. Freshwater plants are absent in areas where mean %P is ~ 22%. In contrast, the mean %P value for areas where saline habitats are present is ~ 22%, which may demarcate the approximate boundary between saline and freshwater habitats. *E. dulcis* is the only freshwater plant class that had mean %P values greater in areas where they were present than where they were absent. The mean %P values for areas where saline habitats are absent are <2%.

Figure18 is a Tornado graph that ranks published salinity tolerances (Appendix B) of freshwater wetland plants listed on Kakadu by Finlayson et al. (1989, 2006), Cowie et al. (2000), Cowie (2003), Camilleri (2004) and available unpublished species lists (Bayliss pers. comm.). Where a range of estimates for a species is provided in the literature the mean value was used. Whilst Hart et al. (1991) suggested that the salinity tolerance threshold value for freshwater biota is about 1ppt; there is obviously variation between and within species, and between locations (Howard & Mendelssohn 1999). Salinity tolerances reported in the literature for freshwater plant species or genera that can occur on Kakadu floodplains ranged between 0.0009ppt (Buffalo clover, *Alysicarpus vaginalis*) to 37.25ppt (Rudravanti, *Cressa cretica*). The typical salinity range found for freshwater and riparian plants in this review is ~<2ppt (Hart et al. 1991, James & Hart 1993, Neilsen et al. 2003, Cowie 2003).

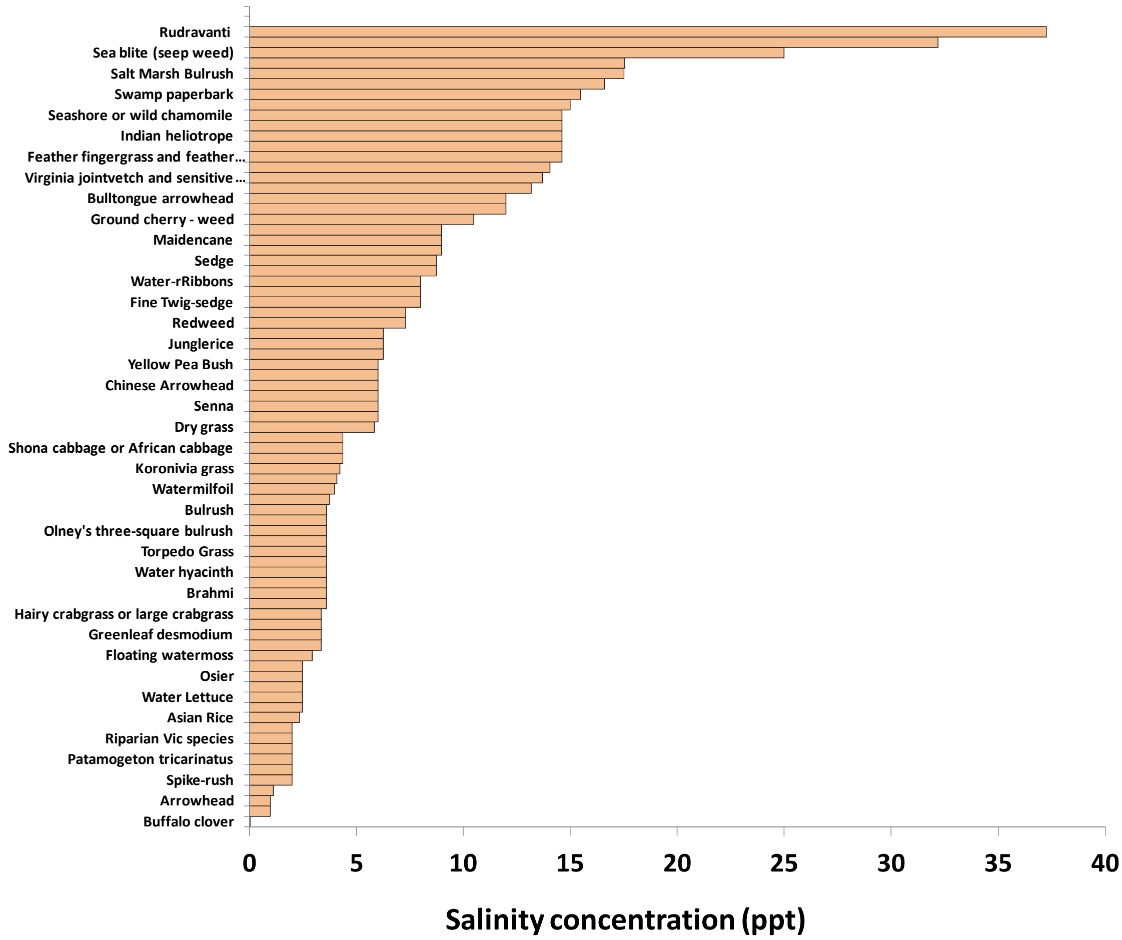


Figure 18. Tornado graph ranking published salinity tolerances (Appendix B) for freshwater wetland plants listed on Kakadu National Park.

The Bailey et al. (2002) national salt toxicity data base was used to statistically characterise their salinity tolerances using a Species Sensitivity Distribution (SSD) ecotoxicological model. Figure 19a&b illustrates the Relative Frequency Distribution (RFD) and associated Cumulative Frequency Distribution (CFD) fitted to the salt toxicity data base using various assessment endpoints reported in the literature (Best Fit model is Log Normal). Similarly, the statistical distribution of salinity tolerances for plants only in the data base is illustrated in Figure 19c&d (BestFit model is Inverse Gauss). The statistical distribution of species-specific salinity tolerances of wetland plants that occur on Kakadu (see Appendix B) is illustrated Figure 19e&f (BestFit model is Log-Logistic).

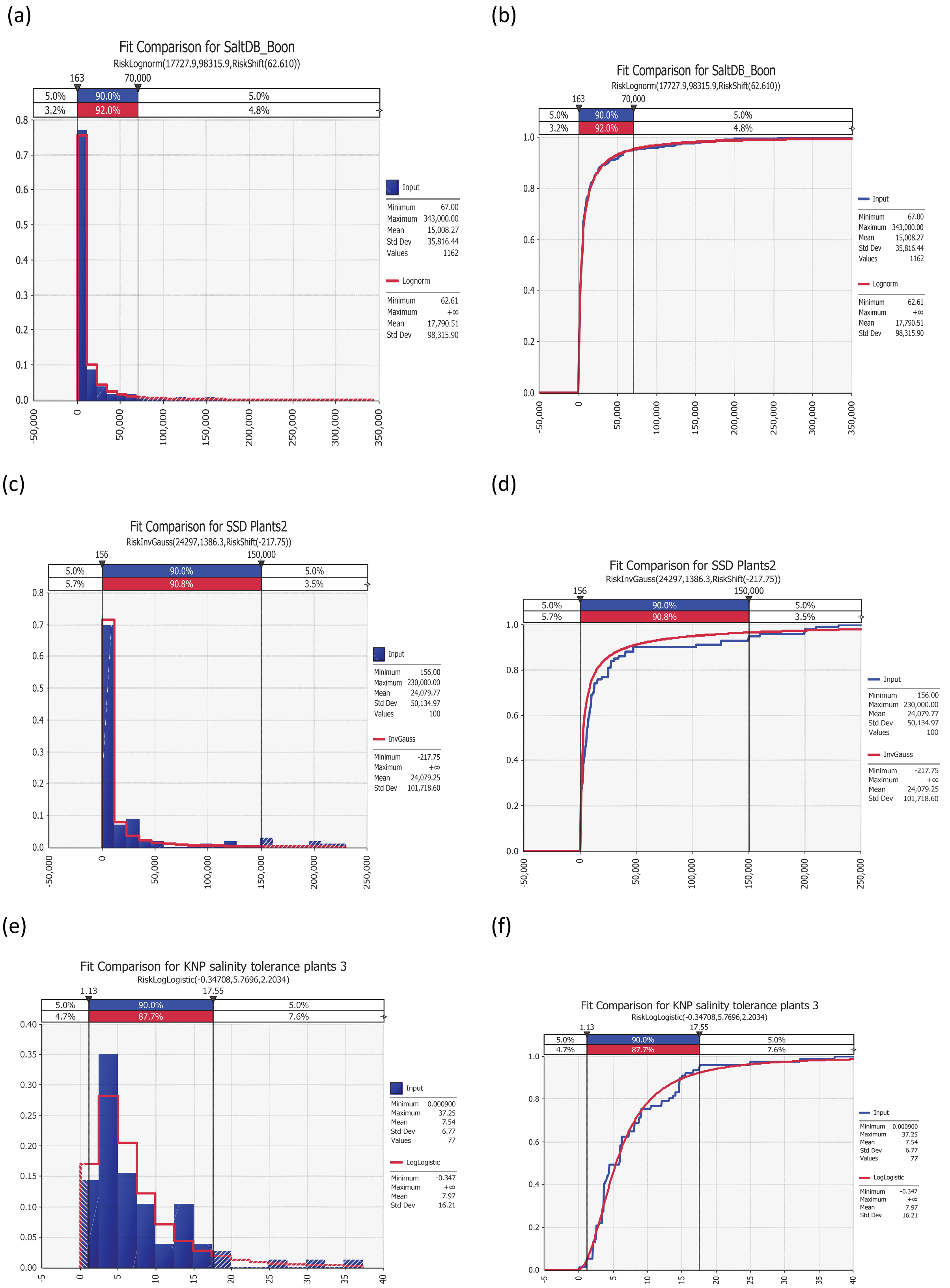


Figure 19a-f. Salt toxicity thresholds. (a&b) The Species Sensitivity Distribution (SSD; Relative Frequency Distribution & Cumulative Frequency Distribution, respectively) of plants and animals to salt concentration (ppt) using the Bailey et al. (2002) salt toxicity data base. The "BestFit" (Palisade 2002) frequency distribution is Log Normal. (c&d) Similarly for plants only in the data base (BestFit is Inverse Gauss), and (e&f) for wetland plant species that occur on Kakadu (BestFit is a Log Logistic).

3.3.2 CASE STUDY WETLAND SITES

Magela Creek floodplain

The relationship between mean salinity (per 50m grid cell) derived by independent hydrodynamic modelling of Magela Creek floodplain (D. Williams pers. comm.) and the frequency of SWI (%P) derived by Stage 1 hydrodynamic modelling is illustrated in Figure 20. The %P values on 60m grid cells were re-sampled to a 50m grid. The linear regression equation predicts that when the %P of SWI is zero (i.e. no tidal inundation on floodplains in the dry season) then salinity is ~ 2ppt, approximating the salinity tolerance for freshwater plants found in our literature review and the boundary between the presence and absence of saline habitats. However, the regression SE is $\pm$ 4.9 encompassing model error and many underlying assumptions. The minimum %P value of Stage 1 model outputs is 0.08%.

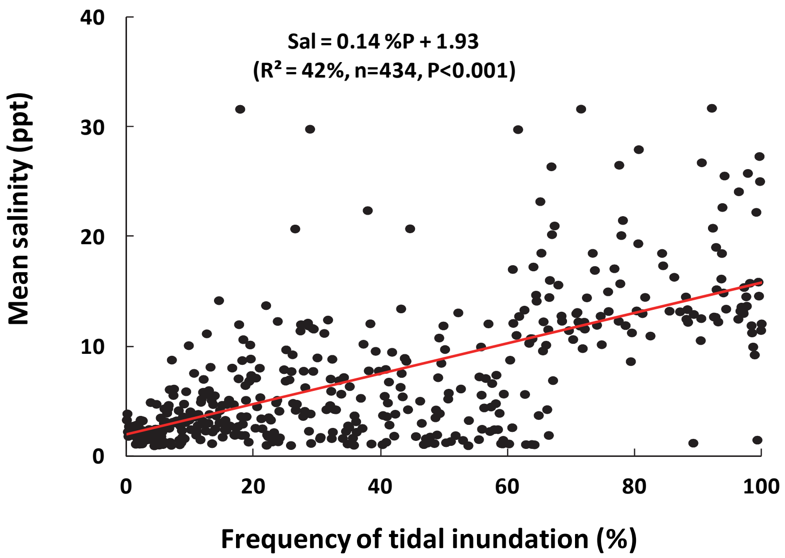
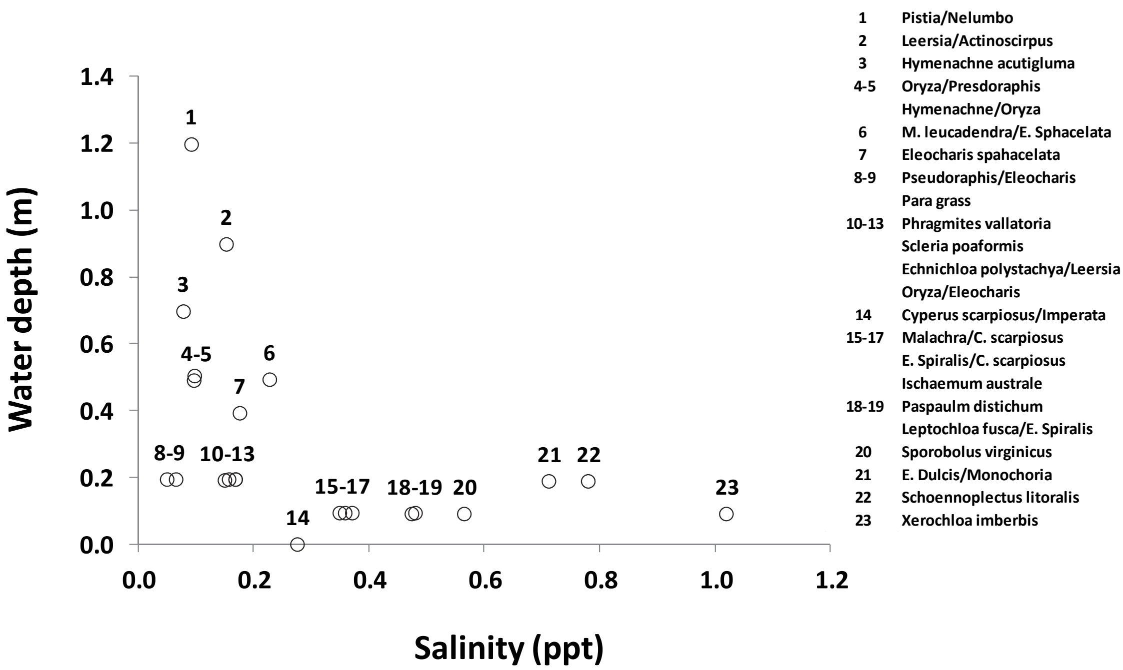


Figure 20. Relationship between mean salinity on Magela Creek floodplain derived by independent hydrodynamic modelling and the frequency of SWI (%P) derived by Stage 1 SLR modelling. Salinity ~ 2ppt when %P of SWI = 0 (i.e. no tidal SWI in the dry season). Regression SE $\pm$ 4.9.

The relationship between water depth (m) and salinity (ppt) for wetland plant classes around Darwin Harbour is illustrated in Figure 21a (from Cowie 2003), and that for Magela Creek floodplain in Figure 21b. Whilst water depth and salinity measurements between the two studies are not exactly comparable (water bodies c.f. river floodplains), the relative position of plant classes on both gradient axes is similar. All emergent macrophytes preferred deep water and salinities < 1ppt. In contrast, *Eleocharis dulcis* prefers deep water also but with higher salinity (~2.8ppt). Regression Tree (or Random Forest) models will be used with Stage 2 SLR model salinity outputs for the 2070 SLR scenario across a 60m grid to predict what type of floodplain vegetation is likely to occur there. These relationships will be tightened using Regression Tree (or Random Forest) models to predict the probability of occurrence of key floodplain vegetation classes based on projected salinity and water depth across a fine spatial resolution grid (60m).

(a)



(b)

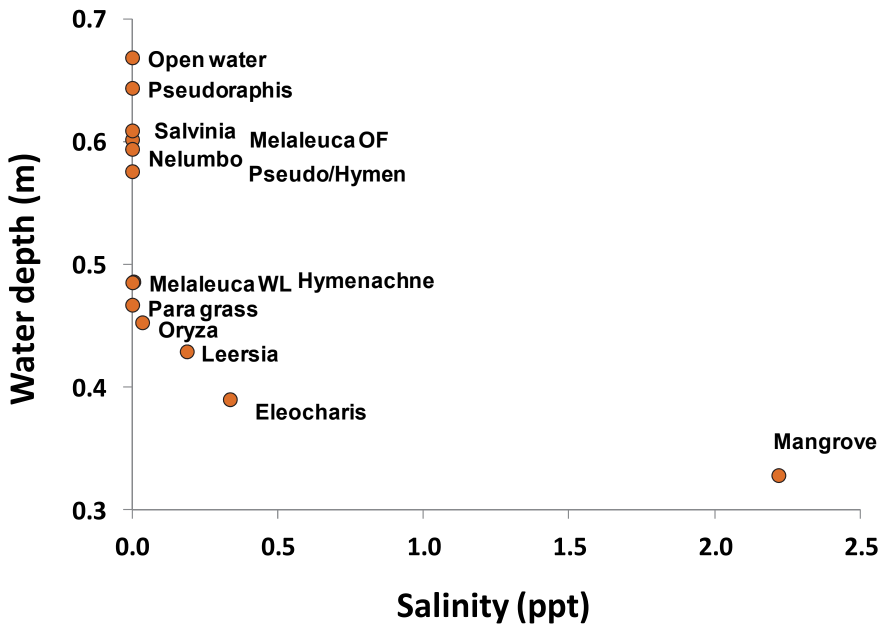


Figure 21a&b. (a) Relationship between water depth (m) and salinity (ppt) for wetland plant classes around Darwin Harbour (from Cowie 2003) and (b) on Magela floodplain (as mapped by Whiteside & Bartolo 2014 in 2010).

Boggy Plain

The salinity profile of Boggy Plain during a King High tide in November 2012 (P. Christophersen & S. McGregor, pers. comm.) is shown in Figure 22a (see Box 22d for salinity ppt colour codes). The saltwater intrusion extends to what's called the "fault line", P. Jolly pers. comm.), and marks the boundary between the SAR and sparsely vegetated saltflats and tidal creeks line with mangroves to the west, and freshwater wetland to the east. Adjacent to this boundary to the east resides the largest patch of *E. dulcis* in the NT (Fig. 22b after Boyden 2004 for March 2004, see Box 22d for % cover class colour codes) and a major feeding ground of Magpie Geese in the dry late dry season (Bayliss & Yeomans 1990b; Saalfeld 1990). The bulbs of *E. dulcis* are a preferred dry season food for Magpie Geese. The fault line marks a sudden 1m increase in water depth (m) (P. Bayliss unpubl. data).

The salinity profile for a 0.7m SLR (2070 scenario) using a local calibration method developed by Dutra et al. 2013) is shown in Figure 22c. Salinity values are for a 50m spatial grid. Sustained salinity values > ~ 2.5 ppt would likely cause *E. dulcis* to die and, in contrast, occasional saltwater flushes from King High tides may produce vigorous growth. Note that there is range of King High tides and that this particular King High (November 2012) is the not the maximum recorded. During greater King High tides the large patch of *E. dulcis* would receive occasional but not sustained salinity flushes.

The Species Sensitivity Distribution (SSD) function for wetland plants on Kakadu to salinity concentration (effects) were combined with the salinity exposures for 2012 and 2070 to undertake a Quantitative Ecological Risk Assessment (ERA) for SLR (after Bayliss et al. 2012). Figure 22e&f illustrates the overlap between the salinity effects and exposure curves for Boggy Plain. There is no overlap in the 2012 exposure curve (Fig. 22e) and as expected no risk from salinity or a 0m SLR. However, in contrast, there the 2070 exposure curve completely overtops the plant effects curve giving an overall risk probability of 1.0 (or 100%). Therefore, just using the proportion of Boggy Plain inundated by saltwater in 2070 (0.84, Table 3) underestimates the risk from SLR because it does not account for the proportion of saline habitats and associated plants with higher salt tolerances.

The relationship between water depth (m) and salinity (ppt) for different wetland plant classes on Boggy Plain in the early dry season of 2003 (from Boyden 2003) is illustrated in Figure 23. Salinity (ppt) and water depth (m) data were calculated across a 50m grid using the locally calibrated empirical method developed by Dutra et al. (2013). Mangroves line deep (1-2m) tidal creek channels on the shallow saltflats adjacent to the SAR and, hence, their water depth readings were adjusted to account for this (blue mangrove symbol in Fig. 23). Even though these results relate to a coastal floodplain under the influence of occasional salinity flushes from King High tides, the relationship between salinity and water depth and the occurrence of wetland plants is similar to that for Magela Creek floodplain (Fig. 21b) and wetlands in Darwin Harbour (Cowie 2003).

Yellow Water

Salinity (ppt) and water depth (m) data were also calculated across a 50m grid on Yellow Water using the empirical method developed by Dutra et al. (2013) for Boggy Plain. Results show there was no effect of salinity exposure on Yellow Water wetlands during the 2012 dry season, apart from the occasional saltwater flush resulting from very large King High tides. Hence, the abundance and composition of floodplain plant classes would largely reflect differences in water depth (Fig. 21).

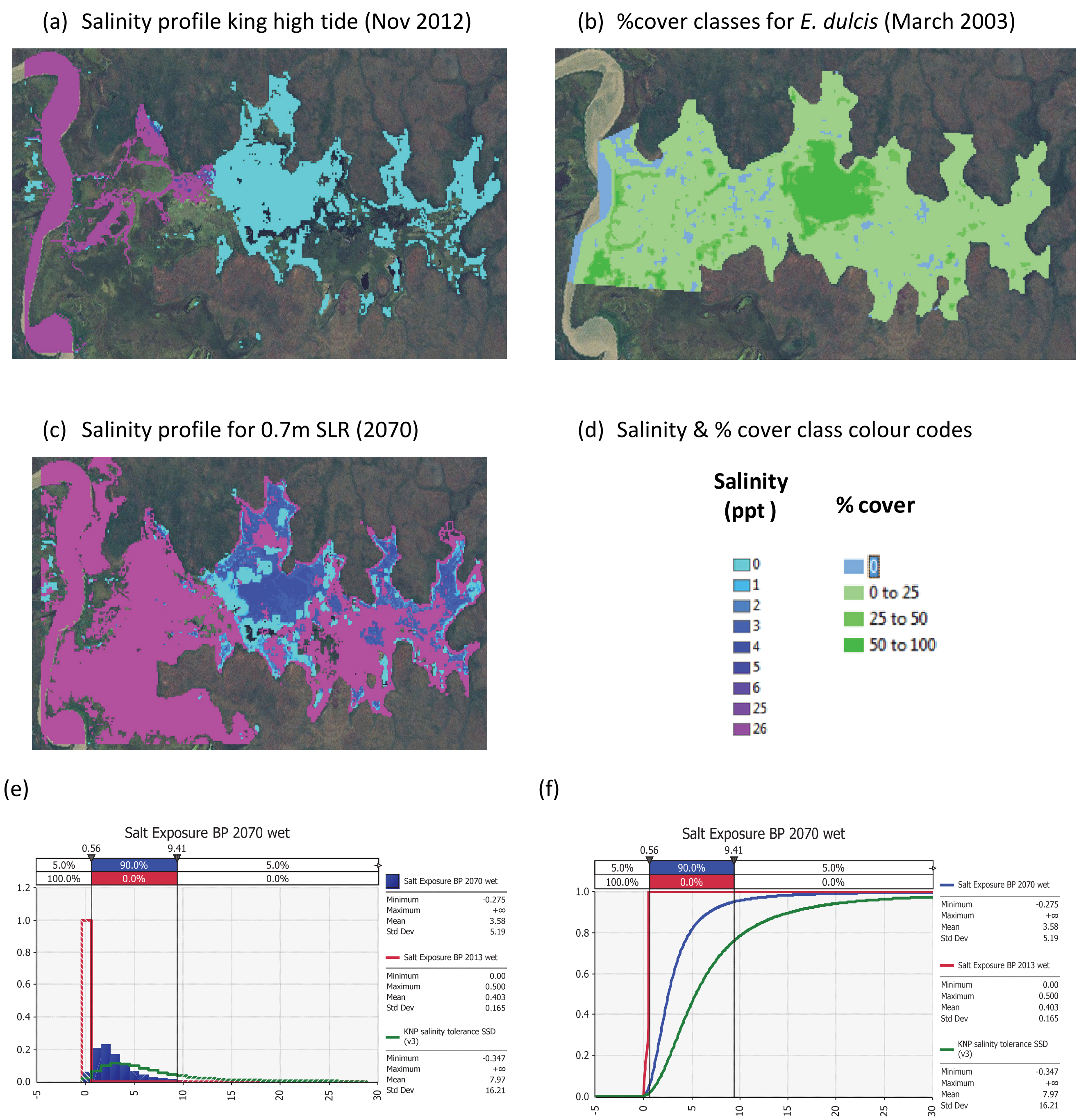


Figure 22a-f. (a) Salinity profile for a King High tide (Nov. 2012) on Boggy Plain (see (d) for colour codes). (b) Salinity profile for a 0.7m SLR derived with a local calibration method (Dutra et al. 2013). (c) % cover classes for *Eleocharis dulcis* (March 2003; see (d) for colour codes) showing a high density patch in the middle of the swamp. (e&f) Overlap between the salinity effects and exposure curves for Boggy Plain, and the combined PDFs for the effects (SSD) and exposure functions with the overlap measuring risk (0m SLR c.f. 0.7m SLR). There is no overlap (or salinity risk) of the 2012 exposure curve, in contrast to a 100% overlap for the 2070 exposure curve.

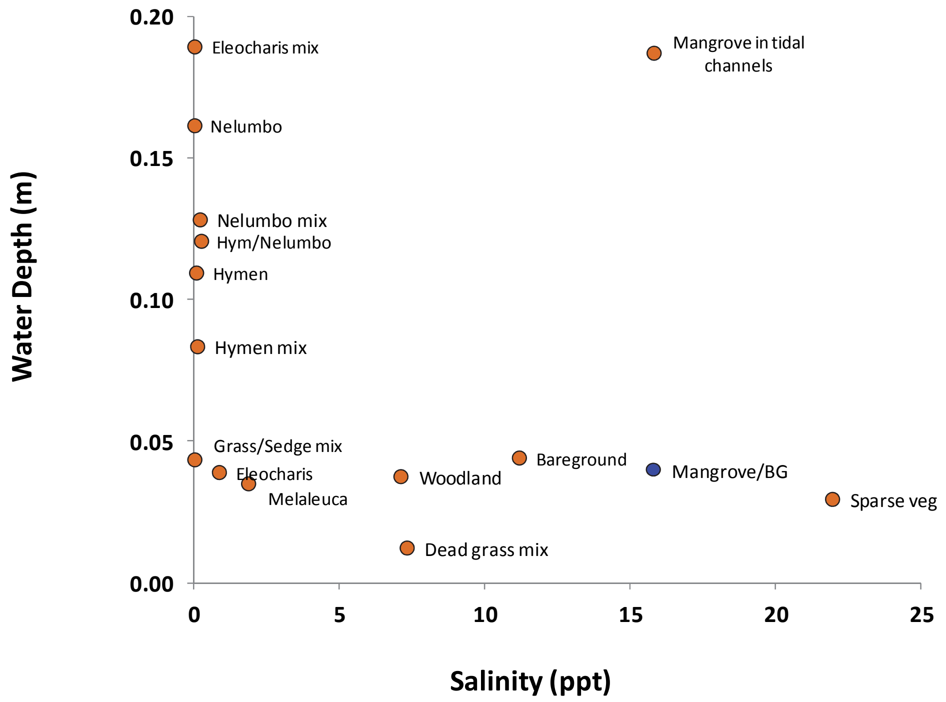


Figure 23. Relationship between water depth (m) and salinity (ppt) for different wetland plant classes on Boggy Plain in the dry season of 2003. Water depth readings for mangroves are adjusted (blue mangrove symbol; see text).

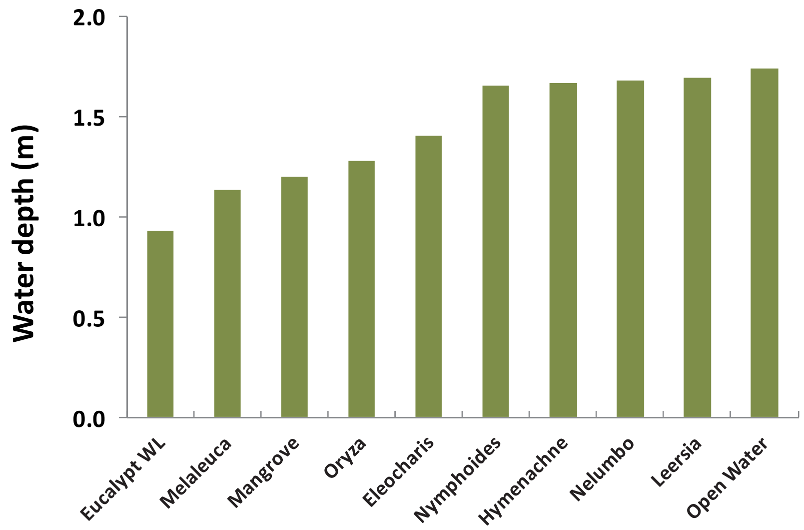
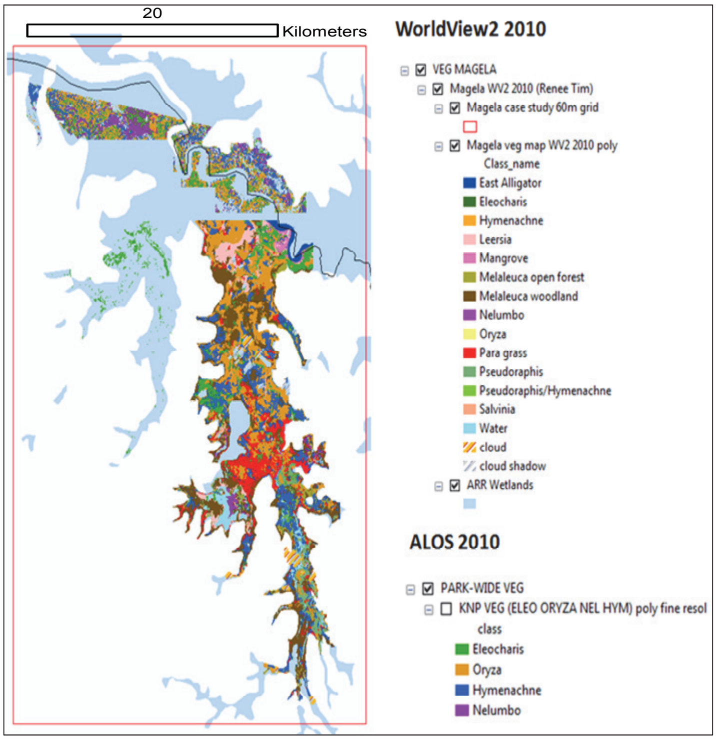


Figure 24. Relationship between water depth (m) and plant class on Yellow Water wetland. The high resolution 2012 WorldView2 vegetation map was used (Anstee et al. 2014, Fig. 25c).

(a) High resolution vegetation map of Magela Creek floodplain (WV2 May 2010)



(b) High resolution vegetation map of Boggy Plain on the SAR (WV2 2012)

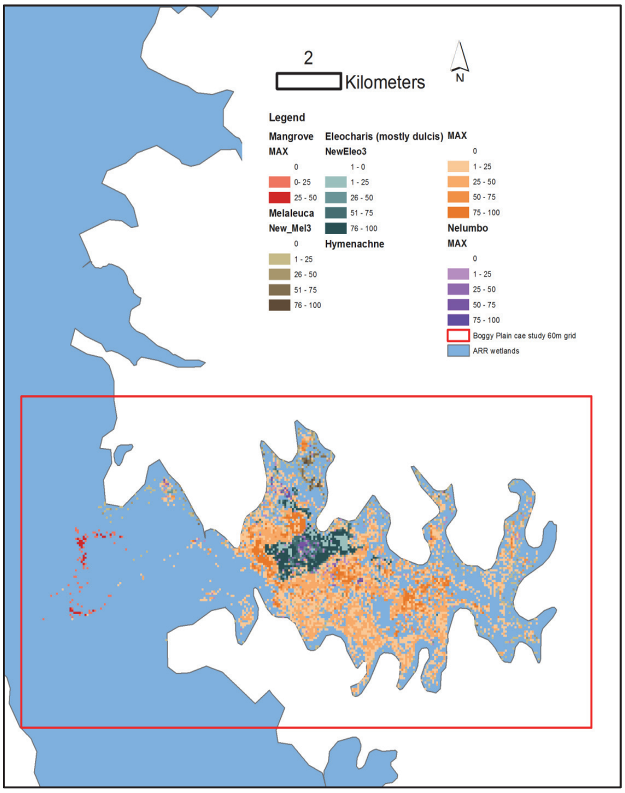


Figure 25a-c. High resolution floodplain vegetation maps for (a) Magela Creek floodplain, (b) Boggy Plain and (c) Yellow Water wetland (see Anstee et al. 2014).

(c) High resolution vegetation map of Yellow Water wetland (WV2 2012)

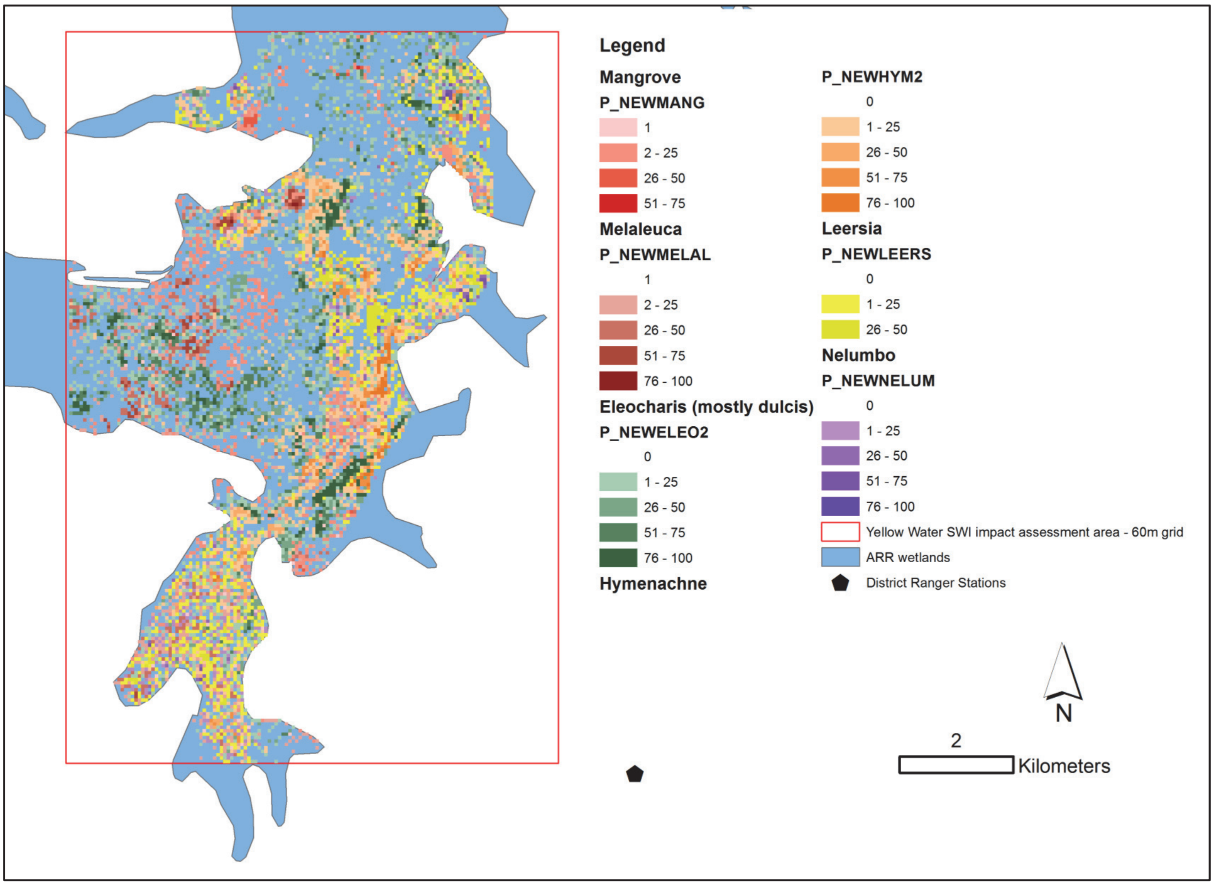


Figure 24c cont.

Other high resolution floodplain vegetation maps

As part of the NERP Project 5.3 Anstee et al. (2014) produced high resolution floodplain vegetation maps for the three case study areas using WorldView2 (WV2) satellite images (Magela, May 2010; Boggy Plain, July 2010 & June 2012; Yellow Water, July 2010 & June 2012). Additionally, a medium resolution 2010 ALOS satellite image was obtained for parts of the park. The overall accuracy of the floodplain vegetation classification results were 64% and 26% for the ALOS South Alligator River and Magela Creek images and 87% and 88% for the WorldView2 Boggy Plains 2010 and 2012 images (& presumably for Yellow Water). Because of the low classification results for the ALOS images they were not used in our assessments, but re-sampled to the 250m weeds grid and displayed as Google Earth layers for communication purposes during participatory workshops. The WV2 vegetation map for Magela Creek floodplain was also not used for detailed analysis given that a map with greater coverage and classification rate had been produced by Whiteside and Bartolo (2014), although still with a large gap in coverage between the East Alligator River and the top of the floodplain (the "Max" gap; see Fig. 25a).

The 2012 WV2 images for Boggy Plain and Yellow Water are of exceptional quality and will be used in more detailed site-based risk analyses using a range of simulated water depth and salinity metrics from Stage 2 modelling outputs after they have been reviewed. In the interim, the high resolution 2m pixel data for Boggy Plain and Yellow Water have been re-sampled to the 60m grid used for simulated salinity and water depth outputs for both Stage 1 and 2 SWI models. The production of one mapping layer of single vegetation classes such as the Magela map means that much high resolution information and discrimination is lost. We therefore adopt a different approach that suites the purposes of detailed quantification of risks at smaller scale, but which likely does not suite the communication purposes of a standard wall map. High resolution WV2 plant classification data are re-sampled to the 60m SWI modelling grid and presented and used as separate data layers expressed on a percentage cover basis (Fig. 25b&c for Boggy Plain & Magela floodplain, respectively).

3.4 Other landscape threats – aquatic weeds & pigs

As a lead into Part II of this report (Integrated assessments) we finalise our risks assessments here by exploring the interactions between invasive species and SLR risks to floodplain values, given that they have different risk characteristics in themselves and will undoubtedly influence how each is managed in isolation or in combination. We choose Para Grass and feral Pigs for invasive species because their risks are current and extensive on Kakadu (see McAlister et al. 2014 & Boyden et al. 2008, respectively). For demonstration purposes other aquatic weed species are ignored. We choose the 2070 scenario for SLR risk given that in our simulations SWI effects do not manifest until then. Additionally, in the 2100 scenario, all floodplains on Kakadu are close to being lost anyway, leaving very little room to consider adaptive management options other than to retreat inland to a completely different landscape and context. Invasive species risks are here and now and, in contrast, risks from SWI in 2070 are 55 years in the future. The effects of SLR are irreversible in contrast to the effects of invasive species, which are reversible given investment in management control and, at worst, investment in restoration. For the purposes of this "what if" exercise in demonstrating integrated assessment we choose Magpie Geese refuge areas from SWI in 2070 for nesting and dry season feeding, and assume that the threats from feral Pigs and Para Grass are managed to current levels for 55 years. We assume also that unmanaged fires in both terrestrial and floodplain habitats are in fact well managed and need not be considered here.

Component 3 of the NERP Floodplains project (Threat from weeds & their management) deals specifically with the threat from Para Grass and Olive Hymenachne (*Hymenachne amplexicaulis*) to floodplain values and is reported separately. The largest core infestation of Para Grass occurs on the Magela Creek floodplain (Bayliss et al. 2012; Setterfield et al. 2014), with high levels of infestation also found on the Wildman River floodplain and with smaller patches occurring on the West and South Alligator floodplain margins (McMaster et al. 2014). The park-wide distribution and abundance of Para Grass based on percentage cover classes on a 250m grid are averaged up to the 2.7km aerial survey grid used for Magpie Geese and pig damage. Similarly, the frequency of SWI on the 60m park-wide grid is averaged up to the 2.7km grid.

The distribution of Magpie Geese nesting and dry season Hotspots is illustrated again in Figure 26a and is used as a reference baseline for the following visual impact assessments. Figure 26b shows the intersection between the seasonal habitats (Hotspots) of Magpie Geese and pig damage. Large areas of nesting habitat (colonies) on the Wildman River floodplain, the west bank of the South Alligator River floodplain, and the northern section of Magela Creek floodplain, are free from the risk of pig damage. However, in contrast, large areas of dry season feeding habitat comprising extensive stands of *E. dulcis* are at risk from pig damage, an unsurprising result given that they also consume large quantities *E. dulcis* bulbs in the late dry season as water level recedes. Figure 26c shows the intersection between Para Grass and the magpie Geese seasonal Hotspots. All dry season Hotspots are not at immediate risk from Para Grass, particularly on the SAR floodplain. Similarly, there is little interaction between goose nesting Hotspots in the western rivers and along the SAR corridor. In contrast, however, goose nesting Hotspots on the Magela floodplain is at serious risk from Para Grass. Figure 26d is the equaliser, and shows major intersections between SWI and both goose nesting and dry season habitat Hotspots with small remnant refuge areas identified in the upper reaches of all floodplains. Figure 26e illustrates the intersection of all risks to goose nesting and dry

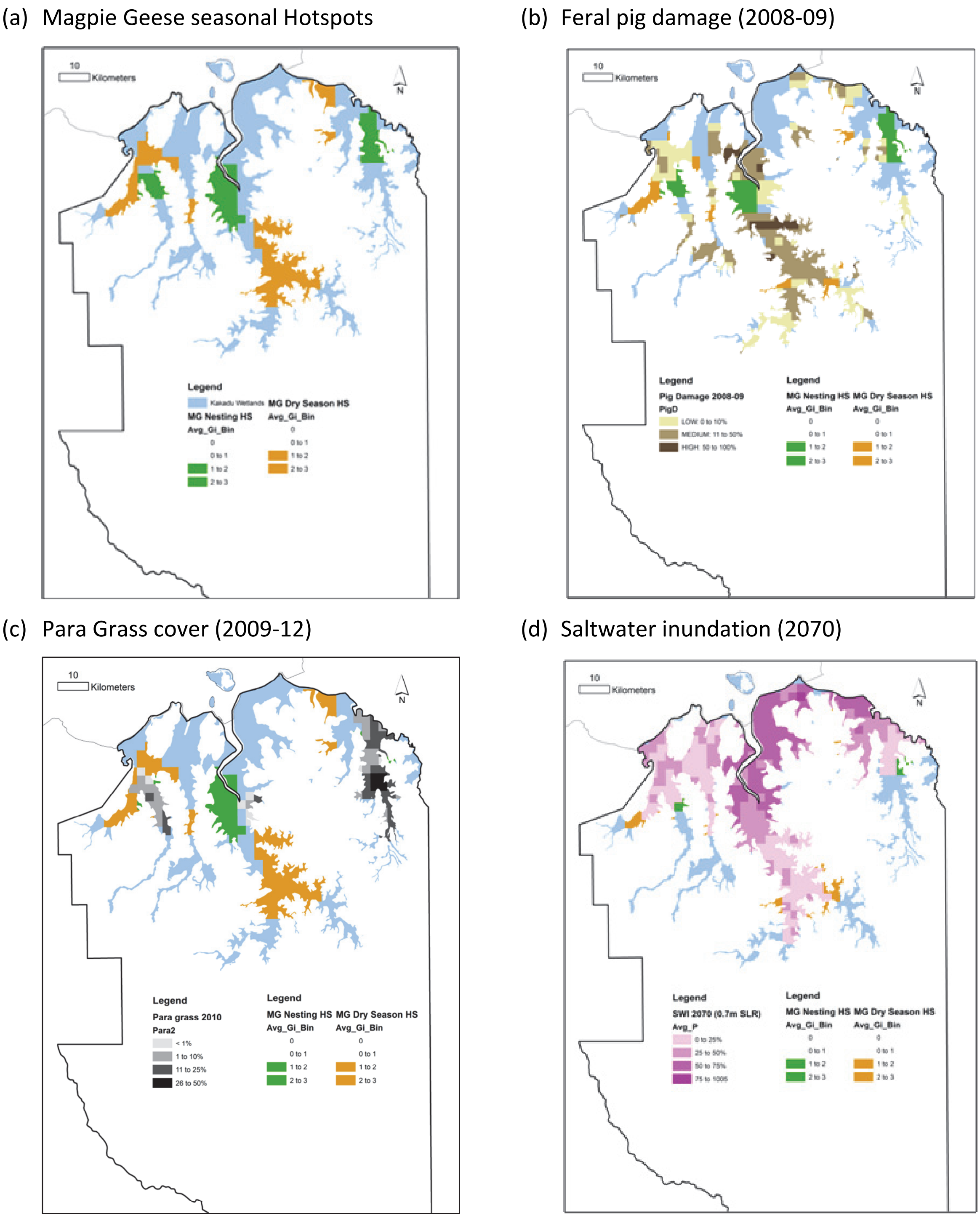


Figure 26a-e. Distribution and abundance of (a) feral Pig Damage (% cover) ascertained by fixed-wing aerial survey in November 2001 and 2003 (from Boyden et al. 2008), and (b) Para Grass (% cover) ascertained by helicopter aerial survey in 2010.

season refuge sites and highlights areas that reversible invasive species management actions that can be implemented, although at present they could be considered too costly. This rapid assessment indicates that intensive pig control is required in the few remnant areas of goose dry season feeding habitats, and that for nesting the extensive patch of Para Grass on the central Magela floodplain would now need to be actively controlled and, if necessary, rehabilitated through revegetation of native plants. Without considering the future impact of SLR the cost of controlling this patch of weed in present day terms may be deemed too costly. Nevertheless, the 2100 SLR scenario needs to be considered also as most floodplains on Kakadu are predicted to be lost to SWI. A mitigating factor in considering this worst case scenario however, is that we could not model and predict the creation of new freshwater floodplain habitat as the sea moves further inland because of constraints with the DEM hugging the current floodplain boundary. We therefore recommend that such additional modelling be undertaken as a high priority.

(e) Combined risks to Magpie Geese SWI refuge areas from Pigs & Para Grass

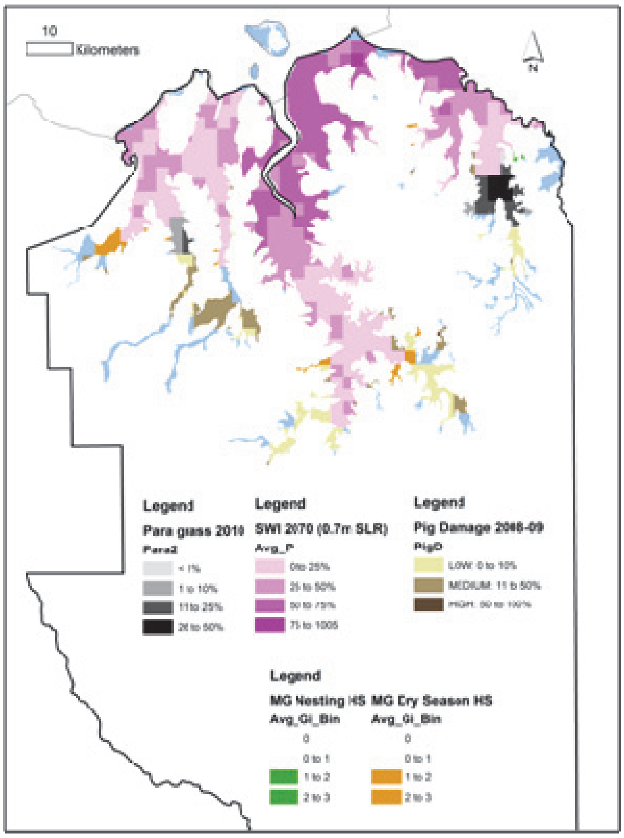


Figure 26e cont.

4 Discussion

Global SLR predictions & uncertainty

Woodwroth et al. (2011) report that acceleration in mean sea levels between the nineteenth and twentieth century is evident in both tide gauge and saltmarsh data at different locations around the world, with the most rapid changes in the rate of SLR occurring around the end of the nineteenth century suggesting anthropogenic causes. They report also that at most locations in Europe and the Mediterranean that they examined, the rates of change of extreme and mean sea levels are comparable. Nevertheless, the rate and magnitude of future climate-induced SLR still remains uncertain. Nicholls et al. (2011) state that the largest source of uncertainty is the response of the large ice sheets of Greenland and west Antarctica to global temperature increases, concluding that increased understanding of climate-induced processes that could contribute to rapid SLR is needed in order to produce better models to quantify likely future rises more precisely. Weber et al. (2014) examined climate model simulations with freshwater forcing and suggest that small perturbations to the Antarctic Ice Sheet can be substantially enhanced, providing a possible mechanism for rapid sea-level rise. Nick et al. (2013) report that over the past decade ice loss from the Greenland Ice Sheet increased as a result of both increased surface melting and ice discharge to the ocean, but nevertheless state that quantifying the future dynamic contribution of such glaciers to SLR remains a major challenge because outlet glacier dynamics are poorly understood. In contrast to the above, however, Watson (2011) argues that analysis of gauge sites throughout Australasia over the period 1940 to 2000 reveals a consistent trend of weak deceleration in mean SLR albeit punctuated with short period trends of acceleration after 1990.

Despite the uncertainty is SLR estimates there remains global concern that large increases in the twenty-first century cannot be ruled out (Nicholls et al. 2011; IPCC 2007, 2012). Nichols et al. (2011) provided a “pragmatic” estimate of SLR of between 0.5 - 2.0m by 2100 for a temperature rise of 4◦C or more, although with a low probability of occurrence of the upper estimate. They argue that if realized within this range the potential impact would be severe, with the forced displacement of up to 2.4% of global population, and that mitigation and adaptation options need to be assessed urgently. Nicholls et al. (2007b) highlighted that implementing coastal protection infrastructure typically has a lead-time of 30 years or more, and therefore argued that sea level monitoring is required to detect any significant acceleration in the rate of rise in a timely manner.

Hydrodynamic SLR modelling

In addition to new and improved SLR monitoring and enhanced global climate models that incorporate the contributions of ice-sheet melt to SLR, new and improved locally calibrated freshwater and saltwater inundation (SWI) models underpinned by hydrodynamic processes and high resolution DEMs are also required in order to better predict and manage future impacts. Ward et al. (2013) assessed the capacity of optical remote sensing methods to monitor the seasonal dynamics of inundation, turbidity and aquatic vegetation cover in the ARR. They found that post-flood waterbody surface area declined by 89% over the dry season with aquatic systems becoming increasingly disconnected, and with 70% of the decline occurring for floodplain water bodies. Ward et al. (2014) then modelled and assessed floodplain inundation and vegetation dynamics in the ARR using optical and radar remote sensing methods, providing a necessary landscape-scale baseline to develop adaption strategies to manage future SLR impacts.

The development of a hydrodynamic model to map the extent of SWI for a given climate change induced SLR scenario in the ARR was staged in two sequential parts to allow the participation of stakeholders in assessing SLR threats. Stage 1 developed a “Bath Tub” type SLR model driven dynamically by dry season tides (October 2013) and projected increases in mean sea level for

Present-day, 2030, 2070 and 2100 climate change scenarios. Model outputs were derived for a high resolution 60m grid across all floodplains in the ARR, and comprised mean water depth (m), maximum extent and the frequency SWI (%F). These outputs were used in all consultations with stakeholders to visualise and communicate SLR risks to natural and cultural floodplain assets in Google Earth since early 2013 (see Part II) and, hence, are used in all assessments reported here.

Stage 2 developed a more complex hydrodynamic model that coupled a rainfall-runoff sub-model to a tidal sub-model for the Present-day and 2070 SLR scenarios only. Model outputs were also derived for the same high resolution 60m grid across the ARR and included both dry (October 2012) and wet (March 2013) season simulations, with the latter including the effects of a heavy rainfall and storm surge event. Outputs included a range of salinity (ppt) parameters, water depth (m) and the extent and frequency of saltwater inundation (% of monthly tides). Stage 2 SLR model outputs will be made available to other researchers on completion of an internal review, and further more detailed assessments of predicted salinity changes on floodplain-dependent plants and animals will be undertaken.

Assessments of the proportion of floodplains lost to SLR were undertaken at a park-wide scale and for the following three case study areas in more detail: Boggy Plain and Yellow Water wetland in the middle and upper reaches of the South Alligator River, respectively; and Magela Creek floodplain, a tributary of the East Alligator River. The predicted proportion of Kakadu floodplains lost to SLR between the Present-day and 2030 scenarios is imperceptible at 3% and, hence, no further assessments of the 2030 scenario was undertaken. However, a threshold apparently exists between 2030 and 2070 where the predicted proportion of floodplains lost to SWI increased rapidly and linearly. By 2070 and 2100 60% and 78% of Kakadu floodplains are predicted to be lost to SLR, respectively. Furthermore, the proportion lost varies by floodplain depending on distance from the sea and tidal influence.

Impact of SLR on biodiversity and cultural values, particularly Magpie Geese

Hence, in addition to increased understanding and knowledge of hydrodynamic processes in the ARR, increased knowledge is also required on ecological processes and, in some places, even baseline information on natural and cultural assets of floodplains (& other landscapes) is required. Whilst Kakadu is a well-researched park with respect to biophysical values and processes, particularly for Magela Creek floodplain downstream of Ranger Uranium Mine (see Bayliss et al. 2012), there remain key knowledge and data gaps for much of its floodplains. Hence, our assessment adopts the following two scales in order to utilise historical data on some wetlands and limited data on others: (i) Whole of Kakadu National Park (& itself nested within the broader Alligator Rivers Region (ARR)); and (ii) for three case study areas that have existing data on floodplain vegetation and waterbird use, particularly for the iconic Magpie Goose (*Anseranas semipalmata*). These are: Boggy Plain; Yellow Water; and Magela Creek floodplain (Fig. 1b). These wetlands are listed also as Ramsar sites in their own right and all lie on a north-south salinity gradient dependent on tidal influence or roughly distance from the coast. The ARR encompasses the Wildman (WR) and West Alligator (WAR) rivers to the west, and the South Alligator (SAR) and East Alligator (EAR) Rivers to the east with the EAR including the Magela Creek system.

Although Magela Creek floodplain and Boggy Plain both exhibit a threshold effect for the predicted proportion of floodplain lost to SLR between 2030 and 2070 as for the whole park, their ecological impacts will be different dependent on the proportion of saline habitats present. For example, a Quantitative Ecological Risk Assessment (QERA) was undertaken for Boggy Plain that combined predicted salinity exposures for the 2070 SLR scenario with plant-salinity effects data. Results show that whilst the proportion of floodplain lost to SLR in 2070 was 84%, the ecological risk to freshwater plants was 100%. The flow-on effects to animals dependent on floodplain plants for habitat would also be substantial, such as for Magpie Geese given its evolutionary dependence on Water chestnut (*Eleocharis dulcis*) as a major late dry season source of high value food required for survival and nesting (Bayliss & Yeomans 1990b; Traill et al. 2010). Previous aerial surveys of Magpie Geese in the Top End of the NT suggests that 70-80% of the entire NT population feeds on Water Chestnut bulbs in the late dry season on Boggy Plain, in addition to stands in the nearby Mumukala wetlands on the Noulangie Creek system of the SAR (Bayliss & Yeomans 1990b; Saalfeld 1990; Whitehead 1998; Delaney et al. 2009). As verified by a high resolution Quickbird^{TM} vegetation map produced by Boyden et al. (2004), and subsequently by Anstee et al. (2014) using WorldView2 satellite captured in 2012, Boggy Plain has a very extensive stand of water Chestnut and is most likely the most extensive in the Top End of the NT and possibly Northern Australia (Bayliss & Yeomans 1990b). Hence, the loss of this wetland to SLR and other similar wetlands on the SAR system to SLR would have a major impact on the abundance of Magpie Geese at all scales: in the ARR; across the NT; and likely across Northern Australia.

The most comprehensive study of the interaction between Magpie Geese and their principal dry season food, the bulbs of *E. dulcis*, is that by Traill and Brook (2011) and is an outstanding benchmark. They described the spatial aggregation of Magpie Geese on Boggy Plain in relation to the dynamics of this ephemeral floodplain. They highlighted that although past broad-scale studies have linked geese to floodplains dominated by the *Eleocharis dulcis* sedge, the type of response has not been determined and nor the impact of their grazing on the dynamics of this species. They examined a range of hypotheses associated with interactive plant-herbivore systems (see Bayliss and Choquenot 2002) using exclosure plots in combination with surveys of grazing (or more “grubbing”) geese density. Their experimental results showed that geese had a clear aggregative response to *E. dulcis* tubers, were forced to depart following floodplain drying, and had a marked negative impact on tuber density. Despite these strong results pointing to an interactive plant-herbivore system they concluded that there was no evidence of a negative-feedback mechanism between plant–herbivore populations and, hence, suggested instead that the system is driven by extrinsic factors such as rainfall (& see Bayliss 1989). Traill and Brook (2011) speculate that floodplain water quality, particularly salinity level, and period of inundation strongly influence the survival of *E. dulcis* plants, and that these require further study.

Other external factors that may affect the distribution and abundance of *E. dulcis* are invasive species such as monoculture of weeds (e.g. Para Grass & *Mimosa pigra*), or even monocultures of native Hymenachne (*H. acutigluma*), and feral animals such as pigs and water buffalo (*Bubalus bubalis*). Traill and Brook (2011) also speculate that past saltwater intrusion associated with feral buffalo damage may have affected Magpie Goose feeding habitats on parts of the South Alligator River and Mary River floodplains (& see Corbett & Hertog 1996). They suggest that the seasonal flooding and drying of tropical floodplains across northern Australia likely allows *E. dulcis* a temporal refuge against bulb predation, which imparts a capacity to regenerate prior to another dry-season cycle of predation exposure. They conclude that the seasonal variation in water levels drives these systems and allows it to persistence.

Feral pigs are known to also consume *E. dulcis* bulbs and were present in high densities in the study area. Traill and Brook (2011) include an additional experimental treatment to account for pig predation on bulbs. A re-analysis of their experimental exclosure data indicates that pigs on their own consumed 46% of available bulbs and that for Magpie Geese 41%. Together they consumed 68% of available bulbs. Water chestnut is a popular permaculture plant given that its bulbs are used extensively in Asian cooking (as “Chinese Water Chestnut”) and, hence, there is much published experimental data available on optimum conditions for growth in the absence of bulb predation. The experimental data of Hopkins (2004) posted on the internet is one example and was re-analysed to examine the relationship between bulb or corm production and stem density of plants. The statistically significant relationship is strongly negative (R^2=99.9%, P<0.001) and if transferable to field conditions would suggest the existence of a strong negative feedback loop between bulb offtake due to predation by pigs, geese or in combination. Hence, further multivariate modelling of the Magpie Goose - *E. dulcis* interaction is required with environmental drivers such as water level and salinity factored in, particularly the latter given that salinity influences the species spatial and temporal distribution (Eliot et al. 1999; Cowie 2003; this study).

Further to the above study that highlighted the importance of salinity to the *E. dulcis* - Magpie Goose interaction, Traill et al. (2010) developed a case study of wetland loss to SLR across tropical north Australia linked to a spatially explicit demographic meta-population model of geese. They used published SLR models through to the year 2400 and found a non-linear trajectory of SWI up to 20m above Present-day. They used coarse DEMs to simulate SLR and the accompanying loss of wetland habitat used by geese, although this was not differentiated into wet season nesting and dry season feeding/roosting sites. Alternative harvest strategies based on present-day estimates of Indigenous and non-indigenous offtake of magpie Geese were also included in their modelling to examine the synergy between wetland loss and hunting on extinction risk. Their results suggest that the widespread and abundant Magpie Goose will collapse to a fragmented population of just a few thousand individuals within the next 200-300 years. This is in contrast to our results using a high resolution DEM and current climate change-induced SLR scenarios, which predict all low-lying freshwater floodplains in the ARR (& by extension coastal Northern Australia) will be inundated by saltwater by the year 2132, 117y from now. This prediction timeframe could be accelerated if future SLR projections show acceleration due to global ice sheets melting. Of more relevance, however, their simulation results suggest that harvests of Magpie Geese could continue up to a ‘‘tipping point’’ of around 5% loss of current wetland habitat, after which populations decline rapidly. The small 5% loss rate as a tipping point is debatable given that floodplains exhibit natural variations in extent over annual and decadal scales far great than this (Bayliss B et al. 1997; Bayliss et al. 2008). Nevertheless, their simulation result simply highlights the fact that at some time in the future remnant populations of Magpie Geese (& many other floodplain biota) would likely need to be managed carefully as a threatened species rather than as an abundant one.

Whilst the focus of our waterbird assessment was on the iconic Magpie Goose because it is also an important bush tucker item for Kakadu Traditional Owners, in terms of biodiversity impact there are many other waterbird species on Kakadu that are dependent on freshwater floodplains for habitat and so deserve attention in any future assessment studies. For example: ducks; egrets; darters; pelicans; herons; ibises; cormorants; grebes; spoonbills; rails; terns and migratory waders (see Bayliss & Yeomans 1990b; Morton et al. 1991; Morton et al. 1993a,b; Chatto 2000, 2006).

The presence-absence distributions of Long-necked Turtles (*Chelodina rugosa*), Pig-nose Turtles (*Carettochelys insculpta*) and Black Bream (*Hephaestus fuliginosus*) on Kakadu sub-catchments reflecting suitable habitat were mapped to assess the degree of overlap with SWI at the 2070 and 2100 SLR scenarios and, similarly, for High Conservation Value Aquatic Ecosystems (HCVAE99). The predicted proportion of all these freshwater bush tucker and high value biodiversity assets lost to SWI was small, ranging between 0.3% and 5.0% across both SLR scenarios, reflecting the fact that they are not confined to floodplain habitats. Whilst Black Bream is a preferred bush tucker item other species of freshwater fish also need to be assessed based on life history attributes (Pusey et al. 2004), known tolerances to salinity and the predicted proportion of habitat lost to SLR (see Bayliss et al. 2011). Additionally, with regards to freshwater fish, other climate related variables need to be examined and an overall assessment undertaken, not just for SLR effects in isolation. Salinity effects may either be exacerbated or ameliorated by changes in water temperature, seasonality, rainfall-flow and so on depending on species life history and habitat attributes. For example, many estuarine fisheries in tropical Australia have freshwater-flow requirements (see review by Robins et al. 2005), and Halliday et al. (2011) found that freshwater flows affect the year-class-strength of Barramundi (*Lates calcarifer*) and other species (see also the review in Bayliss et al. 2014). Although our climate change scenarios predict no change in rainfall pattern, this could change in either direction with improved downscaled climate models.

In contrast to the general lack of knowledge of ecological processes on most freshwater floodplains on Kakadu apart from Magela Creek floodplain, there have been many studies on saltwater intrusion across the park. For example, Winn (1991) studied saltwater intrusion at Point Farewell on the mouth of the EAR and concluded that since 1950 the coastal freshwater wetlands of the ARR have undergone significant morphological change in response to the invasion of saltwater through the landward extension and expansion of tidal creeks. She found that the area occupied by bare saline mudflats on the coastal plain had undergone a 9-fold increase in extent, 64% of the Melaleuca forest had been lost to SWI and the tidal creek had extended 4km inland. Winn et al. (2006) suggested that saltwater intrusion and associated morphological change over time appears to have been driven by drier-than-average monsoonal conditions, low-frequency and low-intensity cyclonic events, and above-average ocean water levels experienced since 1950, particularly since the mid-1980s. These landscape-scale responses to SLR and subsequent saltwater intrusion may be good analogues of what might be expected on the coastal plains with increasing future mean SLR. Cobb et al. (2007) reported that the decadal changes in saltwater intrusion in the coastal wetlands of the ARR has led to encroachment of mangroves, but suggested also that because of Melaleuca regrowth in areas once affected by saltwater intrusion, the observed changes may be part of the natural variability of these systems.

In addition to the above studies, Petty et al. (2005) examined channel changes within the South Alligator River (SAR) tidal interface region from 1950 to 2004. They state that the SAR does not drain water continuously through a channel from its catchment to the ocean as do many other tropical rivers, but instead discharges onto a wetland (Yellow Water), which in turn drains into a mangrove dominated tidal channel that extends ~80 km inland from the coast. The northern end of the Yellow Water billabong system hence marks the boundary between the freshwater system and the tidal limit. They suggested also that the saltwater system is contained by a series of levees at approximately the high Spring-tide level, and that these levees are submerged by seaward flowing freshwater during the wet season. The vegetation classes mapped by Anstee et al. (2014; Fig. 24c) for the Yellow Water case study area reflects this dynamic interchange between freshwater and saltwater systems of the SAR catchment. Wetland vegetation is predominantly freshwater species although a high occurrence of mangroves were also mapped, possibly spread during periods of King High tide, and many mangrove species can live in freshwater environments. Petty et al. (2005) and Bayliss et al. (1997) argue that any significant increase in mean sea level due to global warming will far outweigh the impacts of upstream channel expansion, and likely cause the retreat of freshwater systems within the tidal interface region (Bayliss et al. 1997). Our Stage 1 modelling results for the 2070 and 2100 climate change scenarios support this conclusion.

Better understanding of the effects of salinity on tropical plants & animals needed

High salinity is lethal to freshwater plants and animals because their cells lack water and/or there is an excess of ions (Parida & Das 2005), resulting in a range of toxic effects such as reduced growth, reproduction and eventually death. Hence, the ability of a species to maintain or regulate their optimal internal osmotic concentration against external gradients will determine the salinity tolerance of the species (Hart et al. 1991). Hart et al. (1991) reviewed lethal and sub-lethal effects of salinity on microbes (mainly bacteria), macrophytes and micro-algae, riparian vegetation, invertebrates, fish, amphibians, reptiles, mammals and birds, and concluded that direct adverse biological effects are likely to occur in Australian rivers, streams and wetlands if salinity is increased to around 1000 mg/L or 1 ppt. However, they highlighted also that there is a general lack of data on the sensitivity of freshwater plants and animals to salinity increases. Whilst the driver for their review was the serious agricultural problems associated with dryland salinity and salinity in irrigation regions in southern Australia, their experimental findings are highly relevant to future SWI issues from climate change induced SLR in tropical northern Australia, particularly on high value conservation areas such as Kakadu. Nevertheless, there are variations in salinity tolerance of freshwater biota within species and between locations. For example, James and Hart (1993) reported that four macrophyte species had salinity threshold tolerances of ~2ppt, and Hart et al. (1991) reported tolerance thresholds of ~2ppt for riparian plants. Neilsen et al. (2003) found salinity tolerances for aquatic plants ranging between 1-4ppt (mean of 2.5 ppt), and James et al. (2003) reported that the tolerance levels for submerged macrophytes they studied ranged between 3-6ppt (mean of 4.5ppt). There are few studies of salinity preferences for floodplain plants in the tropics, the study by Cowie (2003) around Darwin Harbour being the notable exception. He reported field salinity values for: *Eleocharis sphacelata* of ~0.60ppt; *Oryza spp* and Native Hymenachne (*H. acutigluma*) ~0.3ppt; and *Peusdoraphis* and Para grass ~0.2ppt. *Eleocharis dulcis* had a higher tolerance for salinity compared to most freshwater aquatic plants (~2.8ppt) and is known to grow vigorously with occasional flushes due to large tides (pers. obs.). Grasses found on the edge of wetlands, such as *Paspalum spp*, *Sporobolus spp* and *Xerochloa imberbis* (Rice Grass) were found to occur in salinities ranging between 2-5ppt with Rice Grass ~4.2ppt. Nikman and McComb (2000) provided estimates of salinity tolerance for a range of Melaleuca species of ~0.16 ppt. Bowman et al. (2010) argued that Melaleuca swamp forests on Kakadu are in retreat due to the synergistic effects of past feral water buffalo damage and climate change (see also Traill & Brook 2011).

In contrast, most mangrove species are able to tolerate a wide range of salinities and are found growing in gradients from seawater to freshwater. Ball and Pidsley (1995) studied the growth responses to salinity in relation to the distribution of two mangrove species (*Sonneratia alba* & *S. Lanceolat*a) found on Kakadu and reported an optimum growth range between 5% of seawater (~<2ppt) up to 50% of seawater (~17ppt). They suggested that seasonal variation in salinity may be an important factor in their survival and explain differences in distribution between the two species. Whilst freshwater floodplain plants on Kakadu are predicted to decline at salinities between 1-2ppt (with the exception of *E. Dulcis*, which may thrive in some places), mangroves may increase in extent given that they prefer a moderate salinity range of 16-50ppt (Ball 1998).

To summarise, James et al. (2003) argued in their review of responses of freshwater biota to rising salinity levels that to maintain biodiversity in aquatic freshwater ecosystems it is important to manage the rate, timing, pattern, frequency and duration of increases in salinity in terms of lethal and sub-lethal effects, sensitive life stages, the capacity of biota to acclimatise to salinity and, last but not least, the long-term impacts on community structure (& see Dunlop et al. 2005; Goodman et al. 2010). They concluded that: we have limited understanding of the impacts of salinity on species interactions, food-web structures and how elevated salinity levels may affect the integrity of communities; little is known about the effects of salinity of complex ecosystem processes involving microbes and microalgae, or the salinity thresholds that prevent semi-aquatic and terrestrial species from using aquatic resources; and lastly the compounding effects of salinity and other stressors are also poorly understood. Their assessment of the state of knowledge of the effects of salinity on freshwater ecosystems is probably as true today as it was about 10 years ago, and even more relevant to tropical systems given that most of the substantive studies on salinity toxicity were undertaken in temperate environments in Southern Australia.

Integrated assessment of other threats (invasive species) over different time frames

The potential of future SLR risk to confound other cumulative risks such as invasive species is examined here, despite the fact that both risks do not interact because their impacts (& hence assessments) operate at very different time scales. For example, the weeds spread and management models are apparently not simulated past 2030 and, in contrast, our simulated SLR impacts do not manifest until 2070. Nevertheless, we can safely assume that invasive species such as feral Pigs and Para Grass will likely still be around in 2070 and that in some form they will interact with each other and with SLR risk. We assume that the interactions are simply additive (i.e. non-synergistic) by virtue of existing in the same space and, in doing so, will confound single threat assessments creating uncertainties. Even so, a comprehensive ecological risk assessment by definition includes all other landscape-scale risks. For examples of the confounding nature of different landscape threats, Douglas and O'Connor (2004) argued that weed invasion changes fire fuel characteristics, and Petty et al. (2005) argued that that in the tidal interface region of the SAR high buffalo densities caused significant channel expansion throughout the 1960s and 1970s before they were intensively culled. Bayliss et al. (2012) overcame potential confounding of effects to a large extent by combining point source risks from Ranger Uranium Mine with landscape-scale risks (SLR, pigs, aquatic weeds & unmanaged fire) by using a Bayesian approach with single and combined risks communicated in a Bayesian Belief Network or BBN (& see Nayak & Kundu 2001; van Puten et al. 2013; Landis 2009). All modelling or assessment methodologies need to explicitly account for uncertainties where possible (Bevan 2000; Burgman 2005).

The final section of Part I of this report (Section 3.4) explores the interactions between threats from SWI and invasive species to Magpie Goose refuge areas for nesting and dry season feeding at the 2070 time frame. For the purposes of this "what if" exercise in demonstrating the power of integrated assessment we assume that feral Pigs and Para Grass are managed to current levels for 55 years, and that unmanaged fires in both terrestrial and floodplain habitats are now managed. Preliminary simulation results at a coarse level of resolution (2.7km grid) show that large areas of Magpie Goose nesting habitat (Hotspot colonies) on the Wildman River floodplain, the west bank of the South Alligator River floodplain, and the northern section of Magela Creek floodplain, are currently relatively free from the risk of pig damage. In contrast, large areas of dry season feeding sites comprising extensive stands of *E. dulcis* are at high risk from pig damage, an unsurprising result given that they also consume large quantities *E. dulcis* bulbs in the late dry season as water levels recede and they become available. All Magpie Goose dry season feeding/roosting sites (Hotspots) are not at immediate risk from Para Grass, particularly on the South Alligator River floodplain. Similarly, there is little interaction between goose nesting sites in the western rivers and along the South Alligator River floodplain corridor. In contrast, goose nesting sites on the Magela floodplain are at very high risk from Para Grass.

Time travel to 2070 and the intersections between SWI and both goose seasonal Hotspot sites are extensive, with small remnant refuge areas identified in the upper reaches of all floodplains. Our visual assessments highlight areas where reversible invasive species management actions can be implemented for net conservation benefit (i.e. not a "sunk cost due to SLR; see Arkes & Blumer 1985, Garland 1991), although they may currently be considered too costly in present day terms because SLR impacts have not manifest. Our integrated assessment indicates also that intensive pig control is required in the few remnant areas of goose dry season sites, and that for nesting sites the extensive patch of Para Grass on the central Magela floodplain should now be seriously considered for active controlled and perhaps restoration through re-vegetation of native wetland plants. Without considering the future impact of SLR, the cost of controlling this weed patch in present day terms may be viewed as cost prohibitive.

However, in terms of avoiding sunk costs in the other direction, the 2100 SLR scenario needs to be considered also as most floodplains on Kakadu are predicted to be lost to SWI. Nevertheless, a mitigating factor in not considering this worst case scenario is that we could not model and hence predict the creation of new freshwater floodplain habitat as the sea pushes further inland over time. The high resolution LiDAR DEM is constraining in that it hugs the current floodplain boundary. We therefore recommend that additional high resolution terrain modelling be undertaken in an envelope surrounding the current floodplain border as a high priority in order to better evaluate future mitigation and adaptive management options.

Part II of this report assesses socio-ecological and cultural aspects of the impacts of SLR, and summarises outcomes of the participatory workshops and interviews used to elicit the small range of management options, in particular potential adaptation responses. A qualitative modelling approach using BBNs to integrate different risks to multiple assets is undertaken. Natural and cultural floodplain values are indexed by assessment endpoints developed here in Part I, given that Magpie Geese are a high value bush tucker species.

To conclude Part II a brief discussion of potential high level adaptive management and policy responses is outlined below, as this “top down” risk management process within broader international, national and regional frameworks will be relevant to Kakadu.

Adaptive Management responses & policy approaches

Climate change threatens the resilience of communities that rely on ecosystems for their well-being. Coastal communities in northern Australia are particularly vulnerable to climate change induced sea level rise impacts because they will exacerbate existing threats to natural and cultural values, such as increasing development pressure and invasive species. These cumulative impacts will reduce opportunities for biodiversity conservation and the growth in ecosystem-based livelihoods such as ecotourism (World Tourism Organisation 2007).

Global sea levels rose 0.17m through the twentieth century and are likely to rise more rapidly through the twenty-first century when a rise of 1.0m or more is possible (Nichols 2011). Despite the uncertainties attached to these predictions there has been a plethora of published works on planning approaches since the late 1990s to help manage the potential impacts of climate change induced SLR (e.g. Nichols & Leatherman 1996; Nichols et al. 2007a,b; Halegatte 2009; Abel et al. 2010; Traill et al. 2011; Nichols 2010, 2011; Inman et al. 2012). The overall consensus of all views is that without adaptation large land areas and millions of people world-wide could be displaced by sea level rise. A key psychological driver for the rapid shift to planning responses in the face of highly uncertain predictions may be the adoption of the ‘commitment to sea-level rise’ philosophy because even if the climate is stabilised immediately, sea levels will continue to rise for many centuries due to the long timescales of the oceans and large ice sheets (Nicholls and Lowe 2006; Nicholls et al. 2006).

Nicholls (2011) suggested that responses can involve climate mitigation (essentially a global response to reduce carbon emissions & temperature) and/ or adaptation (essentially a local response), and argued that a combination of these strategies would be the most appropriate approach to SLR regardless of the level of prediction uncertainty. Furthermore he suggested that adaptation responses can be characterized as either: (i) protect; (ii) accommodate or (iii) retreat, and that these responses need to be integrated with the management of other existing threats. Abel et al. (2011) examined the interaction between future SLR, coastal development and planned retreat as an adaptation option. They developed a generic analytical framework for exploring planned retreat and applied it to South East Queensland and, for a plethora of complex socio-political reasons, found that this option is fast disappearing. To implement planned retreat Abel et al. (2011) argued that significant changes to coastal governance systems would be needed and proposed five guiding principles: (i) allocate authority and resources between levels of governance according to their effectiveness at each level; (ii) strengthen development rules and incentives to relocate as an unwanted threshold is approached; (ii) allow for uncertainties by enabling rules and incentives to be changed when circumstances change; (iv) reassign public and private benefits, costs, risks, uncertainties and responsibilities from governments to beneficiaries of development; and (v) institutionalise catastrophes as opportunities for change, not signals to rebuild. Similarly, Barnett et al. (2013) examined barriers to adaptation to SLR in Australia and found the following five key barriers to implementation of adaptation policy: (i) governance; (ii) policy; (iii) uncertainty; (iv) resources; and (v) psychosocial factors. They suggested that the governance barrier in relation to uncertainty about roles and responsibilities across different levels of government and sectors is one of the most important barriers to adaptation.

Anthoth et al. (2010) modelled the economic impact of substantial SLR and, in contrast to traditional impact assessment, considered impacts after balancing the costs of retreat with the costs of protection, including the effects of coastal squeeze. Their modelling suggested that, while the costs of SLR will increase with a greater rise due to increasing damage and protection costs, an optimum benefit-cost response still remains widespread protection of developed coastal areas. Hallegatte

(2009) examined strategies to adapt to an uncertain climate change and argued that, although difficult due to uncertainties associated with climate change predictions, many long-lived investment decisions already need to take into account climate change. He examined the following five strategies: (i) selecting ‘‘no-regret’’ strategies that produce benefits even in absence of climate change; (ii) favouring reversible and flexible options; (iii) buying ‘‘safety margins’’ in new investments; (iv) promoting soft adaptation strategies; and (v) reducing decision time horizons. He argued that additionally it is essential to consider both negative and positive side-effects of climate change, and any externalities associated with adaptation measures. He suggested that adaptation–mitigation interactions will also necessitate the need for integrated design and assessment of adaptation and mitigation policies.

In contrast to managing the status quo with respect to escalating global change, Hobbs et al. (2011) argued that the inevitable occurrence of widespread “no-analogue environments” and novel ecosystems will render traditional management restoration/intervention goals unachievable. They suggested that returning an ecosystem to even a semblance of an historic state is and will continue to be difficult, if not impossible. Hence, with respect to developing future management options for climate change-induced SLR on Kakadu, this view suggests that future goals need to be carefully considered before evaluating different management strategies, particularly as the original social and ecological context may be completely different after long time frames into the future.

Our final discussion point is that the cultural context of Kakadu with respect to managing future threats from SLR requires more in depth elucidation with Traditional Owners than what was possible over a few years through a series of workshops, interviews and a cultural mapping exercise. This may require a broader multidisciplinary team with a social science skills set than what was available, such as anthropologists and linguists. For example, Reid et al. (2014) reports that a substantial body of Australian Aboriginal stories may exist that represent unique observations of post-glacial increases in sea level from about 13,400–7,500 years BP. They argued that endangered Indigenous languages can be repositories for factual knowledge across time frames far greater than previously imagined, forcing a rethink of the ways in which such Traditional knowledge has generally been dismissed in the human endeavour to respond to anthropogenic climate change.

5 Recommendations

The following recommendations are made based on research gaps identified in Part I of this report, and monitoring requirements that are viewed by Kakadu Traditional Owners as the key strategic and adaptive response to future climate change-induced SLR impacts.

1. That the package of Decision Support Tools developed in this project be continually updated and improved with new knowledge and monitoring data in order to enhance risk assessments. Specifically these are:
   - (i) The Stage 2 saltwater inundation model (post review). Continuous local calibration and validation is required, particularly for high priority management areas identified by Traditional Owners and parks staff. Updates in downscaled regional climate models also need to be incorporated and potential impacts of SWI re-assessed.
   - (ii) The Google Earth (GE) software tool used to visualize and communicate risks during regular consultations (see Part II) needs to be continually updated with new information layers. GE’s video-story telling capability coupled with its ability to zoom-in and out from clan areas to park management zones proved to be a powerful communication and engagement tool. Hence, additional communication modules could be developed by parks staff and TOs

to sustain engagement in the research, which is essentially ongoing. The GE initiative came directly from TOs and parks staff and was in preference to our early use of high end simulation models and GIS, both of which received little traction. A dedicated training course in the use of Google Earth to create story lines would be desirable.

(iii) The integrated assessment framework developed in this report as a proof on concept model on selected threats and assets should be extended to encompass all multiple risks to multiple floodplain. The outputs should then be incorporated into a Bayesian Belief Network (BBN) to capture uncertainties and interactions between different risks. This BBN could also include key social and cultural indicators of floodplain health (see Part II).

2. In relation to 1(i) above, a network of inexpensive tidal gauge/water depth recorders needs to be established on all major rivers and floodplains across the park, and monitoring sites should include inexpensive data loggers that continuously record salinity and other water quality variables. ERISS has the expertise and capacity to implement and manage this network.

3. That dedicated systematic monitoring programs of floodplain threats and assets be developed and implemented and replace the current *ad hoc* opportunistic nature of previous surveys. For example: helicopter weed surveys (including for native floodplain vegetation); fixed-wing aerial surveys of waterbirds and feral animals; and using satellite remote sensing captures to monitor fire scars, vegetation and hydrological condition. The last systematic fixed-wing aerial survey of waterbirds for example, was in 2003 or 12 years ago. Other biodiversity and cultural indicator species need to be identified for future monitoring purposes.

4. That future floodplain monitoring programs are underpinned by careful and cost-effective design, and that they are participatory programs managed jointly with Kakadu Traditional Owners. This will require more effective engagement, consultation and a suite of training programs to build capacity and ensure ownership.

5. There is currently no high resolution LiDAR DEM of adjacent non-floodplain areas across the park needed to model and predict the creation of potential new freshwater wetlands as the sea pushes further inland over time. This is a major gap in knowledge that needs to be filled because it constrains all the assessments presented here to adopt a worst case scenario outlook (which may or may not be correct). Given the cost of LiDAR captures this additional work could focus in areas identified by parks as having management priority.

6. That detailed ecotoxicological studies of the salt toxicities of a range of freshwater plants on Kakadu wetlands be implemented, including laboratory, mesocosm and field studies. ERISS has the expertise and capacity to undertake this research. Our literature review of the salt toxicity of plants that occur on Kakadu floodplains highlighted significant gaps in knowledge for tropical freshwater species in Northern Australia generally. Nearly all of the laboratory and field studies of the salt toxicity of wetland plants were undertaken for species in temperate environments in Southern Australia or overseas. In particular, we recommend experimental studies to test the reproductive capacity of *E. dulcis* under varying levels of predation, water salinity and inundation period as recommended by Traill and Brook (2010).

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Appendix A Metadata for aerial surveys of Magpie Geese

Table 5. Aerial surveys of Magpie Geese and their nests (1981-2003) in the Alligator Rivers Region (ARR) or in Kakadu only.

Scope	Who	Month-Year	Season	Transect width/observer	Both sides of aircraft	Transect spacing (km)
ARR	OSS	6/1981 to 11/1981 (n=6)	Dry	100m	Yes	2.0
ARR	OSS	5/1982 to 11/1982 (n=7)	Dry	100m	Yes	2.0
ARR	OSS	5/1983 to 11/1983 (n=7)	Dry	100m	Yes	2.0
ARR	OSS	5/1984 to 8/1984 (n=4)	Dry	100m	Yes	2.0
ARR	OSS	12/1981 to 4/1982 (n=5)	Wet (no nest counts)	100m	Yes	2.0
ARR	OSS	12/1982 to 4/1983 (n=5)	Wet (no nest counts)	100m	Yes	2.0
ARR	OSS	12/1983 to 4/1884 (n=5)	Wet (no nest counts)	100m	Yes	2.0
NT Top End	NTG	Nov 1983	Dry	200m	Yes	5.4
NT Top End	NTG	Feb 1984	Wet	200m	Yes	5.4
NT Top End	NTG	Nov 1984	Dry	200m	Yes	5.4
NT Top End	NTG	Mar 1985	Wet – nest counts	200m	Yes	5.4
NT Top End	NTG	Mar 1986	Wet – nest counts	200m	Yes	5.4
NT Top End	NTG	Mar 1987	Wet – nest counts	200m	Yes	5.4
NT Top End	NTG	Mar 1988	Wet – nest counts	200m	Yes	5.4
NT Top End	NTG	Mar 1989	Wet – nest counts	200m	Yes	5.4
NT western Top End	NTG	Mar 1990	Wet – nest counts	200m	Yes	2.7
NT western Top End	NTG	Mar 1991	Wet – nest counts	200m	Yes	2.7
NT western Top End	NTG	Mar 1992	Wet – nest counts	200m	Yes	2.7
NT western Top End	NTG	Mar 1993	Wet – nest counts	200m	Yes	2.7
NT western Top End	NTG	Oct 1996	Wet	200m	No – only 1	2.7
NT western Top End	NTG	Mar 2000	Wet	200m	Yes	2,7
Kakadu only	Parks	Nov 2003	Dry	200	Yes	2.7

ARR = Alligator Rivers Region; OSS = Office of Supervising Scientist; NTG = NT Government. NT Parks & Wildlife Commission surveys in the wet seasons of 2006 and 2007 were not used because a different observation platform was used (helicopter cf. fixed wing) requiring derivation of different visibility correction factors. Dry season surveys in 1994 and 1997 were also not used because aerial photography was used compared to aerial observers (Delaney et al. 2009), and results would not be compatible.

Appendix B Literature review of salinity tolerances for plants on Kakadu floodplains

Table 6. Literature review of salinity tolerances for freshwater plants found on Kakadu (see Attachment 1).

Appendix C Project reports & other supporting documents

Table 7a-e. Summary of project reports, activities and other supporting documents.

7a. Northern NERP project 3.2 Final Milestone report CSIRO. SLR component, December 2014

7b. Dutra et al. (2013). Evaluating localised SLR impacts on Kakadu National Park floodplain values using simple empirical methods. Internal CSIRO report.

7c. Saunders et al. (2014). Stage 1 SLR Hydrodynamic modelling in the ARR. Internal CSIRO report

7d. Hilton et al. (2014). Stage 2 SLR Hydrodynamic modelling in the ARR. Internal CSIRO report.

7e. Melo & Dutra (2013). Google Earth Tutorial and Manual. Internal CSIRO report.

Theme:	Aquatic Biodiversity
Project Number:	3.2
Project Title:	Threats to Kakadu Floodplains (sea level rise component only)
Project Leaders:	Sam Setterfield, Peter Bayliss & Sue Jackson
Lead Organisation:	CDU, CSIRO & GU
Key Researchers:	Adams, Petty, Dutra, Melo, Scheepers et al.
Project Start Date:	1/07/2011 **Project Completion Date:** 31/12/2014
Total NERP Budget:	**Total In-Kind Budget:**

Project Description and Outcomes for Book Chapter

(3,000 - 4,000 word limit, 1-2 summary sentence per item, and then elaborated from one to a few paragraphs per point)

- 100 word summary of project and achievements

Sea level rise due to climate change and aquatic weed invasions are key management issues for the river floodplains of Kakadu National Park. Before the project commenced little was known about the potential extent and severity of impacts from either threat or what would be effective management strategies. Hence, the project first aimed to predict the areas of floodplains most at risk from weed invasion and saltwater inundation due to sea level rise and, second, focussed on potential biodiversity and cultural impacts such as the loss of freshwater bush tucker sites. Assessment results were then used in participatory workshops with parks and Traditional Owners to discuss potential management objectives for sea level rise, and associated performance criteria and indicators of healthy floodplains that could be used in monitoring and developing adaptive management responses.

- Principal focus, and why this is of significance

  Climate change and weed invasions are key management issues for Kakadu National Park and, indeed, most low-lying tropical floodplains of northern Australia.

- Distinctiveness of issue to this landscape

  Kakadu's floodplains are low lying (0.2 - 1.2m above MHW) so vulnerable to saltwater intrusion. Using coarse GIS analysis Bartolo et al. (2008) estimated that 72% of freshwater floodplains will be lost to saltwater with a 1.1m SLR by 2100.

- Knowledge status and constraints

  The SLR component of this project used a very high resolution LiDAR DEM and high-end hydrodynamic modelling yet derived a similar overall estimate of freshwater floodplain lost to salt water by 2100. The main knowledge constraint of this early projection using coarse GIS analysis is where on the floodplains will future saltwater inundation likely occurs. Our SLR model outputs that incorporate dry season tidal dynamics provide greater spatial resolution and would be sufficient for local planning purposes.

- Methodological approaches

  Conceptual, ecological and hydrodynamic process modelling; statistical models; spatially-explicit quantitative risk assessment frameworks and models; decision frameworks using Bayesian Belief Networks (BBNs); participatory workshops and semi-structured individual interviews; Google Earth software for visualisation and communicating risk.

- Lessons learnt for this landscape

  Improved understanding of: regional climate in the ARR and tidal dynamics; the dynamic relationship between magpie geese and their principal dry season food, water chestnut bulbs (*Eleocharis dulcis*); potential impacts on current freshwater hunting sites on Kakadu; the risks of salt toxicity to freshwater plants and habitats; and options used to manage sea level rise risks to Kakadu's natural and cultural floodplain values. Both magpie geese and water chestnut sedge are iconic and culturally important species across northern Australia. The Boggy Plain-Mumakala wetland system off the South Alligator River in Kakadu most likely contains the most important magpie goose dry season refuge in the world because of the occurrence of extensive stands of *E. dulcis*.

- National implications of lessons learnt

  As per the 2nd dot point above, future saltwater inundation impact due to sea level rise is a key management issue for Kakadu National Park coastal floodplains and, by extension, for most low-lying tropical floodplains of northern Australia that have high cultural and conservation value.

- Problems addressing the focus and how overcome

  The main research problem/bottleneck was obtaining maps of future saltwater inundation early in the project in order to commence meaningful consultations with parks and TOs about adaptive management responses in the MSE component of the project. This was overcome by CSIRO providing significant additional resources to commission its coastal modelling team to develop Stage 1 model outputs (i.e. "bathtub" type saltwater inundation maps showing maximum extent & frequency over a tidal cycle in the late dry season/October).

- Towards implementation

  See below – future capability needs. Kakadu needs dedicated GIS and planning officers in order to use research outputs for future planning purposes. Additionally, modern computing infrastructure for reliable, safe and fast information and data management is required.

- Looking ahead – future needs

As requested by Kakadu TOs during participatory workshops, and as suggested by senior parks management staff, follow through research is required to help design cost-effective monitoring programs for future SLR/saltwater inundation impacts in order to increase their adaptive resilience. Traditional Owners argue that this should take the form of a "Caring for Country" type program that is lead by indigenous people but managed jointly with parks, and that associated capability training programs for parks staff and TOs are required.

Project Outputs (reporting against M&E Plan, dot points with longer lists as Appendices)

- Complete list of project outputs (tools, reports, deliverables)

1. Report: Northern NERP Project Planning Workshop 2-3 June 2011.
2. Report on Climate change scenarios review for Kakadu.
3. Report on Kakadu Information Management System.
4. Stage 1 Hydrodynamic model outputs for dry season (October) for the following scenarios: present scenario (October 2013. 0m Sea Level Rise/SLR), 2030 (0.14m SLR), 2070 (0.7m SLR), and 2100 (1.1m SLR):
   i. Maximum extent of tidal inundation.
   ii. Average extent of tidal inundation.
   iii. Frequency of tidal inundation.
5. Technical Report for stage 1 hydrodynamic simulations plus videos.
6. Maps showing tidal inundation for present and future sea level rise scenarios (item 4) overlaid on biodiversity and cultural values and information on proportion of floodplain and hunting, fishing and gathering sites inundated by saltwater for each SLR scenario.
7. Report on consultations with Kakadu National Park Staff to develop a management planning framework.
8. Report on consultations with Kakadu Traditional Owners to develop a management planning framework.
9. Report on functional design of levee to protect Yellow Water from sea level rise (including brief with specifications and memo commenting on barrier proposal).
10. Booklet with information about sea level/saltwater inundation prediction and potential impacts on Kakadu.
11. Google Earth Layers (assessment, planning & communication tool).
12. Google Earth Manual.
13. Description of maps and GIS layers produced in the project.

- Complete list of papers published

1. Bayliss P & Winderlich S (eds) 2011. Northern NERP Project Planning Workshop, Kakadu National Park, 2–3 June 2011. NERP Northern Australia Hub, Darwin NT. 155 pages. DSEWPaC SSD, Darwin NT.
2. Sam's book chapter on weeds.

- Number and description of management tools/ models developed for management agencies.

  1. Demonstration NetLogo Agent Based Model (ABM) for sea level rise and weed spread on Magela Creek floodplain.
  2. Google Earth layers and hard cover maps of ecological assets (see Appendices, Data folder), infrastructure and threats from saltwater inundation predicted for four climate change/sea level rise (SLR) scenarios: no change present day; 0.14m SLR 2030; 0.70m SLR 2070; & 1.10m SLR 2100.
  3. Google Earth basics manual – how to display, edit and set up your own layers, story boxes and flyovers.
  4. Bayesian Belief Networks (BBNs) for integrated risk assessment of threats to floodplain natural and cultural values.
  5. CSIRO Data Access Portal (Anstee et al.). Kakadu LIDAR Project 2011 LiDAR_Point_Clouds, Classified. AHD. https://datanet.csiro.au/dap/landingpage?pid=csiro:8186

- Number and description of web and hard copy information products

  1 x booklet (long pamphlet – final draft) on Kakadu sea level rise project (see Appendix).

- Number and description of newsletters, fact sheets, brochures and other communications products.

  13, possibly more.

  1. Departmental publication on Northern NERP Project Planning Workshop, Kakadu National Park (2–3 June 2011), 155 pages (Bayliss & Winderlich eds 2011).
  2. NERP North Australia Hub – Project 3.2: Managing threats to floodplain biodiversity and indigenous values. Flier for research permits consultations (7-11 Nov 2011).
  3. Project 3.2 Managing threats to floodplain biodiversity and indigenous values. Project information summary (24-31 March 2012).
  4. Flier for project 3.2 presentation given at Gunbalanya Stone Country Festival (Oenpelli) (22-23 August 2012).
  5. Invitation and Information about workshop organised by the project team: wetlands, weeds and climate change (27-31 August 2012).
  6. Project 3.2 Summary. Floodplains, weeds and sea level rise (brochure, fact sheet, Feb 2013).
  7. Invitation and Information about workshop organised by the project team: responding sea level rise on Kakadu floodplains (1-6 February 2013).
  8. Project 3.2 - Floodplains, weeds and sea level rise. June 2013 field trip, update (brochure/newsletter).
  9. Open informal invitation to Kakadu parks staff to receive updates on planning SLR modelling and planning component of project 3.2: responding to sea level rise on

Kakadu floodplains (21-23 October 2013). Trial run for December stakeholder workshop.

10. Invitation and Information about workshop organised by the project team: responding to weeds and sea level rise in Kakadu floodplains (1-7 December 2013): http://www.nerpnorthern.edu.au/news/2013/workshop-responding-weeds-and-sea-level-rise-kakadu-floodplains
11. Invitation and Information about workshop organised by the project team: How can we manage sea level rise and weeds on Kakadu floodplains (July 2014): http://www.nerpnorthern.edu.au/news/2013/workshop-responding-weeds-and-sea-level-rise-kakadu-floodplains
12. Booklet/long pamphlet on sea level rise in Kakadu National Park (see Appendix – final draft – July 2014).
13. Invitation and Information flier about workshop organised by the project team: final consults with Traditional Owners and Parks staff (24-29 November 2014).

- Examples of Government policy being changed as a direct result of research outputs

  Input into revised Kakadu Park Management Plan, section 5.3 *Management issues affecting park values, Climate change;* and draft Kakadu Climate Change Strategy and policy (via Louise Harrison Kakadu policy & planning officer).

- Examples of research outputs being cited by Government as evidence that policy change is required

  None – too early to have impact.

- Examples of useful capacity built within the Australian Government as a direct result of project activities.

  Some Parks Australia/Kakadu staff that attended sea level rise workshops gained hands-on experience how to use Google Earth as a planning tool with visualisations (zoom-in/out) capability, and ability to display and overlay spatial information layers (this was at their suggestion in earlier workshops). See above, project inputs into draft Kakadu Climate Change Strategy and revision of Kakadu Plan of Management.

Indigenous Engagement

Please provide the following information for the whole project period:

- List Indigenous groups you have worked with

All Traditional Owners who have coastal floodplains on their country (e.g. Mirarr, Murrumburr, Minitja Limingan, Bunitj, Manilikarr/Gunbalanya).

- Number of consultation meetings held

12 that involve SLR component of project 3.2 listed below. At least 10 informal meetings on SLR with different TOs.

1. June 2011: Northern NERP project planning workshop on Kakadu NP (primarily consultations with Kakadu NERP researchers & handful of parks staff).

2. Consultations with parks staff and Traditional Owners for research permit, November 2011 (Sue, Peter, Dougo).
3. February 2012. Consultation with CDU staff, parks staff and some TOs on *in situ* data management systems and potential economic studies of climate change impacts on Kakadu (Peter, Emma Woodward, Sharon Tickell, Ana Norman).
4. April 2012 (23-31). Consultations with parks staff and some TOs (Victor, Christo & Sandra) on SLR models, in preparation for first large planning workshop in August (Peter & Leo).
5. August 2012 (22-23). Consultation with TOs at Oenpelli on Kakadu SLR project (at Stone Country festival after presentation; Peter, Leo & Emma L).
6. August 2012 (27-31): Project 3.2 workshops: Separate parks and TO workshops. Wetlands, weeds and sea level rise (Leo, Peter, Emma Woodward, Emma Ligtermoet, CDU weeds team).
7. October 2012: Visit to Boggy Plain with TOs Peter Christophersen and Sandra McGregor for field observation and measurements of floodplain dynamics and inundation (Leo).
8. February 2013 (1-6). Consultation with parks staff and some TOs, provide updates (Peter & Leo).
9. October 2013 (21-23): Feedback on SLR model outputs and seek advice from TOs on how to run the December workshop 2013 (Peter & Leo).
10. December 2013 (1-7): Workshop - responding to weeds and sea level rise on Kakadu floodplains. Separate workshops for parks staff and TOs.
11. July 2014 (21-25 July): Workshop - responding to sea level rise on Kakadu floodplains. Separate workshops for parks staff and TOs.
12. November 2014 (24-29): Final project consultations for presentation of products and feedback on products and approach used in the project. Discussion on monitoring. No workshops as such. Met with TOs and gave half-day presentation to parks staff.

- Number of planning meetings held

  30 recorded as listed below including NERP fora.

1. For CSIRO Brisbane-based climate change/SLR staff, on average 1 x 1hr planning meeting per week since July 2011.
2. Many phone meetings with 3.2 project leaders (Peter, Sam, Sue) – about 10.
3. March 28 & 29 2011 – phone meeting with David Parry & others for Kakadu coastal projects.
4. June 2-3 2011 Kakadu NERP project planning workshop.
5. July 7-8 2011. NERP 3.2 meeting Darwin (& for 5.1).
6. November 15 2011. Meeting with Emma Woodward in Brisbane on developing an MSE framework approach for Kakadu (Leo, Emma, Peter).
7. February 21 2012. Meeting CDU 3.2 project.
8. April 26-27 2012. Water modelling workshop/meeting at AIMS Darwin. 3.2 project staff plus David Williams, Tim/Renee (eriss), Doug Ward.
9. 25 May to 1st June 2012. General NERP meeting/forum in Darwin, 3.2 project staff bar Sue met.
10. May 30 2012 Kakadu 3.2 project meeting Darwin/CDU.

11. September 10 2012. 3.2 phone meeting with Sam/weeds (Peter, Sam, Aaron & others).
12. 26 November – 1st December 2012. Project 3.2 SLR meeting at CSIRO, bush tucker layers in GIS and Emma Ligtermoet PhD modelling Boggy Plain (Peter, Kelly, Emma L).
13. January 4 2013. 3.2 project phone meeting (Peter, others? no record of who). Another phone meeting January 10.
14. February 14 2013. Brief 3.2 project meeting CDU Darwin (Peter, Leo, Sam, Dougo, Aaron, Vanessa?).
15. February 22 2013. 3.2 SLR modelling meeting with Mahesh Prakash (CMIS coastal modeller/storm surges) in Brisbane (Mahesh, Peter, Leo).
16. February 24-28 2013. 3.2 project planning meeting CDU Darwin (CDU team, Peter, Leo, Mahesh).
17. May 27-31 2013. 3.2 SLR project meeting Darwin with David Williams AIMS (video link with Mahesh). Peter meets with Aaron on weeds Java code (CDU) and Kelly (cultural values GIS layers) and Emma L (BBNs).
18. June 10-12 2013. Canberra NERP forum. Kakadu projects meeting (Peter, Sam, Sue, Vanessa, Dougo).
19. October 24-25 2013. 3.2 project meeting CDU Darwin (Peter, Leo, Sam, others).
20. December 12 2013. 3.2 project meeting Melbourne with John Childs facilitating (Sue, Sam, Dougo, Peter).
21. February 9-15 2014. Visit to Brisbane Emma L (& Peter N), PhD supervision, socio-ecological SLR risk modelling components of 3.2 project (Peter, Leo, Emma L).
22. March 27-28 2014. NERP2 planning meeting Darwin Airport Hotel, 3.2 SLR project discussed with Peter, Andy and Dave W. David agreed to visit Brisbane in April to follow up on discussions linking our storm surge modelling with his.
23. April 22-24 2014. David Williams visit Brisbane to provide his locally calibrated SLR models outputs for Magela, East AR & SA River (Peter, David).
24. June 17-18 2014. 3.2 project meeting, SLR and cultural values. Sue J visited Brisbane, to plan and prepare for November-December July workshops with parks and TOs (Sue, Peter, Leo & Liza). Sue given all saltwater inundation statistics and Google Earth layers for workshops (i.e. a complete update of SLR project outputs).
25. July 16-17. 3.2 SLR project meeting in Brisbane to plan extra modelling needed to get salinity maps (Peter, Leo, James Hilton).
26. July 25 2014. 3.2 project team meeting at Darwin Airport Resort Hotel (Sam, Vanessa, Sue, Peter, Leo, Lizandra).
27. August 11-13 NERP Forum Darwin Airport Hotel. Brief 3.2 meeting between James Hilton, Peter Bayliss and Leo Dutra on stage 2 (storm surge) saltwater inundation modelling.
28. September 1 2014. Project 3.2 SLR with Mahesh and team, finalise stage 1 model results for re-submission to journal and stage 2 model results.
29. October 21-23 2014 3.2 project planning workshop CDU Darwin (Sam, Dougo, Vanessa, Leo, Peter, Sue on phone).
30. November 24-29 2014 Kakadu. Project 3.2 planning meeting prior to meeting with GAC and parks workshop (Peter, Leo, Lizandra).

- Number of field trips held

  14 trips to Kakadu related to the sea level rise component of project 3.2, in addition to the first Kakadu project planning trip June 2011 (all projects).

- List other public events/conference presentations/jointly authored papers with Indigenous partners

1. REPORT. Bayliss P and Winderlich S (eds) 2011. Northern NERP Project Planning Workshop, Kakadu National Park, 2–3 June 2011. NERP Northern Australia Hub, Darwin NT.

2. PRESENTATION. The threat of the rising sea: adapting to climate change risks to the coastal wetlands of Kakadu National Park using a Management Strategy Evaluation (MSE) framework (2011). Bayliss, Douglas, Dutra, Setterfield, Jackson, Woodward, Ligtermoet, Petty and Winderlich. NCCARF Coastal Ecosystem Response to Climate Change workshop, South Stradbroke Island, Qld. December 2011.

3. PRESENTATION. Managing risks from sea level rise and aquatic weeds to floodplains on Kakadu National Park using a Management Strategy Evaluation (MSE) framework. Bayliss, Setterfield, Woodward, Jackson & Douglas. Oceania Society Conservation Biology conference, 21-23 September 2012, CDU Darwin.

- Number of Indigenous rangers who have participated in meetings/field work (approximation ok)

  Over 3.5 years about 10

- Number of Traditional Owners (non-rangers) who have participated in meetings/field work (approximation ok)

  Over 3.5 years about 20 – 25 (includes Oenpelli people).

- Number of people who received paid work created by your project

  9 people

- Number of days of paid work created

  30 days. Equivalent to 9 days employment as consultation fees paid at workshops, plus 21 days paid work for two TOs (field salinity measurements, plant surveys).

- Number of people employed in ongoing full-time or part-time roles (please describe roles)

2 part-time for short periods (< 10 days for each period).

Please provide the following information for the whole project period:

- Did your project have a human ethics approval to work with Indigenous people? What did the approval cover?

  Yes. The Human ethics approval application through CSIRO received accolades as a good model for others to use, particularly with respect to participation by Indigenous communities/families. The application document is in the Administration folder of the project Appendix.

- Outline how your project helped to meet the research needs and interests of the Indigenous groups that you worked with.

  Through participatory workshops and co-development of decision support/planning tools for future saltwater inundation threats to floodplain natural and cultural resources. The workshops over time covered research needs and interest raised by TOs, including: (i) simple conceptual understanding of the interaction between climate and weather, tides and rainfall run-off processes, that affect the connectivity between seas, rivers and floodplains; potential natural and cultural criteria and indicators for healthy freshwater floodplains that can be used for future monitoring to assess the performance of different management strategies; potential high level and local management objectives for sea level rise; and potential management strategies for saltwater inundation (e.g. hard option levees, soft option mangrove planting, range of adaptive social responses).

- Outline skills acquired by Indigenous people as a result of your project (How many people, type of skills, potential future application)

  During the workshops with Traditional Owners, in addition to presentation of project results, we also ran practical demonstrations on how to use Google Earth and the layers produced in the project so that participants could acquire basic skills on how to use products developed in the project. A Google Earth manual was also prepared to support the development of skills in Google Earth (approximate 11 indigenous people participated in the hands-on Google Earth exercises).

- Outline how non-Indigenous people in your project team have developed increased cultural understanding. (Include how many people have benefited)

  Leo Dutra gained increased understanding of indigenous cultural issues on Kakadu National Park through his participation and interaction.

- What communication products or activities have been used to communicate the project and research results with Indigenous people?

As part of the project we used a combination of formal workshops and informal sessions with individuals and/or small groups to communicate project and research results with indigenous people. Google Earth was used as the preferred communication tool for visualising and communicating risk to floodplain natural and cultural resources. This was at the specific request of parks staff and TOs as it had zoom-in and out capability and was readily accessible (c.f. with GIS software & other software platforms).

- Do you think that the Indigenous groups that you have been working with would be interested in participating in future research projects?

  Yes.

Project Management

- Discussion of project management strengths and weaknesses (e.g. structure of team, interaction with other projects, contracting, K&A)

  To be filled out after discussion with the three sub-project team leaders: Sam Setterfield; Peter Bayliss and Sue Jackson.

- Identify any objectives/ outcomes that have not been met and explain why this occurred.

  To be filled out after discussion with the three project team leaders: Sam Setterfield; Peter Bayliss and Sue Jackson.

Project Legacy

- Where is your data securely stored (long term custodians/ institutional repositories) –

  Data are stored in a secure CSIRO drive that is regularly backed-up.

- Is your research data available for public access, mediated access or private?

  Currently the data can be accessed through mediated access but data is intended to be available for public access at the TERN data portal: http://tern.org.au/TERN-Data-Discovery-Portal-pg17727.html.

- Where has your meta-data been published?

  Metadata for the hydrodynamic model outputs are published in the technical report of the stage 1 hydrodynamic sea level rise model. The report is available in the 'Attachments' section of this report. A description of the GIS SLR and park assets layers used to produce maps for reports and future publications is available also in the 'Attachments' section of this report.

- Have you provided a plain language version of your final research findings to the KA team?

  Yes, members of the KA team have attended workshops at Kakadu and they were also engaged in the production invitation/information material for workshops and in the preparation of the booklet 'Sea level rise in Kakadu'.

- Have you provided to the KA team a plain language description of how your research products can be utilised, including applications and limitations? e.g. map layers, data sets, tools, methodologies.

  Yes, the KA team received text about the project findings and helped develop a plain English booklet aimed to inform Traditional Owners about potential impacts of sea level rise on Kakadu (via Amy & Carli).

- Any other project legacy issues and how they are planned to be addressed

  Follow through work required on "improved participation and interaction between Traditional Owners and Park staff in the management of cumulative risks to natural and cultural floodplain values", as this was an identified key project outcome for the Management Strategy Evaluation (operational adaptive management framework)/MSE component of the project that was not realised.
  .

Appendices

- List of project outputs (publications, information products etc)

Manuscripts in preparation:

1. Sue Jackson, Leo X.C. Dutra, Peter Bayliss, Lizandra F.C. Melo., others (e.g. Kelly Scheepers). *In prep.* Potential impacts of sea level rise on social and cultural values of Kakadu National Park.
2. Leo X.C. Dutra, Peter Bayliss, Lizandra F.C. Melo, et al. (other NERP researchers, TOs). *In prep.* A participatory approach to developing a planning framework to manage sea level rise threats to World Heritage Kakadu National Park values: lessons learnt.
3. Peter Bayliss, Neil Pettit, Lizandra F.F. Melo, Leo X.C. Dutra, Peter Christophersen, Sandra McGregor, Rick van Dam and David Williams. A quantitative ecological risk assessment of increased salinity on freshwater floodplain plants on Kakadu National Park.
4. Peter Bayliss, Emma Ligtermoet, Leo X.C. Dutra, Lizandra F.C. Melo, Peter Christophersen, Sandra McGregor and Violet Lawson. *In prep.* Seasonal Habitat Suitability Models (HSM) for magpie geese on Boggy Plain Kakadu NP: quantifying impacts of invasive species and future saltwater inundation from sea level rise.
5. Leo X.C. Dutra, Peter Bayliss, Peter Christophersen, Sandra McGregor, Doug Ward, Lizandra F.C. Melo, et al. *in prep.* Evaluating local sea level rise impacts on Kakadu NP floodplain values using simple empirical methods.

Outputs in Appendix folder:

1. Report: Northern NERP Project Planning Workshop.
2. Report on Climate change scenarios review for Kakadu.
3. Report on Kakadu Information Management System.
4. Stage 1 Hydrodynamic model outputs for dry season (October) for the following scenarios: present scenario (October 2013. 0m Sea Level Rise (SLR)), 2030 (0.14m SLR), 2070 (0.7m SLR), and 2100 (1.1m SLR):
    i. Maximum extent of tidal inundation
    ii. Average extent of tidal inundation
    iii. Frequency of tidal inundation
5. Technical Report for stage 1 hydrodynamic simulations plus videos.
6. Maps showing tidal inundation for present and future sea level rise scenarios (item 4) overlaid on biodiversity and cultural values and information on proportion of floodplain and hunting, fishing and gathering sites inundated by saltwater for each SLR scenario.
7. Report on consultations with Kakadu National Park Staff to develop a management planning framework.
8. Report on consultations with Kakadu Traditional Owners to develop a management planning framework.
9. Report on functional design of levee to protect Yellow Water from sea level rise (including brief with specifications and memo commenting on barrier proposal).
10. Booklet with information about SLR project.
11. Google Earth Layers (planning and communication tool).
12. Google Earth User Manual for Kakadu NP.
13. Description of maps and GIS layers.

- Attach copies of any relevant products/ reports

  Attachments can be downloaded from a Drop Box folder using the link:
  https://www.dropbox.com/sh/iw6sfc4o80ehjgh/AAC6K18Hgqq3oh7yTQr0b5Qza?dl=0

- Published records of research data/ metadata outputs and links

  A Drop Box link to a Data folder will be established.

- List name of researchers, research assistants employed on this project

  SLR component: Peter Bayliss, Leo Dutra and Lizandra Melo (temporary GIS assistant).

- List of Department staff (incl PM&C staff) & areas engaged through this project

  All Kakadu parks staff, in particular Steve Winderlich and Anne O’Dea. No PM&C staff.

References for Book Chapter

- It is very helpful to the smooth and timely processing of your typescript if you can ensure that everything is in order when the manuscript is presented. The majority of copy-editing queries are generated because of incomplete or inaccurate information in references, which can lead to delays in the production process.

General points

- In the Reference list, if a book or journal article has seven or more authors, list the names of the first three authors, followed by et al. If there are six authors or less, list all of their names
- Cite the edition of the book that contains the reference, even if it is not the current edition
- Use *italic* (rather than underlining) for journal and book titles
- Use initial capitals for book and journal titles, and an initial capital for the first word only for journal articles and book chapters. Please do not give journal articles or book chapters in quotation marks
- Unpublished references should generally be listed in parentheses in the text but should not appear in the reference list, e.g. (S. Shorvon, unpublished observations, 2000) or (J. Pickup, personal communication, 1999)
- It is not necessary to give the total page extents of books and theses
- The dates in the Reference section should match up with the date in the citation in the text
- Institutions cited as authors should be given in abbreviated form where referred to in the text but given in full in the reference list, e.g. (WHO 1989); World Health Organisation, Geneva (1989) *Fisheries Handbook*
- The reference should include the full name of the article, paper or book
- The reference should include the journal name and volume number if appropriate. This can be abbreviated but please make sure that the same abbreviations are used throughout your manuscript for the same journal. Follow official international listings wherever you can and explain all abbreviations
- References from books should include the name of the publisher plus their location

Style of text citation

- For a single author use 'Gaston (1995) suggested that ...' or '... demonstrated in three different species (Gaston 1995)'
- If there are two authors use Gaston and Spicer (2000) or (Gaston & Spicer 2000)
- If there are three or more authors use the name of the first author followed by et al., e.g. 'Bell et al. (1989) showed that ...'
- Add a, b, c etc. to distinguish between two or more references with the same author name and year date (e.g. Roitt 1999a,b)
- List a string of references in chronological order, e.g. (Black 1985; Black 1991; Smith & Baker 1995, or Smith and Black 1995; Carruthers 1999)
- When citing an anonymous editorial in a journal use the name of the journal and the date, e.g. (*Lancet* 1998) and list this reference under 'L' in the list of references

Style of list citation

- Reference lists should appear at the end of each chapter or at the end of the book under the heading 'References'
- List references in alphabetical order by author; do not number the list
- For references starting with the same surname and initials, list single-author works first, in chronological order; list two-author works second, in alphabetical order of the second author, then chronologically; list multi-author works third, arranged only chronologically:

  Brown, F. (1999)
  Brown, F. & Smith, J. (1989)
  Brown, F. & Vested, K. (1983a)
  Brown, F. & Vested, K. (1983b)
  Brown, F., King, L., Evans, R. & Eliot, W. (1987)
  Brown, F., Evans, R. & King, L. (1990)

- Order the items within each reference (authors' surnames, initials, journal article title, journal title, volume number and page range) in a consistent way. *Reordering is a very time-consuming process*

Evaluating localised SLR impacts on Kakadu National Park floodplain values using simple empirical methods

Leo X.C. Dutra, Peter Bayliss, Sandra McGregor, Peter Christophersen, Lizandra Melo and Doug Ward

Introduction

Kakadu National Park (KNP) in northern Australia (Figure 1) has unique ecosystem assets and dependent communities, enshrined in World Heritage and Ramsar listings {Director of National Parks, 2007 #141; Finlayson, 1996 #109}. KNP is currently at risk from existing multiple threats such as invasive plants and animals, unmanaged fire and mining-related activities (refs.). Climate change predictions for this century are expected to exacerbate existing threats to Park values and directly affect ecological dynamics between plants and animals with flow on effects on human (especially Indigenous) resource-use responses to these changes {Bayliss, 1997 #18;BMT WBM, 2011 #57;Hyder Consulting Pty Ltd, 2008 #17;Hennessy, 2007 #28;Director of National Parks, 2010 #253}.

The main driver for impacts in KNP habitats is sea level rise (SLR), intensified by extreme events such as cyclones and storm surges. Aquatic habitats that will be affected by SLR include mangroves, freshwater streams, wetlands and riparian communities. These habitats support much of Kakadu's biodiversity and tourism values, and provide highly significant food and other cultural resources for resident Aboriginal communities.

There is therefore a clear need to develop physical models to evaluate the effects of SLR on floodplain values in KNP. Such models will allow KNP managers to better understand potential SLR impacts on Park values, thus supporting: (i) the identification of threats and opportunities for climate adaptation, and (ii) the design of adaptation measures to mitigate the negative effects associated with SLR.

The objectives of the present study are:

1. To assess the potential use of USGS Landsat TM 5 images of floodplain inundation as surrogates of present and future sea levels.
2. To present and evaluate a methodology to construct empirical SLR models. We evaluate performance of the empirical model by comparing its outputs with outputs from a hydrodynamic model constructed for the whole KNP {Saunders, 2013 #441}.
3. To perform analysis of sea level rise impacts in two case study areas in KNP using the methodology we designed.

Kakadu National Park

The climate in Kakadu is monsoonal with a hot wet season from November to March accounting for 90% of the average annual rainfall {Hamilton, 2005 #75} of 1,077mm {Hyder Consulting Pty Ltd, 2008 #17}. The hydrology of the Park is highly dependant on rainfall patterns, where four major rivers – the South Alligator, (ii) the East Alligator, (iii) the West Alligator and (iv) the Wildmann Rivers (Figure 1) – and associated floodplains inundate during the wet season {Finlayson, 2006 #440}. The Alligator River system, comprise an area of 1675 km^2 (Ward et al. 2013). Floodplains can be underwater for periods of up to four months, where during the dry season they drain and water evaporates from the back swamps. As the water drops, the remaining water bodies become important refuge areas for animals and plants {Hyder Consulting Pty Ltd, 2008 #17;McMahon, 1992 #74}. Important to note is the low-lying relief of KNP wetlands, which are of elevations between 0.2 – 1.2 m above Mean High Water Level and therefore vulnerable to rises in sea level {Eliot, 1999 #80;Bayliss, 1997 #18;BMT WBM, 2011 #57}. Predicted impacts associated with SLR in KNP include the following: changes in the intertidal zone, saline intrusion of freshwater areas, loss of native vegetation and loss of habitat for endemic species to KNP {Bartolo, 2008 #439;Bayliss, 1997 #18;Bayliss, 2012 #98}.

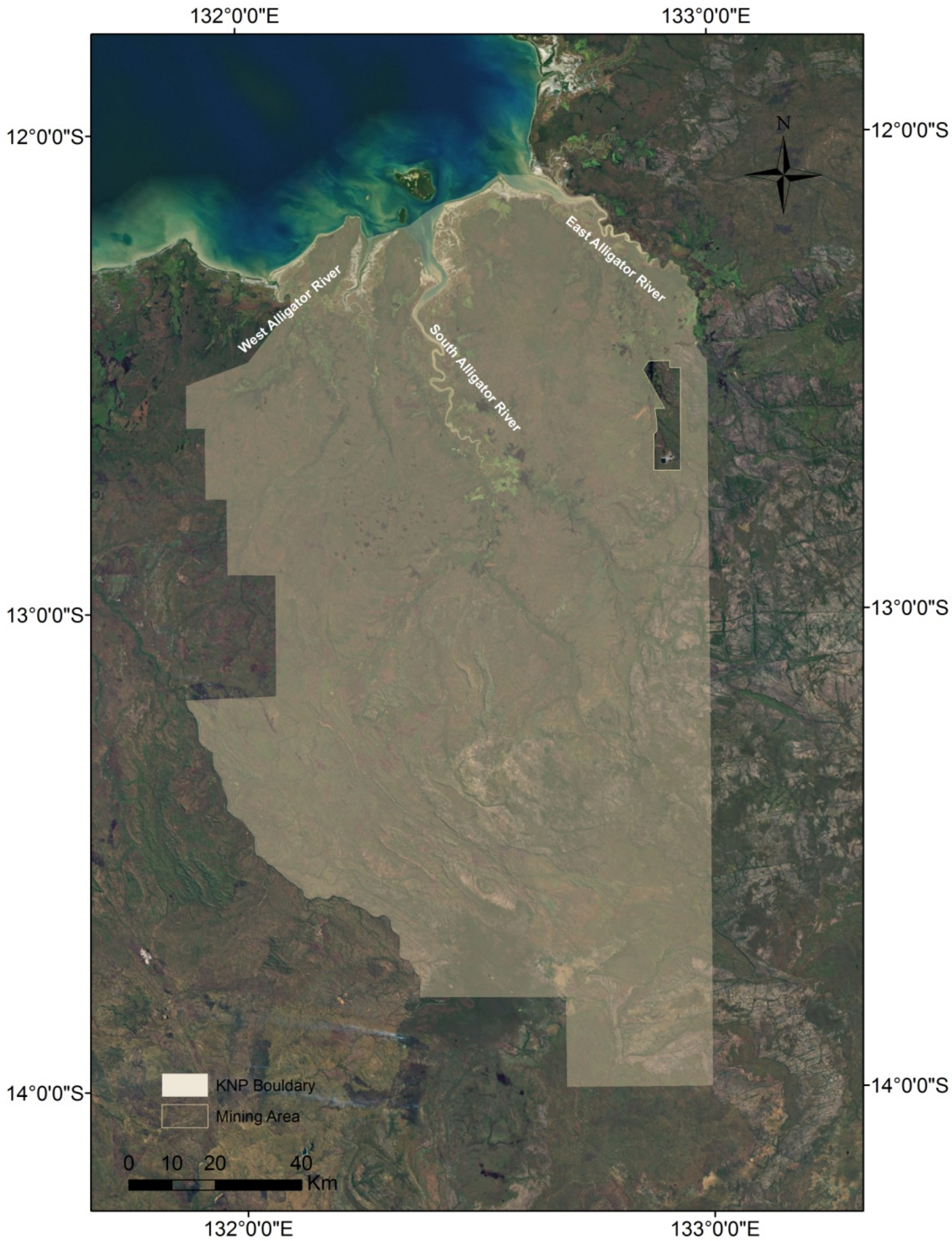


Figure 1. Kakadu National Park encompassing the main rivers of the Alligator Rivers Region.

Methods

Sea level rise scenarios

We use a scenario approach to modelling SLR in KNP. That is, we model SLR and assume impacts will be consistent with previous studies. We conducted a literature review of climate change predictions and impacts for the Kakadu region and selected four scenarios used in our modelling. The criteria used to select the scenarios were the following:

1) Use updated credible information (IPCC, published peer reviewed documents (e.g. journal articles).
2) Use regionalised predictions (Australia, Northern Territory, Alligator Rivers Region)
3) When possible, use scenarios previously applied in assessments that complied with 1 and 2, to improve the knowledge base on particular scenarios, and use the wealth of knowledge and data generated in these studies, thus maximising the investments on model development and data gathering.

The selected scenarios draw substantially on the IPCC Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) {IPCC, 2007 #29}, where global assessments were supplemented with regional and/or more detailed local information, such as CSIRO {CSIRO, 2007 #37;CSIRO, 2012 #87}, Garnaut {, 2008 #54}, Hyder Consulting Pty Ltd {, 2008 #17}, BMT WBM {, 2011 #57}, Commonwealth of Australia {, 2009 #133} and Short and Woodroffe {, 2009 #134} and also on preliminary assessments from IPCC AR5.

Projections for differing emissions scenarios generally do not strongly diverge in the coming two to three decades, but uncertainty in the sign of change is relatively large over this time frame because climate change signals are expected to be relatively small compared to natural climate variability (IPCC, 2012). Therefore, we decided to adopt high-end emission scenarios (A1B for 2030 and A1FI for 2070 and 2100). The choice was based on evidence that current global CO_2 emissions are at the high end of IPCC emission scenarios (between scenarios A1B and A1FI)[1], which would lead to a global-mean warming of 4.2-5.0^{o}C by the year 2100 (CSIRO, 2013). The description for these scenario are as follows (from CSIRO, 2007):

The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Scenario A1FI includes fossil intensive energy sources and scenario A1B represents a future with a balance across fossil and non-fossil energy sources.

In March 2014 CSIRO and the Bureau of Meteorology released the report 'State of the Climate 2014' (Commonwealth of Australia, 2014), which are the latest predictions for Northern Australia. The summary of projections from the report and additional information from CSIRO are provided below (access to predictions for 2030 are available at: http://australianclimatefutures.net/ and predictions beyond 2030 are expected to be in the website by July 2014).

Sea Level Rise

The range of sea level rise predictions for the 21st century varied between, 0.03m (2030) to 2m (2100), potentially reaching up to 5-7m if ice sheets of Greenland and West Antarctica melt completely {Steffen, 2013 #251}. Some authors even suggest that a 9m rise in sea level is likely by 2100 {Foster, 2013 #116}. Pre-historical data supports the 2m range of sea level rise predictions during the Pleistocene where mean global temperatures were 2^{o}C warmer than present {Rohling,

[1] important to note is that in the AR5 there were substantial changes in the names of emission scenarios, and the equivalent to A1 scenario is the RCP 8.5)

2008 #31}. This range is comparable to future projections of climate change {IPCC, 2007 #29;Commonwealth of Australia, 2014 #409;Church, 2008 #56;Garnaut, 2008 #54}.

Climate records from the end of the last interglacial period also showed that when the northern hemisphere ice sheets disintegrated, sea-level rise peaked at a rate of 4 m/century. This indicates that substantially higher rates of sea-level rise than those predicted by the IPCC {IPCC, 2007 #29; Commonwealth of Australia, 2014 #409} have occurred historically and are likely to occur in the future. Therefore, there remains considerable uncertainty about the magnitude of global sea level rise in SLR predictions. There are two fundamental sources of uncertainty that need to be considered: (i) the rate at which greenhouse gases will be emitted by human activities through the rest of the century {Steffen, 2013 #251}, and (ii) the uncertainty around the behaviour of polar ice sheets {Bamber, 2013 #130;Foster, 2013 #116;Steffen, 2013 #251}.

One way of considering uncertainty around rate of emissions is to consider a range of SLR predictions from low to high. This way we focus more on the impact of SLR scenarios and assume that these can occur earlier or later depending on the emission scenario and use the years for the predictions as reference points. In terms of uncertainty around behavior of polar ice sheets, currently IPCC predictions suggest an additional contribution from ice sheets of 0.1 m to 0.2 m {CSIRO, 2007 #37;IPCC, 2007 #29}. Some authors {e.g. \Carlson, 2008 #32; Commonwealth of Australia, 2009 #133;Short, 2009 #134;Shepherd, 2012 #122;Meehl, 2012 #111;Steffen, 2013 #251} suggest that the IPCC projections should be considered "minimum" even without ice sheet dynamics.

The combined scientific observations and modelling evidence for Australia point to changes in the climate system at the upper end of SLR projections–between 0.52m and 0.98m, relative to 1986 to 2005 for the higher emission scenarios {Commonwealth of Australia, 2014 #409} – or even above it, where mid-range of predictions from several authors generally converge above 1m {Rahmstorf, 2007 #21;Rahmstorf, 2007 #22;Vermeer, 2009 #24;Rahmstorf, 2012 #260;Short, 2009 #134;Commonwealth of Australia, 2009 #133; Jevrejeva, 2010 #5;Schaeffer, 2012 #112;Grinsted, 2009 #26}.

Based on the evidence from the literature, we selected the following sea level rise scenarios for the Kakadu region:

1. 0.143m for 2030
2. 0.70m for 2070
3. 1.1m for 2100

The value of 0.143m for 2030 was provided to BMT WBM for the report "Kakadu: vulnerability and climate change impacts" by the Department of Climate Change and Energy Efficiency (DCCEE) and is within the range suggested by CSIRO (2007) 0.03 to 0.17m. The BMT WBM (2011) report was Kakadu-specific, commissioned by the DCCEE and recently published (2011), hence our decision to use their scenario.

The BMT WBM report also used the value of 0.7m in their 2070 scenario, which includes the ice contribution as suggested in the CSIRO (2007) and IPCC (2007) reports, hence our decision to use 0.7m for this scenario. The value for 2070 (0.50m) from Hyder Consulting (2008) used in the Kakadu Climate Change Strategy (Director of National Parks, 2010) did not consider the melting ice contribution to sea level rise, which only recently have received more attention in SLR predictions.

Predictions for 2100 were not presented in regionalized documents (Kakadu/Northern Australia) but overall for Australia {Commonwealth of Australia, 2014 #409}. Our decision to adopt the 1.1m was based on the fact that several authors, including the IPCC, suggest that there is large uncertainty and knowledge gaps on the dynamics of ice melting. Also, the high-end projection of 0.98m by 2100 should be considered "minimum" (see above). Our decision to adopt 1.1m SLR by 2100 is based on the study published by Short and Woodroffe (2009), who proposed the 1.1m SLR by 2100 to be the mid range of projections. The Commonwealth of Australia (2009) also recognised this value, hence our decision to adopt the 1.1m value in the 2100 scenario. Table 1 depicts climate change scenarios used in this paper.

Rainfall

There are contrasting predictions for the Kakadu region. For example, Hyder Consulting Pty Ltd {, 2008 #17} propose extended dry periods and more frequent and intense rainfall periods by 2070, whereas Moise and Colman , 2012 #46} suggest a small mean change in the seasonal cycle of precipitation over tropical Australia, but with prolonged wet seasons. Rainfall predictions are extremely complex in Northern Australia because changes in rainfall regimes are strongly associated with the occurrence of El-Niño and La Niña events. Changes in ocean temperature will affect the occurrence of El-Niño/La-Niña events, There are nevertheless disagreements on future occurrences and intensity of El Niño events {Garnaut, 2008 #54:98} and the IPCC AR4 suggests that there is no evidence that El-Niño events will intensify in the future {Christensen, 2007 #35;IPCC, 2007 #29}. Nevertheless, there is evidence that historical El-Niño like conditions have occurred in the last 1000 years, for periods of up to 160 years that influenced the inundation extent of floodplains in Kakadu as well as the ecosystems they support {Wasson, 2010 #68} with similar findings from elsewhere {Martin, 1993 #76}.

Latest rainfall predictions for Northern Australia suggest that there is still high variability and uncertainty in projections {Bureau of Meteorology, 2013 #78; Commonwealth of Australia, 2014 #409}, ranging from large decrease and increase in annual rainfall for the 21st century {CSIRO, 2007 #37;CSIRO, 2012 #87; Commonwealth of Australia, 2014 #409}. For example, the latest predictions for 2070 range from a 30 per cent decrease to 20 per cent increase in annual rainfall for high emissions. The conclusion is that the annual-average rainfall in northern Australia is "uncertain" and a “no change” for annual rainfall predictions for all scenarios is selected for the sea level rise simulations {Commonwealth of Australia, 2014 #409} (Table 1).

Extreme weather events (cyclones)

The State of the Climate 2014 report suggests that on average there will be fewer tropical cyclones for tropical Australia but with an increased proportion of intense cyclones. However, the report states that the confidence in tropical cyclone projections is low. Predictions for the Kakadu region from a 2011 report {BMT WBM, 2011 #57} are for an increase in maximum potential intensity (wind) of 10% and 20% for 2030 (0.14m increase in sea level rise) and 2070 (0.7m increase in sea level rise), respectively. We adopted the BMT WBM {, 2011 #57} predictions where storm surges will increase in height by 0.15m (2013) and 0.1m (2070).

Table 1. Sea-level rise (SLR) projections used in the models

Scenario	**Present (2013)**	**2030**	**2070**	**2100**
Years from 2013	0	17	57	87
SLR *	**0**	**0.14m**	**0.70m**	**1.1m*** **
Rainfall	0	No change	No change	No change

Based on high emissions scenario IPCC4 (2007)
* Used BMT WBM projections based on DCCEE advice (2011)
** Used projections based on Hyder (2008)
*** From Short and Woodroffe (2009) and The Commonwealth of Australia (2009)

Empirical models

We constructed a statistical emulator that uses water level from gauge stations in the South Alligator River (SAR; Darwin Harbour Tides (G8150029) for the river mouth, El Sharana (G8200045), South Alligator River at the Bridge (G8200041) and Boggy Plain (G8200082)), local knowledge about tidal inundation at Boggy Plain (Peter Christophensen and Sandra McGregor) and remote sensing images of extent of freshwater floodplain inundation (Doug Ward) as inputs in the model (Figure 2). Model outputs are depth and salinity profiles in selected case studies in KNP, which affect socio-cultural (Indigenous) and biodiversity values (Plants and animals).

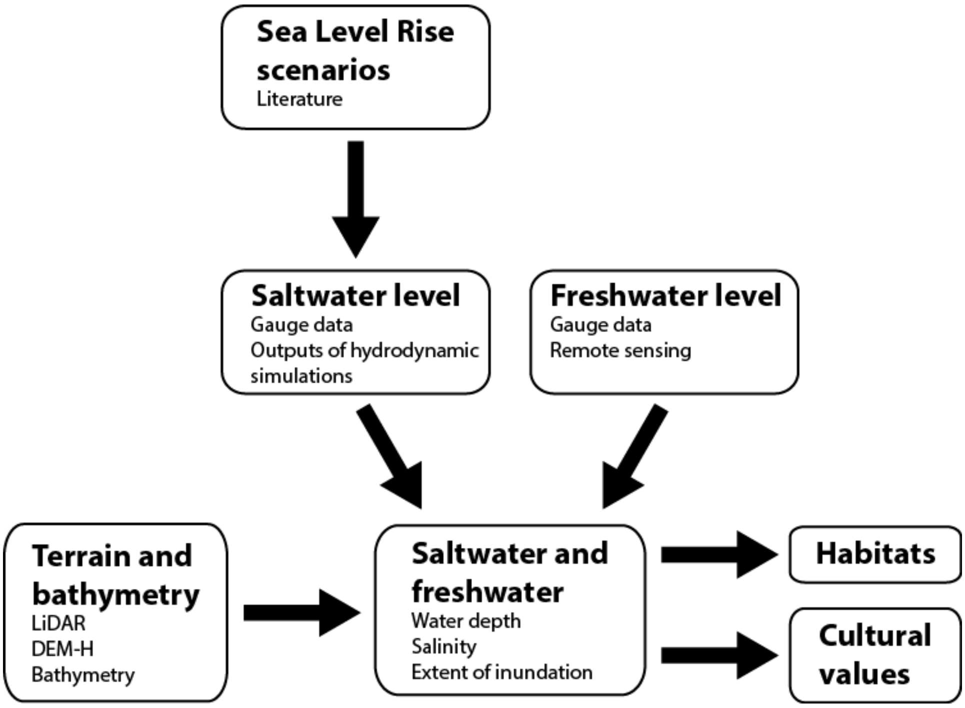


Figure 2. Conceptual model of empirical Sea level rise model and applied in the case study areas: Boggy Plain and Yellow Water.

Defining Floodplain areas in selected case studies

We defined the floodplain areas using the shapefile (from Bartolo 2013) for the whole KNP. In each of the case studies we overlayed our grids for each of the case study areas and used the "Overlay" tool in ARCGIS 10 to get the intersection area between the case study grids (60m resolutions in Fishnet) and the wetland polygon for the entire KNP The final output corresponds to floodplain area in each of the case studies. In ARCGIS 10 we can perform the calculations for total area of flooplain in each case study using the "Calculate Geometry" tool.

Defining the digital elevation model for each of the case studies

The DEM is considered the most important input into the hydrodynamic model (Saunders *et al*. 2013) and we used the DEM prepared by Saunders *et al* in our analyses, as follows. Three DEMs were combined to create a single base DEM for input into the computational model:

1. 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 #1}. 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).

2. 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, 2011 #2}. The projection system of this DEM is WSG84 with a vertical datum of EGM96.
3. 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 #3}.

The combined DEM for input was converted to a projection system of GDA94 MGA Zone 53 and vertical datum of AHD in 60m grid cells. The vertical datum of AHD ensures that the mean sea level within the computational domain is 0m in elevation relative to the time of collection.
The LiDAR survey provides the high resolution DEM required to model saltwater intrusion in KNP as it has vertical accuracy of elevations within 0.1m. The vertical datum of AHD ensures that the mean sea level within the computational domain is 0m in elevation relative to the time of collection.
Spatial grid containing 60m cells for each of the case studies were constructed based on the combined DEM grid. The areas for the Boggy and Yellow Water grids are cckm2 andyykm2, respectively.

Saltwater level

a) Tides: using gauge data to simulate SLR

Because water levels and saltwater intrusion in KNP vary according to location of the area within the tidal stream, rainfall, extreme events and tides {Winn, 2006 #15} SLR simulations for present and future scenarios need to be performed under specific contexts. For example, during the wet season saltwater intrudes only in the first 30-40km of the SAR, whether during the dry season it affects the whole SAR tidal reach {Woodroffe, 1986 #8:35}.

Given the difficulties to have absolute water level values for comparisons it is necessary to establish relative benchmarks. Using tidal gauge data from gauge G82000041 one option is to add sea level rise on top of the relative seasonal water levels. For example, one can look at percentiles of water level to establish benchmarks in which sea level rise scenarios will be added to. We decided to use the 80th percentile of the gauge data for a bathtub fill of floodplains in the case study areas in both late wet and late dry seasons for a typical rainfall year (60th percentile of total rainfall year, corresponding to 2010, Ward et al. in press). The 80th percentile of gauge data is assumed to be within levels of spring high tides .

We used 2005 and 2010 as these correspond to the 40th and 60th percentile of total rainfall year and thus represent 'typical' years with regards to total rainfall. These two years were selected due to the lack of data for gauge G8200041 for October 2010.

Table 2. Percentile stage height for a typical total rainfall year (60th percentile of total rainfall year, corresponding to 2010, Ward et al. in press).

Percentile stage height month of peak flow	2010 (60th percentile total rainfall year) March (m, AHD)	2005 (40th percentile total rainfall year) October (m, AHD)
5th	2.8	-1.1
20th	3.1	-0.5
40th	3.6	0.3
50th	3.7	0.9
60th	3.7	1.5
80th	3.9	2.6
95th	4.1	3.4

a) Sea Level Rise and extent of floodplain inundation

We adapted the terrain contour approach {Bayliss, 1997 #18} – also known as a bathtub fill – to evaluate the extent of floodplain inundation for each of the SLR scenarios. The bathtub fill approach is often used in large-scale studies (Bayliss et al. 2011) and considers that everything that is under a certain elevation gets inundated. In our approach, given the relative small-scale of the case study areas, we also used local knowledge and measurements of a spring high tide and local topography to calibrate bathtub fills (details below).

b) Calibrating SLR model using local knowledge

Given the lack of data for Gauge G8200041 we calibrated our SLR/floodplain inundation model based on local knowledge and measurements. P. Christophersen and S. McGregor measured the extent of inundation during a high tide on the 1st of November 2012. They used a handheld GPS to mark the point of maximum tidal inundation on that day in Boggy Plain. The coordinates collected by Peter and Sandra were used to calibrate the bathtub-fill model of tidal inundation for Boggy Plain, which used LiDAR data as an input.

c) Hydrodynamic simulations (results from Saunders et al. 2014 Stage 1 inundation modelling used to define the river mouth of the SAR for downstream salinity calculations)

We used model outputs from a hydrodynamic model applied in the whole area of KNP to: (i) provide information about present and future location of river mouth – a key input on the salinity model (see section xx), and (ii) comparison with outputs from the empirical model we constructed. The outputs from the hydrodynamic model are (i) water depth, and (ii) maximum extension of saltwater inundation (Saunders *et al.* 2013). The hydrodynamic model considered the following inputs:

- four sea level rise (SLR) scenarios: current day scenario (No SLR, + 0.0m), 2030 scenario (SLR of + 0.14m), 2070 scenario (SLR of + 0.70m) and 2100 scenario (SLR of +1.10m);

- DEM of the KNP topography and bathymetry (same as described above);

- Darwin tidal gauge recording during 1st to 8th October 2013 to simulate tidal behaviour in the South Alligator River.

From this inputs maximum inundation extents outputs were generated for each of the four SLR scenarios for the whole Park. Clips of the case study areas were applied in the maximum inundation outputs to isolate case studies from the rest of the Park.

Freshwater level and extent of floodplain inundation

a) Modelling water level and inundation extent using Doug's images

Our aim is to benchmark water levels (AHD) for each of the Landsat TM 5 f to assess the potential of using the satellite images as surrogates for SLR scenarios. More specifically we compared water level of Landsat images with reference water levels for the dry season: 80th percentile of water level measured at gauge G8200041 during the dry season (October 2005) for each of the images. The difference between water levels of Landsat images and tidal data is assumed to be sea level rise scenarios.

The model for freshwater inundation and depth was based on Ward *et al*. (2013) who used remote sensing to map the seasonal floodplain inundation dynamics of the Alligator Rivers Region (ARR). Ward *et al*. (2013) applied a fusion of microwave (L-band SAR) and optical (Landsat TM 5) to capture seasonal floodplain inundation dynamics. The USGS Landsat TM 5 image archive was sampled between 1985 and 2011, to give the average post wet season flooded extent for specific periods covering the wet, mid- and dry seasons for the whole ARR.

The selection of images was based on water year rainfall total percentiles where Monthly rainfall records at Jabiru (120°40' S, 132°54' E) were aggregated to water year rainfall totals (October to September) and used to identify a representative range of annual inundation extents corresponding approximately to the 5th, 20th, 40th, 60th, 80th, and 95th water year rainfall total percentiles. The same Landsat 5 TM images were used to calculate the seasonal inundation states the series of image capture years. For each year with available imagery, 3 seasonal image samples corresponding to the end of the wet season (March / April), mid-season (June / July), and dry season (August / September) were captured. Because of cloud cover during the wet season, it is not possible to capture the absolute maximum flood extent for a wet season. However, images captured at the end of the wet season in March / April were captured close to the last rainfall peak and are less than—but indicative of—the maximum flood extents.

Table 3. Landsat TM 5 image capture dates used to calculate inundation frequency for the Alligator River Region {from Ward, 2014 #442}(from Doug Ward documentation – Remote Sensing seasonally inundated floodplains in tropical north Australia DRAFT.pdf, pg 13).

Year	Percentile rain year total	Image capture month
1988	5th	April, June August
2009	20th	April, June, October
2005	40th	April, June, August
2010	60th	March, August
2004	80th	March, June, September
2007	95th	March, July, September

b) Calculating percentage of floodplains inundated by freshwater

Two separate clips were applied for the case studies and each of them contained data on presence and absence of water. We created a mask to remove non-floodplain areas (i.e. main channel of South Alligator river and its western side in Boggy; no mask in Yellow Water was applied) and overlayed the floodplain shapefile (see above) with the presence/absence of water shapefile to calculate the proportion of floodplain inundated by freshwater for each of the images.

c) Benchmarking water levels for Satellite images based on gauge data

The second stage in our modelling approach is to benchmark freshwater water level inside floodplains in Australian Height Datum (AHD). This is used to calculate water level (AHD) for each of the satellite images. We used data from two gauges in this stage: (i) a gauge located in Boggy Plain

(G8200082), and (ii) a second tidal gauge located at the South Alligator River (G8200041), which is positioned less than 3km from the tidal channels entering Boggy Plain) (Figure xx)to benchmark water levels for satellite images.

d) Empirical correlations to calculate water level for andsat TM 5 imagery

Local data for Boggy Plain exists (G8200082), however the data set covers only the period between 1/12/1959 and 1/08/1973 and the satellite image captures correspond to the period between 1988 and 2011. So we need to model local water level at Boggy based on data from a gauge station which data set overlaps the period covered by both Boggy gauge and remote sensing images.

We use the long-term dataset from El Sharana (G8200045) to model water level at Boggy (G8200082) as the time series is relatively long (1/12/1958 to 1/06/2010) and mostly overlaps with the data for both Boggy Plain (G8200082) and remote sensing captures. However, El Sharana is located approximately 100 km upstream of Boggy and there is considerable time delay between water level measurements at El Sharana and Boggy due to amount of time it takes for rainfall/runoff in El Sharana to reach the gauge at Boggy. We performed a analysis of best correlation between mean Log_{10} monthly mean water level at El Sharana and Boggy to estimate time lag between the two gauges.

Based on time-lag analysis we used a linear correlation between Log_{10} monthly mean water level at El Sharana and Boggy to calculate a time series of mean monthly water level at Boggy. The modelled data set now provides water levels for most of the remote sensing images, but these are in the gauge datum, not in AHD.

e) Translating gauge datum into AHD

There is no available information on AHD levels for Boggy Plain gauge (G8200082). Thus, we constructed an empirical model to convert water level inside Boggy floodplain, using data from (i) the area of floodplain inundation and (ii) gauge at the South Alligator River (G8200041).

In the first step we use the remote sensing images of floodplain inundation to construct a linear correlation model (2nd order polynomial) that predicts water level at Boggy (G8200082) based on area of floodplain inundated. Input data was area of floodplain inundation for each of the remote sensing images and modelled mean monthly water level at Boggy Plain (G8200082). We then used local knowledge (P. Christophensen and S. McGregor) to calculate water level at Boggy Plain (based on measurements of floodplain inundation during a high tide on the 1st of November 2012). For the measurements a handheld GPS was used to mark the point of maximum tidal inundation on that day in Boggy Plain.

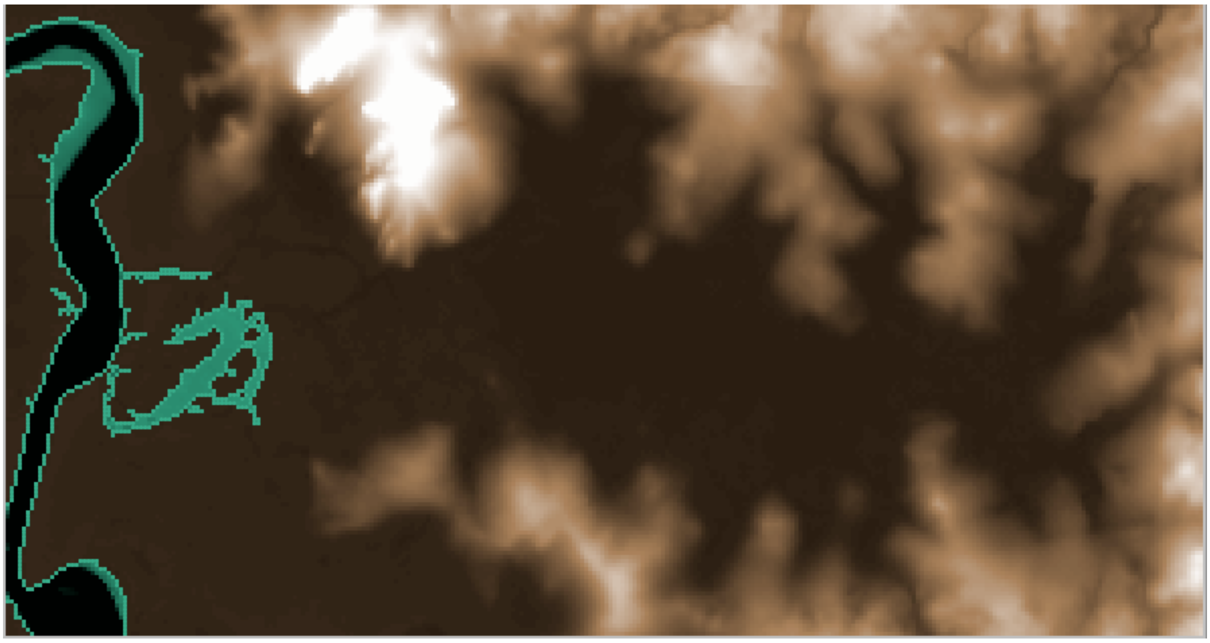


Figure 3. Extent of saltwater intrusion during a king high tide. Data collected by the authors (P. Christophensen and Sandra M.). Digital elevation model used in Netlogo is a combination of LiDAR and the DEM-H (prepared by Kate Saunders).

We used netlogo to inundate the area corresponding to the tide extent measurements and to calculate the area of floodplain inundation corresponding to the high tide data collected by P. Christophensen and S. McGregor. The water level at Boggy was then calculated based on the area of inundation using equation from Figure 4:

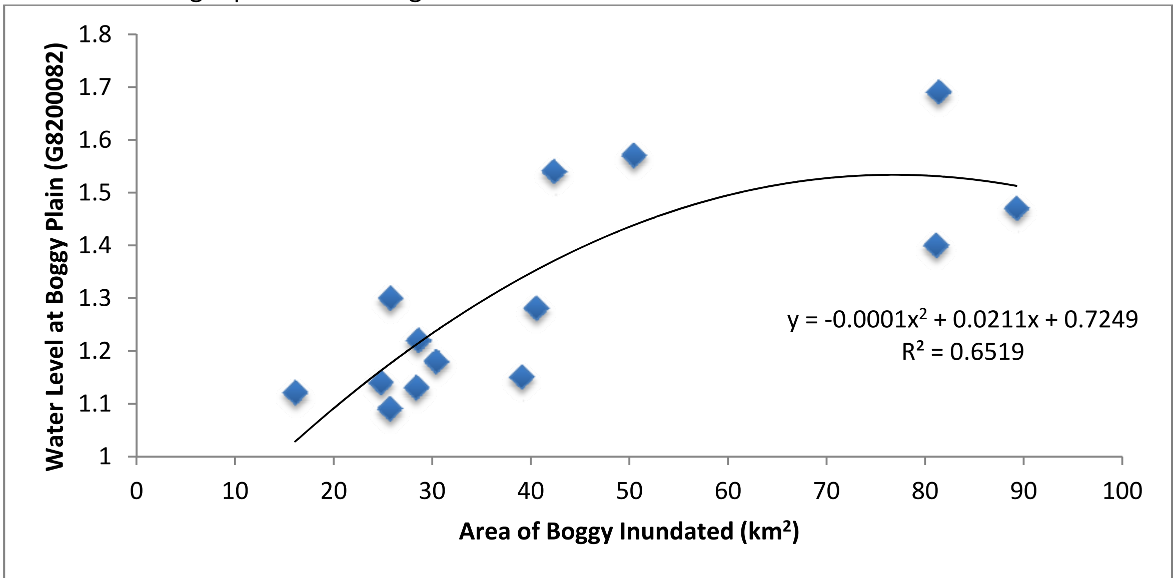


Figure 4. Correlation between the area inundated in Boggy (km^2) and modelled mean monthly water level at Boggy (m).

The calculated water level at Boggy Plain for the high tide observed by Peter C and Sandra is **0.88m** (GD). The next step is to find the equivalent water level in AHD at Boggy Plain. We constructed a linear correlation model (2nd order polynomial), which uses data from the South Alligator River gauge (G8200041) (in AHD) and modelled mean monthly water levels for Boggy Plain (G8200082). We use the model to calculate water level (AHD) for the modelled water level of 0.88m (GD), which corresponds to the water level (GD) for the tidal inundation measured in Boggy Plain.

Calculating water depth

a) Freshwater

Freshwater depth was estimated using the USGS Landsat TM 5 images of floodplain inundation (Ward et al 2014) and the DEM. We used ARCGIS to calculate mean elevation of the contour of water bodies from satellite image captures. The value of the mean contour was assumed to be the level of surface water and then the DEM value for each grid cell was subtracted from this value and assumed to be the depth of the grid cell.

b) Saltwater

For the dry season we used outputs directly from hydrodynamic model and for the wet season the saltwater depth was calculated by subtracting the DEM value from the water level value used for each of the SLR scenario. The inundation corresponding to the 80th percentile of tidal data (2.6m AHD) is very similar to the maximum extent of inundation from the Stage 1 inundation model of Saunders et al. (20154).

Calculating salinity

The water depths (salt- and freshwater) were used to calculate salinity profiles in the case study areas following these steps:

Saltwater depths from SLR scenarios were used to calculate volume of saltwater in each grid cell; the area of each grid cell is 3600m^2 and with the depth it is possible to calculate the volume of water. In Boggy the peak flows occur in March (

1. Figure 6) and we use Doug Ward's images as surrogates for dry season freshwater inundation superimposed by SLR scenarios from Kate & Mahesh which run in October 2013 to calculate salinity in Boggy Plain for each of the SLR scenarios. We assume that salinity in October (or 200 days after peak river flow; Figure 5) will be constant, calculated based on the diffusion model {Woodroffe, 1986 #8:35}.

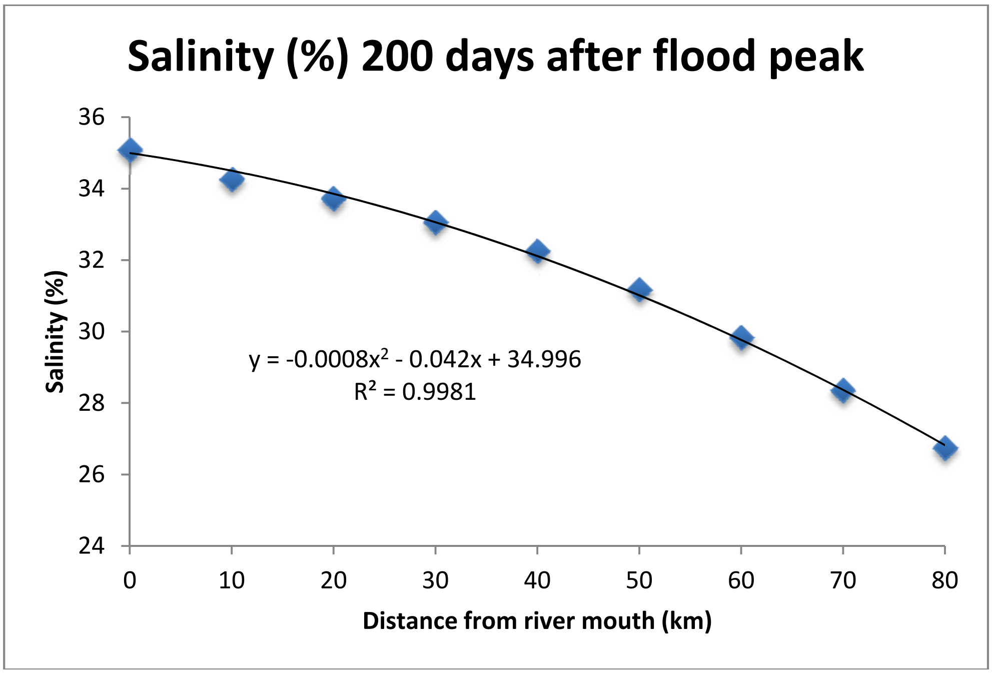


Figure 5. Diffusion model to calculate salinity for the South Alligator River for 200 days after peak flood (April) (based on \ \Woodroffe, 1986 #8:35}. (use exponential model instead).

Salinity at the entrance of Boggy Plain was calculated based on a numerical diffusion model {Woodroffe, 1986 #8:35} (Figure 3). The salinity model for the SAR is based on observations after peak river flows, which occur in March for Boggy (

2. Figure 6).

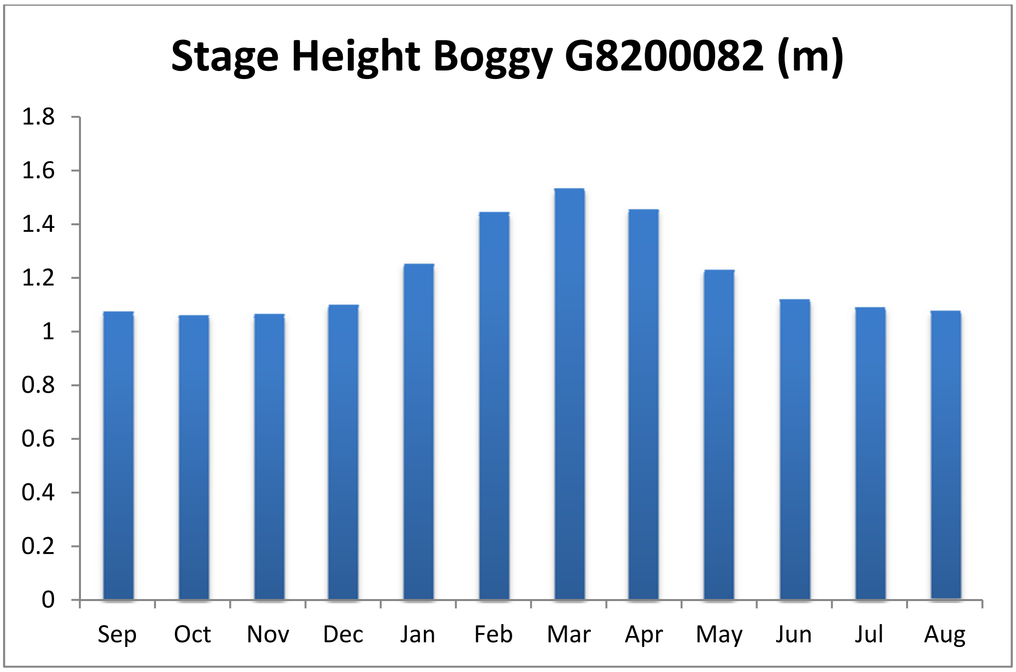


Figure 6. Mean monthly stage heights for Boggy Plain (gage G8200082) from 1969 to 2010 showing peak water levels are in March.

3. The volume of freshwater in each grid cell at Boggy Plain was calculated based on freshwater depth estimated from satellite imagery (Ward et al., 2013) (see section 2.2.2).
4. The current distance from the entrance of Boggy Plain to the mouth of the South Alligator River (56km) was measured using ArcGIS tool distance calculation, with the assumption that the river mouth will move upstream as a result of SLR and this will affect the salinity diffusion model (Table 4).

5. Predicting where the location of the river mouth in the future is challenging because of the combination of sediment re-suspension and deposition due to hydrodynamics. For our exercise, we defined the mouth of the river to be where there is a defined river channel in which the frequency of tidal inundation from hydrodynamic modelling was ≥ 0.75. There is little difference between the frequency of inundation from present and 2030, so we assume this will be the same for these two scenarios. However, the mouth of the South Alligator River will move further upstream in 2070 and 2100 (Figure 7).

Table 4. Distances from case study areas to the mouth of the South Alligator River calculated for each SLR scenario.

SLR Scenario	Boggy (km)	Yellow Water (km)
0m SLR (Present 2013)	56	90
0.14m SLR (2030)	56	90
0.70m SLR (2070)	10	44
1.1m SLR (2100)	0	34

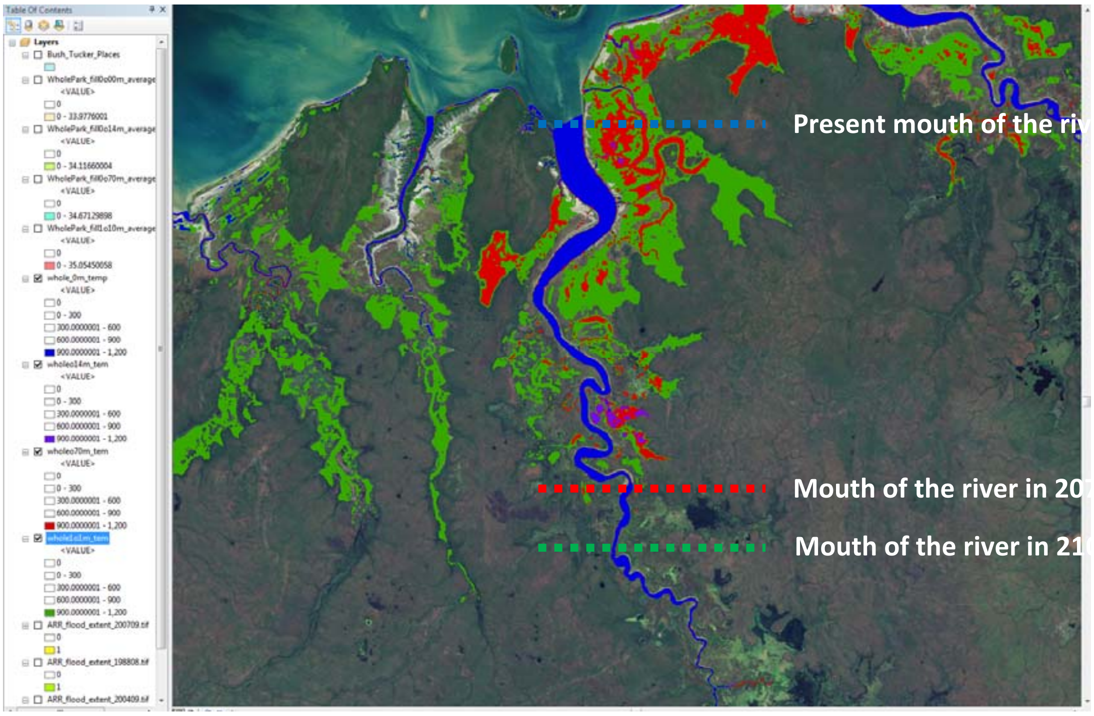


Figure 7. Frequency of tidal inundation => 0.75, which was used to define the river mouth for sea-level rise scenarios. The mouth of the river for present and 2030 were assumed to be the same.

6. Salinity during the dry and wet seasons was calculated in each grid cell by overlapping output files of saltwater and freshwater inundation. We use freshwater outputs from 2010 (60^{th} percentile of total rainfall year as per Ward et al. (2013)).
7. Salinity (*S*) is calculated as follows:

$$S = \frac{(VFW \times CsFW) + (VSW \times CsSW)}{VFW + VSW}$$

where,
VFW: volume of freshwater
CsFW: concentration of salt in the freshwater, assumed to be 0.5g/L
VSW: volume of saltwater
CsSW: concentration of salt, from Woodroffe et al. (1986)

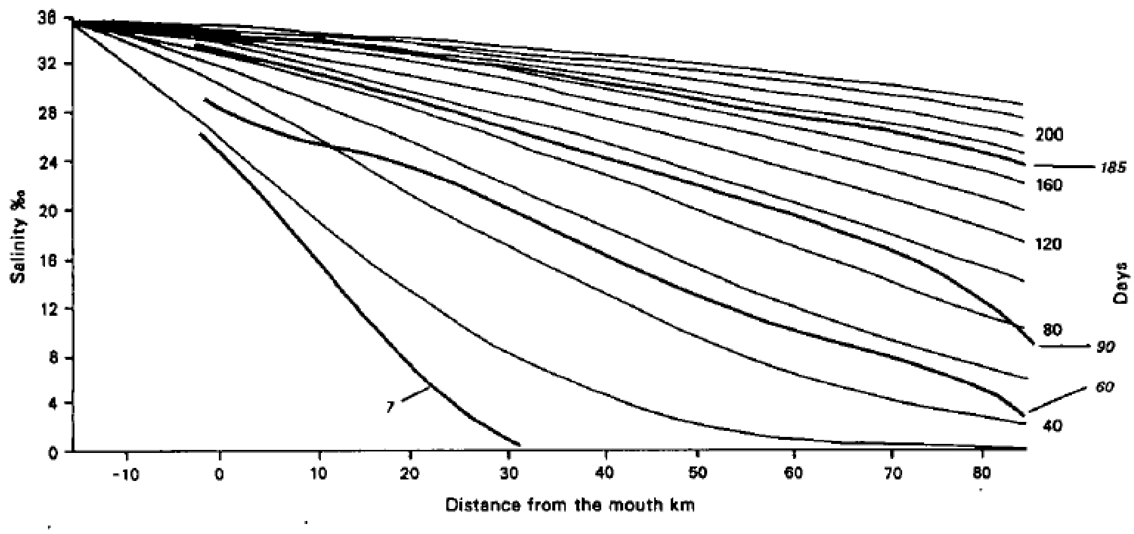


Figure xx. Salinity profiles for the South Alligator River through the dry season. Fine lines represent modelled salinity profiles and thick lines observed salinity profiles. Italic numbers show time in days after last flood peak in wet season (April) at which observations were made. Other numbers show model day-numbers {from \Woodroffe, 1986 #8:35}.

Results

Landsat TM 5 images as surrogates for SLR scenarios

Time-lag Analysis

There is a 2-month time lag between rainfall at El Sharana and effects at Boggy Plain (Figure 8).

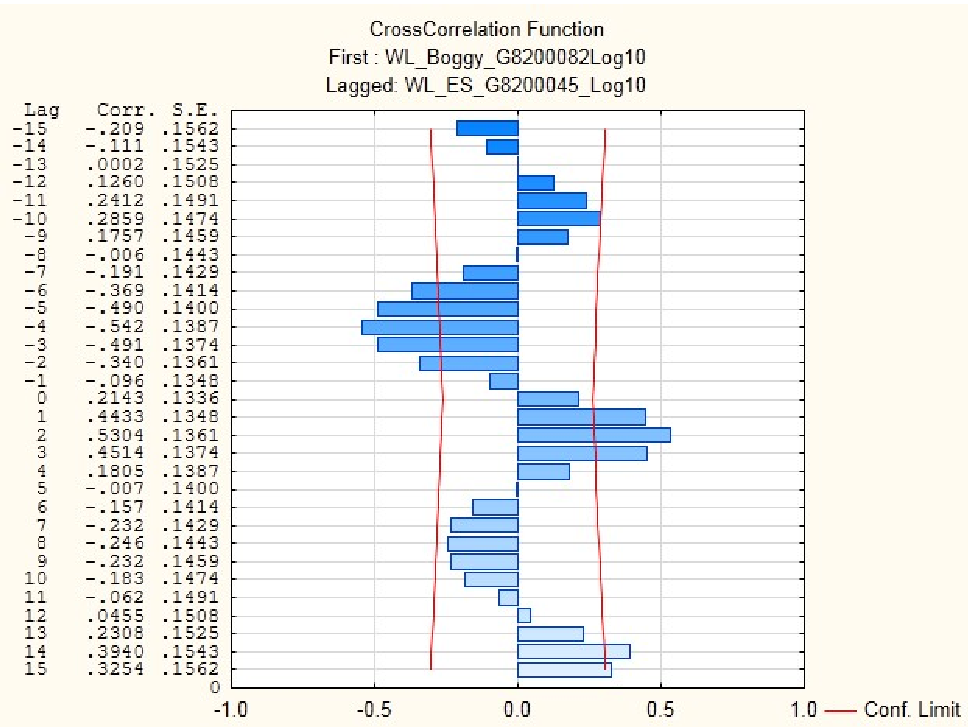


Figure 8. Time lag analysis between Log_{10}Water Level for El Sharana (G8200045) and Log_{10}Water Level for Boggy plain (G8200082) gauge stations

The linear correlation between water level in El Sharana and Water Level in Boggy Plain with the 2-month time lag is depicted in Figure 9.

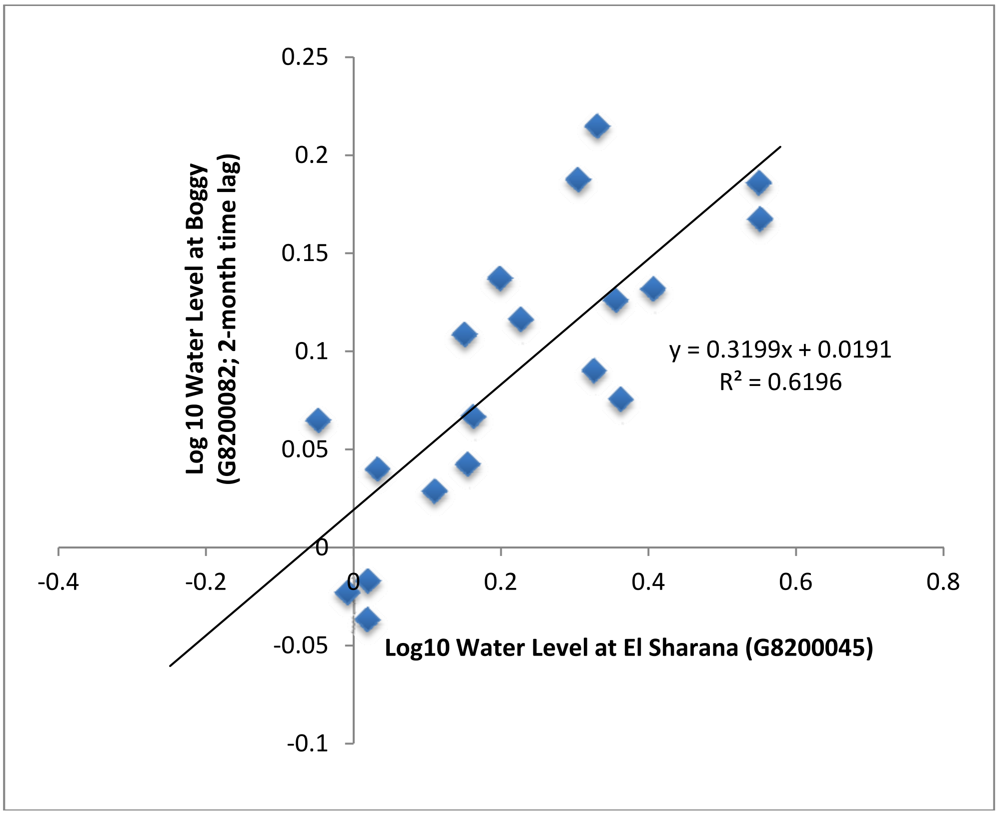


Figure 9. Linear correlation between monthly mean Log_{10} water level at Boggy and mean log_{10} Water Level at El Sharana. Data from 1/12/1959 to 01/08/2973.

Linear model (2nd order polynomial), which uses data from the South Alligator River gauge (G8200041) (in AHD) and modelled mean monthly water levels for Boggy Plain (G8200082) to estimate water level (AHD) for each of the Landsat TM 5 images. We use the model depicted in Figure 10 to calculate water level (AHD) for the modelled water level (0.88m GD) corresponding to the extent of inundation measured by peter and Sandra. The calculated water level for the extent of tidal inundation based on the model from Figure 10 is **3.27m (AHD)**.

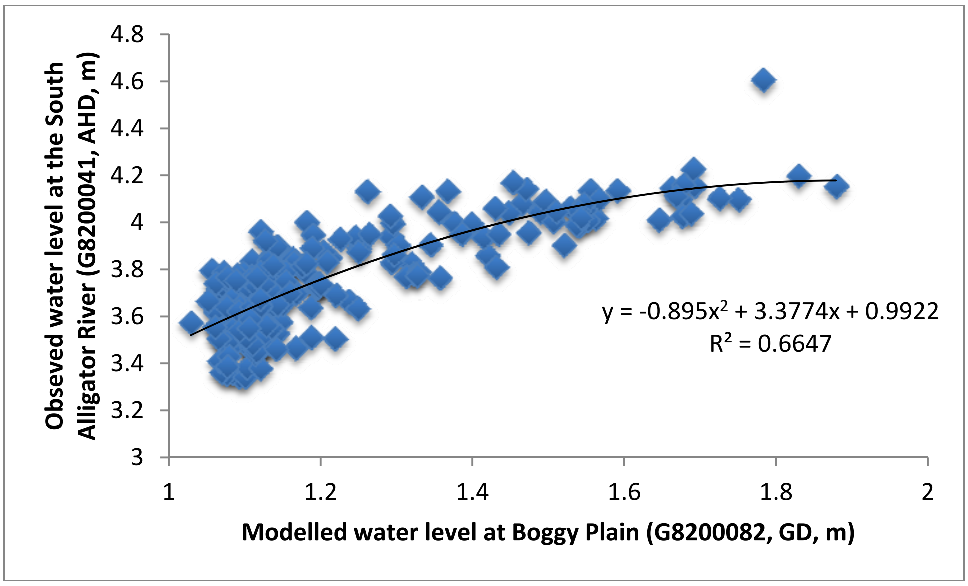


Figure 10. Observed maximum monthly water level at the South Alligator River (AHD, m for gauge G8200041) versus modelled water level at Boggy Plain (GD, m for gauge G8200082).

Key results:

All water levels of satellite images are between 1 and 1.6m higher than the 80th percentile of water level corresponding to October 2005.

If using as surrogate, best is to focus on images captured during the wet season during a high tide (e.g. image XX) as they will show connectivity between main river channel and floodplains.

If using satellite images as surrogate consider that they represent inundation from both fresh and salt water and are probably a good indication of total extent of inundation.

Landsat images probably over-estimate total area of inundation (especially if using images from the dry season) due to presence of billabongs and other disconnected water bodies that are a result of water accumulated during previous wet season (not a result of saltwater inundation).

Need pictures showing the above and select the an image showing connectivity during wet season

The method could be used in initial assessments of SLR impacts and requires gauge data and Landsat or other satellite imagery which are easily available.

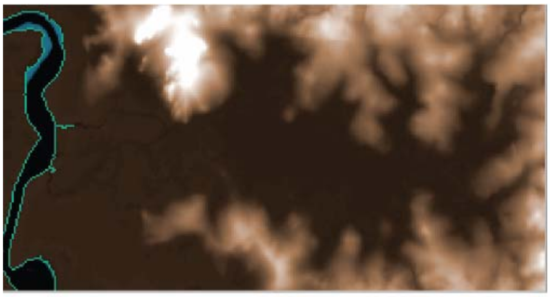
Table 5. Monthly mean water level (m) calculated for Boggy Plain (G8200082) and proportion of floodplain area inundated for Boggy Plain and Yellow Water based on Landsat TM 5 images.

Flood Extent Images	Date & Time of image captures (Darwin)	Percentile rain year total	Modelled Water Level @ Boggy Plain with 2-month time lag (GD, m)	Modelled Water Level @ Boggy Plain with 2-month time lag (AHD, m)	Area of floodplain inundated (m2) (Boggy)	Proportion of floodplain inundated (Boggy)	Area of floodplain inundated (m2) (Yellow Water)	Proportion of floodplain inundated (Yellow Water)	Metres above 80th percentile water level (from modelled data)
198804	23/04/1988, 10:17	5th	N/A	N/A	45002089	62.21%	36673749	70.06%	N/A
198806	26/06/1988, 10:18	5th	1.28	3.85	23891936	33.03%	18010345	34.41%	1.25
198808	13/08/1988, 10:18	5th	1.09	3.61	17871159	24.71%	11296047	21.58%	1.01
200403	03/04/2004, 10:26	80th	1.47	4.02	67059480	92.70%	49127504	93.86%	1.42
200406	22/06/2004, 10:29	80th	1.57	4.09	37983678	52.51%	34082746	65.11%	1.49
200409	25/08/2004, 10:30	80th	1.15	3.69	29130009	40.27%	20465712	39.10%	1.09
200504	08/05/2005, 10:34	40th	N/A	N/A	32327461	44.69%	28222513	53.92%	N/A
200506	09/06/2005, 10:34	40th	N/A	N/A	23034047	31.84%	23820341	45.51%	N/A
200508	28/08/2005, 10:35	40th	1.13	3.67	18540398	25.63%	12863084	24.57%	1.07
200703	27/03/2007, 10:42	95th	1.4	3.97	62545268	86.46%	48749809	93.13%	1.37
200707	01/07/2007, 10:41	95th	1.3	3.87	17190088	23.76%	255486738	48.69%	1.27
200709	19/09/2007, 10:40	95th	1.14	3.68	16775631	23.19%	11989842	22.91%	1.08
200904	01/04/2009, 10:34	20th	1.54	4.07	31714861	43.84%	30149008	57.60%	1.47
200906	20/06/2009, 10:35	20th	1.18	3.73	19837497	27.42%	26159977	49.98%	1.13
200910	10/10/2009, 10:37	20th	1.12	3.65	8522984	11.78%	8996529	17.19%	1.05
201003	19/03/2010, 10:38	60th	1.69	4.14	61240313	84.66%	45180859	86.32%	1.54
201008	26/08/2010, 10:37	60th	1.22	3.78	19604542	27.10%	20223621	38.64%	1.18

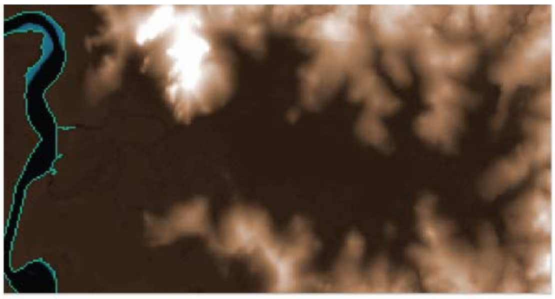
Extent of tidal inundation based on empirical model and comparison of model outputs with hydrodynamic model

There is reasonable agreement between outputs of maximum tidal inundation empirical and hydrodynamic models for present and 2030 scenarios (Figure 11).

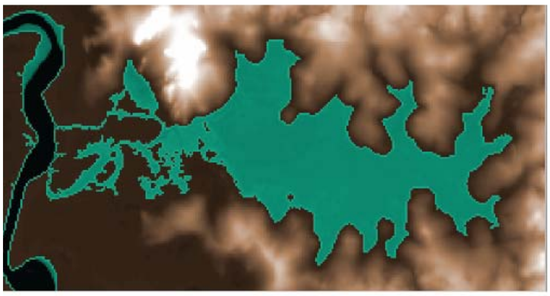
- Need to quantify percentage of floodplain inundation scenarios for both approaches for comparison and tabulate analysis.
- Need to replace figures and use pics produced in ARCGIS only, putting all 3 scenarios and one colour per scenario for each modelling approach.



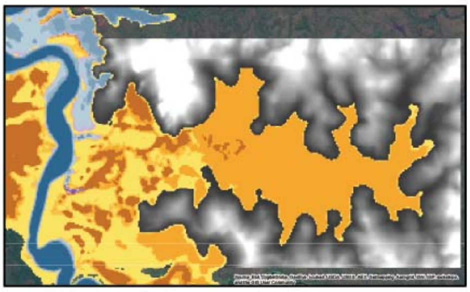
Outputs from empirical model (placeholder): Present scenario



Outputs from empirical model (placeholder): 2030 scenario



Outputs from empirical model (placeholder): 2030 scenario



Outputs from hydrodynamic model (placeholder): Present scenario (blue), 2030 (purple), and 2070 (Yellow/orange)

Figure 11. Comparison of outputs for Present (blue on hydrodynamic model and green in empirical model) and 2030 (purple) scenarios.

Water depth at case study areas (Boggy and Yellow Water)

Dry and We seasons – maps of water depth for Yellow Water and Boggy

Salinity at case study areas (Boggy and Yellow Water)

Dry and wet seasons - maps of salinity for Yellow Water and Boggy

Calculating salinity at case study areas (Boggy and Yellow Water) during the wet season

During the wet season we assume a perfect mix of salt- and freshwater in the case study areas. We modelled salinity at the peak flow (March) for similar percentile rain year total (Table 3) where for present scenario we use a bathtub fill of the floodplain using the 50th percentile of the maximum stage height for the SAR gauge G8200041 (Table 7) to account for the tidal influence in Boggy Plain and the Landsat images from Doug to account for rainfall effects (and freshwater trapped in the floodplain). Sea level rise scenarios are added to the 50th percentile of gauge data for the peak flow month of each year (March or April) for each of the rain year total from Table 3. Salinity is then calculated based on the diffusion model from Woodroffe et al. {, 1986 #8:35} where the mouth of the river is estimated based on for each of the sea level rise scenarios **Error! Reference source not found.**.

Rainfall year (October to September) for each of the rain years total sourced from Doug Ward to identify the month of the peak flow.

Table 6. Monthly mean stage height (G8200041) for each of the rain year total years to identify peak flow month (m, AHD).

Mean monthly stage height	1988 (5th)	2009 (20th)	2005 (40th)	2010 (60th)	2004 (80th)	2007 (95th)
October	0.578	0.593	0.556	0.538	0.587	
November	0.621	0.629	0.662	0.512	0.585	
December		0.754	0.76	0.548	0.764	
January		1.26	1.496	1.423	1.609	
February	1.199	1.652	N/A	1.246	1.84	1.21
March	1.13*	1.408	N/A	1.253	1.643	2.711
April	1.17*	0.921		1.085	0.967	1.064
May	0.893			0.718	0.764	0.62
June	0.742				0.594	0.583
July	0.705				0.505	0.469
August	0.686				0.487	0.498
September			0.573		0.482	0.512

*** calculated from mean daily data**

Table 7. Percentile max stage height day (G8200041) for month of peak flow (m, AHD) for each of the rain year totals.

Percentile stage height month of peak flow	1988 (5th) **February**	2009 (20th) **February**	2005 (40th)	2010 (60th) **March**	2004 (80th)	2007 (95th) **March**
5th	2.8614	1.41375		2.79		1.5625
20th	3.196	1.443		3.132		1.732
40th	3.4588	1.7042		3.551		1.993
50th	3.496	1.727		3.649		2.101
60th	3.526	1.745		3.703		2.191
80th	3.9668	1.7762		3.922		3.544
95th	4.0472	1.81195		4.127		6.1

Questions for David Williams:
For the calculations of salinity we excluded the main river channel and assumed the salinity in the main river channel to be based on Woodroffe's model and everything that is outside the ain river channel than mixes with the freshwater from Doug's images. Another approach would involve assuming all saltwater outputs to have the salinity as per Woodroffe's model and no need to calculate salinity. UIsing this approach means that there will only be two salinities, one based on the decay finction for Mahsh's output and a econd value for putre freshwater for Doug's images. Which oune would you recommend?

For Yellow Water there is no clear definition of what the main channel is and given we could not app[ly the same principle used for Boggy (where the main channel was defined as the area in which all images from doug coincided. The maiximum number of images from Doug coinciding for Yellow Water was 11, hence we assumed there ws no clear definition of the main river channel. Given the low lying relief the water will simply inundate further inland with rise in SLR. As a resut the salinity output files are simply the mix between Mahesh's and Doug's images.

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

Kate Saunders, Fletcher Woolard and Mahesh Prakash
Stage 1 Report
20th January 2014

Internal Client: CSIRO Marine and Atmospheric Research, Wealth from Oceans Flagship
External Client: Northern Australia Hub (NERP)

CSIRO Computational Informatics
CSIRO Marine and Atmospheric Research
Wealth from Oceans Flagship

Citation

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Copyright and disclaimer

Important disclaimer

Contents

Figures

Tables

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Dr. James Hilton for the continued development and maintenance of the Shallow Water Code.

Executive summary

Sea level rise threatens to detrimentally impact the low-lying floodplains of Kakadu National Park through the saline inundation of freshwater areas, loss of native vegetation and 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

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., 2008b).

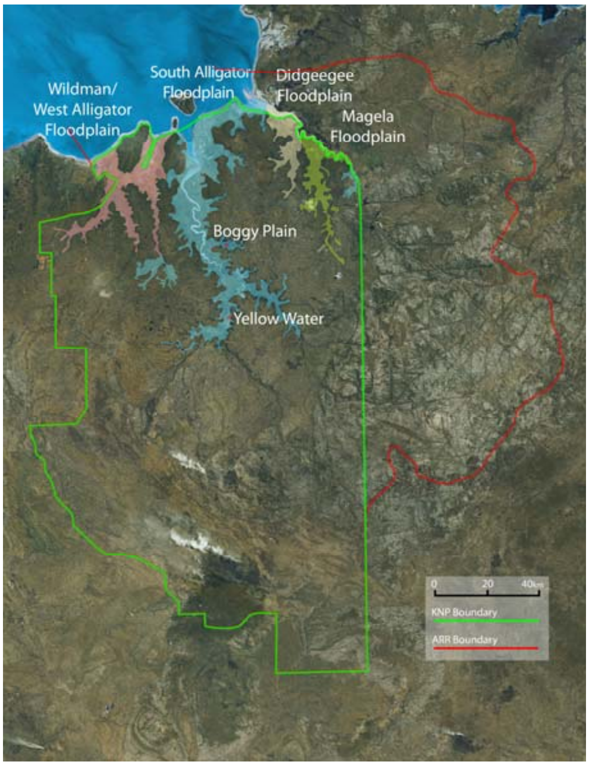


Figure 1 The four river systems of Kakadu National Park and the associated floodplains. The boundaries of Kakadu National Park and the extended Alligator Rivers Region are as marked.

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).

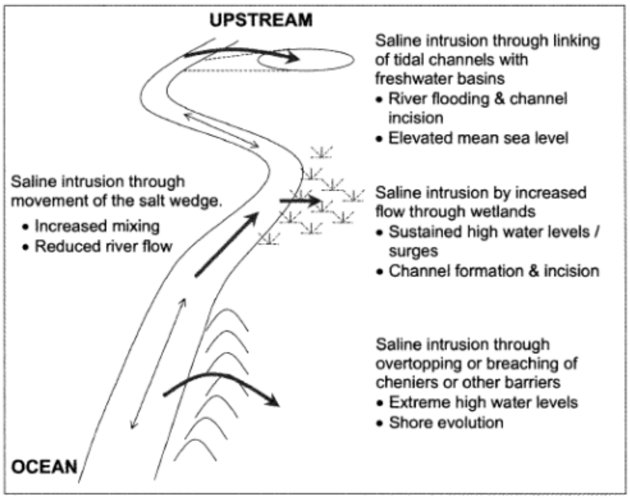


Figure 6. Potential mechanisms of saltwater intrusion. Variation in the expected form of saline water intrusion with distance upstream from the river mouth.

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., 2008b). 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. (2008b) 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., 2008b).

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 (A1FI)	0.26m - 0.59m; central estimate 0.43m + 0.1 – 0.2 from ice sheets	Global	(CSIRO, 2007)

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 was forced to use 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., 2008b).

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. In keeping with the most recent vulnerability assessments made we consider the two scenarios; 2030, a sea level rise of +0.143 m, and 2070, a sea level rise of +0.70 m (BMT WBM, 2011). Another scenario will consider a rise of +1.1m, an estimate in the upper to mid range of global predictions for 2100 (Table 1). For base comparison and validation, a current day scenario of +0.00 m will 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.

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,

$$\frac{\partial h}{\partial t} + (\nabla \cdot \boldsymbol{q})h = 0$$
$$\frac{\partial \boldsymbol{q}}{\partial t} + (\nabla \cdot \boldsymbol{u})\boldsymbol{q} + \frac{g}{2}\nabla h^2 - \boldsymbol{s} = 0$$
$$\boldsymbol{s} = gh\,\nabla b + gn_m^2 h^{\frac{-1}{3}}\boldsymbol{v}|\boldsymbol{v}|$$

where *h* is height of the water, ***q*** is the unit discharge from a given cell, ***u*** and ***v*** are the horizontal velocities, g is gravity and ***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.

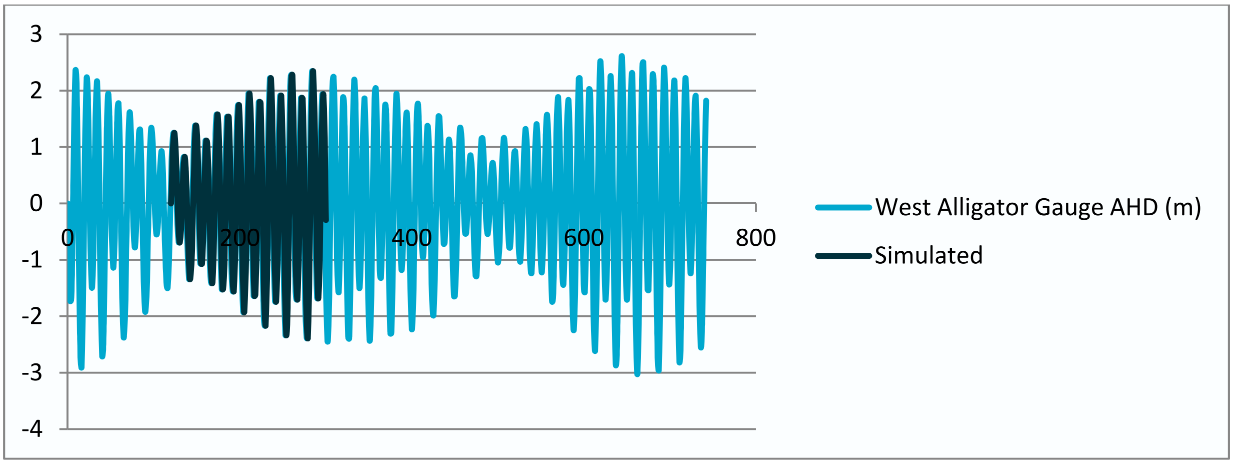
It is important to note that the combined DEM used was not without its data limitations. Artificial and inaccurate striping of river elevations was present within the LiDAR generated DEM and required manual editing. Sounding data within the region is also limited, particularly within the river mouths 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.



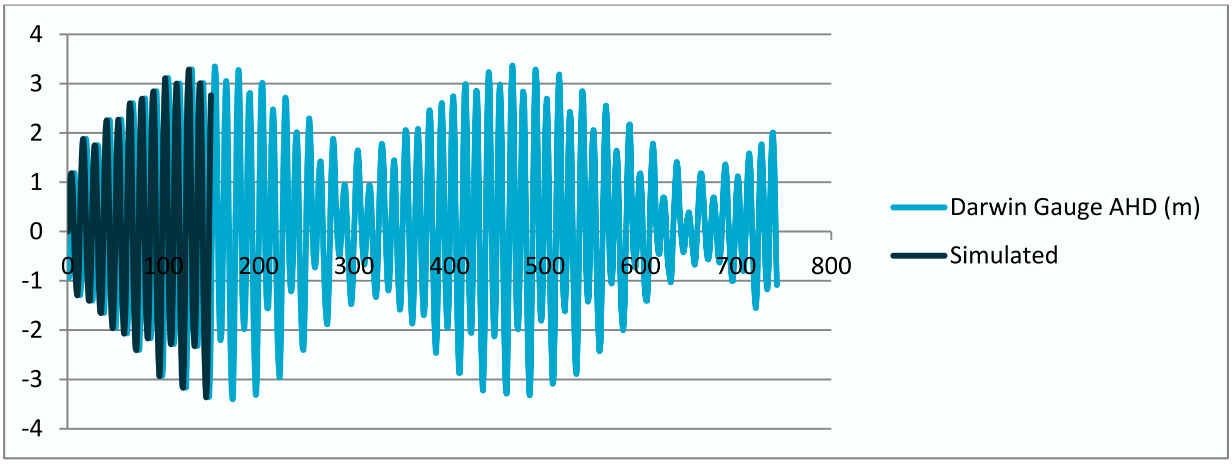


Figure 3 Tidal inputs for the month of October from the West Alligator Gauge 2007 and the Darwin Gauge 2013. The tidal cycles highlighted in navy are those used to generate the results.

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).

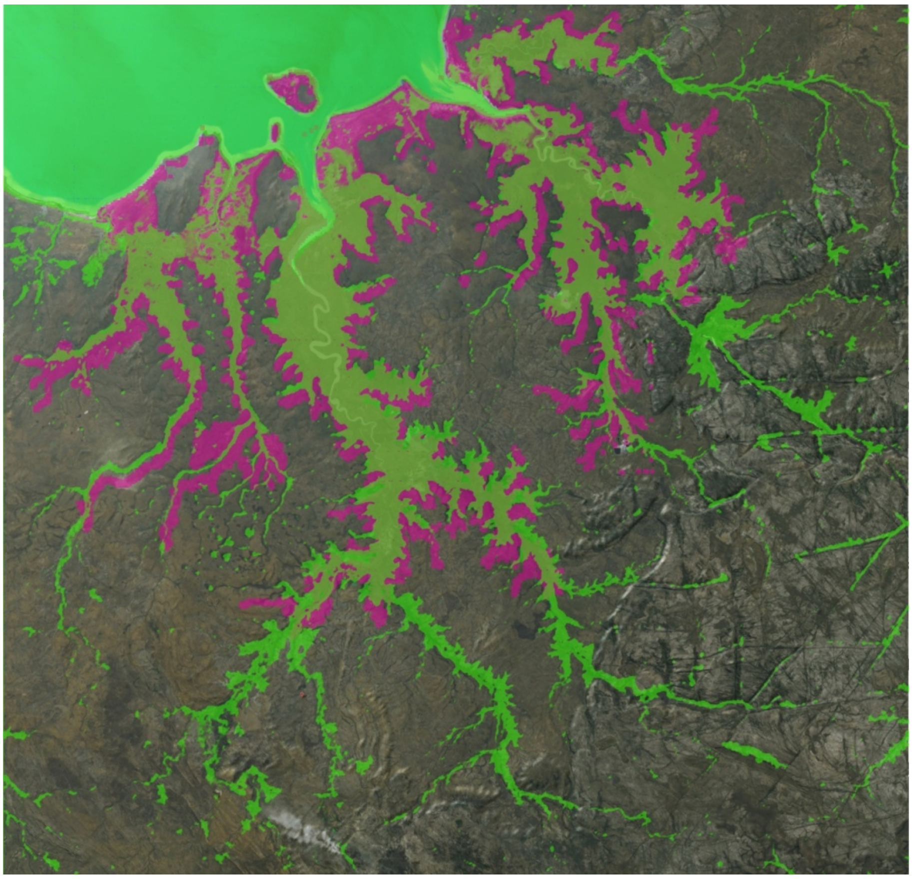


Figure 4 Simulated flood extent (green) as compared with cumulative landsat data of the inundated floodplains captured during a series of wet seasons (pink).

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.

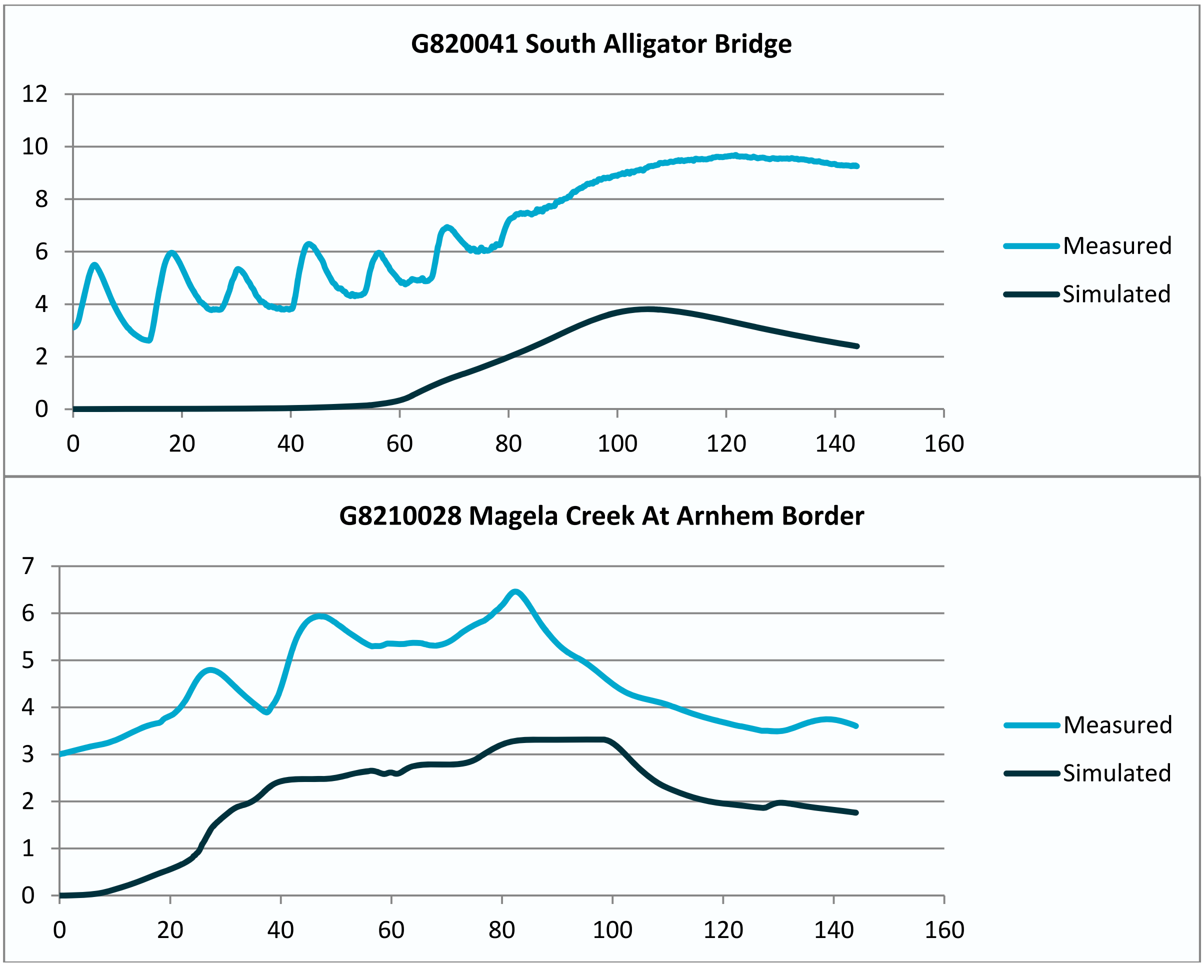


Figure 5 Simulated and measured results for G8200041 the South Alligator Bridge Gauge and G8210028 for Magela Creek at Jabiru.

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.

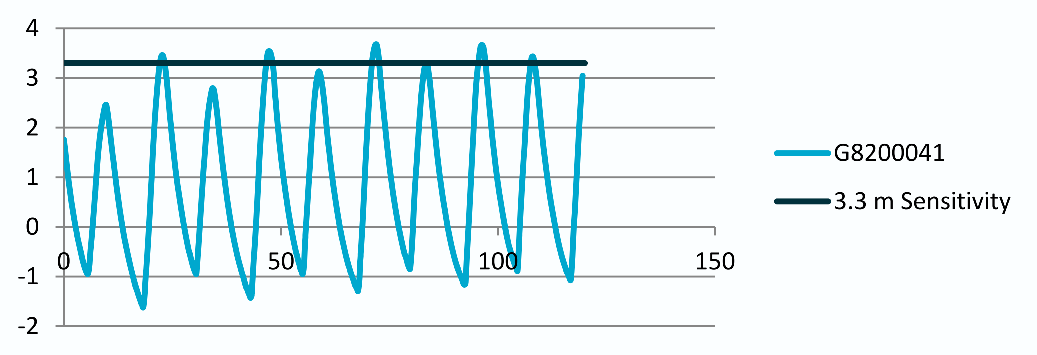


Figure 7 Measurements of river height AHD at the South Alligator River bridge gauge, G8200041, from the 1st to the 5th of February. The dark blue line is the threshold for inundation to occur into Boggy Plain.

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.

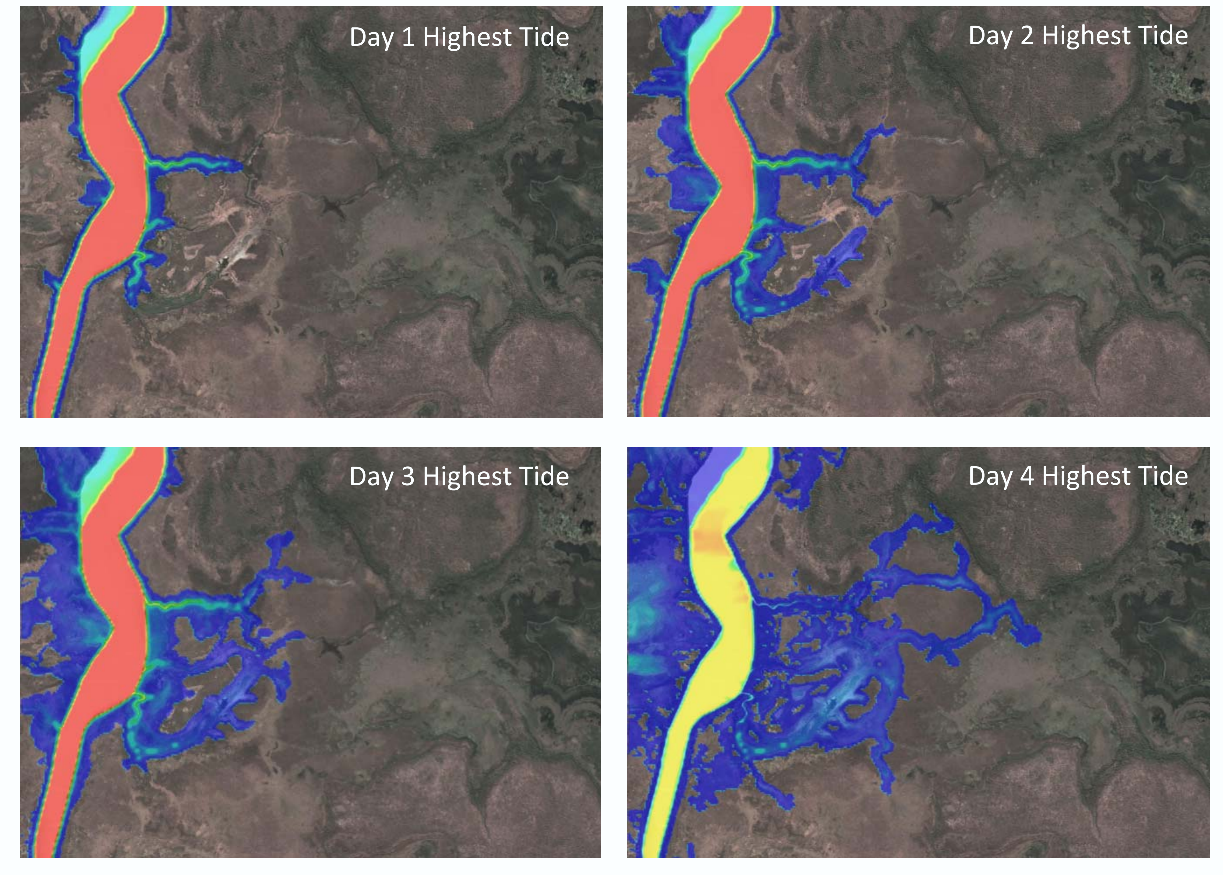


Figure 8 Tidal extents at the four highest tides during the 1st to 5th of February.

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. This does 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.

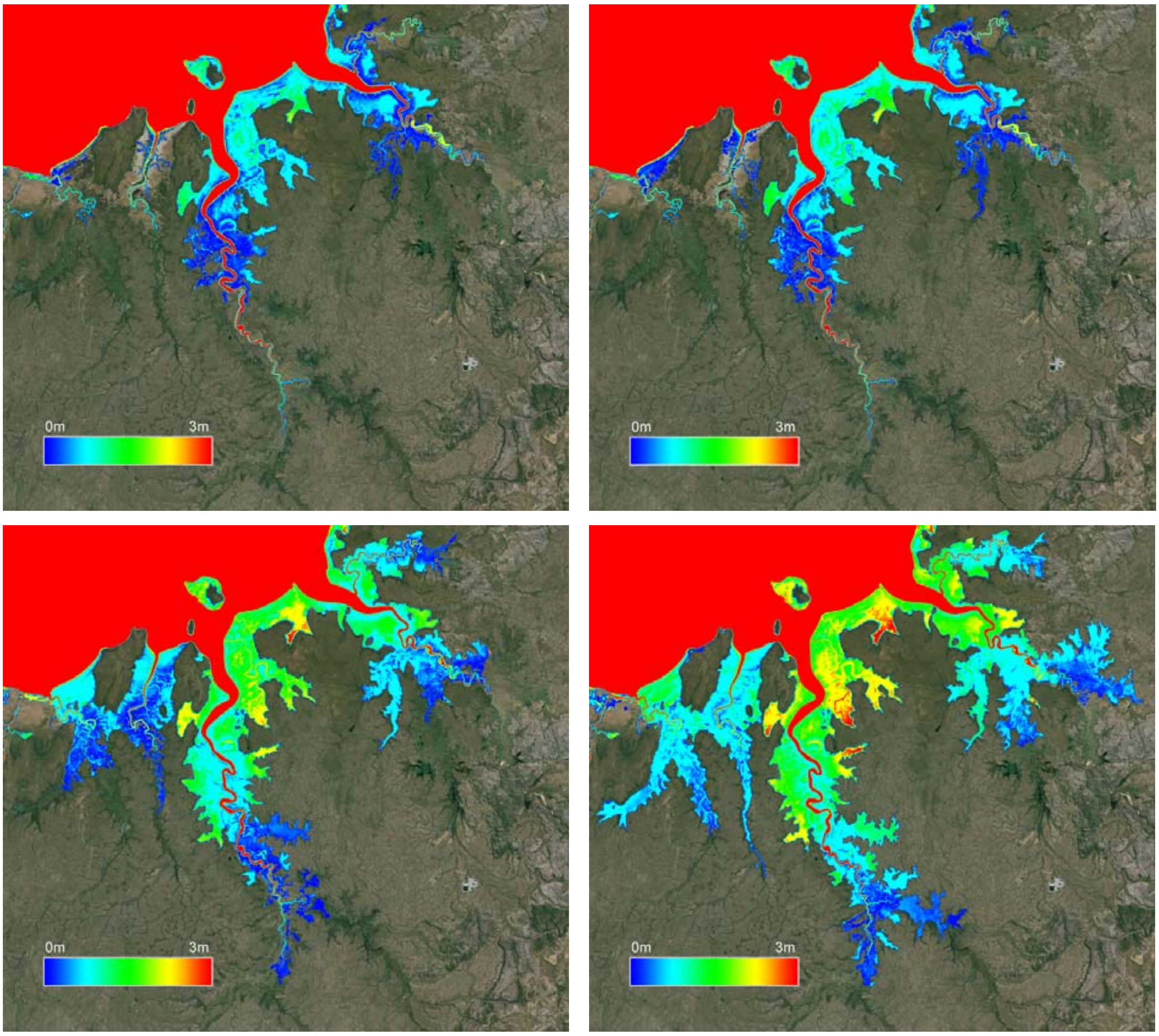


Figure 9 The maximum simulated tidal extents for the scenarios of current day, 2030, 2070 and 2100. The water is shaded by depth with red of depth 5m or greater and dark blue at depth 0 m.

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.

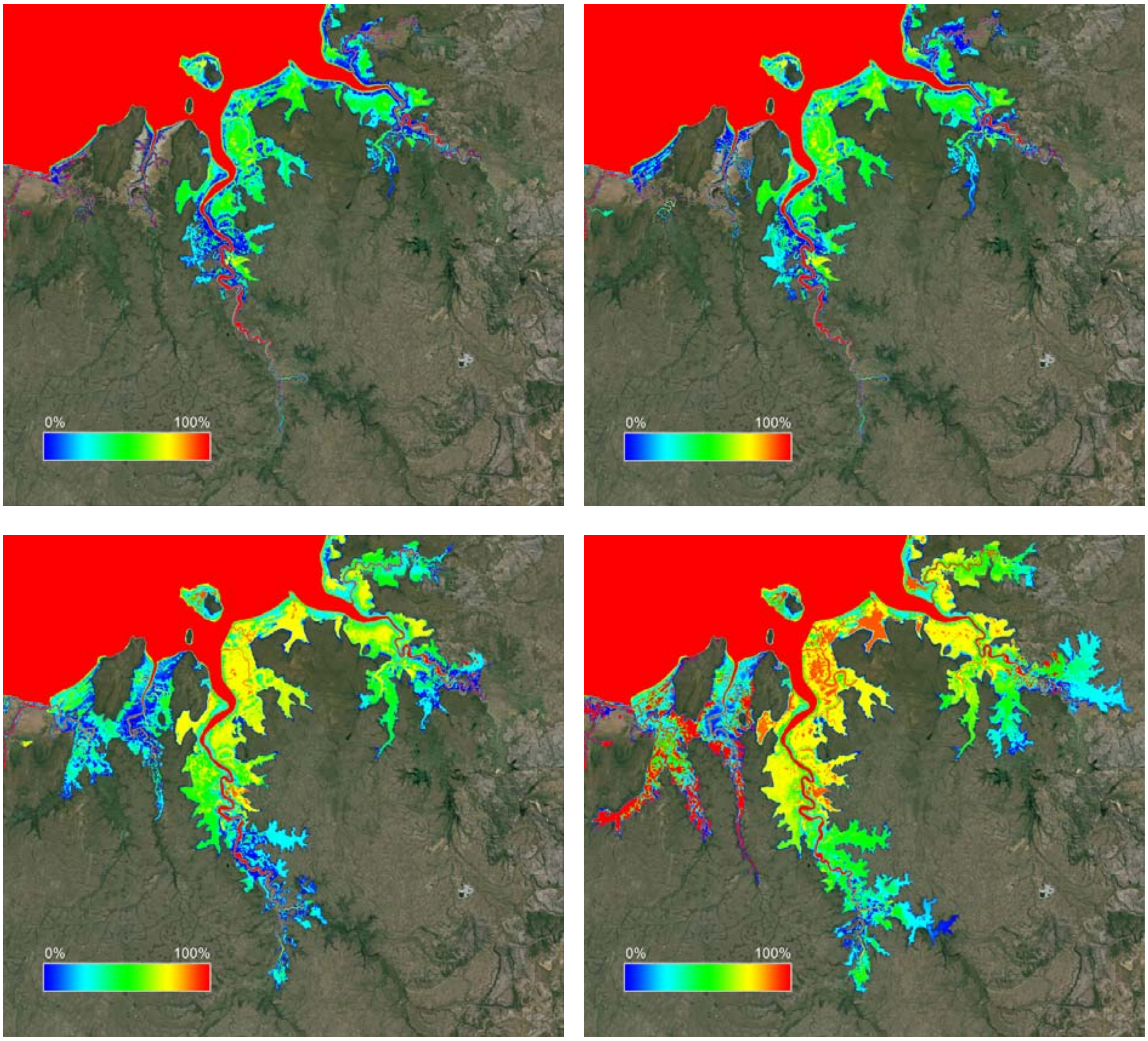


Figure 10 The frequency of inundation for the scenarios of current day, 2030, 2070 and 2100. The water is shaded as a percentage with red of depth 100% inundated or and dark blue 0% inundated.

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.

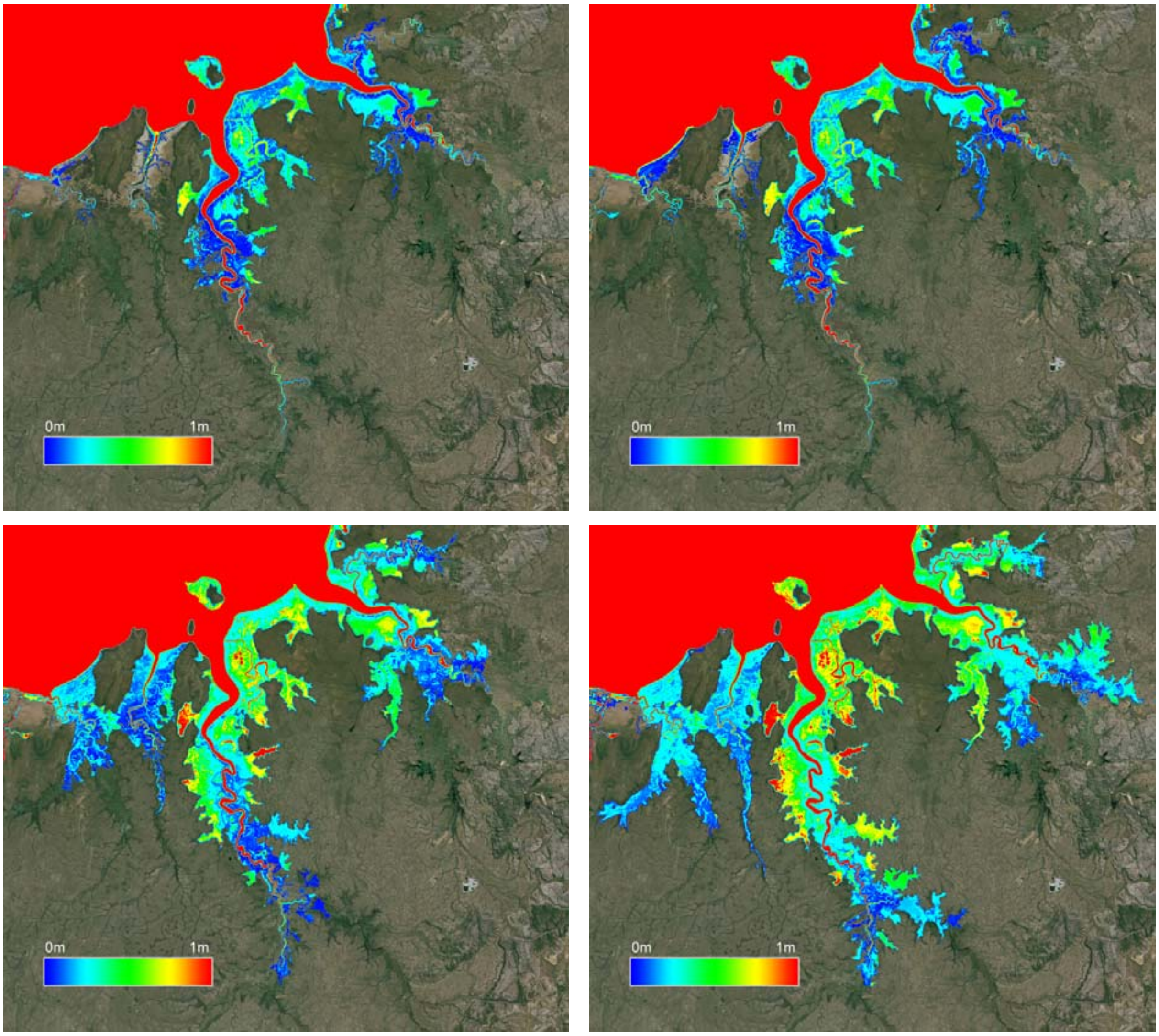


Figure 11 The average depth of inundation for the scenarios of current day, 2030, 2070 and 2100. The water is shaded by depth with red of depth 1m or greater and dark blue at depth 0 m.

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.

6 Discussion

Mangrove growth provides an indicator for area saline inundated by tide. 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. (2008b) 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., 2008b). 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., 2008b). 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. (2008b), 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. 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. (2008b) 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., 2008a). 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, 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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Hydrodynamic Modelling of Saline Inundation from Sea Level Rise in Kakadu National Park

James Hilton, Fletcher Woolard and Mahesh Prakash

Stage 2 Report

1st September 2014

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Contents

Figures

Tables

Acknowledgments

Wealth from Oceans Flagship

Executive summary

Kakadu National Park is a World Heritage Site in the Northern Territory. The freshwater floodplains and wetlands of the park support many of the bird, reptile and fish species found in Australia. Saltwater intrusion through potential sea level rise or cyclonic storm surges may impact these freshwater ecosystems. Effects of saltwater intrusion include loss of habitat for freshwater species, along with changes in traditional hunting and cultural heritage sites. In stage 1 of this project, the effects of potential sea level rise on Kakadu national park was examined and saltwater intrusion estimated from maximum inundation extents. In this stage of the project, phase 2, we apply a computational model to predict quantitative salinity values over inundated regions. An evapotranspiration model is used to ensure the correct prediction of deposition of salt on floodplains due to evaporation. In addition to sea level rise we also examine saltwater intrusion during storm surges caused by cyclones with associated heavy rainfall events. The scenarios investigated were for months in the wet season (March) and the dry season (October) using current day sea levels and a sea level rise of 70 cm. Additional wet season scenarios with a 3 meter storm surge were also carried out. The maximum area of saltwater intrusion was found to increase for both storm surges and sea level rise. However, heavy rainfall was found to potentially mitigate the effect of saltwater intrusion in upstream areas.

1 Introduction

Kakadu National Park is the largest and one of the most diverse national parks in Australia. The park is located within Arnhem land, at north eastern part of the Northern Territory, and runs from Van Diemen gulf in the north 200 km south to the escarpments of the Arnhem Land plateau. The northern part of the park is dominated by lowland floodplains, which are inundated by freshwater during the wet season, and the four major river systems: the East, South and West alligator rivers and the Wildman river. The park encompasses the entire catchment of the 160 km long South alligator river. One third of the bird species in Australia can be found in Kakadu, and the floodplains are the seasonal home to around 2.5 million waterbirds. The park is also home to one quarter of Australian freshwater and estuarine fish species as well as many species of small mammals and reptiles, including threatened species such as the saltwater crocodile (World Heritage Convention UNESCO, 2014).

Figure 1 - The Northern Territory and Van Diemen gulf, with Kakadu national park outlined in black.

The area has also been continuously inhabited by humans for over 40,000 years and the current Aboriginal people living in the region are part of the oldest surviving culture in the world. Both the ecological and cultural uniqueness of the park led to the addition of the park to the UNESCO World Heritage List, encompassing “all the natural and cultural attributes necessary to convey its outstanding universal value”. However, amongst the protection requirements for the site is a range of adaption and mitigation measures to manage the consequences of climate change in the region. Such consequences include potential sea level rise, changes in precipitation and changes in seasonal temperature ranges (Bayliss et al., 1997).

Saltwater intrusion of freshwater areas through sea level rise may result in the contraction of freshwater habitats and the spread of saline mudflats into vegetated areas. For the Kakadu wetlands this could lead to the loss of crocodile breeding grounds and magpie geese habitat, as well as affect the ability for the local people to gather food within these regions (Saynor et al. 2004). Saltwater intrusion on floodplains occurs through the expansion and creation of tidal creeks (Winn et al., 2006). A rapid expansion of a tidal creek network (30 km inland in 40 years) has been reported in the Mary river system, adjacent to Kakadu national park (Knighton et al. 1992). The high speed of the intrusion has been attributed to a number of factors, including the flat floodplains in the region and the high tidal ranges in the van Diemen gulf. The flat floodplains allow breaching of freshwater regions during exceptionally high tides which quickly form channels due to scouring action of the high tidal ranges (Bayliss et al., 1997). Additionally, feral buffalo form swim channels in the wet season, greatly accelerating the formation of tidal creeks.

This phase of the study investigates saltwater intrusion and mixing with freshwater regions using a hydrodynamic model. The models are run over monthly periods in the dry (October) and wet (March) seasons and tidal cycles, rainfall (during the wet season) and evaporation are taken into account. Additionally, the effect of cyclonic storm surges, and the associated heavy rainfall events, are investigated in two of the scenarios. A set of scenarios with a sea level rise of 70 cm is also considered. As detailed in phase 1 this corresponds to a potential sea level rise in 2070 (BMT WBM, 2011). Metrics such as the maximum and median salinity and inundation extents are presented and discussed.

2 Methodology

The hydrodynamics were modelling using a conservative finite volume formulation of the shallow water equations. The shallow water equations are based on the assumption that the height of the water is much less than the width and length of the domain, allowing the vertical velocity to be depth averaged. This assumption allows the hydrodynamics to be reduced to a two-dimensional formulation, considerably simplifying the computational cost of modelling such systems. The depth-averaged assumption holds in this case as the tidal height is small in relation to the expanse of computational domain. The conservative shallow water equations are given by (Kurganov and Petrova, 2007):

$$\frac{\partial h}{\partial t} + \nabla \cdot \boldsymbol{q} = 0 \tag{1}$$

$$\frac{\partial \boldsymbol{q}}{\partial t} + \nabla(\boldsymbol{uq}) + \frac{1}{2} g \nabla h^2 + \boldsymbol{s} = 0 \tag{2}$$

$$\boldsymbol{s} = gh\,\nabla B + g n_m^2 h^{-\frac{7}{3}} |\boldsymbol{q}|^2\, \widehat{\boldsymbol{q}} \tag{3}$$

where *h* is the height of the water above the base level *B*, $\boldsymbol{q}$ is unit discharge given by $\boldsymbol{q} = h\boldsymbol{u}$, $\boldsymbol{u}$ is the horizontal velocity vector and *g* is gravity. The vector $\boldsymbol{s}$ combines a source term from the gradient of the base and a lossy drag term. The drag is based on a Manning drag formulation (Begnudelli and Sanders, 2007), where , n_m is the Manning drag coefficient.

Our computational formulation is based on a solution method presented by Kurganov and Petrova (2007). This method obeys both *well-balanced* and *positivity preserving* properties which are essential for realistic and stable shallow water simulations. The well-balanced property ensures that the numerical scheme does not perturb solutions which should remain stable, for example, a lake of water at rest. The positivity preserving property ensures that the height, *h*, remains positive everywhere. This is an especially difficult requirement to meet at interfaces between wet and dry regions within the simulation domain. Although such requirements appear conceptually straightforward, a scheme that meets both of these requirements is difficult to construct and has been the focus of much hydrodynamic research. The Kurganov and Petrova scheme uses a number of novel methodologies to ensure both of these essential properties are satisfied. These include a reformulation of the shallow water equations in terms of the total height above a given vertical datum, local small-scale reconstruction of the input base topography to ensure a well-balanced solution and a modified linear reconstruction method for the water heights in the finite volume method. In our simulations we also include a minimum water height cut-off of 1 μm to prevent floating-point round-off error at very small water depths.

The salinity component was modelling using the depth averaged scalar advection-diffusion equation (Gross et al. 1999):

$$\frac{\partial(sh)}{\partial t} + \nabla \cdot (s\boldsymbol{q}) - \nabla(\varepsilon h \nabla s) = 0 \tag{4}$$

where s is the depth-averaged scalar concentration and ε is the diffusivity coefficient. Eq. (4) can be re-arranged using Eq. (1) to give:

$$h\frac{\partial s}{\partial t} + \boldsymbol{q} \cdot \nabla s - \nabla(\varepsilon h \nabla s) = 0 \tag{5}$$

In this study s was the depth averaged salinity value (in parts per thousand) and ε was set to be constant, based on an estimate of the maximum turbulent diffusion in the system. This was calculated as $\varepsilon \sim \frac{1}{6}\kappa h u^*$, where u^* is the shear velocity (Cea et al., 2007) and $u^* = u\sqrt{g}nh^{-\frac{1}{6}}$, so $\varepsilon \sim \frac{1}{6}\kappa q\sqrt{g}nh^{-\frac{1}{6}}$. Eq. (5) was solved using an explicit finite difference method.

The evapotranspiration component was modelled using the Penman-Monteith formulation. Due to the large number of unknown variables in the standard formulation, the FAO-56 model was used, which gave the rate of evapotranspiration from a fixed reference type of vegetation with a height of 0.12 m, a surface resistance of 70 s/m and an albedo value of 0.23 (Smith et al. 1992). Despite the use of a single vegetation type the model predicted values consistent with measured rates of approximately 6mm/day (Fig. 2). The Penman-Monteith equation used was:

$$R = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T + 273.3}\right)u_2 e_s\left(1 - \frac{R_h}{100}\right)}{\Delta + \gamma(1 + 0.34u_2)} \tag{6}$$

where Δ is the slope of the saturated pressure curve, R_n the net radiation flux (MJ m^{-2} day^{-1}), G the heat flux into the ground (MJ m^{-2} day^{-1}), calculated as $G = c_s R_n$, where c_s is the soil heat flux coefficient, γ is the psychrometric constant, estimated as $\gamma = 6.65\times10^{-4}P$, where P the atmospheric pressure (kPa), T is the mean air temperature (°C), u_2 the wind speed 2 m from the ground (m s^{-1}), e_s the mean saturated vapour pressure (kPa) and R_h the relative humidity (%). The slope of the saturated pressure curve, Δ, was calculated as:

$$\Delta = \frac{4098\left(0.6108e^{\left(\frac{17.27T_m}{T_m+273.3}\right)}\right)}{T_m + 273.3} \quad (7)$$

where T_m is the mean daily temperature. The mean saturated vapour pressure, e_s, was calculated as:

$$e_s = 0.6108e^{\left(\frac{17.27T}{T+273.3}\right)} \quad (8)$$

For the simulations in this study we used a constant Manning's drag of 0.015, corresponding to drag for light land usage. The inputs required for the model are a base digital elevation model (DEM) of the topography and bathymetry for the region, the elevation of mean sea level and a tidal time series for boundary forcing. For the salinity component an initial distribution of salinity is required, which was approximated using the limiting behaviour in the wet and dry seasons. The diffusion coefficient ε was set to 0.1, based on a height O(10 m) and velocity O(10 m/s). For the evapotranspiration component, air temperature, wind speed, relative humidity and solar radiation time series inputs are required. The mean pressure used was 101.3 kPa and the mean temperature used in Eq. 7 was set to 20°C. The ground was assumed to be perfectly absorbing, with c_s = 0.

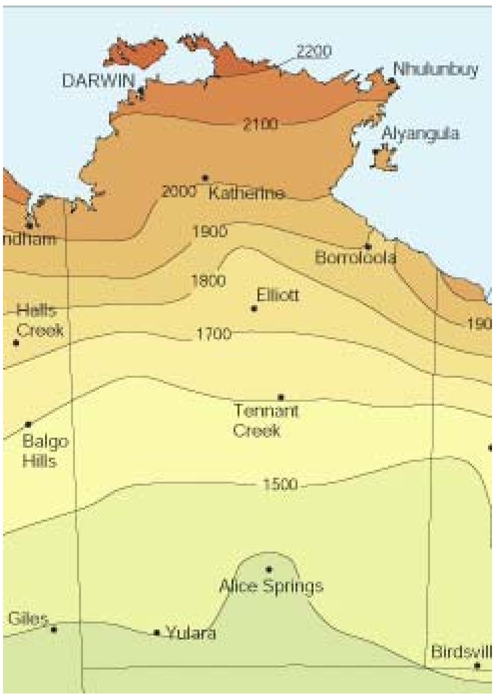


Figure 2 - Evapotranspiration rates in mm per year across the Northern Territory.

3 Simulation Inputs

3.1 Digital Elevation Models

The digital elevation model (DEM) was the same 60 m model used in phase 1 of the project. This was composited from three separate DEM sources: a LIDAR survey, Shuttle Radar Topographic Mission (STRM) data and a bathymetric DEM (Geoscience Australia, 2009). For details on the construction and processing of the input DEM, please refer to the phase 1 report. A small refinement was made to the river depths in the South Alligator river in this phase, which had previously been taken from the bathymetric DEM. The depth of the river was reconstructed based on transects carried out by Woodroffe et al. (1986). Where the transects did not cross the river system the depth of the river was estimated from paleochannels in the transects. This correction resulted in river depths lower than used in the previous DEM.

3.2 Tidal Boundary Forcing

Due to the lack of available data in the Van Diemen Gulf, tidal records from Darwin were used for the tidal input. These tides were scaled to match present day observations of maximum tidal inundation in the downstream region around Boggy plain. Tidal time series from March and October 2012 were used in the model. Additionally, a tidal time series incorporating a 3 m storm surge event was used, shown in Fig. 4. The value of 3 m was estimated as a worst-case scenario, occurring at the peak of the tidal cycle. The estimation was based on storm surges recorded in Darwin (2 m for cyclone Tracey, 1974) and areas surrounding the gulf (5-6 m for cyclone Monica, 2006, in Junction Bay, ‘several meters’ for cyclone Ingrid, 2005, at Drysdale Island).

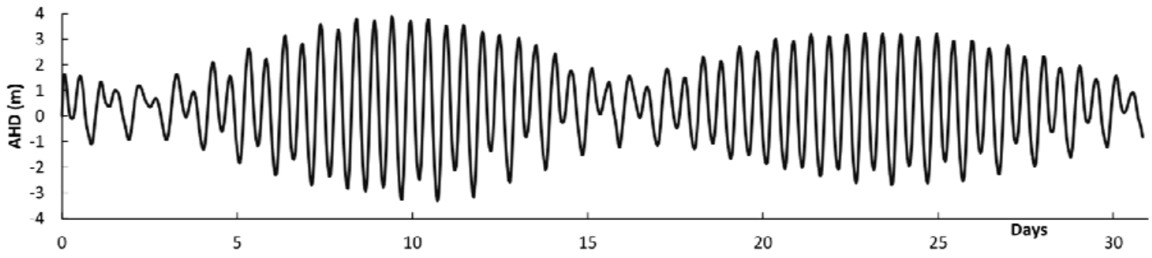


Figure 3 - Darwin March 2012 tide

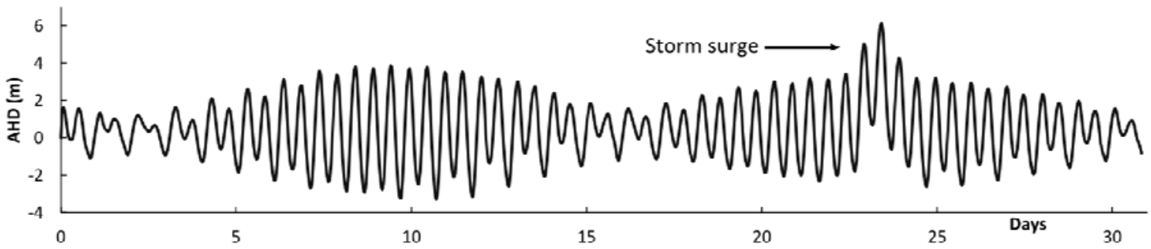


Figure 4 - Darwin March 2012 tide with storm surge event

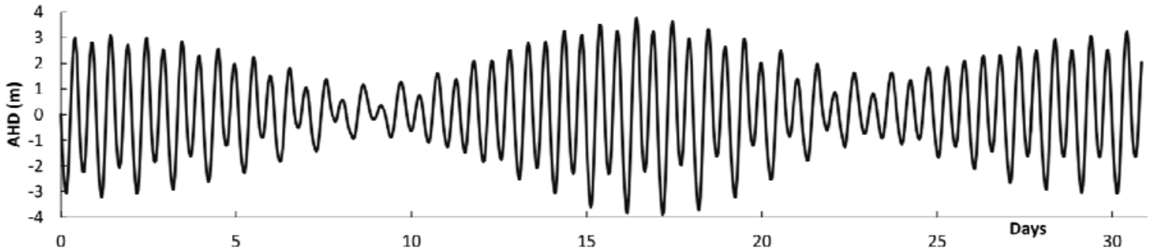


Figure 5 - Darwin October 2012 tide

3.3 Salinity model

The salinity model required a starting condition for the initial salinity distribution. No spatial large-scale salinity data was available over the modelled region to use for these conditions. However, salinity values have been measured within the South Alligator river system (Woodroffe et al., 1986). The peak dry season values given by Woodroffe et al. (1986) were used for the initial conditions for the October simulation, which started at sea level salinity (36 ppt) at the mouth of the South Alligator, falling to approximately 26 ppt 80 km from the mouth. The same salinity decrease as a function of distance from the mouth was assumed to hold for the East and West Alligator river systems. The initial salinity distribution for the October scenarios is shown in Fig. 6 (left). For the wet season (March), it was assumed that the river was entirely freshwater. The offshore distribution was not known and was assumed to linearly rise with distance from the shore to the mean sea salinity value of 36 ppt. The initial salinity distribution for the March scenarios is shown in Fig. 6 (right).

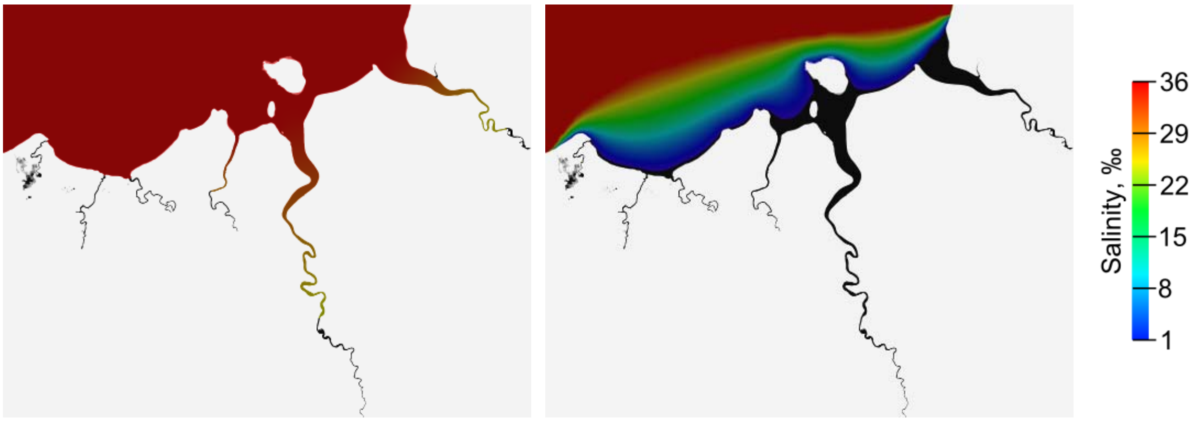


Figure 6 - Initial salinity condition for October (left) and March (right) scenarios

3.4 Scenarios

The scenarios considered are summarised in the following table:

No	Month	Sea level	Storm surge	Rainfall
1	March	present day	None	5mm per day
2	March	present day	3 m	5 mm per day, 100 mm over 2 days during storm
3	March	+ 70 cm	None	5mm per day
4	March	+ 70 cm	3 m	5 mm per day, 100 mm over 2 days during storm
5	October	present day	None	None
6	October	+ 70 cm	None	None

Table 1- Scenario conditions for all cases considered

4 Validation

Validation of the salinity component was carried out using comparison to measured data reported by Woodroffe et al. (1986). Further validation, including onshore salinity levels, are currently being carried out using newer data recently gather from the region. There is a strong dependence of salinity on both rainfall, tidal cycles and existing saline deposits making comparison to measured data difficult. Data given by Woodroffe et al. (1986) shows the increase in salinity over time during the dry season since the 'last flood peak in wet season'. To replicate this event, we assumed that the river was entirely freshwater from the flood event and became saline at the mouth of the river. The model was run for seven days and compared to the observed salinity measured by Woodroffe for the same period. The initial conditions for the simulation are shown in Fig. 7 (inset) and the comparison of the results are shown in the main figure. The simulation results are shown as 3 hour averages, with one standard deviation shown as vertical error bars. No bounds on the measured data ranges were given.

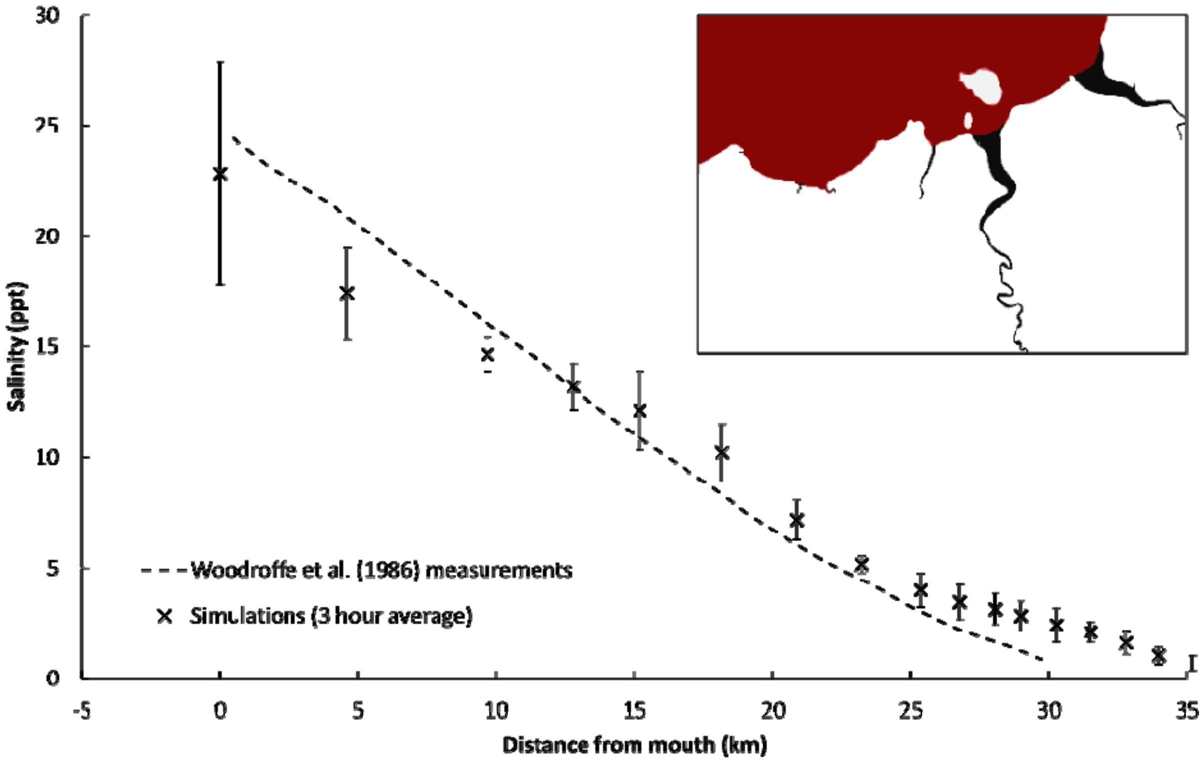


Figure 7 - Validation of the salinity model against observed data; Inset: initial conditions for the simulation

The simulation results give a good match to the observed data ranges and trend.

5 Results

Results from the simulations are shown in the following sections. For the purposes of assessing environment impact the maximum water heights and salinity values over each month are given. These give the worst-case areal extents of inundation due to sea level rise or storm surge, and the corresponding saltwater intrusion. These maximum values do not give a complete picture, however, as they may persist for only a short period of time (especially in the case of a storm surge). To show the baseline trend the median values over each month are also given. The relative difference between the median and maximum values can be used to gauge the overall trend of the inundation conditions. Temporal trends are also shown using percentages of time the water level or salinity is over a threshold value.

5.1 Maximum water levels

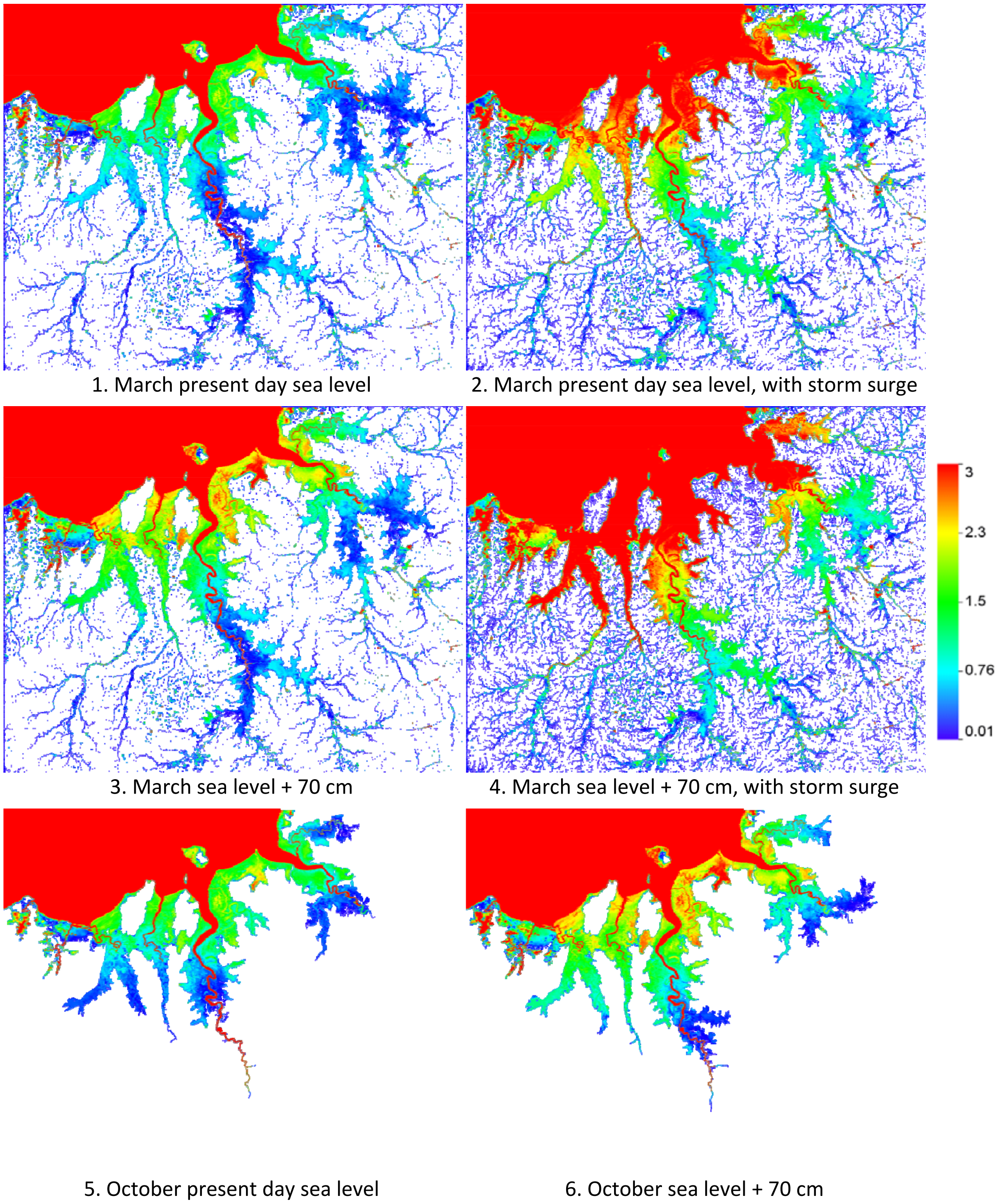


Figure 8 - Maximum water levels (m) and inundation extents

Maximum water levels are shown in Fig. 8 for all scenarios. Note that rainfall is used in the March simulations and the water levels in the catchment network are therefore shown. Storm surge events can be seen to have much higher inundation levels near the coastline. As with phase 1, the boggy plain region is found to flood for the increased sea level scenarios.

5.2 Median water levels

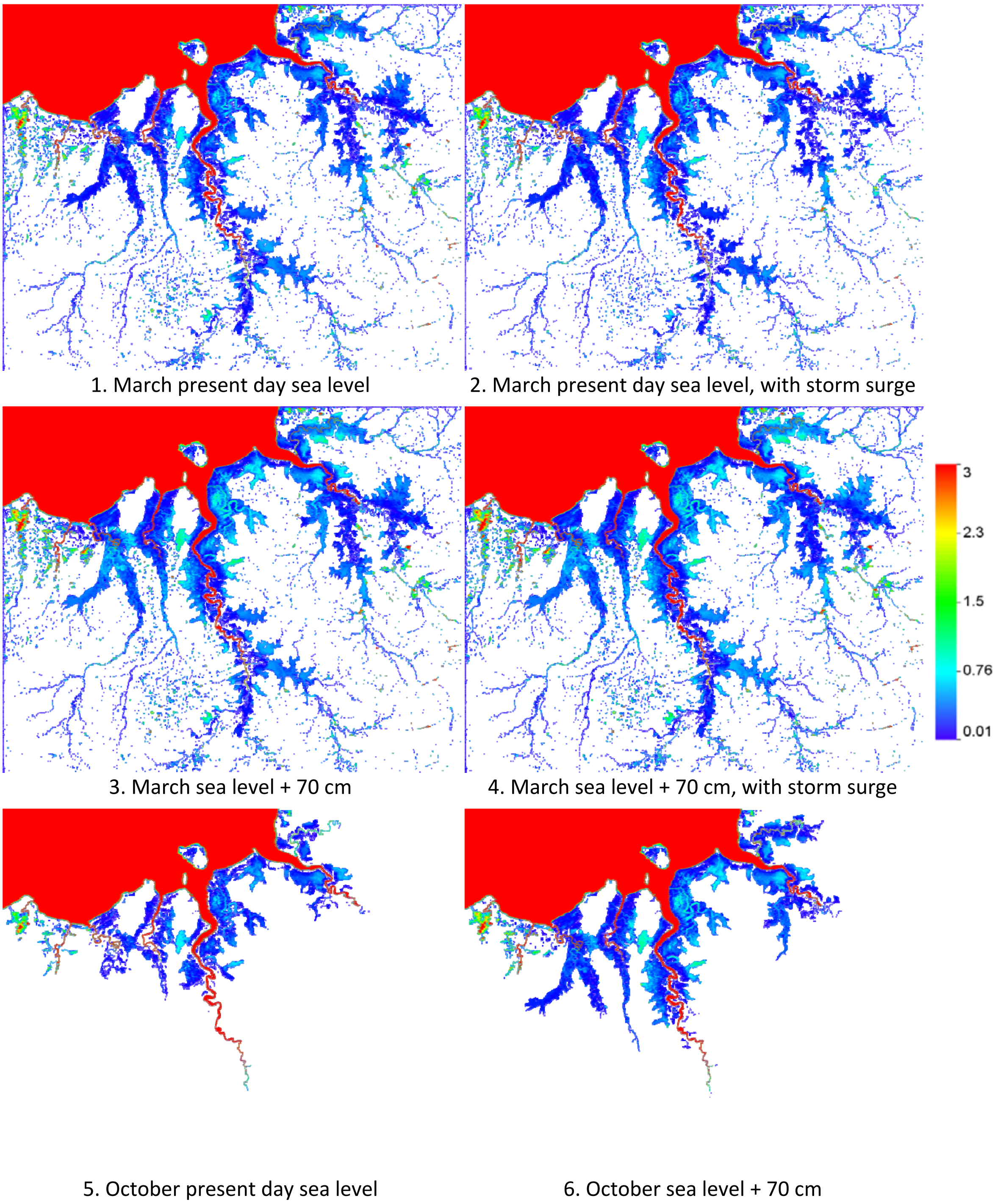


Figure 9 - Median water levels (m)

Median water levels are shown in Fig. 9 for all scenarios. It can be seen that there is are negligible differences between the scenarios with and without with storm surges, showing that the maximum inundation shown in Fig. 8 is a rapid temporal event. However, median upstream water levels for all river systems are much higher for the sea level rise scenarios.

5.3 Inundation frequency

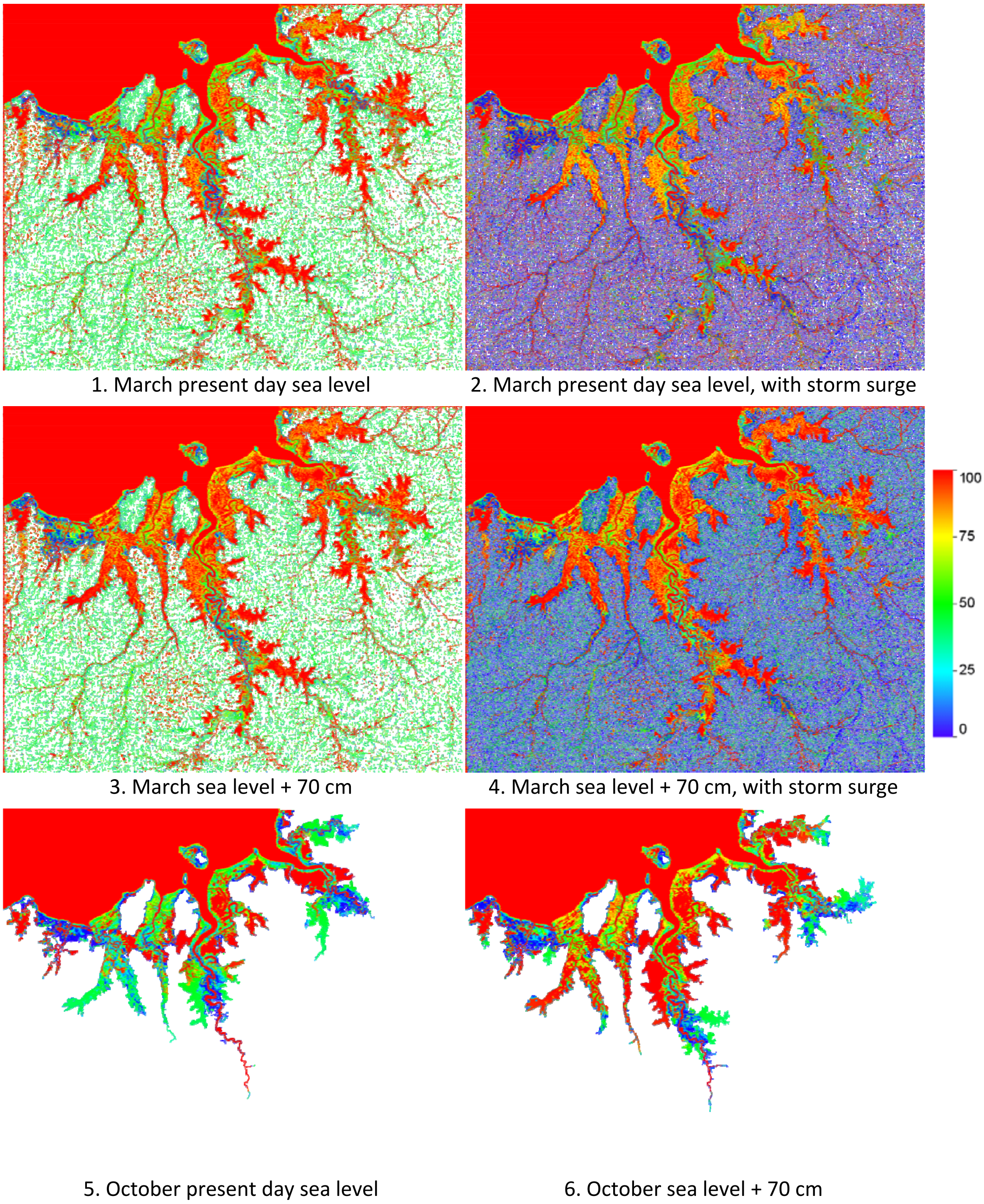
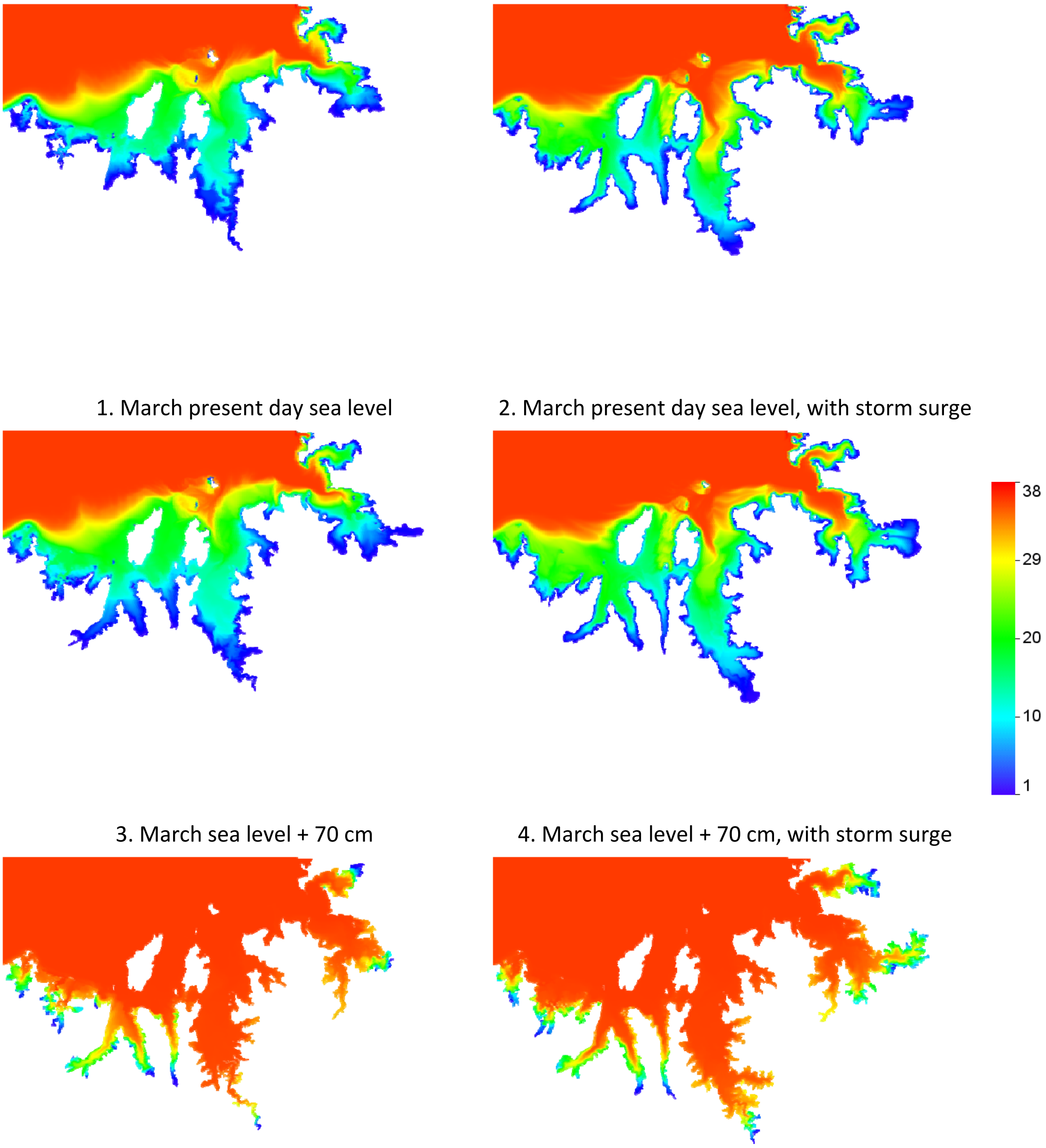


Figure 10 – Inundation frequency (%)

The percentage of time a region has a water level over 1 mm is shown in Fig. 10. Again, there are negligible differences between the scenarios with and without with storm surges. The frequency of inundation in the dry season (October) scenarios is found to increase from 50% for the present day to 100% in upstream regions for all river system.

5.4 Maximum salinity levels



1. March present day sea level
2. March present day sea level, with storm surge
3. March sea level + 70 cm
4. March sea level + 70 cm, with storm surge
5. October present day sea level
6. October sea level + 70 cm

Figure 11 - Maximum salinity levels (ppt)

Maximum salinity levels are shown in Fig. 11 for all scenarios. The storm surge can be seen to have a strong effect on the saltwater intrusion, giving greater areal coverage and increasing the salinity in the upstream regions. Likewise, an increase in the maximum salinity coverage is found in the sea level rise scenarios.

5.5 Median salinity levels

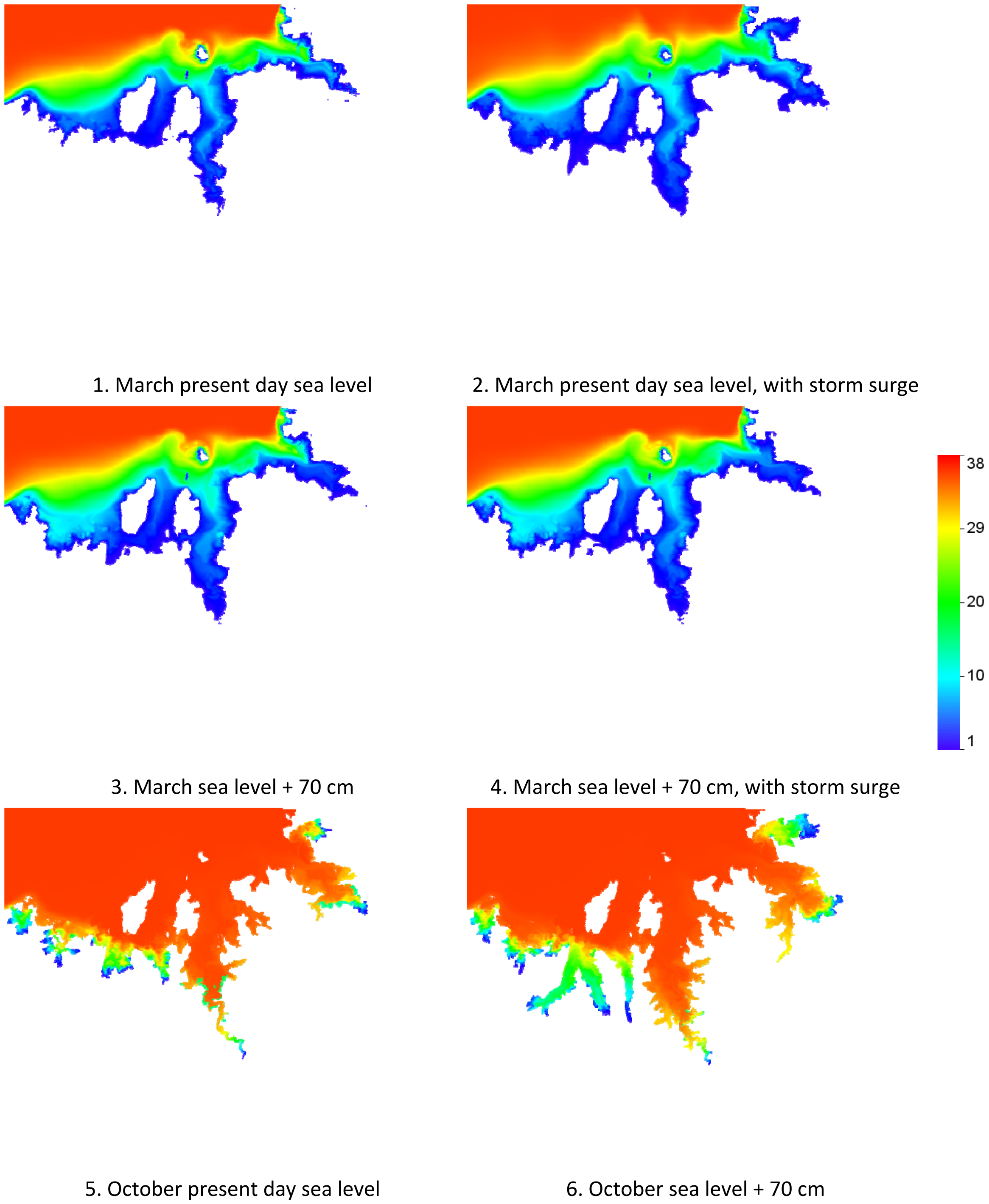


Figure 12 - Median water levels (m)

Median salinity levels are shown in Fig. 12 for all scenarios. Unlike the median water levels, the area affected by saltwater instruction increases during storm surges. The mechanism for this is saltwater being driven onto land during the surge and evaporating, leaving saline deposit. The sea level rise scenarios also shown an increase in the areas affected by saltwater intrusion.

5.6 Salinity threshold

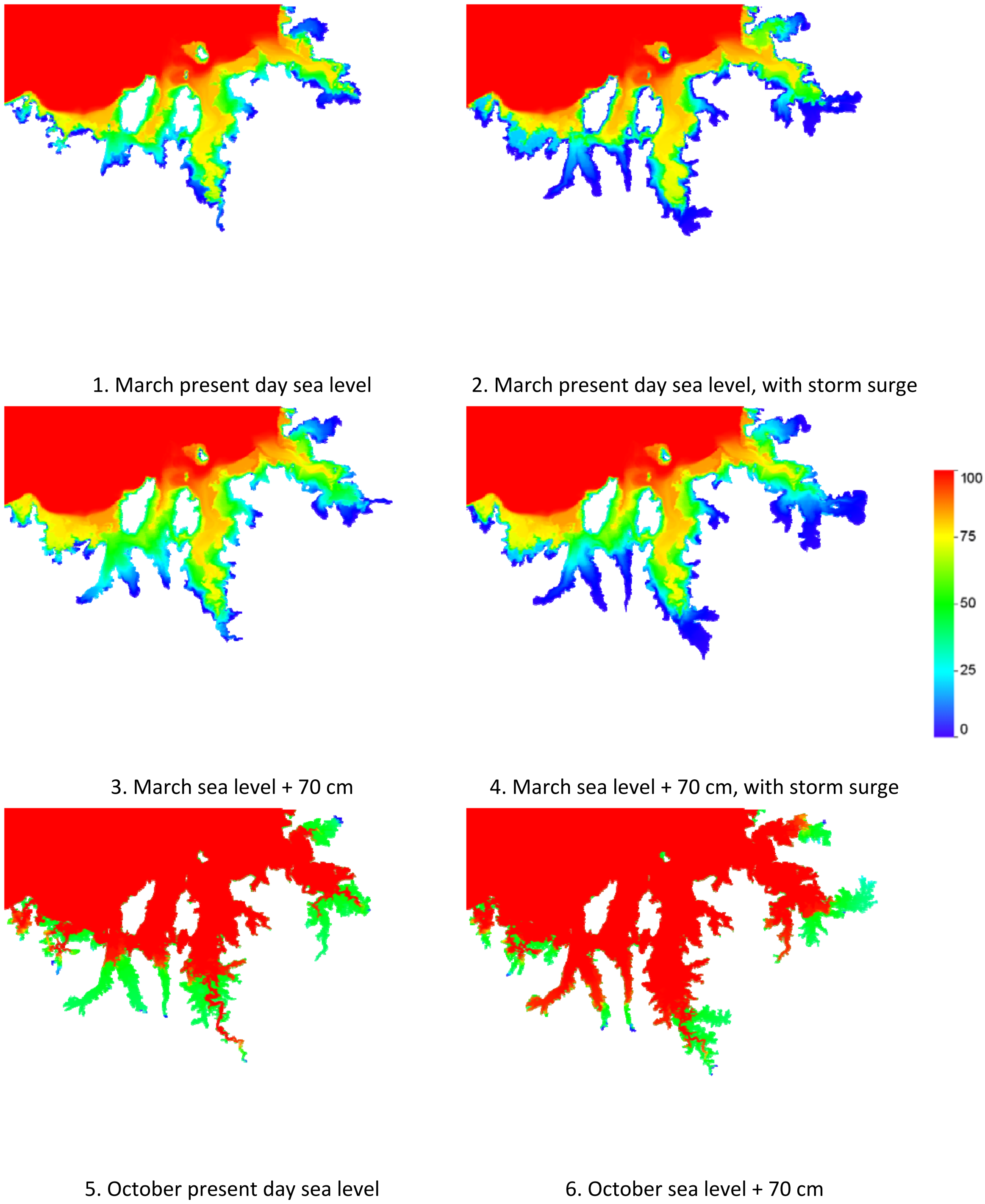


Figure 13 – Percentage time over threshold salinity of 2 ppt (%)

The percentage of time a region has a salinity above 2 ppt is shown Fig. 13. This threshold was chosen based on the salinity tolerance of many freshwater plants in the region. As with the median values, storm surges increase the area where the salinity is over this threshold value. The sea level rise scenarios show a similar trend.

5.7 Dynamic flushing of saltwater in Boggy Plain

The upstream area of Boggy Plain, adjacent to the South Alligator river, is a site of special interest due to significance to traditional owners and the large freshwater habitat which serves as a refuge for waterbirds during the dry season. This area was investigated in detail in phase 1, and it was of interest whether this area would be subject to saltwater intrusion during storm surge events.

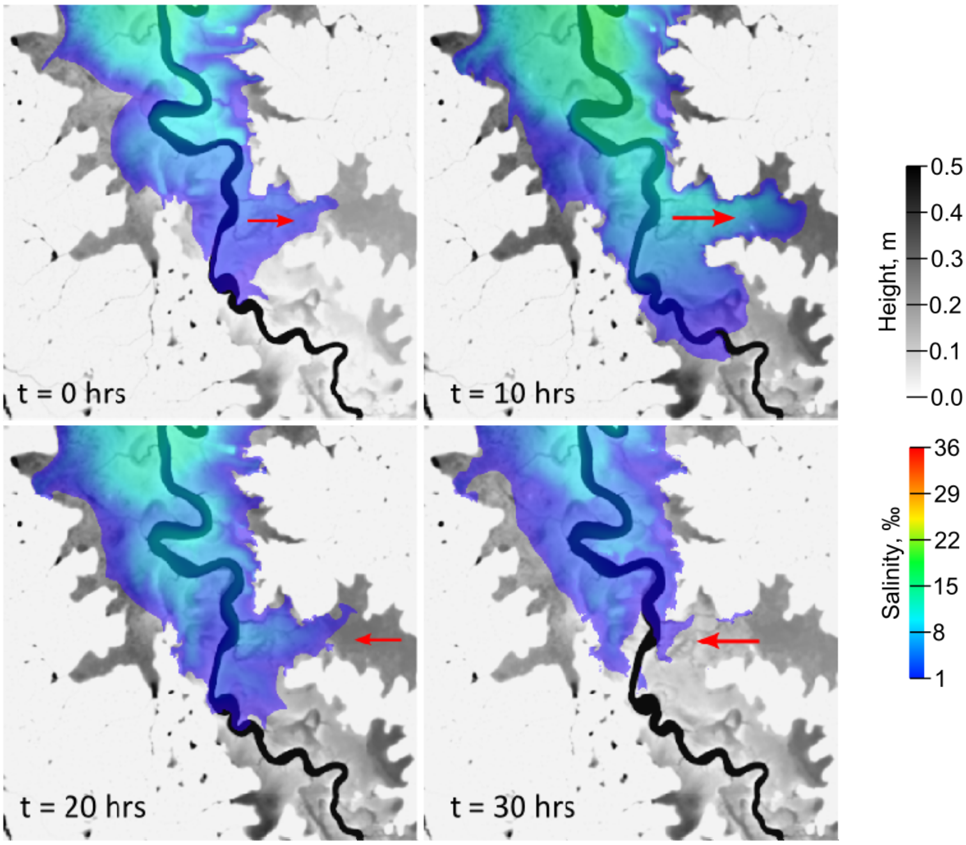


Figure 14 - Saltwater flushing at the entrance to Boggy Plain

Results from the study for the March present day case with a storm surge (scenario 2) are shown in Fig. 14. Water level is shaded from white (dry) to black and the salinity (in parts per thousand) is overlaid in colour. The system showed dynamic behaviour due to the interaction between the transport from the storm surge and the associated heavy rainfall event. The initial effect of the storm surge was to transport saltwater up the South Alligator river and into Boggy plain (Fig. 14, top). However, the heavy rainfall event caused high volumes of water in the catchment which drained into Boggy Plain around 20 hours later, reversing the flow and flushing the saltwater back into the river. Saltwater intrusion into this region is therefore a balance of these effects and will depend on both the severity of the storm surge and any associated rainfall event.

6 Conclusion

We have carried out coupled hydrodynamic and salinity transport modelling for several scenarios in Kakadu National Park. These were used to gauge saltwater intrusion for storm surges and sea level rise in the wet (March) and dry (October) seasons. The model gave a good match to salinity values measured in the South Alligator river. The results for maximum inundation extents match results of phase 1, with upstream areas in all major river systems affected by potential sea level rise. Storm surges were found, as expected, to cause greater inundation along coastal areas and in downstream regions of all the major rivers but to have marginal effects on long term inundation levels. However, storm surges were found to have a significant long term effect on median salinity levels in downstream areas, as saltwater was transported overland during the storm surge and remained as the water evaporated. Sea level rise was also found to cause significant saltwater intrusion into upstream regions of all the major river systems. The saltwater intrusion in some regions was found, though, to be dynamic and depend on a balance of transport from saline regions and flushing from rainwater. Future work may be necessary to investigate this dynamic process in more detail.

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KAKADU NATIONAL PARK WORKSHOP

DRAFT: GOOGLE EARTH – BASIC SKILLS

CSIRO - Oceans and Atmosphere Flagship

November 2014

Contents

I. Introduction

This document was created to help usrs of the Google Earth files that were generated as part of the Kakadu NERP project to open the spatial layers and interact/modify them. The document is a summary of several information sources and tutorials available on the web.

Google Earth (GE) is a virtual globe program that maps the Earth by the superimposition of images obtained from satellite imagery and aerial photography[1] allowing viewers to visualize data of the Earth's surface. Launched in 2005 and released to the public in 2006, Google Earth fast became a household name hailed as a revolution for humanitarian development, much as Geographic Information Systems (GIS) were several decades ago[2].

GE allows users to mark points, lines and areas (polygons) using a limited set of symbols. When used in to map environmental and cultural values, Google Earth allows users to map infrastructure, sites where animals and plants were observed, administrative, political, and cultural boundaries. The program can be used for many different purposes and different sectors of society.

This tutorial is designed to introduce Google Earth (free version) to users who wish to develop basic skills such as: customizing layers, creating placemarks (eg. Balloons, which allows users to tell their own stories with images), polygons to delimit areas of interest, and paths which allows for features such as fly-overs, and other functions available in Google Earth.

II. Google Earth x Google Earth Pro

Google Earth Pro includes the same easy-to-use features and imagery as the free version of Google Earth, but with additional professional tools designed specifically for business users[4]:

- Utilize data layers to locate target demographics
- Compute distances and areas using measurement tools
- Use Movie Maker to produce movies
- Print high-resolution images for presentations and reports
- Import large vector image files to quickly map GIS data
- Map addresses with the Spreadsheet Importer

1 "Introduction to Google Earth", American University, accessed August 29, 2014, http://www.american.edu/ctrl/upload/Intro-to-Google-Earth.pdf

2 " A Rough Google Earth Guide" , University of Edinburgh, accessed August 28, 2014, http://www.humaninet.org/maps2/mc-google-earth-final.pdf

3 " Guide to Using Google Earth", MSF, accessed August 28, 2014, http://evaluation.msf.at/fileadmin/evaluation/files/documents/resources_MSF/Google_Earth_guide_FINAL.pdf

4 "Google Earth User Guide: Google Earth Pro", accessed August 29, 2014, https://www.google.com/earth/explore/products/desktop.html

Table 1: Main differences between Google Earth (free version) and Google Earth Pro. Adapted from Dodsworth (2008)

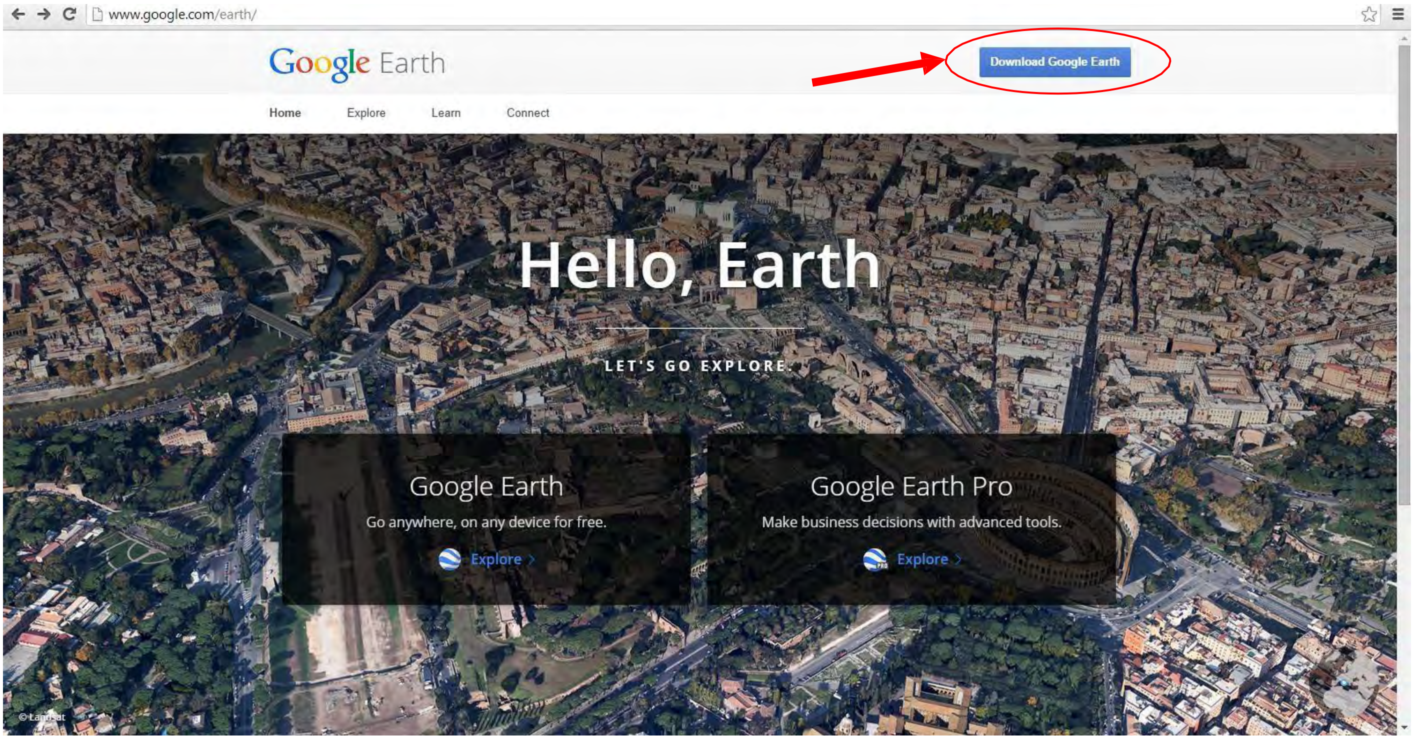
<table>
<tr><th>Features</th><th>Google Earth</th><th>Google Earth Pro</th></tr>
<tr><td>License</td><td>Download free on the internet (see Downloading GE)</td><td>Purchase Professional version for $400 annual subscription free</td></tr>
<tr><td>Geographical Contents</td><td colspan="2">Identical in both versions. E.g.:
Satellite Imagery/Orthoimagery
StreetView
Search for Points of Interest (schools, parks, hotels, etc).
Driving Directions
Explore featured content (Rumsey maps, National Geographic, etc).</td></tr>
<tr><td>Geospatial Data Import</td><td>- Google Earth (KML, KMZ)
- GPS (.gpx, .loc)</td><td>- Google Earth (KML, KMZ)
- GPS (.gpx, .loc, .mps)
- Imagery (GeoTiff)
- ESRI (.shp)
- MapInfo (.tab)
- ERDAS Imagine (.img))</td></tr>
<tr><td>Other Data Import</td><td>- Images (jpg, tif, png, gif)</td><td>- Images (jpg, tif, png, gif)
- Text (.txt, .csv)
- GPS data imports for Magellan and Garmin devices</td></tr>
<tr><td>Mapping Tools</td><td>Drawing Tools
Ruler Measure Distance</td><td>Drawing Tools
Open Attribute Table
Ruler – measure distances and areas incl. polygons and circles.</td></tr>
<tr><td>Screen Print and Save</td><td>- Prints lower quality images (1000 pixels)

- Saves lower quality jpg images (1000 pixels)</td><td>- Prints higher quality Images (4800 pixels)
Saves higher quality jpg images (4800 pixels)</td></tr>
</table>

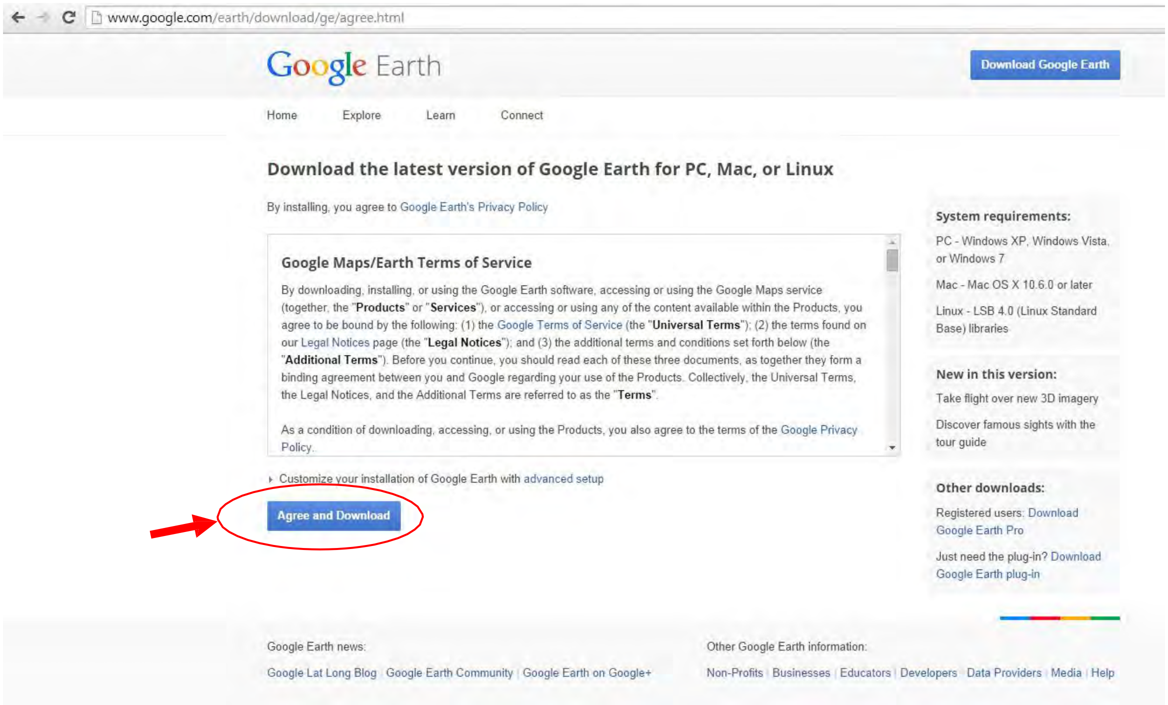
III. Downloading and Installing Google Earth (Free Version)

Google Earth free version is available on the internet. To download, visit http://earth.google.com.

1. Click the 'Download Google Earth' button in the top right corner of the screen



2. Click ' Agree and Download'



3. Click ‘Run’ to start installation

The program is now installed on your computer.

IV. Common Functions

Once opening Google Earth, the main window will be divided in 2 sections: The Earth appears on the right hand section and this area is called **3D viewer**. The 3D viewer always appears in Google Earth and shows your imagery, terrain and information about places around the globe[5]. On the left hand side is the legend and is used to control which data is shown, to find locations and to manage user and Google Earth data[6].

The right- and left-hand sections are divided in the following 5 sub-sections:

1- **Search bar**- Users can insert the name of a place, such as a country, city or other popular landmark and “fly to” it (eg. type the name of the place you would like to “fly to”, such as “Kakadu National Park” and click Search)[7].

2- **Places** – All layers and folders produced for Google Earth (e.g. the layers for the Kakadu NERP project) will appear in this panel. Placemarks (*see Creating Placemarks*) and shapes will also appear in this sub-section. Note that the “Temporary Places” folder appears by default[7]. And layers imported to Google Earth will be initially placed in this folder and need to be moved to the ‘Places’ sub-section after importing to Google Earth.

3- **Layers** – In this sub-section users can explore layers available in Google Earth and created by other GE users and choose to hide or reveal these layers, which can add new features to your existing project (e.g. roads, hotels, and other points of reference)[7].

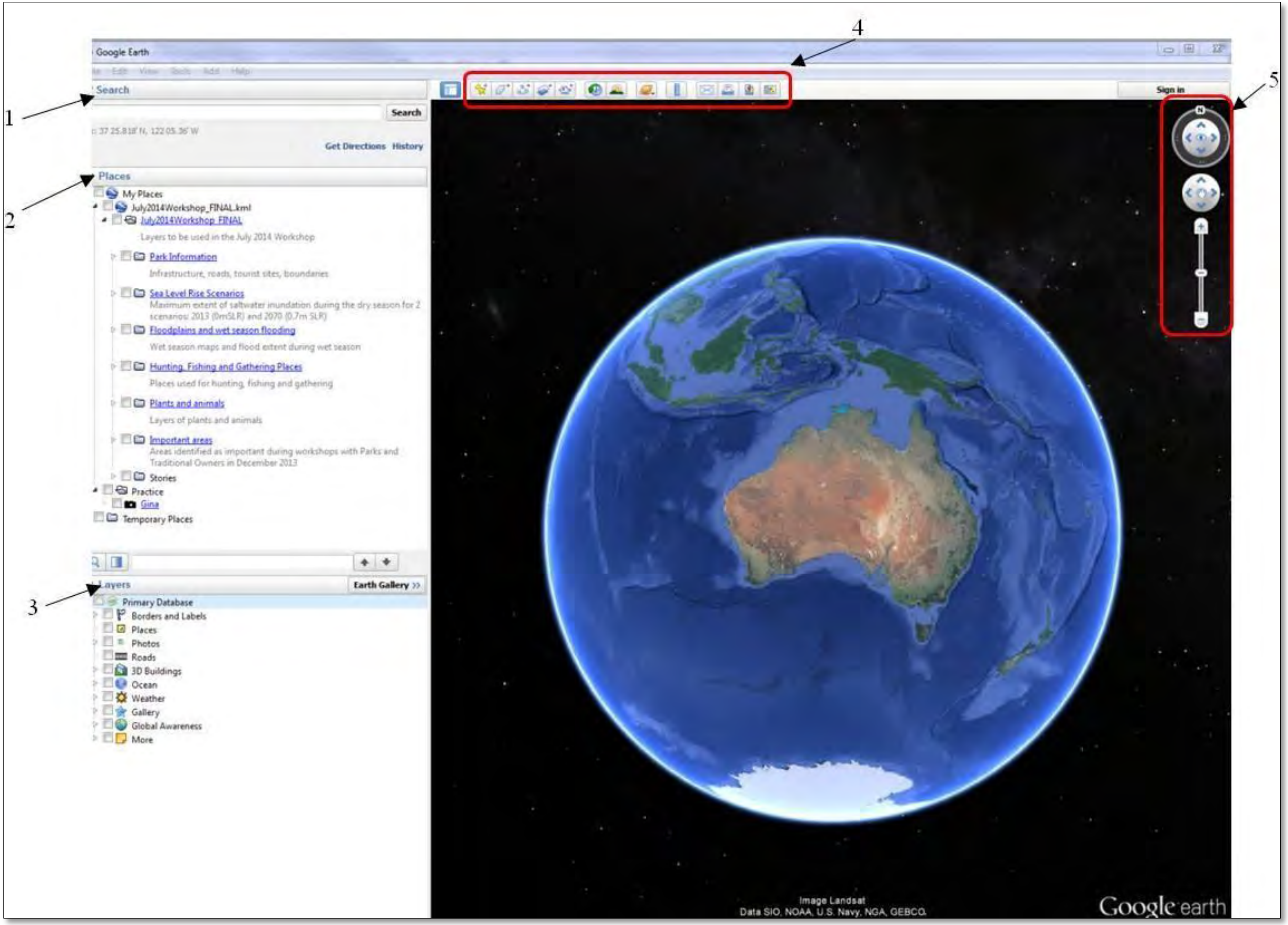
4- **Toolbar** – There are several tool options in this sub-section which allow customizing maps (eg. placemark, polygon, path, history, record a tour, set the time of day using sunlight across the landscape, etc) [7].

5- **Navigation controls**- Use the arrows to zoom in and out of the globe and control the camera to view maps in unique perspectives, including tilting and rotating the view[7].

5 Adapted from “ Google Earth User Guide: Navigating on the Earth”, accessed September 01, 2014, https://support.google.com/earth/answer/176674?hl=en

6 “ Guide to Using Google Earth”, MSF, accessed August 28, 2014, http://evaluation.msf.at/fileadmin/evaluation/files/documents/resources_MSF/Google_Earth_guide_FINAL.pdf

7 Adapted from “Introduction to Google Earth”, American University, accessed August 29, 2014, http://www.american.edu/ctrl/upload/Intro-to-Google-Earth.pdf


1
2
3
4
5
Google Earth
Search
Search
Get Directions History
Places
My Places
July2014Workshop_FINAL.kml
July2014Workshop_FINAL
Layers to be used in the July 2014 Workshop
Park Information
Infrastructure, roads, tourist sites, boundaries
Sea Level Rise Scenarios
Floodplains and wet season flooding
Wet season maps and flood extent during wet season
Hunting, Fishing and Gathering Places
Places used for hunting, fishing and gathering
Plants and animals
Layers of plants and animals
Important areas
Areas identified as important during workshops with Parks and Traditional Owners in December 2013
Stories
Practice
Gina
Temporary Places
Layers
Earth Gallery
Primary Database
Borders and Labels
Places
Photos
Roads
3D Buildings
Ocean
Weather
Gallery
Global Awareness
More
Sign in
Image Landsat
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google earth

Navigating on the Earth

The navigation controls are composed for 4 parts[8]:

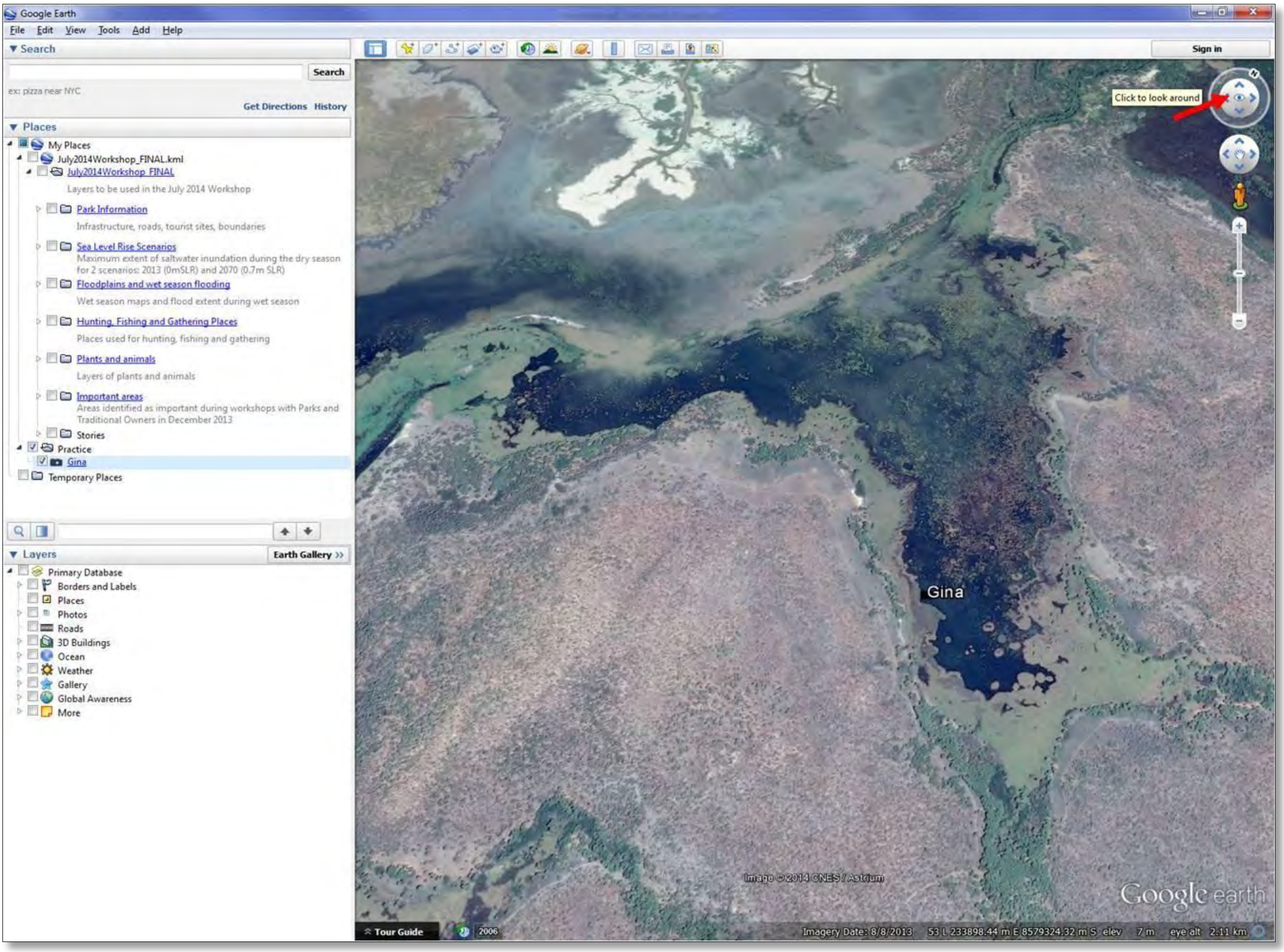
1- North (N) - click the north-up button to reset the view so that north is at the top of the screen. Click and drag the ring to rotate your view.

- Practice – Resetting the view of the extent of saltwater inundation in a 2070 sea level rise scenario on freshwater floodplains on Kakadu National Park

8 Adapted from " Google Earth User Guide: Navigating on the Earth", accessed September 01, 2014, https://support.google.com/earth/answer/176674?hl=en

2) Look joystick - look around from a single vantage point, as if you were turning your head. Click an arrow to look in that direction or continue to press down on the mouse button to change your view. After clicking an arrow, move the mouse around on the joystick to change the direction of motion.

- Practice 1 – Click to look around any area in Kakadu National Park



8 Adapted from " Google Earth User Guide: Navigating on the Earth", accessed September 01, 2014, https://support.google.com/earth/answer/176674?hl=en

3) Move joystick - to move your position from one place to another. Click an arrow to look in that direction or continue to press down on the mouse button to change your view. After clicking an arrow, move the mouse around on the joystick to change the direction of motion.

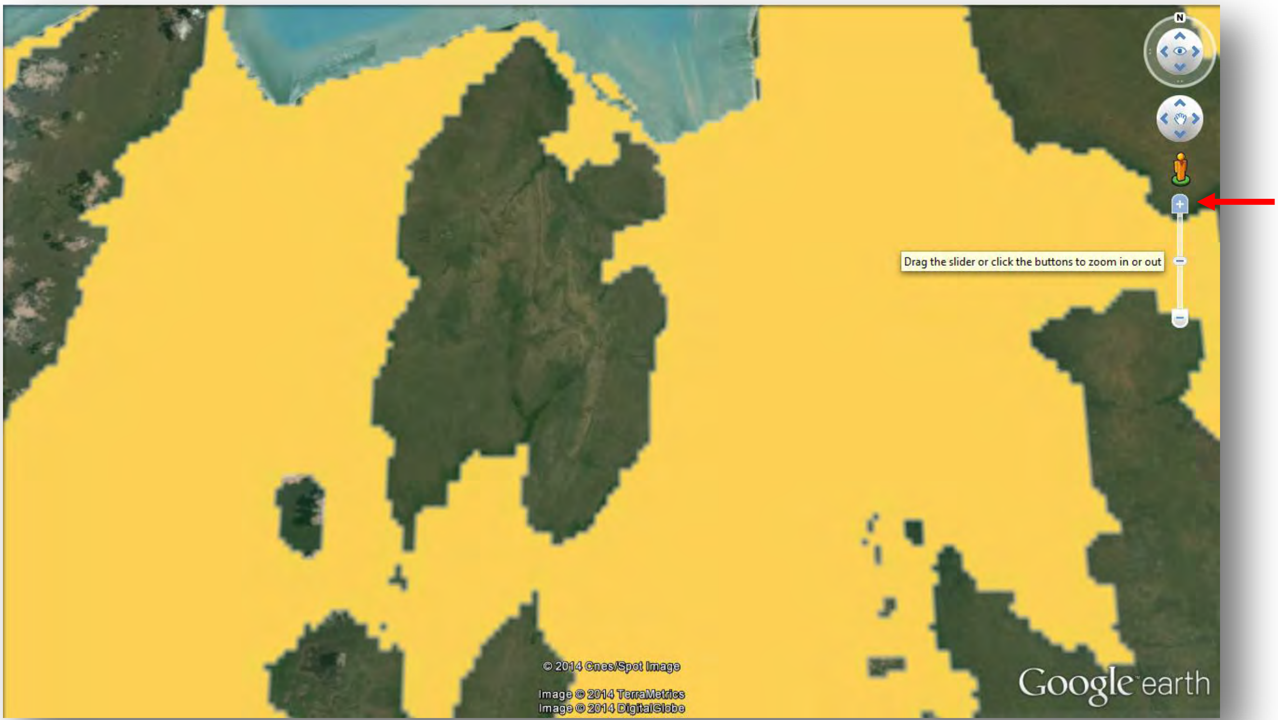
- Practice 2 – Click to move around any area in Kakadu National Park

8 Adapted from " Google Earth User Guide: Navigating on the Earth", accessed September 01, 2014, https://support.google.com/earth/answer/176674?hl=en

4) Use the zoom slider to zoom in or out (+ to zoom in, - to zoom out) or click the icons at the end of the slider. As you move closer to the ground, Google Earth swoops (tilts) to change your viewing angle to be parallel to the Earth's surface. You can turn off this automatic tilt (Tools > Options > Navigation > Navigation; Mac: Google Earth > Preferences > Navigation > Navigation controls).

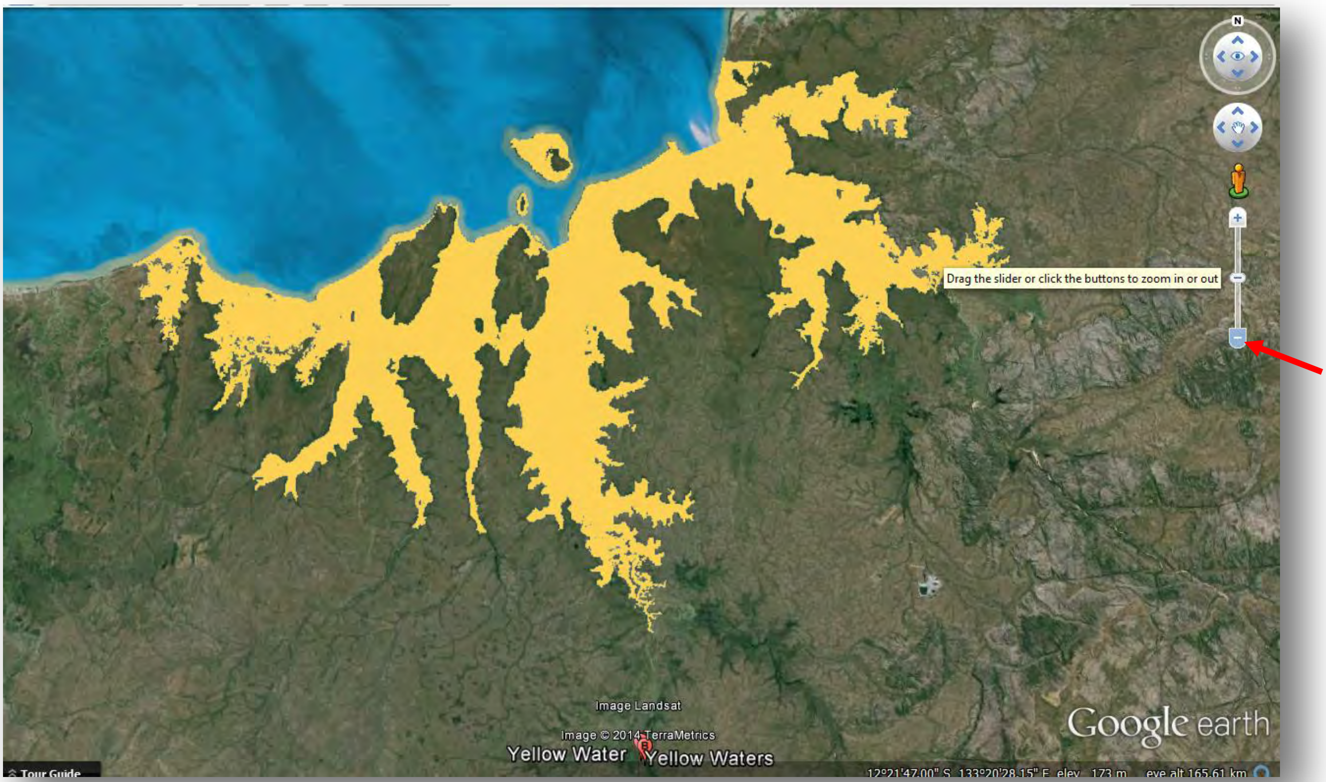
➢ Practice 3 –Click to Zoom in and out of the extent of saltwater inundation in a 2070 sea level rise scenario on freshwater floodplains on Kakadu National Park

Step 1 – Zoom in to a specific location.



8 Adapted from " Google Earth User Guide: Navigating on the Earth", accessed September 01, 2014, https://support.google.com/earth/answer/176674?hl=en

Step 2 – Zoom out: When you finish zooming into extent of saltwater inundation in a 2070 sea level rise scenario on freshwater floodplains on Kakadu National Park you can now zoom out. Just click on the "-" button until you get the view of the region you want.



8 Adapted from " Google Earth User Guide: Navigating on the Earth", accessed September 01, 2014, https://support.google.com/earth/answer/176674?hl=en

Street View

To view street-level imagery for a specific location, zoom into an area, such as Jabiru. You will see a pegman icon appear at the top right corner below the navigation controls[9].

- Practice 4

Step 1 - Click and drag the icon across the 3D viewer in a street in Jabiru.

9 Adapted from " Google Earth User Guide: Street View in Google Earth", accessed September 01, 2014, https://support.google.com/earth/answer/1067358?hl=en

Step 2: Note that when dragging the icon a blue border will appear around roads that have street-level imagery available then you can choose areas where there are the blue border to use street view.

9 Adapted from " Google Earth User Guide: Street View in Google Earth", accessed September 01, 2014, https://support.google.com/earth/answer/1067358?hl=en

Step 3: You can activate the Street View button to navigate along the streets using all navigating controls or your mouse. To come back to 3D Viewer , you can exit Street View selecting the **Exit Street** View button located at the top right corner.

*NOTE: If you don't see navigation controls on the top-right corner of the 3D viewer, you may have disabled them. Go to **View > Show Navigation** and make sure Automatically or Always is selected.*

9 Adapted from " Google Earth User Guide: Street View in Google Earth", accessed September 01, 2014, https://support.google.com/earth/answer/1067358?hl=en

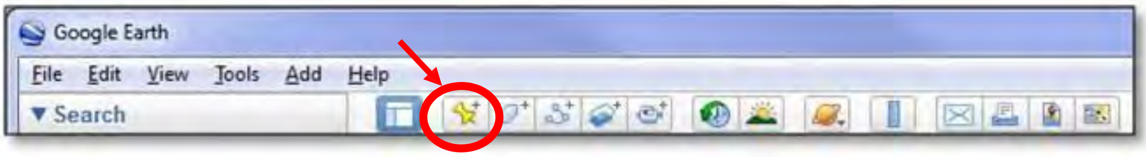
Creating Placemarks

A placemark is a point that allows marking and storing any location in the 3D viewer on Google Earth. When creating a new placemark, the layer will be added into "My Places" folder in the Place panel. This folder is created by default appearing automatically when opening Google Earth and it is the place in which the users' generated information is stored[10]. To add a placemark simply follow the following instructions from the Google Earth User Guide[11]:

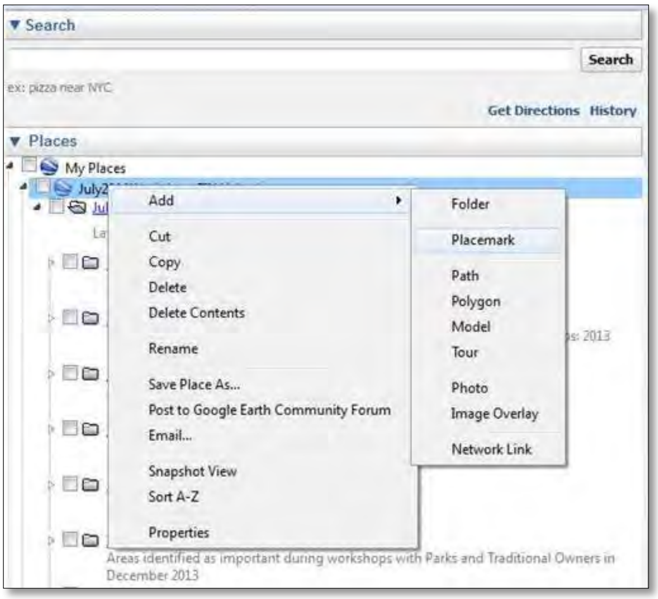
- Position the 3D viewer to contain the spot you want to placemark. Consider zooming into the best viewing level for the desired location. Choose any one of the following methods:

a) Select Placemark from the 'Add' Menu.

b) Click the Placemark icon in the toolbar menu at the top of the screen.



c) Right click on the selected folder in Place panel, select Add> Placemark



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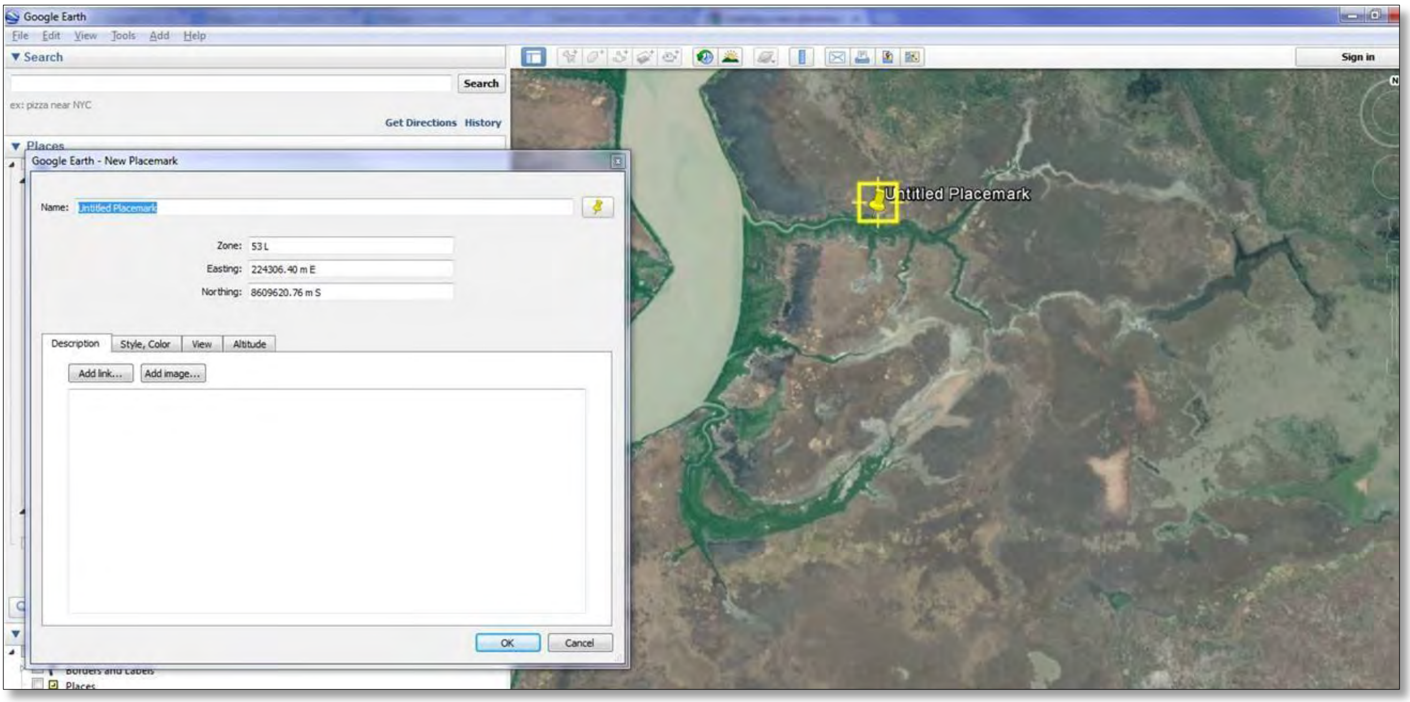
10 " Guide to Using Google Earth", MSF, accessed August 28, 2014, http://evaluation.msf.at/fileadmin/evaluation/files/documents/resources_MSF/Google_Earth_guide_FINAL.pdf

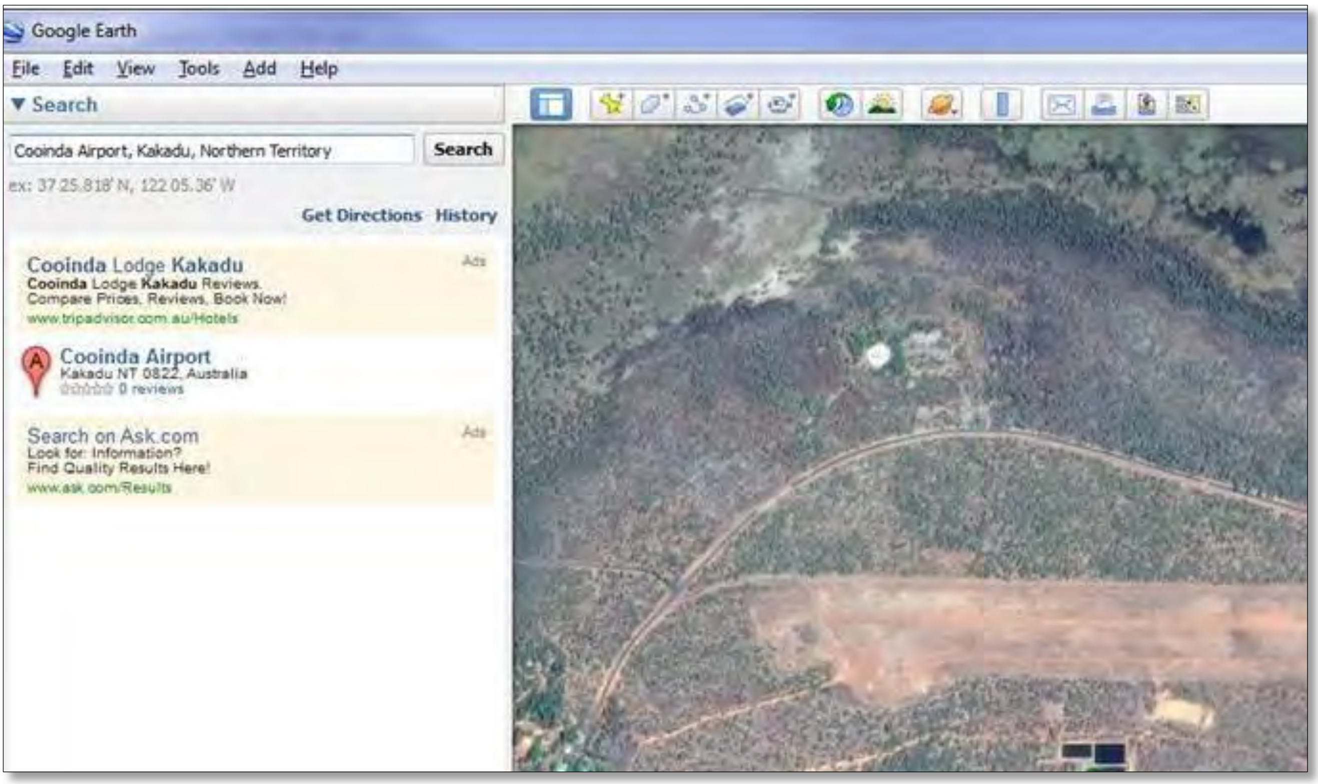
11 Adapted from " Google Earth User Guide: Creating a new placemark", accessed September 02, 2014, https://support.google.com/earth/answer/148142?hl=en

The 'New Placemark' dialog box appears and a 'New Placemark' icon is centered in the viewer inside a flashing yellow square. The example below adds a 'Placemark' in Boggy Plain. To do this, position the cursor on the placemark until the cursor changes to a pointing finger and drag it to the desired location. The cursor changes to a finger pointing icon to indicate that you can move the placemark.



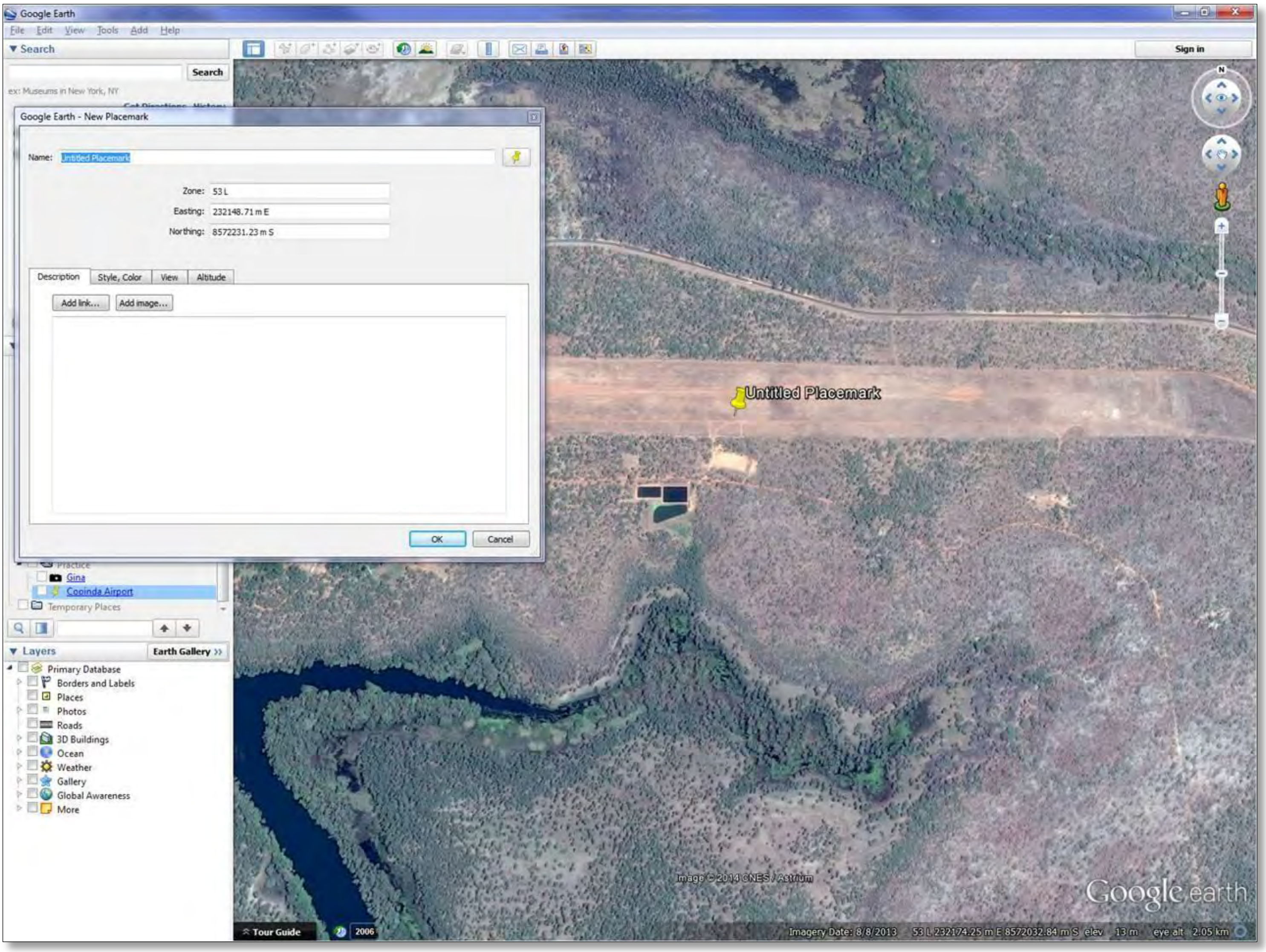
- Practice 5 [12] – Editing the placemark. In this practice we will create a new placemark for Cooinda Airport located in Kakadu National Park. Let's follow the steps below to edit our new placemark:

1- Find Cooinda Airport in the section 3D Viewer. The quickest way to do it is typing the name's location in Search panel.



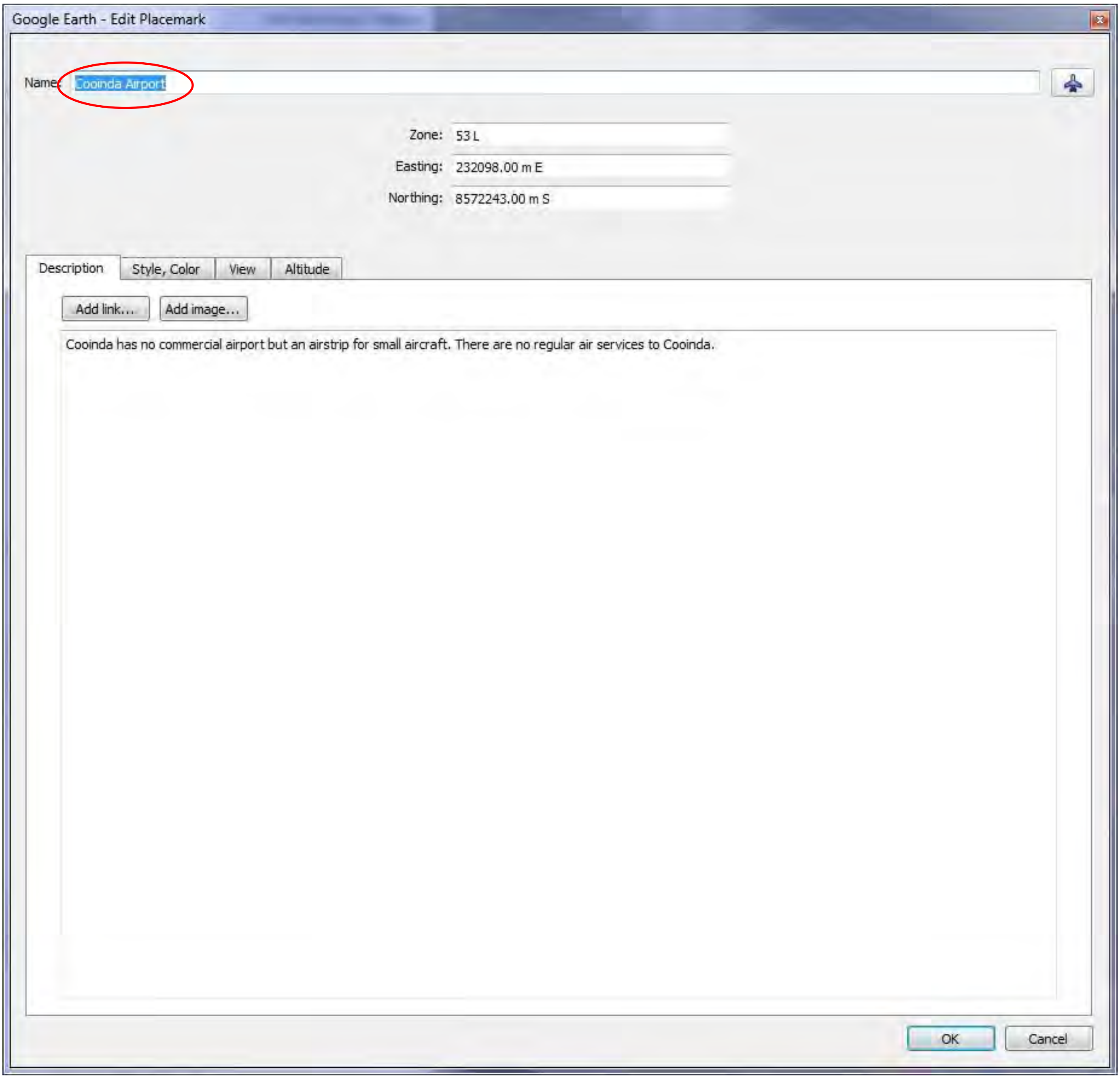
12 Adapted from " Google Earth User Guide: Marking Locations", accessed September 03, 2014https://support.google.com/earth/answer/176683?hl=en

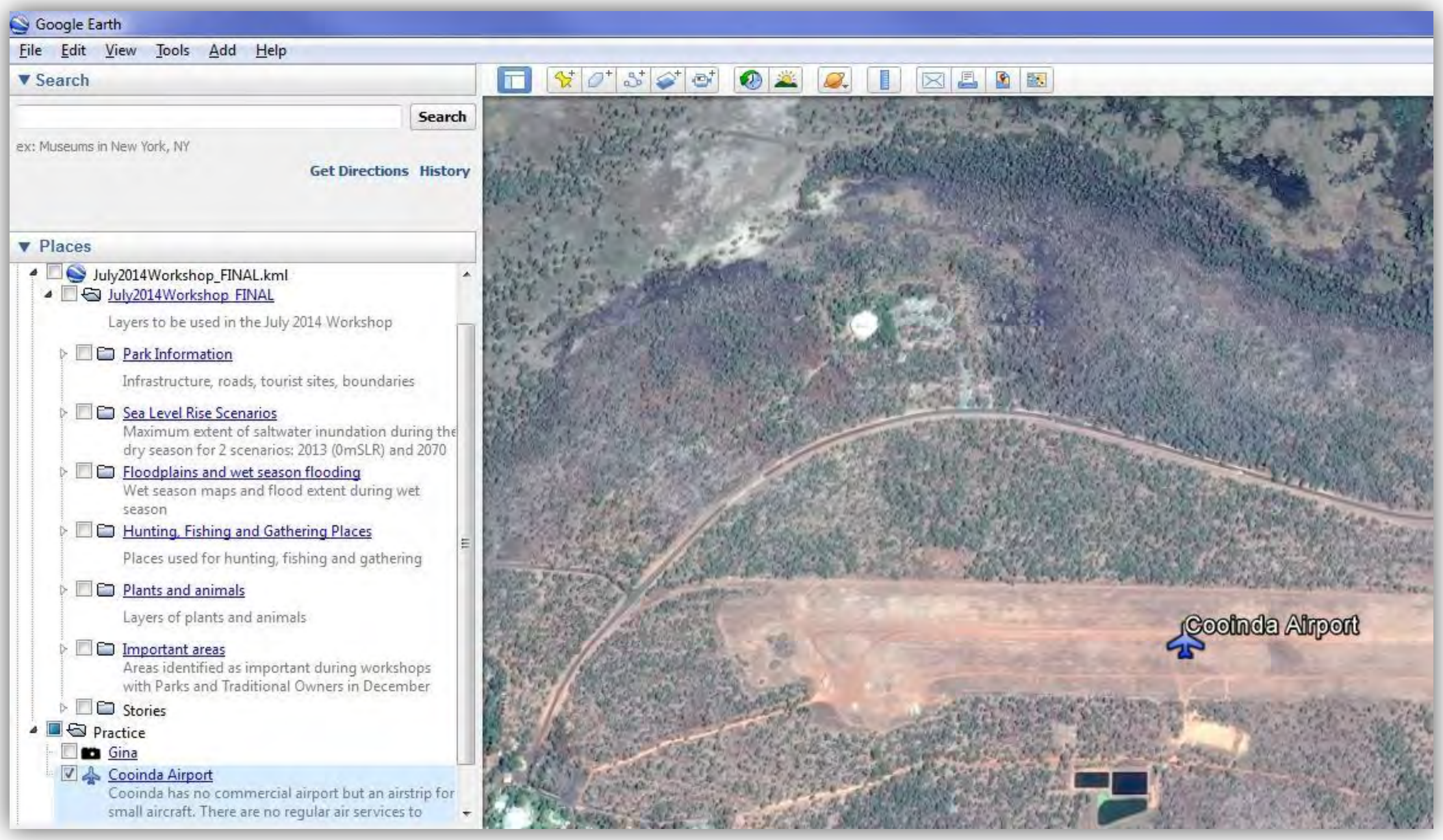
2- Add a placemark choosing one of the options (a,b or c) above. The quickest way is clicking in the placemark icon in the toolbar menu. The new dialog box appears and a placemark icon will appear in Cooinda Airport in the 3D Viewer.



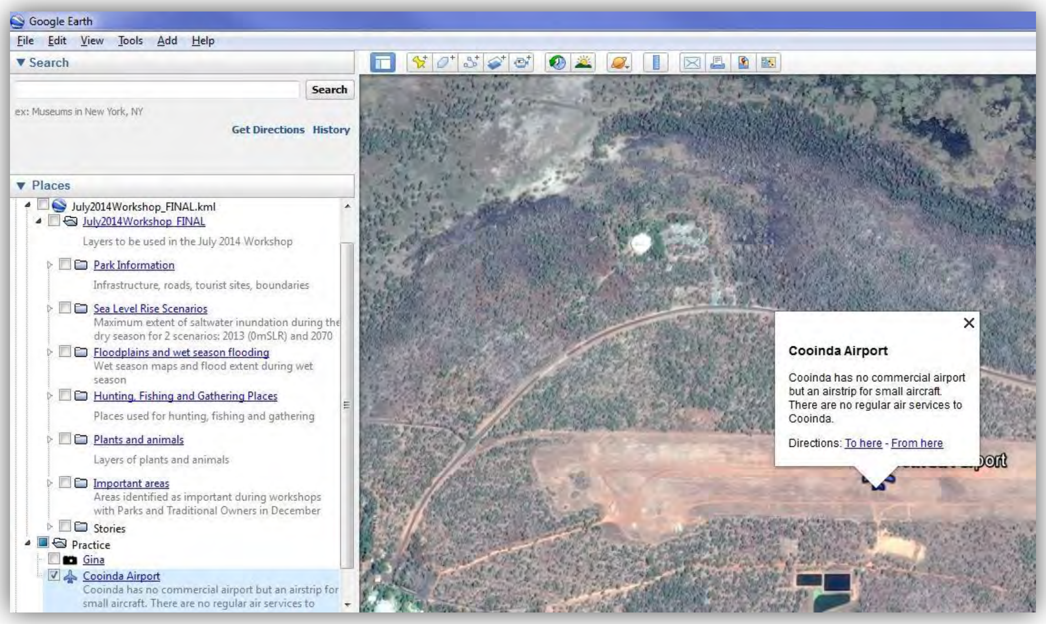
3- In the Google Earth - New Placemark dialog box, enter the following information:

- Name: "Cooinda Aiport"
- Description:"Cooinda has no commercial airport but an airstrip for small aircraft. There are no regular air services to Cooinda."
- Google Earth's default placemark is a yellow pushpin. You can change the placemark icon by clicking the placemark button to the right of the Name field and selecting a new icon. You can even add a custom placemark icon that corresponds to a local image or web image.
- Click OK. Google Earth displays your placemark in the 3D viewer and at the selected folder in the Places panel.





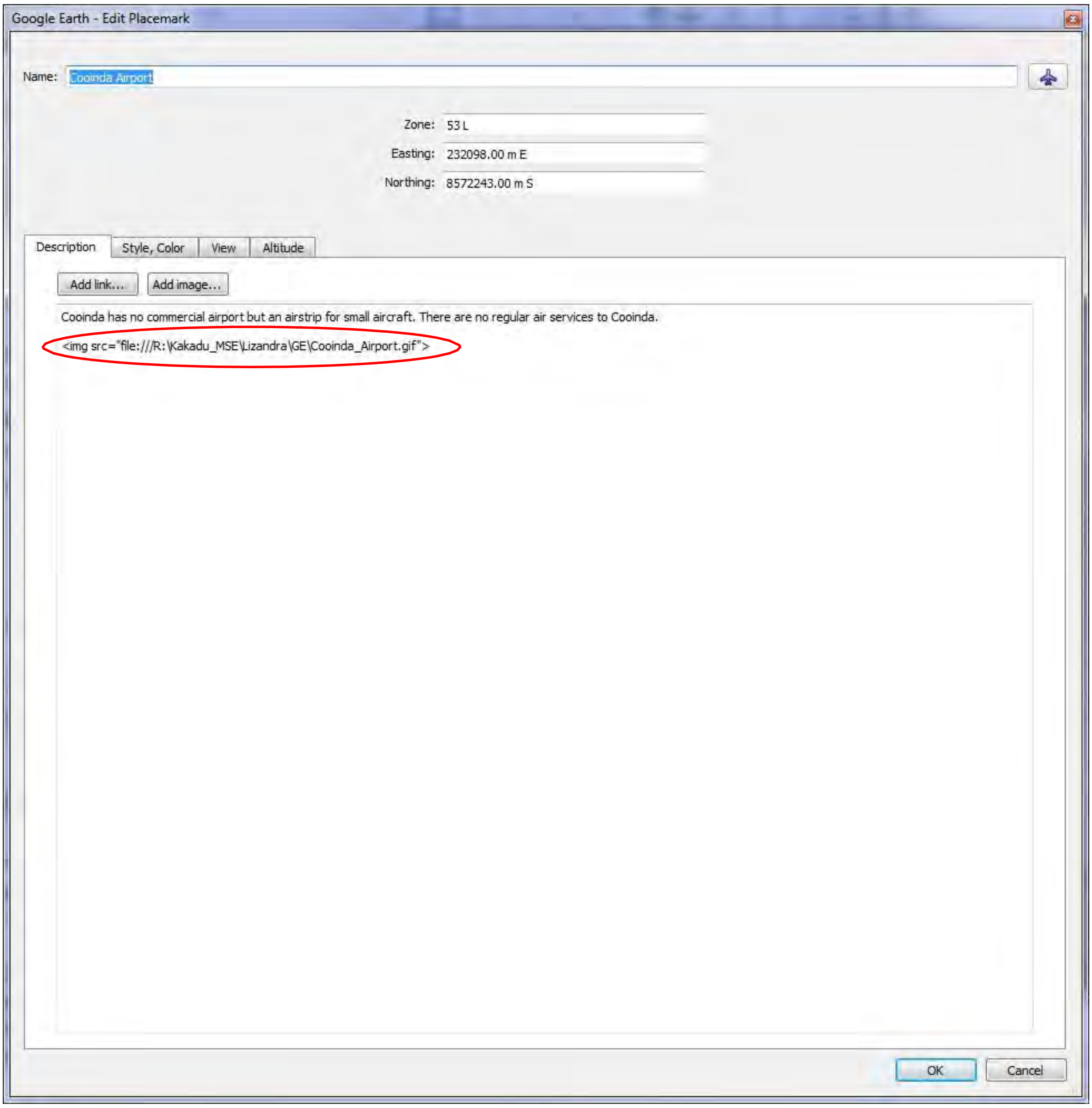
To visualize the placemark balloon, double-click the placemark in the 3D viewer or in the Places panel.



To delete the placemark, right-click the placemark in the 3D viewer or in the Places panel and choose Delete.

- Practice 6 [13,14] – Editing the placemark. This practice we will insert an image into our Cooinda Airport placemark description.

  - You can use one of your photos or alternatively you can download the photo ‘Sunset at Cooinda’ by Roger Bradley (licence under creative commons in Flickr: https://flic.kr/p/a5CyCm).
  - Save the photo in your local hard drive.
  - Open the dialog box by right-clicking the placemark in 3D viewer or in Places panel and select Properties.
  - In the Description box (bellow the text which we have inserted in Practice 1) type the following html code <img src = “
  - Copy and paste the file path for the image and finish off the code with ”>
  - Click ok.



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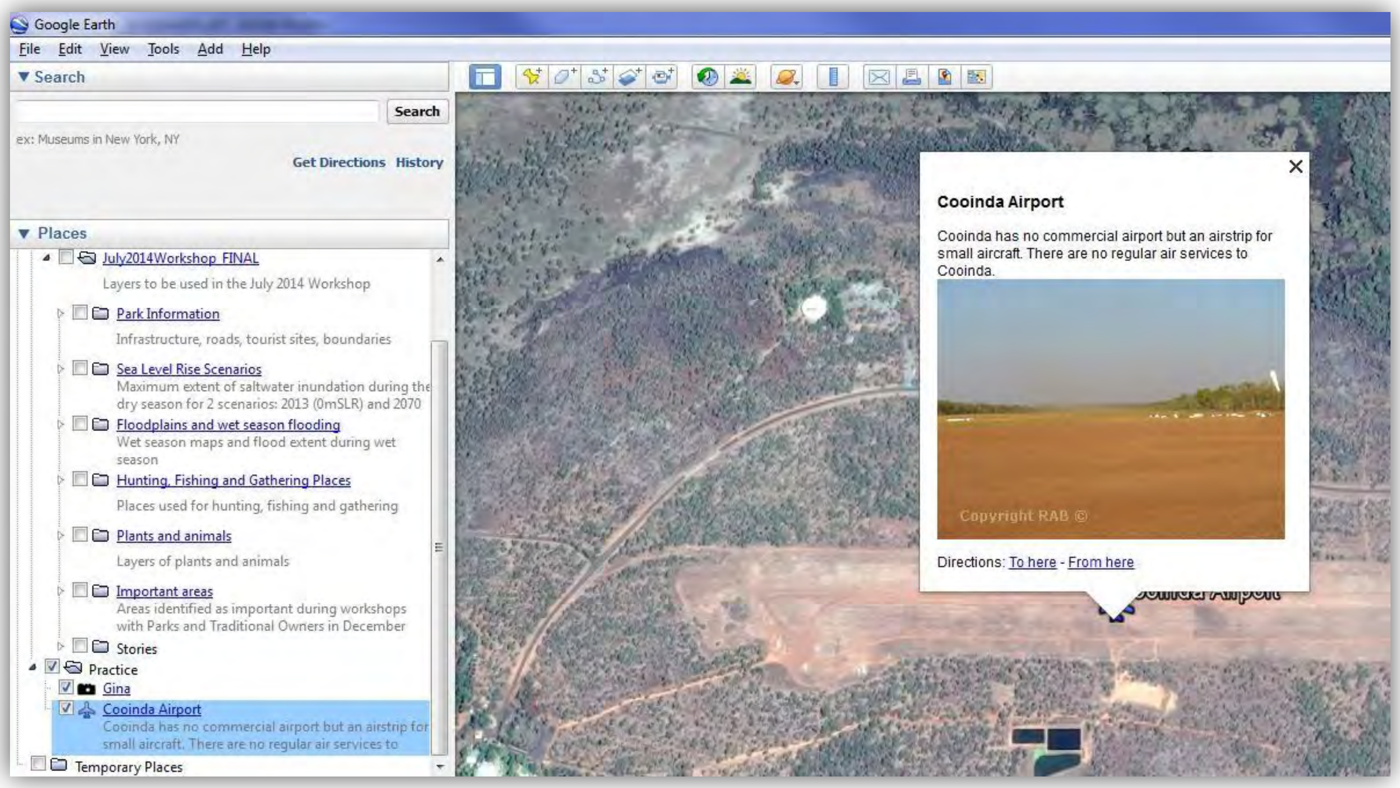
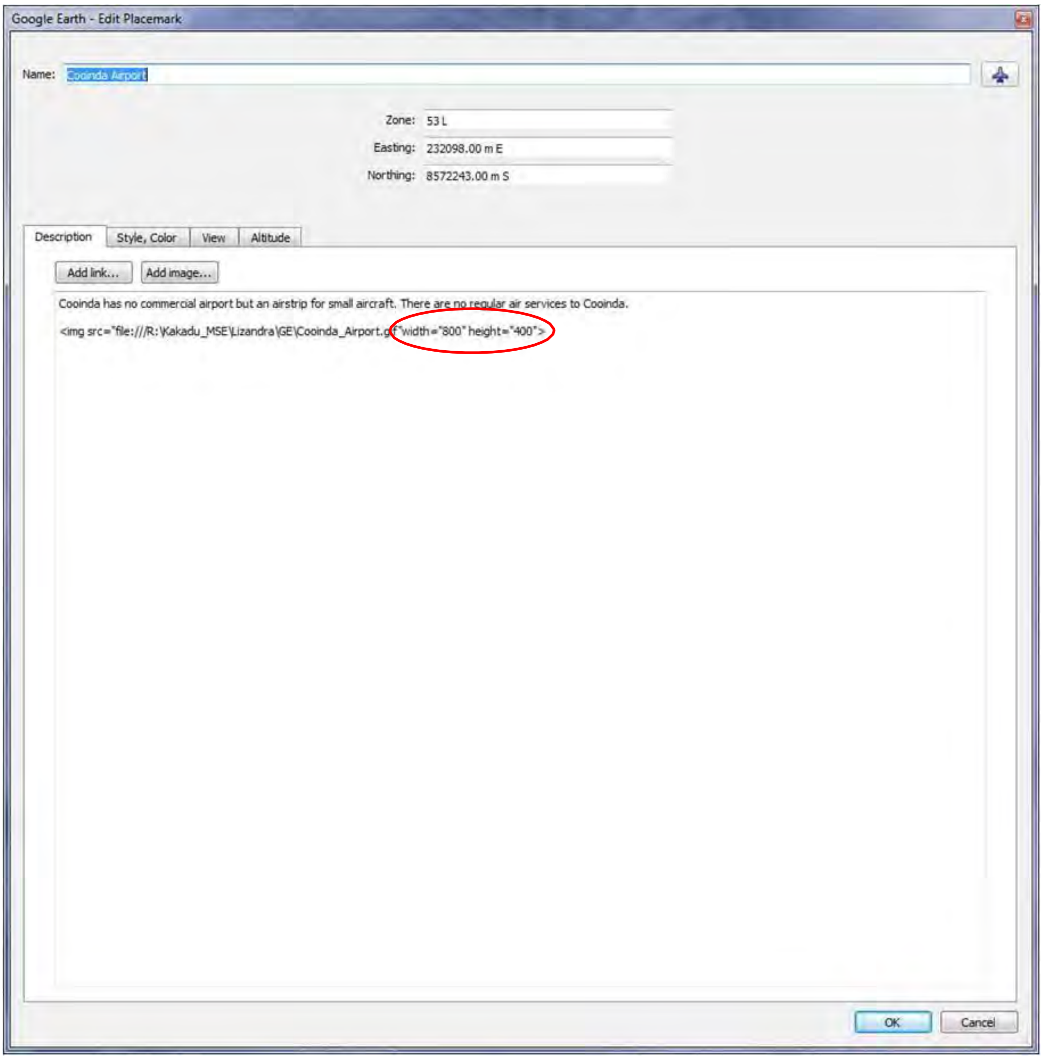
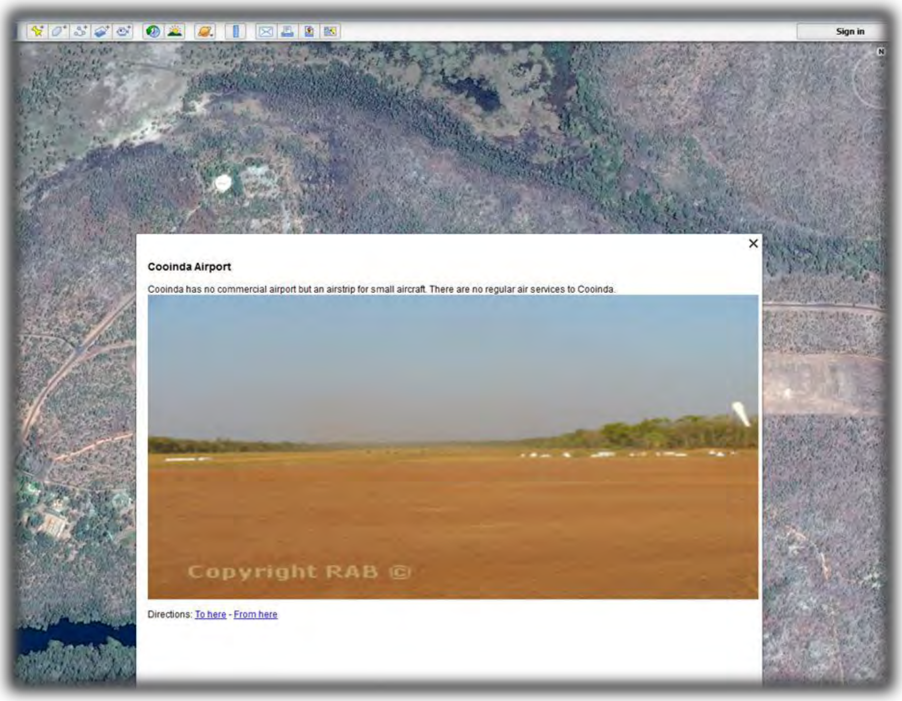
13 Adapted from “ How to put pictures into Google Earth placemarks”, accessed September 03, 2014 http://www.rgs.org/NR/rdonlyres/54500F26-5BC2-4678-8A96-08CA065DB815/0/KS3_Conflict_6GoogleEarthinformationsheets.pdf

14 Image and text were extracted from http://www.kakadunationalparkaustralia.com/Cooinda_Airport.htm (accessed September 03, 2014)



If you want to change the size of the picture then you need to add width="800 "(or any number of pixels) and height= "400" . Experiment with putting in different numbers until you get the size of image that you want.





Creating StoryBox - Balloons

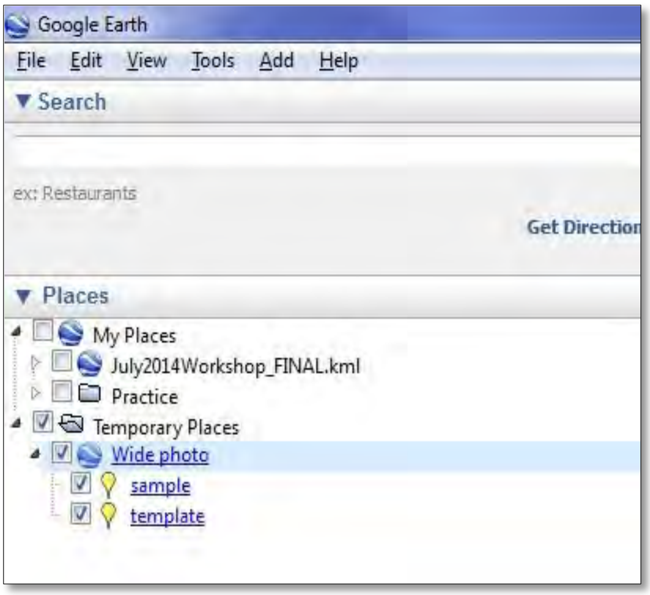
Google Earth has done many HTML templates to help users when creating their own balloons. You can download the templates use for Practice 7 at:
http://www.google.com.au/earth/outreach/tutorials/balloon.html

➢ Practice 7[15] - Adding the Balloon Template

1- Open the KMZ file (**Wide Photo KMZ**) available at:
http://www.google.com.au/earth/outreach/tutorials/balloon.html#

2- Import this file in GE: file>open> C:\balloons_templates. The **sample** placemark contains sample text and images, and the **template** placemark contains placeholders for you to customize.

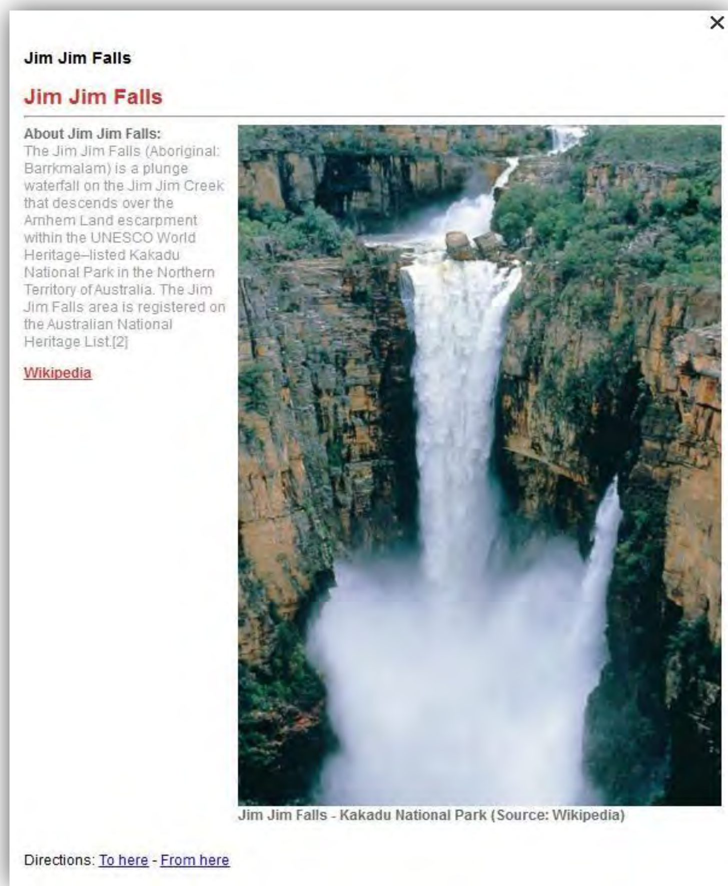
Note the template will be located in Temporary Places folder in the Places panel and this balloon was created inspirited by American Institute Architects layer and the location is in San Francisco (USA).



15 Adapted from " Building Better Balloons", accessed September 11, 2014 http://www.google.com.au/earth/outreach/tutorials/balloon.html

➢ Practice 8[16] - Customizing your own Balloon using the HTML Template

1- In GE, type Jim Jim Falls in Search Panel and click Search.
2- Add a placemark and Edit the name for Jim Jim Falls using methods shown in *Create Placemarks.*
3- Drag Jim Jim Falls placemark to My Places in the Places Panel.
4- Copy the HTML for the Template placemark ‘Wide Photo’:
   - right-click the **template** placemark.
   - Select Properties from the context menu.
   - In The Description tab select all HTML for the placemark.
   - Right-click Select Copy and close the dialog box .
5- Paste the HTML from the ‘Wide Photo’ template to the description tab of the Jim Jim Falls placemark
   - right-click the **Jim Jim Fall** placemark.
   - Select Properties from the context menu.
   - In The Description tab right click and paste.
6- Customizing the HTML section:
   - In the comment section at the top, each placeholder appears (all caps in curly braces, such as {LOGO_URL}) followed by its description. Don't worry, this comment section won't appear in the actual balloon.
   - In the HTML section below the comments, find and replace each of the placeholders with your own text or links to images. Be sure to replace the entire placeholder, including the curly braces and you can delete that placeholder which you don’t need to use. In our example as we are not talking about an organization we don’t need to use the placeholder {LOGO_URL}.
   - Click OK.



16 Adapted from “ Building Better Balloons”, accessed September 11, 2014 http://www.google.com.au/earth/outreach/tutorials/balloon.html

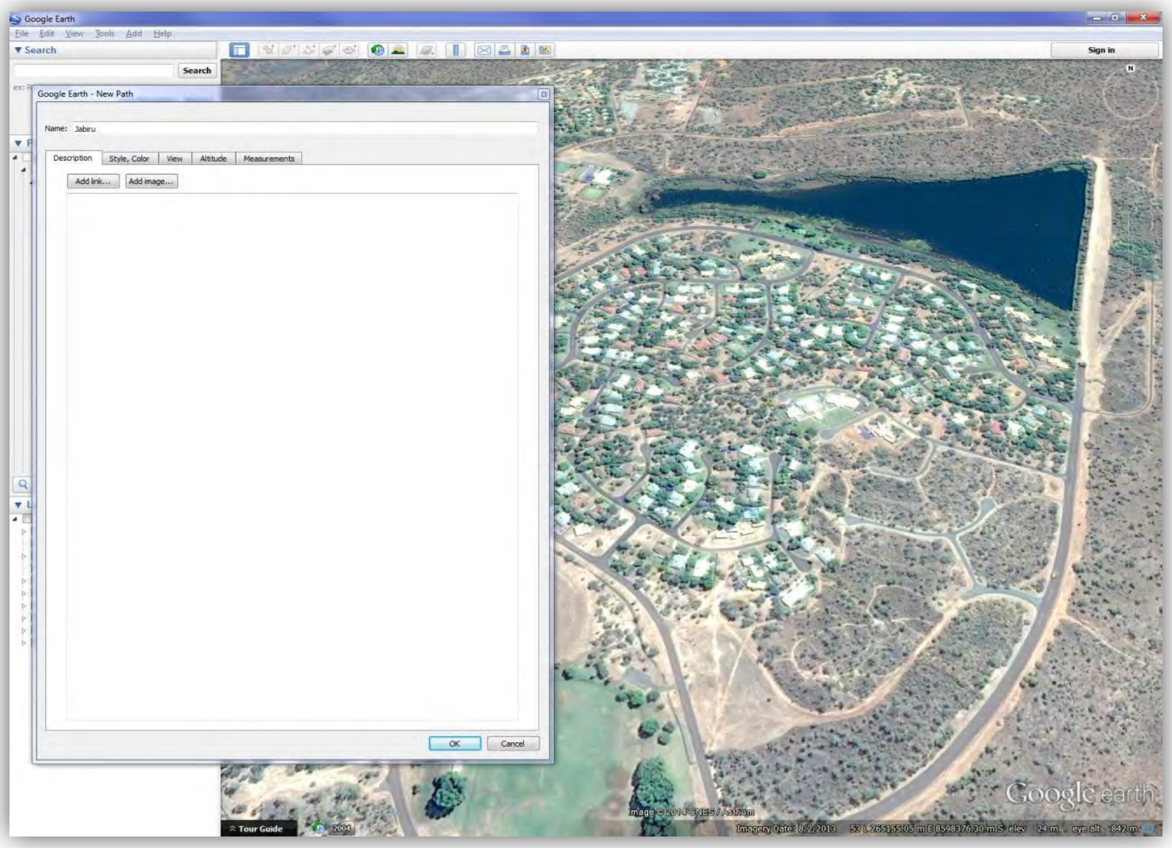
Drawing Paths (Fly Over)[17]

A helpful feature in Google Earth is the ability to draw a line, or path, over a particular region so that you can navigate/fly over it. You can draw free-form paths in the 3D viewer and save them in your My Places folder just as you would a placemark. Paths share all the features of placemark data, including name, description, style view, and location. Once you create a path, you can even select and play a tour of it.

- Practice 9 [17] Adding a path in Google Earth

1. Position the 3D viewer to best contain the region you want to mark. In the example below we are using Jabiru. The more detailed your view, the more closely your drawing can follow the land feature.
2. From the Add menu, select Path (Ctrl + Shift + T), or click the Add Path icon on the toolbar.

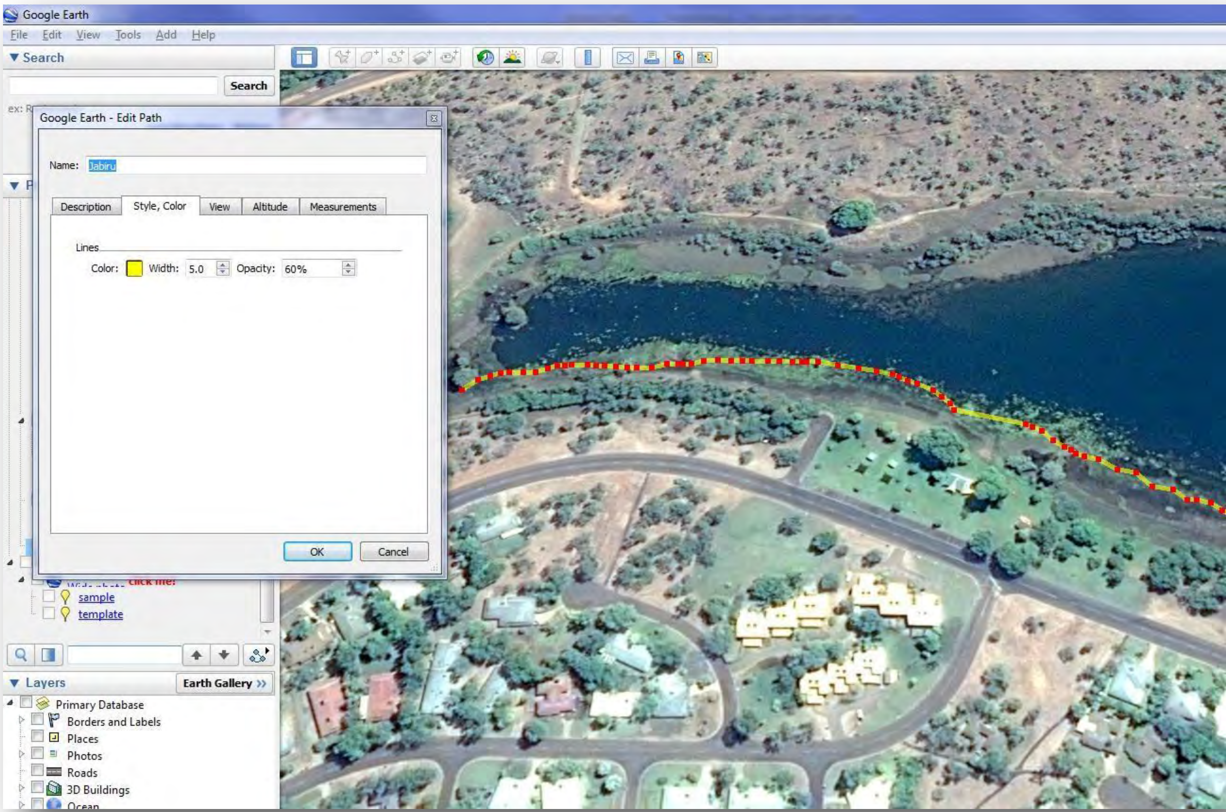
2. The New Path dialog box appears and the cursor changes to a square drawing tool. Click in the viewer to start your drawing.



17 Adapted from " Drawing Paths", accessed September 11, 2014 http://www.usawaterquality.org/conferences/2010/ThursdayPDF/GE_Fly_Over_Guide.pdf

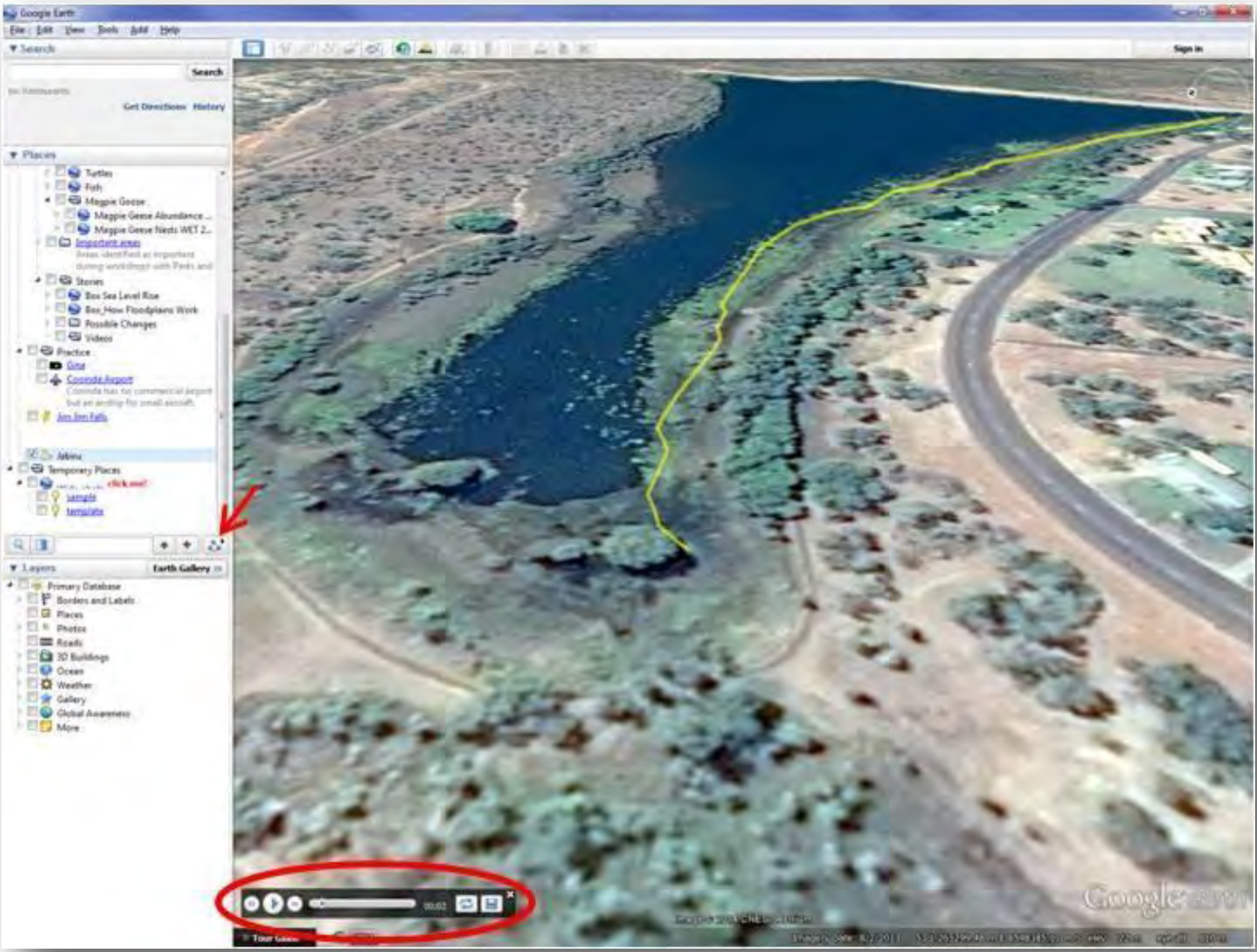
3. Setting Line Color and Width

With the New Path dialog box open, you can use the Line properties in the Style,Color tab to modify the display of the line in the 3D viewer. You can even make the line invisible!



4. Fly over the path

- Double click the path in the Places panel.
- Click the Play Tour button. The tour begins playing in the 3D viewer and the tour controls appear in the bottom left corner of the 3D viewer.



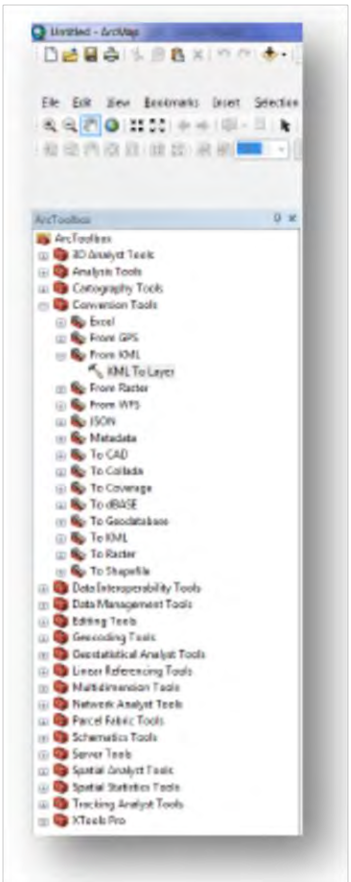
Importing Data from Google Earth to ARCGIS and vice versa

1. From GE to ARCGIS

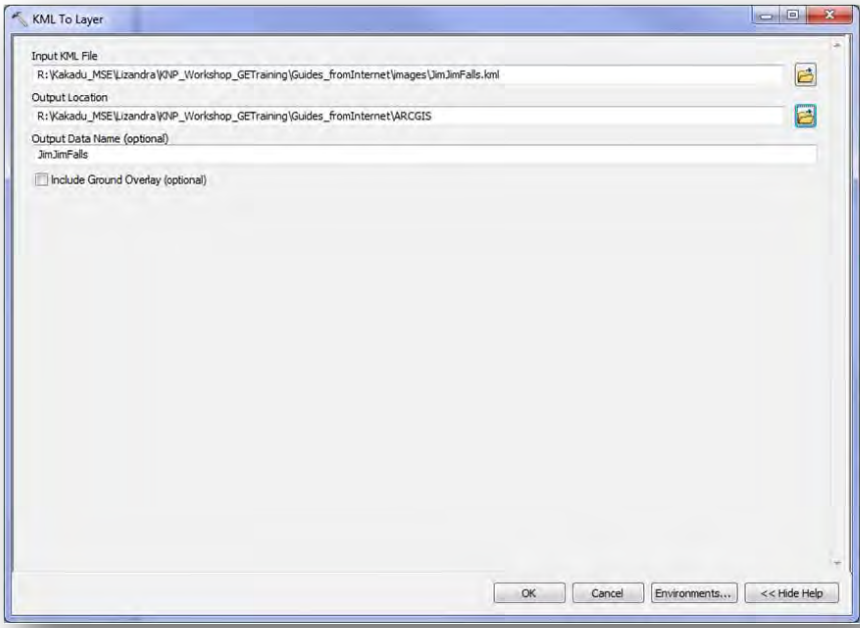
Google Earth files can be of two files extensions: 1) KML is an XML-based language provided by Google for defining the graphic display of spatial data in applications such as Google Earth and Google Maps., and 2) KML enables these applications to support the open integration of custom data layers from many GIS users. KML is a popular format for sharing data across the Internet and for use in online mapping applications. Its default projection of WGS84 allows it to be displayed and used in a variety of GIS applications[18] . A KMZ file consists of a main KML file and zero or more supporting files that are packaged using a Zip utility into one unit, called an *archive*. The KMZ file can then be stored and emailed as a single entity[19]. Translating KML and KMZ files into feature classes inside a geodatabase allow these common features to be used in ArcGIS .

➢ Practice 10: Exporting Jim Jim Falls placemark to ARCGIS

- In GE in the Place Panel right click the Jim Jim placemark
- Select Save Place as
- In Save as Type select the option Kml (*.kml)
- Check if the file is the desired location and click save
- In ARCGIS ArcToolbox >Conversion Tools>From KML>KML to Layer
- Set the KML file address in Input File, choose a location for your new ARCGIS layes in Output Location and click ok.



- Output will be generated in the WGS84 coordinate system but it can be reprojected to another coordinate system using the Project tool.



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18 " An Overview of the From KML toolset", accessed September 19, 2014 http://resources.arcgis.com/en/help/main/10.2/index.html# An_overview_of_the_From_KML_toolset/00120000004z000000/

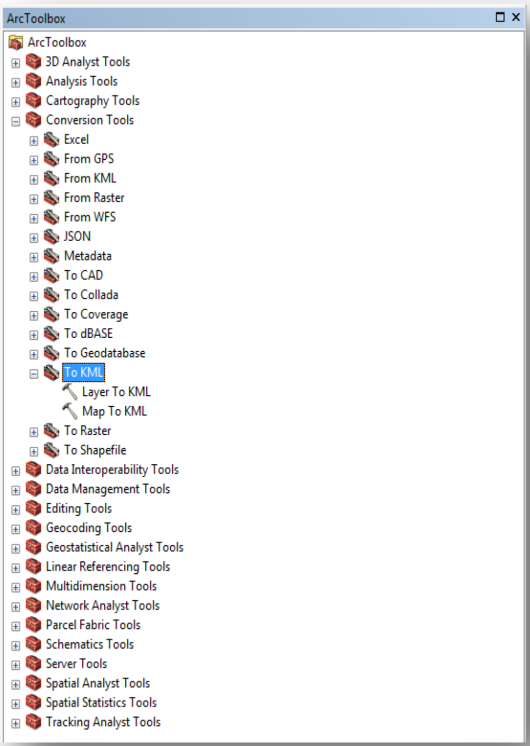
19 " KMZ Files", accessed September 11, 2014 https://developers.google.com/kml/documentation/kmzarchives

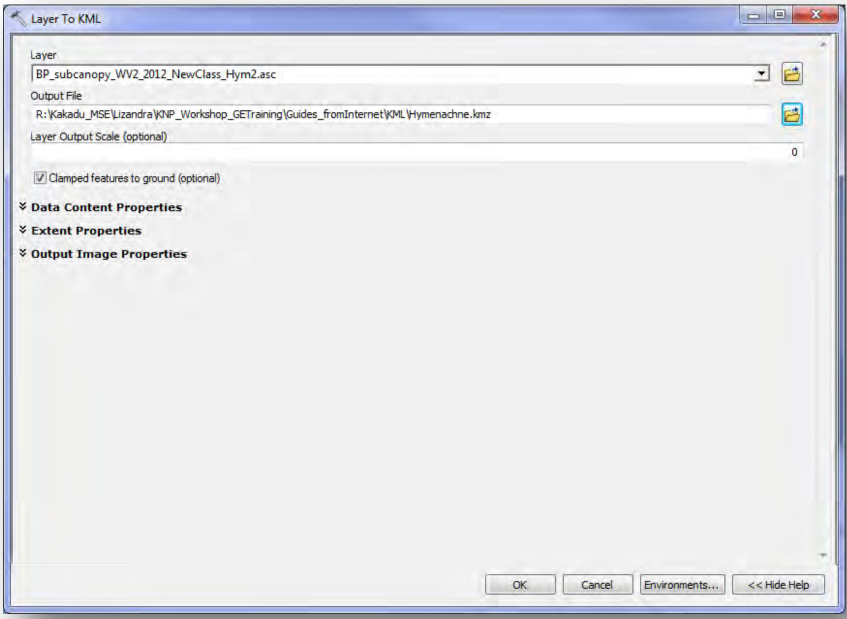
2. From ARCGIS to GE

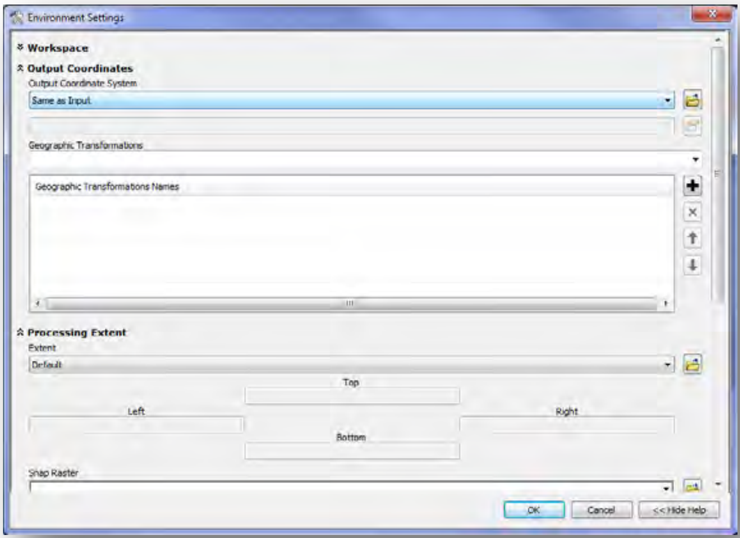
There are two geoprocessing tools available for creating KML files from ArcGIS data: Layer To KML and Map To KML. Both tools create a KMZ (compressed KML) file in the output location.

➢ Practice 11: Exporting the ASCII file WV2 2012 Hymenachne to GE

- In ARCGIS ArcToolbox >Conversion Tools>To KML> Layer To KML
- Set the ASCII file address in Layer, choose a location and a name for your new KML in Output file.
- In Environments> Output Coordinates choose the same coordinates as the ASCII file and click ok. Finally, go to GE and open your KML in GE.







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Managing threats to floodplains biodiversity and cultural values on Kakadu National Park

Part II: Participatory methods and integrated assessments

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Contents

Figures

Tables

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We would like to thank the Traditional Owners and Park staff of Kakadu National Park (Bininj) for their support and enthusiasm throughout the length of the project.

Executive summary

In Northern Australia predicted rises in sea level associated with climate change are expected to directly affect ecological dynamics with flow-on effects on human resource use in response to these changes. Here we report the outcomes of the development and application of a participatory sea level rise management planning framework developed in Kakadu National Park (KNP) as part of the NERP project 3.2 'Managing threats to floodplain biodiversity and cultural values'. Our framework uses a combination of literature reviews and participatory workshops using modelling outputs with managers of KNP (Bininj–the Aboriginal people of Kakadu National Park–and Park staff). The purpose of the participatory workshops was to present and discuss potential threats associated with sea level rise; obtain feedback about the kind of information required to manage the Park; determine how such information could be usefully presented, and identify what kind of management actions can be used to manage sea level rise (SLR) in KNP. In particular we report on: (i) a diagnostic framework created to portray the existing configuration of one of Kakadu National Park's (KNP) freshwater floodplain systems (Yellow Water) including the governance system and biophysical characteristics of the resource system and its users; (ii) outcomes of a workshop held in KNP to identify opportunities and actions to deal with sea level rise impacts; (iii) a semi-quantitative approach for the assessment of predicted sea level rise impacts in the Yellow Water Social-Ecological System (SES) that combines qualitative modelling and Bayesian Belief Networks (BBN) (including uncertainty levels), and (iv) stakeholder evaluation of the participatory methods applied.

As part of KNP, Yellow Water is governed by a joint management arrangement, which enables Bininj Indigenous land owners to participate in conservation planning and management of country. Joint management brings together two different governance systems operating in parallel, and these are: (a) an Indigenous nodal system that evolved over millennia to manage natural and cultural resources; and (b) a more recent management based on western scientific knowledge traditions and for KNP, specifically drafted in 1978, which includes World Heritage and Ramsar-listed wetlands. The biophysical component of Yellow Water encompasses seasonal river-floodplains that support a variety of freshwater plants and animals used by local Indigenous people. Both Indigenous culture and biodiversity values guide the management of KNP and are also major foci of the ecotourism industry, which brings important economic benefits through entrance fees, local businesses and livelihoods. The predicted impacts associated with sea level rise at Yellow Water include saltwater inundation of freshwater habitats, cultural sites and infrastructure (e.g. housing, roads, tourist facilities). Climate change may provide an opportunity to bring together Indigenous and non-Indigenous knowledge and governance systems towards a commonly perceived threat. Local mitigation strategies may be required to manage sea level rise threats (e.g. levees), however climate adaptation requires a combination of (i) strategies to facilitate Bininj to use and manage resources (e.g. through hunting, fishing and gathering activities), which will allow them to improve their understanding about biophysical dynamics and facilitate local learning about how to use new resources that may result from saltwater inundation (e.g. saltwater species in previously freshwater environments), and (ii) an adaptive management approach underpinned by a research and monitoring program in order to manage and understand the consequences of saltwater inundation on floodplain values in addition to assessing the effectiveness of any management strategy.

Part II Participatory Methods and Integrated Assessments

1 Introduction

Managing potential sea level rise (SLR) threats to maintain or improve Social-Ecological Systems (SES) is difficult for many reasons. First, resource use and exploitation often lead to a polarization between the need for economic development and the need to preserve or conserve the resource base of this development in the long-term, often because the beneficiaries are different groups to those that are affected by impacts (Lichatowich, 1992). Secondly, decision-making often involves a diverse set of government organizations (local, state, federal) that control or regulate access to or use of the resource (e.g. fisheries, forestry, land for agriculture and conservation) (Acheson, 2006; Bella, 1992). This control in turn influences the decisions of resource exploiters who derive economic benefits from harvesting or using natural assets, with impacts on others who use the resource for recreational, social and cultural purposes. Thirdly, because of the diversity of stakeholder groups affected by and involved in natural resource management (NRM) decisions and the often divergent values and management objectives (environmental, socio-economic and cultural) that may not be well articulated, nor made explicit to the wider society (Burt, 2011; de Geus, 1988; Ludwig, 2001; Walters, 2007). This can lead to tensions within and between stakeholder groups due to lack of transparency in the decision process, which also affects the way actions are chosen and implemented.

Because of the feedback and inherent uncertainty in SES, it is generally difficult to provide one 'best' (or optimal) policy to improve the condition of the resource (Rittel and Webber, 1973). However, decision frameworks that assist collective decision-making on a course of action to regulate natural resource-use have been successfully developed and implemented to solve natural resource management (NRM) issues. This includes adaptive management, a decision framework that has been frequently applied to marine fisheries management (Walters, 2007) and a subsequent but related approach, management strategy evaluation (MSE) (Bunnefeld et al., 2011; Dichmont et al., 2006; Dichmont et al., 2013; Fulton et al., 2011b; McDonald et al., 2006; Pantus et al., 2008; Smith, 1994), a framework that deals with multiple objectives by comparing the trade-offs of alternative management strategies.

Our objective is to report on the development and application of the Kakadu management planning framework to support the management of, and adaptation to, potential threats to floodplain biodiversity and cultural values associated with predicted SLR. The overarching structure for the Kakadu SLR management planning framework follows adaptive management (Walters, 1986) and Management Strategy Evaluation principles (de la Mare, 1996; Dutra et al., 2010; McDonald et al., 2008; Smith, 1994), which involves:

- **Informing** stakeholders (learning) about potential areas that could be inundated with predicted rise in sea level and limitations of modeling approach
- **Choosing** relevant spatial layers and visualization tool to support decision-making process
- **Eliciting management objectives, and actions** via using SLR model outputs to mediate interactions and discussions with stakeholders about management objectives, actions, and indicators in relation to SLR

- **<u>Testing management options/strategies</u>** using modeling to assess potential effects of options against objectives, which feedbacks into informing/learning again.

Adaptive management focuses on decision-making under uncertainty and models the learning that occurs progressively over time as resources are exploited and managed (Smith and Walters, 1981; Walters, 1986). It treats policy choices as deliberate, large-scale scientific experiments (Walters, 1997; Walters, 2007) for which the decision-making process generates relevant and reliable information about the natural resource system. Adaptive management requires a set of objectives, such as what managers and stakeholders want to achieve and by when, as well as an effective monitoring protocol to evaluate the consequences of decisions – in relation to objectives – to adjust actions based on the feedback received via the monitoring protocol. In principle, adaptive management can help managers understand the current state, and make explicit the desired states of the natural resource system, considering also uncertainty and a limited understanding of key underlying processes (Bennett et al., 2005; Cinner et al., 2006; Mapstone et al., 2008; Sainsbury et al., 2000).

MSE supports the design and implementation of adaptive management by enabling experimentation with alternative management strategies in a 'safe' simulation environment rather than in the real world. It assists resource managers in dealing with uncertainty and multiple objectives by allowing the comparison of often conflicting social, environmental and economic trade-offs, while testing multiple management strategies (Bunnefeld et al., 2011; Dichmont et al., 2006; Dichmont et al., 2013; Fulton et al., 2011b; McDonald et al., 2006; Pantus et al., 2008; Smith, 1994).

The presumed effectiveness of adaptive management and MSE is based on the assumption that a manager acts as a single agent that manipulates a set of regulatory levers to achieve objectives. They do so with more or less well-known consequences on the natural resource system being managed and in response to the information (and uncertainties) received back from the system via monitoring and assessment models (mental or computer-based models). Adaptive management regards decision-making as 'rational'. That is, it assumes that improved information necessarily leads to improved decisions, where the aim is to identify and adapt pre-determined courses of action depending on the feedbacks received about the system's response to past actions (refer to Arthur, 1992 for more on 'rational decision-making').

Under the paradigm of rationality, it is expected that scientific recommendations on resource use should seek to provide the best possible assessments of the natural resource, which is expected to play a key role in decision-making (de Oliveira et al., 2009; Walters, 2007). However, NRM decision-making usually involves a number of complex drivers related to governance structures and group dynamics, including leadership, which also influences which management decisions are chosen and how they are implemented (Dutra et al., 2014). Participatory methods have been used to effectively link these complex drivers with information, thus allowing a more inclusive and effective decision-making process.

2 Methods

Adaptive management and MSE have been applied worldwide to NRM based on the theoretical background of system dynamics and its control. Somewhat contrary to the intuitive idea of controlled dynamic systems, from the early days these applications have included a strong stakeholder participation component (Smith et al., 1999). Although this may be the result of the intuition of researchers or fisheries managers in the early applications, the importance of participatory approaches incorporated in MSE has increasingly been formally acknowledged. In this approach, the objectives of engaging and interacting with stakeholder groups is seen as a key to success in fostering learning about NRM issues (Boschetti et al., 2011; Dutra et al., 2014; Fulton et al., 2011a). This has even led to dedicated efforts to improve the interactivity of MSE tools, which requires the underlying simulation models to run faster (e.g. de la Mare et al., 2012).

The participatory Kakadu SLR management planning framework includes the following staged elements to support stakeholders to (Figure 1): (i) identify and deal with governance structures, (ii) identify key values and management objectives, (iii) develop methods which fully consider the available information, (iv) recognize avenues for choice under uncertainty that limit the sources of individual biases, and (v) respond to perceived changes in SES. The details for the application of the framework in Kakadu are described below.

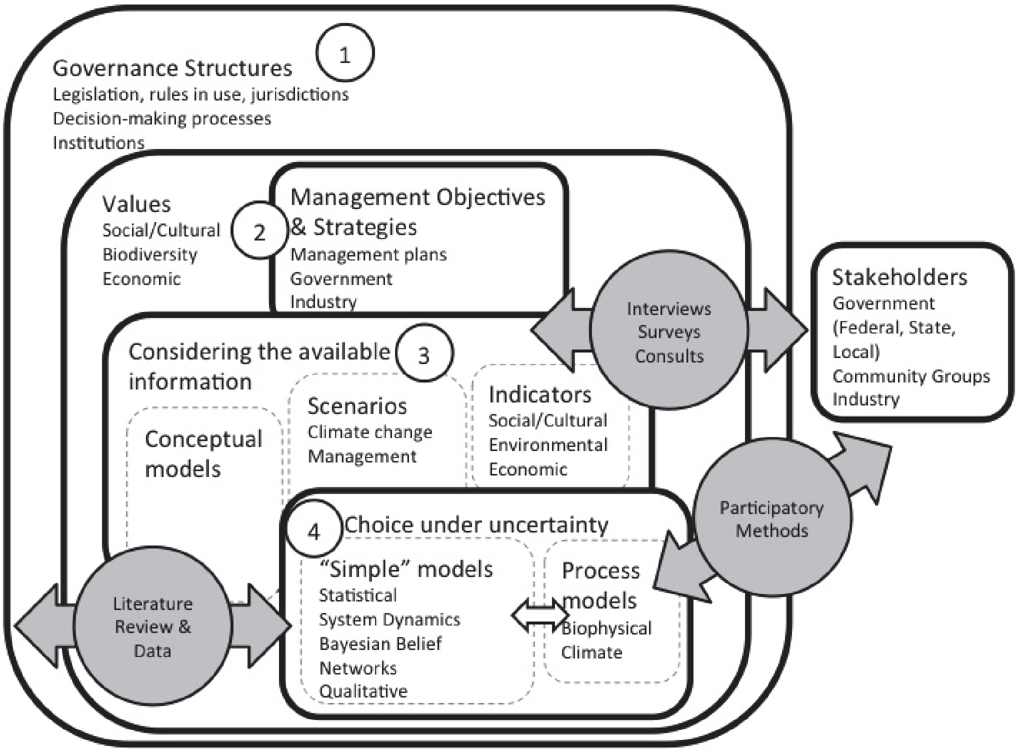

Figure 1. Graphical representation of the project methodological framework for the Kakadu sea level rise management planning framework. The framework considers the following stages: (1) dealing with governance; (2) identification of key management objectives and values to guide decisions; (3) methods to synthesize the available information; and (4) avenues for choice under uncertainty. The investigation of governance structures (1) is informed by all the other stages: values, management objectives and strategies (2), consideration of available information (3) and choice under uncertainty (4) are the proposed stages to develop participatory MSE. The dashed-line boxes are the necessary activities, such as the construction of conceptual models, elicitation of scenarios, and indicators for use in the MSE, as well as the construction of "simple", quantitative and process models. Note that all stages/activities are connected. Each stage has its specific methods (in grey; see also Table 1), such as scenario planning and participatory modeling under "Participatory Methods", questionnaires and interviews under "Interviews, Surveys and Consults". From Dutra et al., submitted.

2.1 Identifying and dealing with governance structures

2.1.1 DIAGNOSTIC FRAMEWORK

We use Ostrom's diagnostic framework (Ostrom, 2007, 2009) to examine "the nested attributes of a resource system and the resource units generated by that system that jointly affect the incentives of users within a set of rules crafted by local, distal, or nested governance systems to affect interactions and outcomes over time" (Ostrom, 2007). The framework helps to identify relevant variables for studying SES, including the people who rely on it, which is important to understand the elements required for climate adaptation.

The description of the multilevel, nested framework for analysing outcomes achieved in SES is presented below and also with the support of Figure 2 and Table 1. The description of methods is from Ostrom (2009) unless otherwise stated. Figure 2 shows the relationships among four first-level core subsystems of an SES that affect each other as well as linked social, economic, and political settings and related ecosystems. The subsystems are (i) resource systems (e.g., a designated protected park encompassing a specified territory containing forested areas, wildlife, and water systems); (ii) resource units (e.g., trees, shrubs, and plants contained in the park, types of wildlife, and amount and flow of water); (iii) governance systems (e.g., the government and other organizations that manage the park, the specific rules related to the use of the park, and how these rules are made); and (iv) users (e.g., individuals who use the park in diverse ways for sustenance, recreation, or commercial purposes). Each core subsystem is made up of multiple second-level variables (e.g., size of a resource system, mobility of a resource unit, level of governance, users' knowledge of the resource system), which are further composed of deeper-level variables (Table 1).

We used information gathered from a literature review (Appendix A) to present the diagnostic framework for Kakadu/Yellow Water. We have also conducted a literature review to identify key governance attributes that support adaptive capacity in coastal Australia (Dutra et al., 2015) summarized in the Results and used in the context of Kakadu in the discussion.

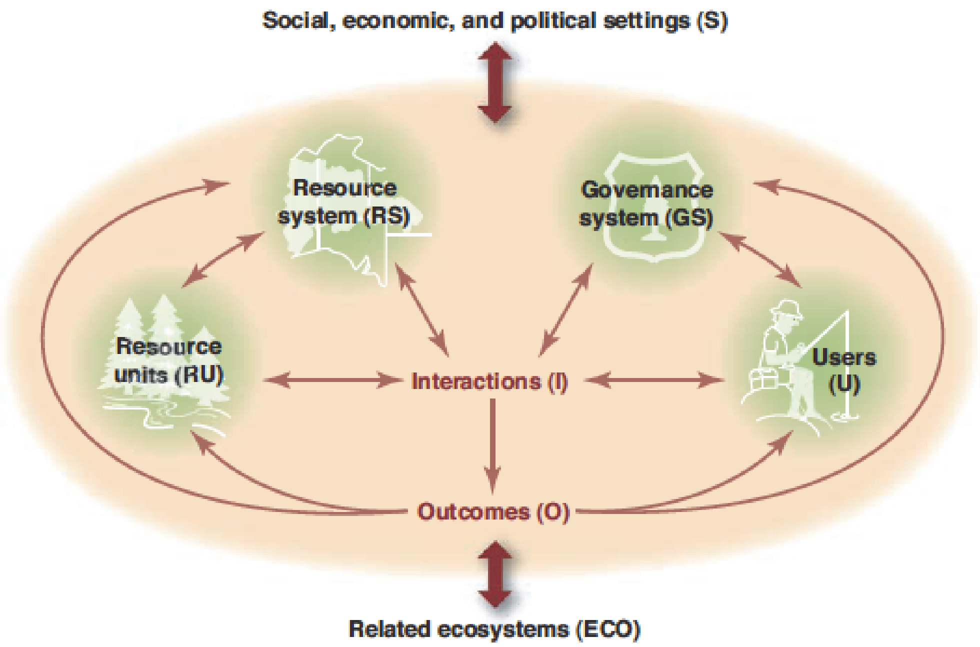

Figure 2. Core attributes in a framework for analysing socio-ecological systems (from \ Ostrom, 2009 #82}.

Table 1. Detailed framework for analysing a SES (from Ostrom, 2007).

Social, economic, and political setting (S)	
S1 Economic development	
S2 Demographic trends	
S3 Political stability	
S4 Government resource policy	
S5 Market incentives	
S6 Media organisation	
Resource system (RS)	**Governance system (GS)**
RS1 Sector	GS1 Government organisations
RS2 Clarity of system boundaries	GS2 Nongovernment organisations

RS3 Size of resource system	GS3 Network structure
RS4 Human-constructed facilities	GS4 Property rights system
RS5 Productivity of system	GS5 Operational rules
RS6 Equilibrium properties	GS6 Collective-choice rules
RS7 Predictability of system dynamics	GS7 Constitutional rules
RS8 Storage characteristics	GS8 Monitoring and sanctioning processes
RS9 Location	
Resource units (RU)	**Users (U)**
RU1 Resource unit mobility	U1 Number of users
RU2 Growth or replacement rate	U2 Socioeconomic attributes of users
RU3 Interaction among resource units	U3 History of use
RU4 Economic value	U4 Location
RU5 Number of units	U5 Leadership/entrepreneurship
RU6 Distinctive margins	U6 Norms/social capital
RU7 Spatial and temporal distribution	U7 Knowledge of SES/mental models
	U8 Importance of resource
	U9 Technology used
Interactions -> outcomes	
I1 Harvesting levels of diverse users	O1 Social performance measures
I2 Information sharing among users	O2 Ecological performance measures
I3 Deliberation process	O3 Externalities to other SESs
I4 Conflicts among users	
I5 Investment activities	
I6 Lobbying activities	
I7 Self-organising activities	
I8 Networking activities	
Related ecosystems (ECO)	
ECO1 Climate patterns	
ECO2 Pollution patterns	
ECO3 Flows into and out of focal SES	

2.2 Identify management objectives and options to deal with sea level rise

2.2.1 WORKSHOPS TO IDENTIFY MANAGEMENT OBJECTIVES AND POTENTIAL MANAGEMENT ACTIONS TO DEAL WITH SEA LEVEL RISE IMPACTS

The data elicited about options to manage sea level rise in KNP refers to the workshop held in December 2013 at separate workshops with Parks (ten participants on 03/12/2013) and Bininj (eight participants on 6/12/2013). The aims of the workshops were to:

- Provide updated saltwater inundation maps for four SLR scenarios,
- Introduce high-level management objectives for SLR rise on Kakadu and associated performance indicators,
- Undertake hands-on group sessions using maps and Google Earth to:
  - identify priority areas where it might be possible to mitigate for impacts of saltwater intrusion
  - discuss what actions may be taken to manage the impacts of saltwater inundation due to sea-level rise (in more detail during the afternoon session), and
- Evaluate the workshop.

The workshop started with a presentation about the project (refer to Appendix B for details about engagement and elicitation methods applied in the workshops). Updated saltwater inundation maps were presented to the group with the use of the interface-friendly Google Earth platform. This was chosen as it is readily available online and used by Bininj (the Aboriginal people of Kakadu National Park) and Parks. The research team presented a live demonstration of Google Earth including multiple GIS layers prepared for the workshop.

Participants were then divided into groups for hands-on group session with Google Earth. Each group was provided with a computer set up with Google Earth and the sea level rise inundation layers and bush tucker layers. Researchers worked closely with groups and individuals to show Google Earth capabilities as a management tool, and provide support on technical issues. Groups were asked to use Google Earth and they also had the option to use hard copies of maps distributed to groups to give comments on presentation.

High-level objectives (Parks and Climate Change, Figure 3) were presented during the workshop and participants were asked to answer the following questions and write their answers on maps and butcher's paper:

1. What are the areas that might be impacted by saltwater in the future (Priority Areas, focus is the 2070 scenario)
2. How do you think these areas will be affected (what is the issue)?
3. What kind of management actions will be required to minimise impact of sea level rise on Park values?

At the end of the session, each group presented their main findings which were summarised on butcher's paper. The group summaries were aggregated into a global workshop table, presented in the results section.

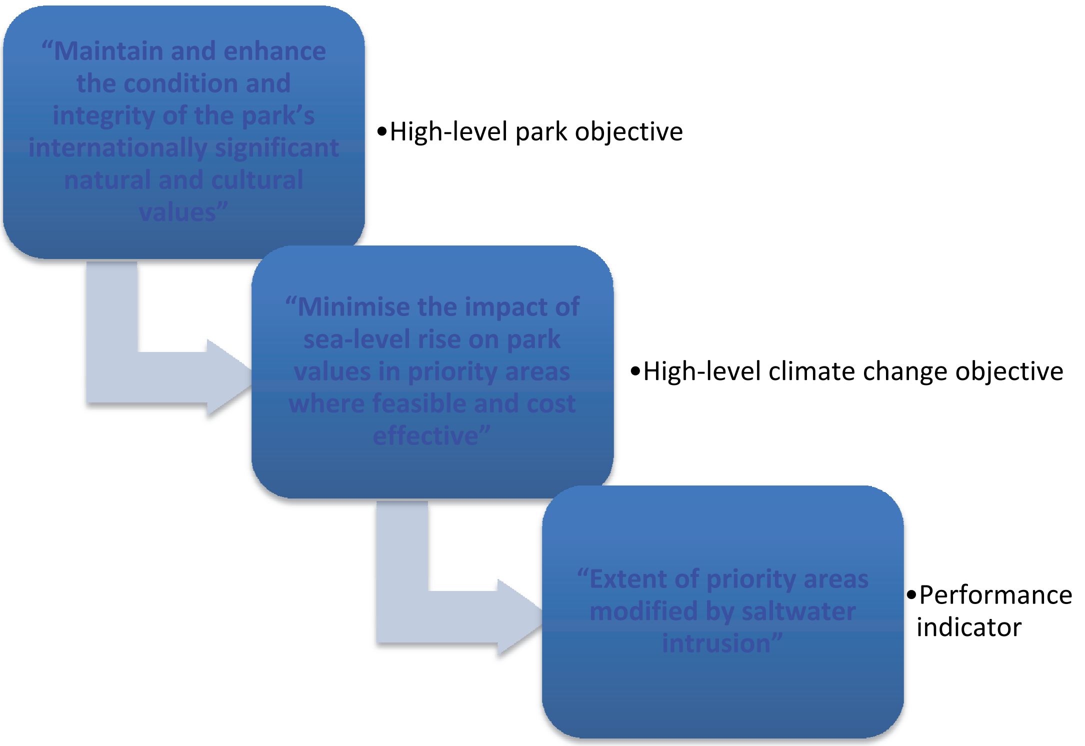

Figure 3. Examples of a high-level park objective, high-level climate change objective and performance indicator.

A more detailed list of Park objectives and performance indicators from the KNP management plan and other relevant documentation from the Park, which are relevant to this study, is provided in Table 2. It depicts two kinds of objectives: (1) fundamental (high-level) and (2) means objectives, which were used to synthesis information presented in Figure 3. Fundamental, or end objectives are those that are important because they directly reflect human values, while means objectives are those that are important because they contribute to the achievement of fundamental objectives (Clemen and Reilly, 2001). Fundamental objectives are used to guide management decisions (Keeney, 1992) (i.e. management strategies). In our semi-quantitative assessment of management strategies were performed against fundamental (high-level) objectives.

Table 2. Objectives from Kakadu National Park sourced from the literature.

Fundamental Objectives	Means objective	Indicator	Reference
Effective Joint Management	Ensure that traditional skills and knowledge associated with looking after culture and country, and Bininj cultural rules regarding how decisions should be made, continue to be respected, maintained and integrated with modern Park management practices	Satisfaction of indigenous people with the level of traditional knowledge that is used in Park management and implementation of Management Plan	(Director of National Parks, 2007:7,33)
		Satisfaction of Bininj with how well country in being looked after through management of fire, weeds and feral animals and how much involvement Bininj have in the design and implementation of management programs	(Director of National Parks, 2007:63,76,79)
	Increase Bininj responsibilities in Park management through capacity building	Number of Bininj trained in modern management practices (i.e. modern Park Management Skills are transferred across to Bininj)	(Director of National Parks, 2007:38)
		Number and type of capacity building initiatives provided for Bininj (including young aboriginals)	(Director of National Parks, 2010:5)
	Facilitate stakeholder engagement and increase satisfaction of stakeholders with joint management (Director of National Parks, 2007:33; 2010:7,8)	Level of satisfaction of stakeholders with the transparency and accountability of decision-making for the Park's management	(Director of National Parks, 2007:33)
		Perception of quality of initiatives (e.g. workshops, meetings) to formally engage stakeholders to communicate, inform and discuss matters related to Parks management (e.g. fire, weed and feral animal control, climate change)	-
	Maximise compliance with relevant legislation as a result of effective education and enforcement programs (Director of National Parks, 2007:133)	Number, severity and type of non-compliance incidents detected and reported	(Director of National Parks, 2007:133)
		Number of staff trained in compliance and enforcement	(Director of National Parks, 2007:133)

Fundamental Objectives	Means objective	Indicator	Reference
Effective Protection and conservation of biodiversity	Maintain World Heritage status for natural values Conserving the distribution, abundance and diversity of native plants and animals and communities is a fundamental objective of Kakadu National Park management. For the most effective approach to management of native plant and animal populations, land management programs must integrate fire, weed, and feral animal and visitor management considerations.	Abundance of species of natural significance	(Director of National Parks, 2007:68; 2010:6)
		Area of floodplain with acceptable levels of weeds	(Director of National Parks, 2007:13)
		Percent area of floodplain damaged by feral animals	(Director of National Parks, 2007:13; Petty et al., 2005)
	Maintain floodplain function and structure (healthy ecosystems)	Proportion of floodplain area affected by unplanned or adverse fires	(Director of National Parks, 2007:63)
		Area of floodplain with acceptable levels of saltwater (acceptable meaning occasional intrusion due to king tides/storm surges)	-
Protection and Conservation of cultural values (EPBC Act)	Maintain or increase traditional knowledge (spiritual, cultural, environmental)	Percentage of roads and tracks that provide access to spiritual / cultural sites not affected by weeds, ferals and permanent inundation permanently inundated (salt- and freshwater)	(Director of National Parks, 2007:32)
		Number of Bininj involved in businesses based on commercial use of wildlife (i.e. opportunities to be out on country)	(Director of National Parks, 2007:73)
		Extent to which Bininj are satisfied that people are using country in accordance with traditional law	(Director of National Parks, 2007:40)
		"Healthy Ecosystems": Abundance of species important to Bininj customary economy, ceremonial responsibilities and land management practices	(Director of National Parks, 2007:40, 67)
	Ensure aboriginal people are able to look after country (Protection of landscapes, soils and water)	Proportion of cultural sites with acceptable levels of weed infestation	(Director of National Parks, 2007:32,56)
		Proportion of cultural sites with acceptable impacts of saltwater intrusion (i.e. occasional king tides and storm surges)	-
		Proportion of cultural sites with acceptable impacts of feral animals	-

Fundamental Objectives	Means objective	Indicator	Reference
Improve sustainable economic benefits to Bininj (Director of National Parks, 2007:32,73,79)	Protection of natural and scenic areas (floodplains for YW) for tourist purposes	Area with acceptable level of weed infestation	(Director of National Parks, 2007:32)
		Level of visitor and tourism industry satisfaction with recreational and tourism opportunities in the Park	(Director of National Parks, 2007:85)
		Net present value associated with harvest of natural resources	-
		Number of skilled, unskilled, temporal and permanent jobs related to tourism	(Director of National Parks, 2007:9)
	Ensure responsible boating and recreational fishing	Level of visitor satisfaction with fishing and boating opportunities	(Director of National Parks, 2007:103)
		Level of Bininj satisfaction with management of fishing and boating, and their involvement in planning and management of these activities	(Director of National Parks, 2007:103)
		Linear channel changes in the tidal interface region	(Petty et al., 2005)
Promote social well-being	Impact on cultural and recreational sites	Proportion of area used for recreational and cultural purposes are accessible (i.e. within acceptable levels of weed infestation, feral animal damage, and inundation)	(Director of National Parks, 2007:32)
		Bininj perception that visitor impacts are within acceptable levels. Level of Bininj satisfaction with the nature, scope and impact of recreational (rec fishing, boating) and tourism opportunities in the Park	(Director of National Parks, 2007:85)
	Promote Bininj satisfaction	Proportion of indigenous people working on land-related activities (e.g. fire management, land management, hunting, gathering, arts & crafts, bush tucker tours, hunting, feral and weed control etc.)	(Director of National Parks, 2007:32,73,79)
		Number of indigenous enterprises that make significant contributions to maintenance of cultural values of the Park	(Director of National Parks, 2007:73)
	Improve health and safety in Kakadu	Number and seriousness of safety related incidents	(Director of National Parks, 2007:103)
		Number of crocodiles in areas where swimming is allowed and/or in locations that present a higher than usual risk to people	(Director of National Parks, 2007:69)
		Extent to which potable drinking water at Park facilities is in accordance with Australian Drinking Water Guidelines	{Director of National Parks, 2007 #141:56

2.3 Methods which fully consider the available information

2.3.1 STAKEHOLDER PRESENTATIONS AND PARTICIPATORY WORKSHOPS

We used a mix of stakeholder presentations and participatory workshops to present outputs of SLR model on selected spatial layers. The workshops were used for the research team to provide information about sea level rise outputs of hydrodynamic models for four climate change scenarios (2013: 0m SLR; 2030: 0.14m SLR; 2070: 0.7m SLR; 2100: 1.1m SLR; Saunders et al., 2013) and get feedback from participants on presentation of model outputs, advise on spatial layers to assess SLR impacts and planning for future workshops, potential management options and indicators.

2.4 Avenues for choice under uncertainty

The evaluation of management options and adaptation was done by integrating qualitative models and BBN, following the work from Metcalf et al. (2014) and Hosack et al. (2008), detailed below. The models were constructed based on the diagnostic framework (section 2.1.1) to explore possible system trajectories (exploratory analysis; Brugnach, et al. 2008: 53).

2.4.1 QUALITATIVE MODELLING

Qualitative modelling techniques have been successfully applied to gain improved understanding of system dynamics and allowing the identification of key factors affecting system stability (Fulton et al., 2011b; Metcalf et al., 2014) and the integration of non-quantifiable aspects into SES to test a range of management actions and/or strategies. It allows the systemic exploration of coupled SES by conceptually representing causal relationships using signed di-graphs (Dambacher et al., 2003; Dambacher and Ramos-Jiliberto, 2007; Levins, 1974; Levins, 1998).

The symbology used in signed di-graphs is relatively easy to understand and allows the representation of key relationships relevant to the system under question. The following example (from Metcalf et al., 2014) is used to depict the signed di-graph technique. A fishery has a direct negative effect on a target fish species (—•) and the fish species has a direct positive effect on the fishery (—>) (Figure 5). Birds are shown to prey on the target species and also feed on bycatch thrown overboard by fishermen. Negative self-effects are used to represent intra-specific density-dependence or a reliance on factors that are external to the modelled system, such as the impact of markets on the fishery. All direct interactions between variables (+, - ,0) can also be represented in a community matrix (Figure 4, Eq.1). Following established mathematical protocol, this matrix can be used to calculate the predicted direction of response to perturbation (sustained disturbance, such as increase in fishery, or a management action, such as a decrease in fishery) using the adjoint of the negative community matrix {Figure 4, Eq. 2, for details refer to \Dambacher, 2003 #1172;Puccia, 1985 #1188}. Perturbed variables read down matrix columns, while the response of variables to perturbation is read across matrix rows. The numbers at the top of each column correspond to the variable name at the start of each row:

$$\mathbf{A} = \begin{array}{l} \text{1. Fishery} \\ \text{2. Fish} \\ \text{3. Birds} \end{array} \overset{\begin{array}{ccc} 1. & 2. & 3. \end{array}}{\begin{bmatrix} - & + & 0 \\ - & - & - \\ + & + & - \end{bmatrix}} \quad (1)$$

$$\text{adj.}\,(-\mathbf{A}) = \begin{array}{l} \text{1. Fishery} \\ \text{2. Fish} \\ \text{3. Birds} \end{array} \overset{\begin{array}{ccc} 1. & 2. & 3. \end{array}}{\begin{bmatrix} + & + & - \\ - & + & - \\ +,- & + & + \end{bmatrix}} \quad (2)$$

Figure 4. Equations 1 and 2 (from Metcalf et al., 2014).

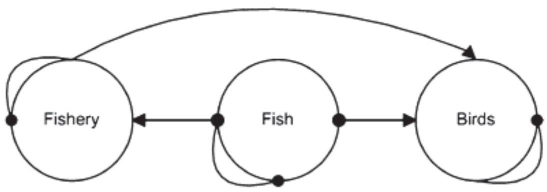

Fig. 1 Signed digraph showing birds and a fishery removing fish from the system (negative effect on fish, ●——), fish providing food for birds and product for the fishery (positive effect on birds and fishery, ◄——), and the fishery providing birds with additional food through releasing bycatch (positive effect). Negative self-effects represent density-dependence or a reliance on factors external to the system (e.g. market demand, profit, habitat)

Figure 5. Signed digraph (from example from Metcalf et al., 2014).

After the definition of the structure of the system we can analyse the system's feedback to assess qualitative conditions for system stability and perturbation response (Dambacher et al., 2007). Prediction signs are calculated as the net feedback cycles between a perturbed variable and the variable of interest using Maple 13 (Dambacher et al., 2003). The example from Metcalf et al. (2014) depicted in Figure 5 shows that the response of the fishery to a perturbation (increase) in fish abundance has only one feedback cycle. As a result the fishery is predicted to increase its production in response to an increase in fish abundance. However, two feedback cycles are involved in the response of birds to an increase in fishery. In the first feedback cycle, the fishery may have a direct positive impact on birds through the reduction of fish or an indirect impact on birds through the reduction of fish abundance. The prediction of responses is therefore ambiguous because these feedback cycles are countervailing. Metcalf et al. (2014) suggest that 'ambiguity of predictions is important because, when the strength of the interactions is taken into account, one strong feedback cycle may outweigh multiple weak cycles in the opposing sign. In this way, particularly as systems become more complex, ambiguity may result in an unexpected response to change.' The 'probability of sign determinacy' (Hosack et al., 2008) is used as an indication of the reliability of response.

It is important to note that in qualitative modelling negative feedback is stabilising, because it 'opposes change and allows a return to the former state' (Metcalf et al., 2014). Positive feedback, however, enhances the effects of original changes (Levins, 1998) and contributes to instability. Model stability is measured using weighted feedback (wFn) to assess the degree to which the overall feedback system is dominated by stabilizing negative or positive cycles. Values of wFn close to - 1 are perfectly stable (Dambacher et al., 2003). Stable systems tend to return to equilibrium following a perturbation. Values for wFn that are close to +1 are totally unstable and they may switch to an alternative equilibrium (Metcalf et al., 2014). Unstable system means that the system can no longer be adequately represented by the current model (Dambacher et al., 2003). A weighted feedback of 0 represents a system that is equally likely to be stable or unstable. Particularly influential interactions and feedback cycles can be identified and modified to increase system stability, predictability and management outcomes. These modifications, in addition to the mediation of external negative impacts, essentially form the identified adaptation strategies (Metcalf et al., 2014).

In our analysis we favour adaptation strategies that increase model stability because they provide greater predictability, which is useful for assessing the potential outcomes of different strategies. Similarly, adaptation strategies that benefit (i.e. are predicted to improve/increase) important model variables, such as target species, particular socio-cultural activities and economic sectors, are also favoured. For example, strategies that increase the capacity of the community to cope with change or increase the abundance of species targeted by Bininj are favoured.

2.4.2 BAYESIAN BELIEF NETWORK

BBNs are a semi-quantitative approach that allows the calculation of conditional probabilities for change in any variable, given change in another (Marcot et al., 2001). Similar to qualitative modelling, BBNs use a graphical notation to illustrate linkages between different system components. The difference between the qualitative models and BBNs is that all links in the BBNs are probabilistic, while links in qualitative models are purely directional (Metcalf et al., 2014). BBNs use relationships between variables to form the basis for conditional probabilities and are used to determine: (1) predicted changes following the implementation of management actions/adaptation strategies, (2) the probability of different actions/strategies to minimize unwanted impacts and (3) the model most likely to represent particular situations.

The conditional probabilities that are central to BBNs can be calculated using the community matrix information developed in the qualitative modeling exercise (Hosack et al., 2008). Linking BBNs and qualitative modeling means that the BBN structure is equivalent to the associated signed digraph where each variable in the signed di-graph becomes a node with its own conditional probability table (CPT) in the BBN. Similarly, perturbations impacting the signed digraph are shown as input variables in the BBN. BBNs were developed and analysed using **Netica 4.16** following input from qualitative models using **Maple 13**.

The probabilities of sign determinacy, calculated as part of the qualitative modelling analysis, are translated into probabilities for use in the CPTs for the BBN (Hosack et al., 2008). For example, each variable/node in a qualitative model and associated BBN has the potential to increase, decrease or undergo no changes in response to a disturbance to the system. Therefore, if there is no knowledge of the direction of change, there will be an equal likelihood of an increase, decrease or no change (i.e. Pr = 0.3) in the BBN. In contrast, a probability of 0.8 that a variable will increase will have corresponding probabilities for a decline and no change of 0.1. The cyclical nature of signed digraphs is embedded in the BBN through these CPTs and the relationships between nodes and their input variables (Metcalf et al., 2014).

The measure of uncertainty we applied for the results of the BBNs is the following: (i) high likelihood, whereby probabilities (Pr) of 0.8 and higher are regarded as likely based on the model structure; (ii) moderate likelihood, where predictions with probabilities between 0.6 and 0.8, and (iii) low likelihood of occurring, where predictions of probabilities are less than 0.6 (Dambacher et al., 2003; Hosack et al., 2008).

We have developed a qualitative model and associated BBN to represent aspects of a specific SES in Kakadu (Yellow Water) as a way of demonstrating and testing the approach in the report. Subsequent models and refinements of existing models will be done in subsequent journal publications. The SES we depict in this demonstration exercise shows impacts from external and internal changes (called press perturbations) reported to affect the Yellow Water SES. An associated alternative structure incorporates identified potential adaptation strategies to allow for the assessment of management actions and adaptation strategies. In our approach inputs from the diagnostic framework were used to develop the graphical structure of the signed digraphs for the YW SES and YW Alternative SES.

Based on outputs from the workshop with Parks and Bininj we used the following management options to evaluate social, economic and ecological responses in the BBN:

(i) Direct mitigation through building infrastructure (e.g. levee banks), and relocate infrastructure (roads, tourism infrastructure, buildings). This is represented in the model by adding a negative effect in *Saltwater Intrusion*.

(ii) Increase in floodplain management, which includes fire, weed and feral animal management via focusing on learning about possible consequences of climate change in animals and plants through improved communication between stakeholders, and improved indigenous participation in the planning and execution of management activities.

The interactions, dynamics and press perturbations represented in the Yellow Water SES models under climate change that were developed to test management scenarios are summarised in Table 3.

Table 3. Models constructed to assess the performance of climate change and management scenarios under climate change

Model	Dynamics represented	Press perturbations (climate change impacts)
YW SES	Perceived interactions between, physical, ecological, socio-cultural and economic drivers under climate change scenario	Increase in Invasive Species Decrease in Tourism
YW SES Alternative Model	Yellow Water with adaptation strategies	Increase in Invasive Species Decrease in Tourism

The management scenarios depicted in Table 4 were tested in the modelling exercise.

Table 4. Management scenarios tested in the Yellow Water Social Ecological System.

Management scenario	Press perturbations	
	Impacts	Management Actions
1	Increase in Invasive Species Decrease in Tourism	None
2	As above	Decrease in Saltwater Inundation (Barrier)

3	As above	Increase in Floodplain Management
4	As above	Decrease in Saltwater Inundation (Barrier) Increase in Floodplain Management

2.5 Incentives to respond to perceived changes in performance

Because the full effects of climate change and sea level rise are not currently experienced in KNP and existing weed and feral animal infestations are currently the big threats to floodplains in the Park there are little incentives to respond to changing climate. However, KNP stakeholders believe that increasing their knowledge about potential impacts will be essential to adapt to predicted changes. As a result the project team developed a series of communication products−13 in total through the life of the project− as a way to improve their knowledge base. The communication products we have developed are listed below.

1. Departmental publication on Northern NERP Project Planning Workshop, Kakadu National Park (2–3 June 2011) (Bayliss and Winderlich, 2011).
2. NERP North Australia Hub – Project 3.2: Managing threats to floodplain biodiversity and indigenous values. Flier for research permits consultations (7-11 Nov 2011).
3. Project 3.2 Managing threats to floodplain biodiversity and indigenous values. Project information summary (24-31 March 2012).
4. Flier for project 3.2 presentation given at Gunbalanya Stone Country Festival (Oenpelli) (22-23 August 2012).
5. Invitation and Information about workshop organised by the project team: wetlands, weeds and climate change (27-31 August 2012).
6. Project 3.2 Summary. Floodplains, weeds and sea level rise (brochure, fact sheet, Feb 2013).
7. Invitation and Information about workshop organised by the project team: responding sea level rise on Kakadu floodplains (1-6 February 2013).
8. Project 3.2 - Floodplains, weeds and sea level rise. June 2013 field trip, update (brochure/newsletter).
9. Open informal invitation to Kakadu parks staff to receive updates on planning SLR modelling and planning component of project 3.2: responding to sea level rise on Kakadu floodplains (21-23 October 2013). Trial run for December stakeholder workshop.
10. Invitation and Information about workshop organised by the project team: responding to weeds and sea level rise in Kakadu floodplains (1-7 December 2013): http://www.nerpnorthern.edu.au/news/2013/workshop-responding-weeds-and-sea-level-rise-kakadu-floodplains
11. Invitation and Information about workshop organised by the project team: How can we manage sea level rise and weeds on Kakadu floodplains (July 2014): http://www.nerpnorthern.edu.au/news/2013/workshop-responding-weeds-and-sea-level-rise-kakadu-floodplains
12. Booklet/long pamphlet on sea level rise in Kakadu National Park (see Appendix B – final draft – July 2014).

13. Invitation and Information flier about workshop organised by the project team: final consults with Bininj and Park staff (24-29 November 2014).

The project team produced also a number of outputs that were presented to stakeholders during formal project presentation and workshops, and distributed where applicable. The complete list of project outputs (tools, reports, and deliverables) is the following:

1. Report: Northern NERP Project Planning Workshop 2-3 June 2011.
2. Report on Climate change scenarios review for Kakadu.
3. Report on Kakadu Information Management System.
4. Stage 1 Hydrodynamic model outputs for dry season (October) for the following scenarios: present scenario (October 2013. 0m Sea Level Rise/SLR), 2030 (0.14m SLR), 2070 (0.7m SLR), and 2100 (1.1m SLR):
   - Maximum extent of tidal inundation.
   - Average extent of tidal inundation.
   - Frequency of tidal inundation.
5. Technical Report for stage 1 hydrodynamic simulations plus videos.
6. Maps showing tidal inundation for present and future sea level rise scenarios (item 4) overlaid on biodiversity and cultural values and information on proportion of floodplain and hunting, fishing and gathering sites inundated by saltwater for each SLR scenario.
7. Report on consultations with Kakadu National Park Staff to develop a management planning framework.
8. Report on consultations with Kakadu Bininj to develop a management planning framework.
9. Report on functional design of levee to protect Yellow Water from sea level rise (including brief with specifications and memo commenting on barrier proposal).
10. Booklet with information about sea level/saltwater inundation prediction and potential impacts on Kakadu.
11. Google Earth Layers (assessment, planning and communication tool).
12. Google Earth Manual.
13. Description of maps and GIS layers produced in the project.

2.6 Evaluation of participatory workshops

We have formally evaluated the participatory workshops from December 2013 (Bininj and Parks) and July 2014 (Park staff only due to no attendance of Bininj in the workshop). We used a standard evaluation form to assess expectations, needs, and get overall feedback about workshops from stakeholders. The questions asked to workshop participants were the following:

1) Was the information provided during the workshop useful and well presented?
2) Was there anything you expected to be covered in the workshop that was not presented?
3) What worked well and what did not work so well?
4) What would you do differently?
5) Do you have further comments to make?

3 Results

3.1 The Yellow Water SES (diagnostic framework)

A review in the literature, provides the critical factors affecting the Yellow Water SES under the headings identified by Ostrom (2007, 2009), which are identified below and Appendix A (refer also to Table 1). Yellow Water contains Ramsar-listed wetlands and associated floodplains and is also a World Heritage Area for its cultural and biodiversity values (S).

Floodplains and wetlands of Kakadu support a variety of plants and animals, which are important economic and cultural resources for Bininj (RS1). These habitats have sustained traditional Aboriginal economies for thousands of years, and Bininj continue to use and manage these resources. Yellow Water wetlands are also a major focus of Kakadu's tourism industry, which also provide economic opportunities through local businesses and jobs (McGregor et al., 2010). Conflicts occur sometimes between Bininj and some Park users over clarity of system boundaries (RS2). For example, some Park users have a different perception about land rights of Aboriginal land-owners within the Park and the role these land-owners have in Park decisions (Palmer, 2004b).

The size of the Yellow Water SES is important as the species harvested occur in a limited area (RS3). The human-constructed facilities (RS4) are composed of Parks infrastructure (buildings and roads (Director of National Parks, 2007:58), Tourism infrastructure (accommodation (Gagadju Lodge Cooinda) (BMT WBM, 2011:70; McGregor et al., 2010), Roads and bridges (Boustead, 2009:31; Director of National Parks, 2010; Hyder Consulting Pty Ltd, 2008) and Housing (Director of National Parks, 2010; Hyder Consulting Pty Ltd, 2008).

The resources (plants and animals) are renewable (RS5) and their predictability is influenced by seasonal (monsoonal) wet/dry cycles (RS6). The wet season (November to March) is characterised by heavy periodic rains and generally hot and humid conditions and the dry season (April to October) is characterised by dry and mild to warm conditions (Finlayson and Oertzen, 1996:4). Most of the 1300-1500 mm of annual rainfall comes from monsoonal depressions and intense downpours during the wet season. The climate dynamics is very complex due to inter-annual and inter-decadal weather patterns that include rain bearing monsoonal fronts and cyclones (Finlayson and Oertzen, 1996:4).

Resource Units (RU) are animals and plants used by Aboriginal people, which inhabit, feed and breed in Yellow Water floodplains (Bayliss and Yeomans, 1990; Director of National Parks, 2007:77; McGregor et al., 2010). The animals, especially the waterbirds, pigs (invasive species) and fish are mobile. Some species, such as the magpie geese perform long annual migration and these migration cycles and breeding seasons are taken into consideration in determining hunting seasons. Fish, such as the barramundi, catfish, saratoga, black bream, and freshwater turtles are important resource for aborigines and Park visitors (Palmer, 2004b). Plants such as water lilies and lotus seeds also grow in the floodplains and are part of aboriginal diet (McGregor et al., 2010).

Growth or replenishment rate of harvested species (RU2) depend on complex ecological processes related to annual patterns of rainfall and floodplain inundation, occasional saltwater intrusion, fire regimes and management, abundance of native grasses (especially *Hymenachne acutigluma*) and invasive species (feral animals (e.g. buffaloes, pigs, horses) and weeds) (Bayliss and Yeomans, 1990; BMT WBM, 2011:12; Director of National Parks, 2007; Douglas and O'Connor, 2004; McGregor et al., 2010; Petty et al., 2005; Setterfield et al., in press; Skeat et al., 1996:161; Woodward et al., 2010). River shape, tidal flow, vegetation cover or landform can facilitate the entry of salt water into freshwater areas, which in the short term negatively affects freshwater vegetation and the animals they sustain (Director of National Parks, 2007:57).

Fire is a major RU2 driver as it affects plant and animal growth and abundance. It is a natural part of the floodplain landscape and a fundamental expression of Aboriginal knowledge and their connection to their environment. Indigenous people have used fire as a management tool to encourage the regrowth of desired grasses and clear access to hunting and cultural sites for thousands of years. This traditional practice has created a mosaic of unburnt, early and late burnt patches that is important for maintaining species and habitat diversity (Director of National Parks, 2007:63-64; McGregor et al., 2010; Petty et al., 2007:5; Petty et al., 2005:40; Russell-Smith et al., 1995). Invasive species (weeds and feral animals) also affect growth and replenishment rates of important plants and animals. Aquatic weeds alter natural fire regime (Boustead, 2009:40-41; Douglas and O'Connor, 2004) and feral animals affect ecological relationships between plants and animals and also facilitate the dispersal of weeds (Director of National Parks, 2007:79; Skeat et al., 1996:161; Woodward et al., 2010). Altered fire regimes and the spread of weeds and feral animals have influenced the composition of native plant and animal communities in the Park (Director of National Parks, 2007:67).

Resource units strongly interact (RU3). For example, plant species (e.g. sedge *Eleocharis dulcis* and surrounding wild rice *Oryza* spp) form preferred nesting and feeding grounds for magpie geese (*Anseranus semipalmata*). Hydraulic connectivity (floodplain inundation and saltwater intrusion) is also an important element of interaction between resource units (RU3)(McGregor et al., 2010). Other examples of interactions among resource units are provided as follows: the invasive species Para grass is spreading across KNP. This weed can alter the natural fire regime by displacing native plants (e.g. wild rice). Para grass increases the fuel load, resulting in more intense fires and flame height, which can cause deaths of native Melaleuca trees, monsoon rainforest species and turtles aestivating in the mud (Douglas and O'Connor, 2004). Increased spread of weeds (such as para grass) into magpie goose habitat, an important resource for Bininj, is likely to decrease the availability of food sources such as wild rice and *Eleocharis* spp. (Bayliss and Yeomans, 1990). Buffalo were widespread in Yellow Water in the past (Petty et al., 2005) and caused significant impacts via grazing, trampling, and the formation of pads and wallows. Buffalo impacts include (Petty et al., 2005; Skeat et al., 1996:159; Woodward et al., 2010): (i) reduction in vegetation biomass, change in species composition (including dispersal of weeds) and, locally, complete removal of vegetation which affect population of birds such as the magpie geese; (ii) compaction of soils and soil erosion; (iii) changes to surface hydrology, including reduced retention of fresh water in flood basins and intrusion of salt water into freshwater swamps; and (iv) increased turbidity in water bodies resulting from trampling, wallowing and grazing, as well as their contamination by buffalo faeces and urine. It is therefore paramount to maintain numbers of feral animals low through active population control.

Floodplain species are an important economic asset for Aboriginal communities in Yellow Water (RU4) because these species can be hunted or harvested for consumption instead of purchasing food (e.g. meat) in the markets. For example the value of wild harvested magpie goose can be as high as $20/bird (Australian Greenhouse Office, 2004), and their hunting provides important economic (as well as social and cultural) benefits (replacement cost) to Bininj. The floodplains are also a major focus of the tourism industry in Yellow Water. Tourist visitation depends on good ecological conditions of floodplains (Prouse and Crawford, 2006:4). Economic benefits associated with the tourism industry include opportunities for jobs and local businesses (Director of National Parks, 2007:85; Harris, 2012:74; McGregor et al., 2010). The importance of tourism in Yellow Water is enormous for the whole KNP as the tourist resort of Cooinda, next to Yellow Water floodplains is the most visited site of KNP and the floodplains constitute the main attraction for tourists (Tremblay, 2006).

The dynamics of the Yellow Water SES are driven by a combination of biophysical processes, human use and relationships between managers and users *(U, GS1, GS2)* – traditional land owners (Bininj), Parks Australia and Park users. Aboriginal people have been using and managing natural resources in Yellow Water for thousands of years (U3). The resources are important for economic and socio-cultural reasons and also for their biodiversity values (Ramsar, World Heritage status) (U8) (McGregor et al., 2010).

As part of KNP Yellow Water is governed by a joint management arrangement (GS) between the Director of National Parks (Parks Australia) (GS1) and Bininj (GS2), which enables indigenous people to participate in conservation planning and country management (Director of National Parks, 2007:67; McGregor et al., 2010). Joint management brings together two distinct governance systems operating in parallel (GS3); these are: (a) an indigenous nodal system that evolved over the millennia to manage natural and cultural resources and (b) a more management based on western scientific knowledge traditions and for KNP, specifically drafted in 1978. We provide below a synthesis about these governance systems based on previous published work (Director of National Parks, 2007; Robinson et al., 2005; Woodward et al., 2010) unless otherwise stated.

Smith (2008) describes indigenous governance systems in Northern Australia as decentralised, based on laws, kinship and marriage systems, behavioural and gender norms, family values, religious beliefs and moral system, principles of land ownership (GS4), ceremony and ritual. Bininj governance can be understood as a 'nodal network' where its members (nodes) are essentially autonomous units that are interconnected and interdependent (GS3). This 'governance network' emphasises the interconnected distribution and exercise of a group's decision-making and shared leadership to achieve collective goals. There are particular decision-making nodes in the network represented by male and female leaders. These leaders have respect and influence within their communities and are able to mobilise people and resources to create order and collectively get things done. Leadership is therefore shared through the nodes, and constitute the circuitry of governing order and authority that enables things to be achieved over time (G6). Central to the Bininj governance system is the set of institutions, or rules, which enable nodal leaders to legitimately activate social networks (GS3) (Smith, 2008). Such networks are also at the core of the process of knowledge production and in KNP there is not one indigenous group throughout the Park (Palmer, 2004b).

Palmer (2004b) asserts that "in Bininj negotiations, attention is typically paid to the landowners' primary rights to speak for country and resources, while at the same time respectfully recognizing the perspective of others (GS5). In this way, the negotiation practices between land-owning groups involve attention both to the legitimacy of individuals representing groups of others, and 'an acceptance of the rights of participants to speak for their own territories" (GS8).

The non-indigenous hierarchical system created to manage KNP is supported by two constitutional rules (GS7), these are:

a) The Land Rights Act provides for the granting of land to Aboriginal Land Trusts for the benefit of the traditional Aboriginal owners and requires land granted in the Alligator Rivers Region to be leased to the Director of National Parks (Director of National Parks, 2007:7).

b) The Commonwealth Environmental Protection and Biodiversity Conservation Act 1999 (EPBC 1999). The act provides for the Park to be managed by the Director in conjunction with the Bininj through a Board of Management that has a majority of members who are nominated by Bininj (the joint management arrangement). The EPBC act gives the director the function of administering, managing, controlling, and protecting biodiversity and heritage in the Park, including power to determine park entry and use charges to control certain activities, veto and to issue permits. The director must carry out these functions and use these powers in accordance with the KNP Management Plan. Under the Park leases the Director is required to consult with Northern Land Council (NLC) about general park management issues and also in preparation of the management plans. The Park is therefore not public land but privately owned by Bininj (GS4) even though the perception of some Park users is that KNP is public land (Palmer, 2004a). This misconception causes conflicts between Bininj and Park users (I4) due to different ideas on how the Park should be managed, which is heavily influenced by differences in perception, world views and values (for details refer to Palmer, 2004a).

The Board of Management (BoM) has Indigenous majority, which allows for strong representation of Bininj in the decision-making process. The Board has the function of preparing the Management Plan with the Director, who will comply with the decisions of the Board that give effect to the plan. Parks Australia staff assists the Director and manages daily operations of the Park in consultation with Bininj. The BoM meets every three months and generally makes high-level policy and strategic decisions about Park management. Park staff makes day-to-day management decisions and exercise powers on behalf of the director in accordance with the management plan, Board decisions and the EPBC act and other legislation.

The Board established Advisory Committees (e.g. Kakadu Tourism Consultative Committee (KTCC) and the Kakadu Research Advisory Committee (KRAC)) to help them make informed decisions. The KTCC provides the Board with advice on tourism issues and the views of tourism stakeholders in a structured way. The KRAC provides advice to the Board on research issues and priorities for the Park.

One consequence of the Bininj governance structure is that due to customary decision-making structures (i.e. collective-choice rules; GS6) Bininj members of the BoM (GS5) are reluctant to make decisions that directly affect the rights and obligations of other Bininj on their country (Field et al., 2006). The model of stakeholder negotiation within the hierarchical governance structure of KNP "aims to balance competing interests". The ontological differences in value-systems between Bininj and non-indigenous managers makes the negotiation process between them sometimes difficult; from a Bininj standpoint power is unequal because (under their value system) it does not follow customary laws, but from a non-indigenous perspective power is equal because interests were balanced by allowing parties to argue pro or against decisions (Palmer, 2004b). Palmer stresses that third-party interest groups, such as the tourism and fishing industries, which are outside the Park's formal joint management arrangements, assert their own ideologies and environmental management visions for the Park and complicate the joint management situation by demanding even further compromises by Bininj.

Climate change is expected to pose a major threat to Yellow Water socio-ecological system (ECO1) via saltwater intrusion, and changes in fire and rainfall regimes (BMT WBM, 2011:60; CSIRO, 2012, 2013; Hyder Consulting Pty Ltd, 2008; Petty et al., 2005:44). These factors will alter the dynamics between native and invasive species which will create challenges but also opportunities for aboriginal communities that depend on Yellow Water resources.

3.1.1 GOVERNANCE ATTRIBUTES THAT SUPPORT ADAPTIVE CAPACITY

The literature suggests that some key attributes of governance may give communities an improved capacity to adapt in the face of climate change. Such key governance attributes, identified in the literature (Dutra et al., 2015) are depicted in Table 5, and are used to discuss opportunities and limitations for climate adaptation in KNP.

Table 5. Key governance attributes that can stimulate adaptive capacity (from Dutra et al., accepted).

Attributes	Components	Meaning
Leadership	Communication and collaboration Trust Transparency in management processes	When leaders are trusted, perceived as legitimate and carry on transparent negotiation and management processes they can make significant contributions toward more-effective governance of coastal resources and therefore build adaptive capacity (Herrfahrdt-Pahle and Pahl-Wostl, 2012).
Cross-sectoral cooperation and coordination	Definition of roles and responsibilities Flexibility Autonomy and redundancy in authority and capability	The institutional framework should clearly define responsibilities and management jurisdictions to facilitate adaptive capacity. Legislation, policies and actions should be clear, flexible and focus on both coastal and fisheries management issues (Espinosa-Romero et al., 2011; Jones, 2013; McCarthy et al., 2011; Sporne and Dale, 2009). As knowledge about socio-ecological systems increases with learning, the institutional setting should be flexible enough to allow for modifications in governance and management procedures when required.
Effective integration of knowledge and insights	Planning framework Sense of resource ownership	This relates to the effective integration of local, traditional and 'modern' scientific knowledge in management decisions and refers to the perceived value of interested parties in sharing information (Costanza et al., 1991; Folke et al., 1998; Folke et al., 2005; Jones, 2013; Leith et al., 2012; Roberts and Jones, 2013)
Learning approach to natural resource management and governance	Adaptive management	This relates to ensuring that interested parties learn from each other, from management actions and processes. Also ensure that there are regular reviews of governance and management procedures and policies are treated as experiments and are adjusted as required (Folke et al., 2005; Muro and Jeffrey, 2008).
Human capacity and coordinated participation in decision-making	Funding Organizational knowledge Bridging organizations	This requires that human and financial resources are in place to effectively manage natural resources.

3.2 Management objectives and options elicited from stakeholders

The results of SLR model simulations indicate that substantial saltwater inundation of freshwater habitats would happen with a SLR of 0.7m (predicted for 2070). Maps including outputs of SLR inundation scenarios and key layers of Present day wetlands (example for 2 scenarios depicted in Figure 6) and fishing, hunting and gathering sites with basic inundation statistics (Table 6) were presented to participants. This component of the project drew on the work of Sue Jackson's team, which mapped hunting and fishing sites. For a discussion of methods employed in gathering this information see Adams et al. in prep. The maps represent maximum inundation during a spring high tide in the dry season (December 2013, see Saunders et al., 2014 for details). All scenarios presented during the workshops represent maximum inundation, i.e. spring high tide plus SLR. The proportion of floodplains and hunting, fishing and gathering places inundated by saltwater for four scenarios is presented in Table 6.

Sea level rise will also affect bush tucker (BT; animals and plants used by Bininj); SLR effects are expected to be widespread for most bush tucker species analysed, especially from 2070 (Table 7). For example, magpie geese habitat (nesting sites (wet season) and feeding sites (dry season)) is expected to decrease park-wide due to SLR (details in Part I of the report). Magpie geese are a major BT item. Lilies are also an important BT item and are expected to be similarly affected by SLR in the future (Table 7). The important point is that with SLR whatever happens park-wide will also affect the availability of magpie geese as a BT item at specific locations in the Park (such as Yellow Water used as our case study – section 3.4), especially in the dry season as these sites include Yellow Water and wetlands just north of it.

Interestingly, turtle species and black bream do not show much impact because they are not confined to floodplains and consequently the percentage of their habitat lost due to saltwater intrusion associated with SLR is much lower when compared with magpie geese and lilies (Table 7).

Table 6. Proportion of current floodplain areas, and hunting, fishing and gathering areas inundated by saltwater in Present and future sea level rise scenarios.

		Floodplains		Hunting, fishing and gathering places	
Scenarios	**SLR (m)**	**Whole Park**	**Yellow Water**	**Whole Park**	**Yellow Water**
Present	0	31%	0.3%	9%	0%
2030	0.14	35%	0.8%	11%	0.2%
2070	0.7	60%	23%	35%	41%
2100	1.1	78%	42%	59%	59%

Table 7. Percentage of habitat loss to saltwater intrusion in future sea level rise scenarios: 2070 (0.7m SLR) and 2100 (1.1m SLR) (details provided in Part I of the report).

Key Ecological Attribute	2070	2100
Magpie Goose dry season Hotspots	57%	90%
Magpie Geese wet season Nest Hotspots	76%	97%
Red, Blue and White/Yellow Lilies	65%	89%
Long-necked Turtle	10%	13%
Pig-nose Turtle	0.3%	1.7%
Black Bream	2%	4%

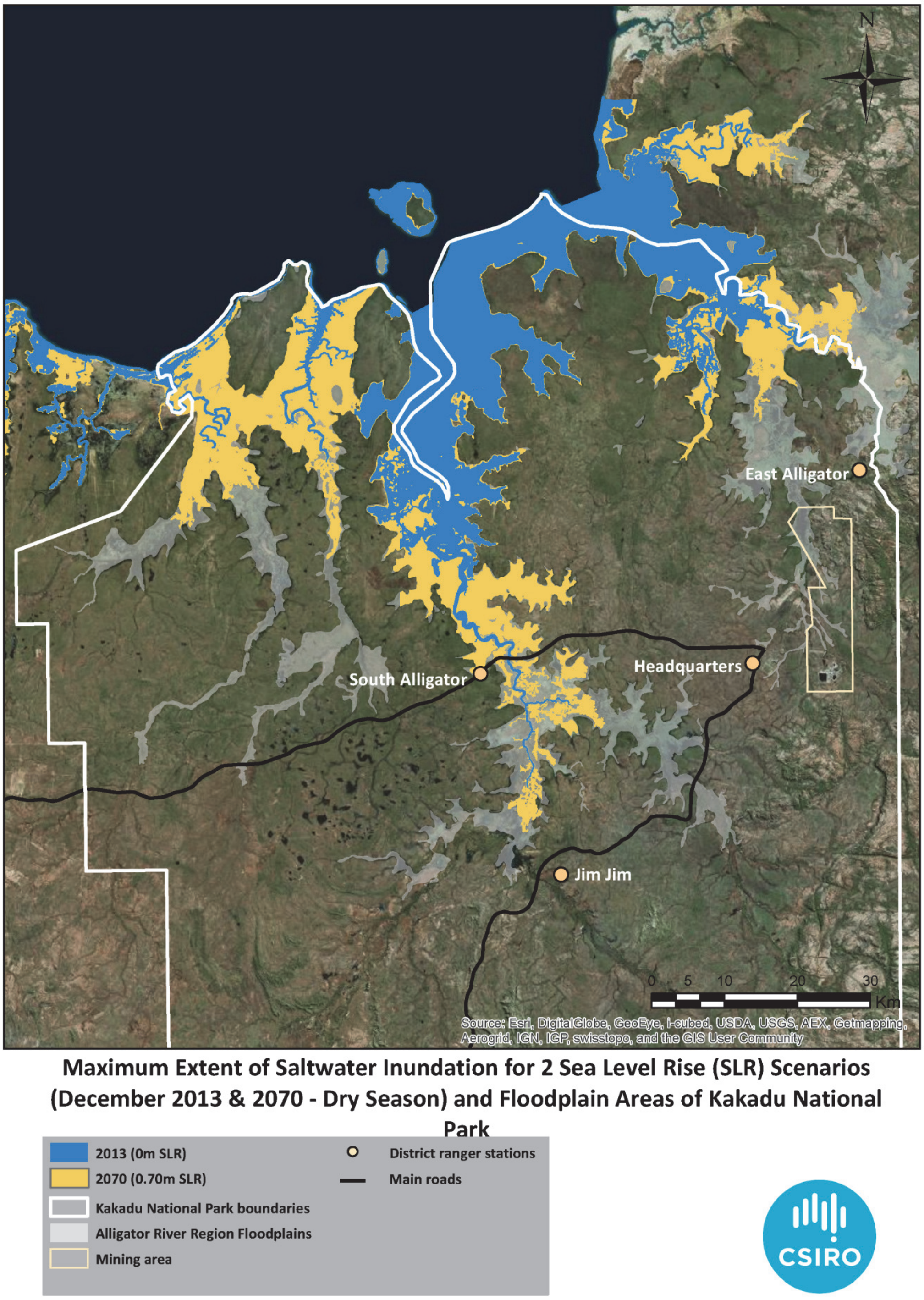

Figure 6. Example of inundation map presented during workshops: Two sea level rise scenarios (Present day and 2070) and floodplains in Kakadu National Park.

3.2.1 MANAGEMENT ACTIONS IDENTIFIED DURING WORKSHOP

After the presentation of sea level rise issues in the Park and maps, participants of workshop were divided into group to discuss possible management actions to manage saltwater inundation. The summary of actions are presented in Table 8, which shows that participants perceived that the issues associated with saltwater inundation due to sea level rise are expected to affect biodiversity and cultural values, and also tourism infrastructure. Most of the actions identified by participants (six out of nine) were related to adaptation and focused on learning to adapt. Monitoring and models appeared in four of the actions, thus emphasising the importance of them to facilitate learning and adaptation. Three actions (out of nine) were hard engineering solutions (move infrastructure and build levee banks), but it was suggested that levee banks should be designed to allow freshwater flow during the wet season and retain saltwater associated with sea level rise.

It was out of the scope of the research to design levee banks and test specific locations of levees. However, with collaboration from an engineer from Melbourne Water (Mr. Keith Boniface) a preliminary desktop assessment of levee design was prepared and handed-over to Parks Australia for consideration in future studies (Appendix C). An alternative to hard engineering solutions that was also suggested by participants was a more soft approach that builds up the land naturally to facilitate mangrove growth (GIZ, 2012; Naohiro et al., 2012; Schmitt et al., 2013). Such soft barrier would also provide opportunity for people to go to country and learn (by doing and experiencing) about potential effects of saltwater inundation in plants and animals. At the same time it could use local knowledge and science outputs to locate areas, thus providing more local job opportunities via activities related to country. It would also be valuable to consider the history of past experimental levee construction efforts and the learning arising from these (Ligtermoet and Jackson in prep.).

An introductory desktop review of barriers (hard and soft) was presented during a formal workshop in July 2014 contrasting designs, effectiveness, pros and cons, and rough cost estimates provided in the literature and with input from Bininj (Table 9). It was noted during the workshop that a thorough assessment of levee bank technology and costs is needed, along with detailed modelling to understand possible unintended consequences of levees on the floodplains prior to any action to be taken. In our modelling exercise the assumption is that the levees would function as they were designed for.

Table 8. Possible issues related to saltwater inundation due to sea level rise in Yellow Water.

What is the issue	Actions to manage impacts of saltwater inundation	Type of action
Floodplain biodiversity - Magpie geese (nesting and feeding) - Water fowl (ducks) - Freshwater fish - Loss of freshwater habitat due to saltwater inundation with impact on native freshwater plants and animals - Loss of hunting sites	Levee bank that mimics current water flow regimes – keeps saltwater out but let freshwater flow to avoid freshwater inundating other areas – Need for study on technology and effectiveness of levees	Mitigation / Information
	Salt water could kill Salvinia	Adaptation
	Reduce impact of feral animals and weeds (maybe with saltwater) to reduce other stress on country especially buffalo. Focus should be on priority areas based on less inundation and more bush tucker	Indirect / Adaptation
	Model where new / increased freshwater areas might be to inform planning for future (also for all infrastructure)	Information
	Monitor population of hunted species	Information
	Select refuge areas and focus management on	Information

What is the issue	Actions to manage impacts of saltwater inundation	Type of action
	these areas.	
	Tag birds and monitor their movements in response to saltwater impacts	Information
Tourism (especially important) - Inundation of boat ramp by saltwater - Inundation of Warradjan cultural centre	Boat ramp reassessed and moved to Home Billabong	Mitigation
	Relocate infrastructure to higher ground	Mitigation

As requested by Bininj during workshops, and as suggested by senior park management staff, follow through research is required to help design cost-effective monitoring programs for future SLR/saltwater inundation impacts in order to increase their adaptive resilience. Bininj argue that this should take the form of a "Caring for Country" type program that is lead by indigenous people but managed jointly with parks, and that associated capability training programs for Park staff and Bininj are required. Interviews conducted by S. Jackson and E. Ligtermoet revealed a thirty year history of levee building in KNP (Ligtermoet and Jackson in prep). This history should be drawn on to inform any future responses to saltwater intrusion.

Table 9. Contrasting hard and soft barriers to manage saltwater intrusion in Floodplains.

Hard Barrier	Soft Barrier
Built with concrete and/or earth and large pipes	Build the land up naturally and allows mangroves to grow
Effective at stopping saltwater	They can be built with fallen trees, timber poles, bamboo matting and fish nets
They can protect high value land and property during times of flood	May provide opportunity for people to go to country
They block the river and floodplain	Soft barriers and healthy mangroves could protect some parts of the floodplains
Possible to build a special ramp to help fish move past	Soft barriers are not as strong as hard barriers
Very expensive to build (estimated around A$ 0.7M-1.8M per km) and maintain, and not suitable to protect all areas	They still cost a lot to build (estimated around A$30k-100K per km for labour costs only and could use local materials) and maintain, but they are much cheaper than hard barriers
Requires specific studies and modeling to get design right	Soft barrier may create more natural and adapted environments
	They do not work as quickly as hard barriers and saltwater might still come past the barrier
	This could provide time for people to learn how to build them in Kakadu and to create more diverse ecosystems

3.3 Considering available information

3.3.1 PRESENTATIONS AND PARTICIPATORY WORKSHOPS

The series of meetings and workshops run by the project team leading up to the formal workshop to elicit management actions (5 below) is depicted below:

1. April 2012 (23-31). Consultations with parks staff and some Bininj on SLR models, in preparation for first large planning workshop in August.
2. August 2012 (27-31): Project 3.2 workshops: Separate parks and Bininj workshops. Wetlands, weeds and sea level rise.
3. February 2013 (1-6). Consultation with parks staff and some Bininj, provide updates on SLR modelling.
4. October 2013 (21-23): Feedback on SLR model outputs and seek advice from Bininj on how to run the December workshop 2013.
5. December 2013 (1-7): Workshop - responding to weeds and sea level rise on Kakadu floodplains. Separate workshops for parks staff and Bininj: management objectives, indicators and potential actions.
6. July 2014 (21-25 July): Workshop - responding to sea level rise on Kakadu floodplains. Separate workshops for parks staff and Bininj.
7. November 2014 (24-29): Final project consultations for presentation of products and feedback on products and approach used in the project. Discussion on monitoring. No workshops as such. The research team met with Bininj and gave half-day presentation to parks staff.

During consultations in February 2013 stakeholders requested model outputs to be presented using Google Earth so that stakeholders could use the zoom in and zoom out capability to focus on particular areas of the Park. The following GIS layers requested by participants in previous workshops were gradually added to the Google Earth Kakadu project presented in the workshops run in December 2013, July 2014, and November 2014, using the Google Earth Tool:

- KNP borders: Park boundaries and Alligator River Region (from KNP)
- Infrastructure: roads, tracks, tourism sites, district ranger stations, air strip and outstations (from KNP).
- Floodplains (Renée Bartolo, ERISS) and wet season flooding (Ward and Petty, 2014).
- Hunting, fishing and gathering sites (Jackson et al.).
- Mangroves and saline features (Doug Ward, Griffith University)[1]
- Vegetation (*Eleocharis*, *Oryza spp* (Wild Rice), *Nelumbo* and *Hymenachne* for a 250m grid (see Part I)
- Pig nosed and long-necked turtles (Mark Kennard, Griffith University)
- Black bream (fish) (Mark Kennard, Griffith University)
- Magpie geese (see Part I).

[1] This dataset is an extract of the Australia - Northern Territory Coastal Wetlands, clipped to the boundaries of the TRIAP project area. The TRIAP (Tropical Rivers Inventory and Assessment Program) is a collaborative program between the partners of the of the NCTWR, funded by Land and Water Australia and the Natural Heritage Trust.. A coastal wetland community classification produced as the first phase of the FRDC funded project, Methods for monitoring the abundance and habitat of the Northern Australian mud crab, Scylla serrata. The Landsat TM/ETM+ derived classification includes mangroves and saltmarsh communities.

Following from suggestions from stakeholders the project team presented SLR model outputs and spatial layer of interest using two methods:

- Hard copies of maps with outputs from hydrodynamic modeling on selected spatial layers
- Goggle Earth project containing SLR model outputs and selected spatial layers, including practical approach to use the tool.

3.3.2 EVALUATION OF PARTICIPATORY WORKSHOPS

We evaluated the workshops December 2013 (Bininj and Parks) and July 2014 (Park staff only due to no attendance of Bininj in the workshop) workshops using a standard evaluation form to assess expectations, needs, and get overall feedback about workshops from stakeholders. A total of 14 evaluation surveys (6 from Bininj workshop and 8 from Parks workshop) were completed for the December 2013 Workshop and 4 evaluation surveys were completed for the July 2014 workshop. The questions included in the form and responses from workshop participants are presented below.

Table 10. Summary of workshop evaluations.

	Workshop December 2013								Workshop July 2014			
	Bininj (%)				**Parks (%)**				**Parks (%)**			
Question	Y	N	N/A	Comments	Y	N	N/A	Comments	Y	N	N/A	Comments
1) Was the information provided during the workshop useful and well presented?	83	0	17		100	0	0		100	0	0	
2) Was there anything you expected to be covered in the workshop that was not presented?	33	67	0	More community participation Information about future rainfall predictions Information about saltwater fish that could live in the areas predicted to be inundated by saltwater	25	75	0	More infrastructure maps Maps showing areas that will be permanently inundated	50	50	0	More information on how saltwater could affect vegetation and in turn important bush tucker animals/plants More cultural sites/historic sites layers
3) What worked well and what did not work so well?	**Worked Well** Communication with others Workshop worked well for a day's workshop Everything was good **Did not work well** Venue was noisy Communication with others				**Worked Well** Google Earth is very user friendly Map exercise worked Google Earth was good to visualise layers and learn about what the future holds Maps showing changes **Did not work well** Need to fix Island colours in Google Earth Laptop/GIS layer issues and screen very dark							
4) What would you do differently?	More attendance Go somewhere where more people could come together Having breaks outside the area				Change colours to identify e.g. bush tucker now and in 10 years time Need to be able to look at overall impact inundation not just tides and then overlay significant areas (e.g. cultural areas)				Don't organise workshop on a pay week or when there is a long weekend			
5) Do you have further comments to make?	More surveys on river and wetland areas Would like to know more about saltwater impacts inland				Exercise was useful Very useful exercise to go away with Useful information to better understand SLR in future Still not quite clear how to use this as a management tool to help decide what actions to take, where and how to evaluate what you did				Fly-overs were great It would be more meaningful if areas affected by saltwater could be more obvious			

3.4 Avenues for choice under uncertainty

3.4.1 MODEL 1: YELLOW WATER SOCIAL-ECOLOGICAL SYSTEM

The semi-quantitative assessment of management options is illustrative for the qualitative modelling/BBN approach we applied and the main lessons from the application of the approach and modelling outputs are used in the discussion. The project team will refine the models in future publications.

Model Structure

The Yellow Water Social-Ecological System (YW SES) model (Figure 7) depicts the basic relationships between social, ecological and economic drivers of the floodplain, as well as the management process as described in the diagnostic framework. The key ecological, social and economic values depicted in the model are *Freshwater Floodplains* (FWFP), which includes the habitat and native animals and plants, *Aboriginal Culture* (Cult, i.e. ideas, customs and social behaviour), and *Local Income* (LocInc). *Saltwater Intrusion* (SWI) and *Fire* (Fire) are the physical processes affecting these values. Rainfall and seasonality are implicit in the model via a self-negative effect depicted in FWFP. Biological drivers of the system are *Invasive Species* (InvSp), such as aquatic weeds predicted to increase with climate change (e.g. *paragrass)* and feral animals (e.g. pigs). Bininj utilise and manage FWFP via activities related to looking after country, such as fire management to control weeds and native grasses (*Hymenachne*), which also depend on the ability they have to access these sites. Saltwater inundation associated with predicted SLR is expected to reduce the abundance of *Bush Tucker* and their perceived abundance is also influcenced by their ability to access these resources. BT benefits Bininj both culturally and economically. *Aboriginal culture* and *Freshwater Floodplains* are the main *Tourism* (Tour) attractors in Yellow Water. The issues related to *Differences in Perception* (DifPerc) between indigenous and non-indigenous value systems are depicted through the positive effects between Cult and DiffPer. These differences in perception, along with Cult are currently perceived by Parks to be positively influencing floodplain management (FPMgt) via the joint management arrangement.

Climate Change

Climate change is depicted in the model as a press perturbation (Figure 8) and is expected to cause a sustained increase saltwater intrusion (Figure 8) and invasive species and decrease in tourism numbers due to higher mean temperatures (refer to The Yellow Water SES (diagnostic framework and Appendix D for details). Saltwater intrusion is also expected to reduce abundance of Bush Tucker (Figure 8).

Analysis

The Yellow Water Social-Ecological System (YW SES) model under climate change is unstable (wFn = 0.71), which means that the reliability of model predictions is low. The key dynamic influencing how the system responds are the short positive feedbacks between *Freshwater Floodplains*, *Floodplain management, Bush Tuckers*, *Tourism*, and *Culture*. This structure emerged from the diagnostic framework analysis, which shows the dependency of Bininj and tourists on freshwater floodplain resources (both socio-cultural and biological).

The positive feedback loop cannot only lead to a continual increase in freshwater floodplain resources, culture, tourism and local income, but it can lead also to a continual decrease in the variables. For example, a reduction in *freshwater floodplain* leads to less freshwater species, less opportunities for Bininj to harvest *Bush Tucker* and do activities in country, and consequent reductions in *Culture*, the capacity of Bininj to manage resources, and in the number of *Tourists*.

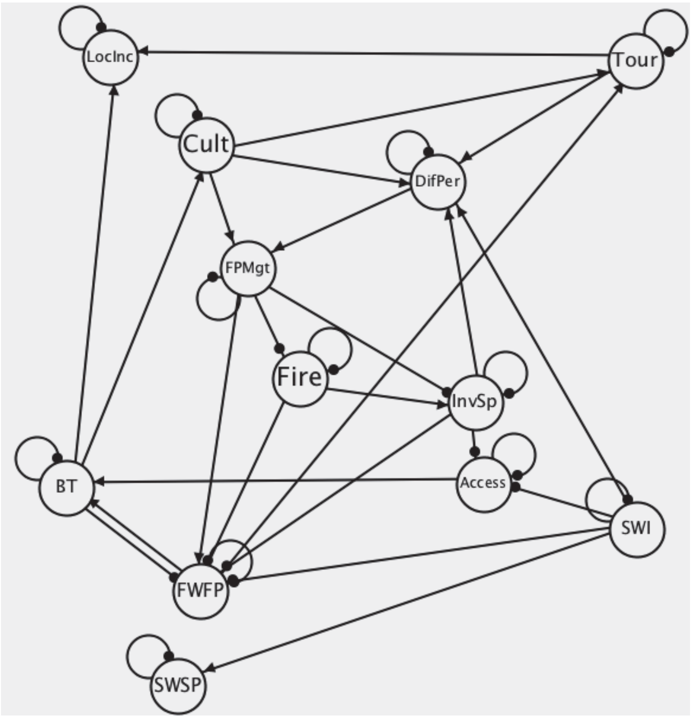

Figure 7. Model structure of Yellow Water SES.

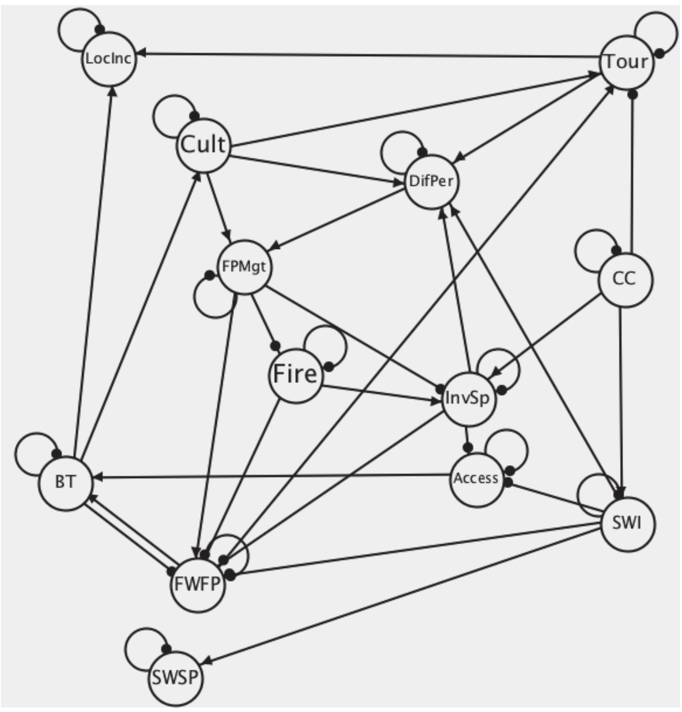

Figure 8. Model structure of Yellow Water SES with Press perturbation from climate change (CC).

Alternative Yellow Water SES

Adaptation options that increase the capacity of communities to cope with predicted changes due to climate change were identified in the diagnostic framework and workshops. The Yellow Water Alternative SES model (Figure 9) includes the following adaptation options: (i) a direct link between *local income and culture* (e.g. using income to fund activities related to look after country), (ii) a direct positive link between saltwater species and bush tucker, which reflect learning's that can be used to facilitate changes in species currently used by Bininj (e.g. from freshwater species to saltwater species), and finally (iii), a negative link between differences in perceptions into floodplain management. This reflects that rather than increasing *floodplain management*, *differences in perception*, which often leads to conflicts between KNP managers, can be used to counter-balance floodplain management by accommodating an approach that is more in line with Aboriginal values and governance systems.

Analysis

The alternative Yellow Water SES model is moderately stable (wFn=-0.21), which is more robust than the YW SES model, but still suggests that the Yellow Water system is subject to occasional shifts in stable states. For example, due to changes in long and short-term dynamics (e.g. extreme weather events, decadal rainfall regimes, wet/dry regimes).

Probabilities of sign determinacy for the variables of both YW SES and the YW Adaptation SES models under the predicted effects of climate change (Increase in saltwater intrusion and invasive species, and decrease in tourism) range from moderate to low likelihood of occurrence. However, the directions of change are quite different. For example, *Freshwater Floodplain*, *Invasive Species*, and *Bush Tucker*, and *Floodplain Management* are predicted to decrease in YW SES (Pr = 0.54, 0.47, 0.52, 0.52, and 0.63, respectively) and to increase in the YW Adaptation SES (Pr = 0.47, 0.40, 0.41, 0.53, respectively). *Tourism*, *Unmanaged fires*, and *Bush Tucker* are expected to increase in the YW SES model (Pr = 0.46, 0.63, 0.46, respectively) and to decrease in the YW SES Adaptation model (Pr = 0.51, 0.53, and 0.41, respectively). *Local Income* had the same probability (Pr = 0.42) to either increase or decrease in the YW SES, and is predicted to decrease (Pr = 0.45) in the YW Adaptation SES. Similarly, *Culture* has the same probability to either increase or decrease in the YW SES Adaptation model (Pr = 0.39) and is predicted to decrease in the YW SES (Pr =0. 52). *Saltwater intrusion* and *saltwater species* are predicted to remain unchanged in both models (Pr = 0.37 for both variables in YW SES, and Pr = 0.42 for both variables in the YW Adaptation model).

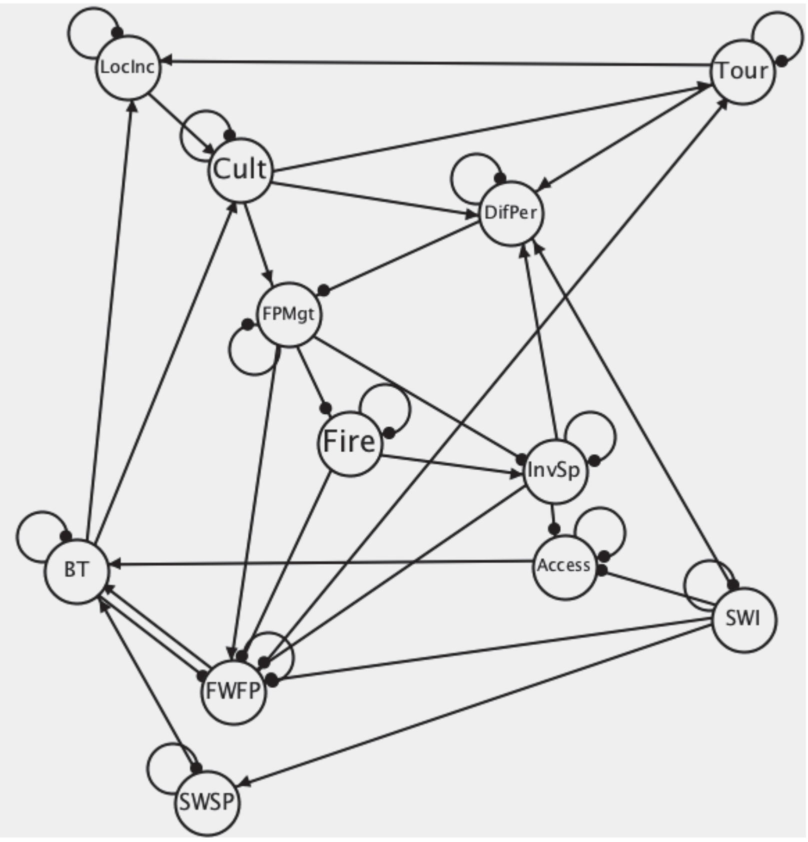

Figure 9. Model structure of alternative model for Yellow Water SES.

3.5 Management Strategies

Given that the YW Adaptation SES has a markedly higher stability (wFn = -0.21) when compared with the unstable YW SES model (wFn = 0.71), the trial of management actions was performed using the YW Adaptation SES model. In terms of achieving the high level objectives depicted in Figure 3, the following directions of change are expected in model variables:

Freshwater floodplain: no change / increase

Invasive Species: decrease

Indigenous Culture: increase

Bush Tucker: no change

Local Income and businesses: increase

Tourism: no change/increase

Differences in Perception: increase

Unmanaged Fires: decrease

Saltwater Intrusion: no change / decrease

Saltwater Species: no change

Bush Tucker: no change / increase

We compared 4 contrasting scenarios (Table 4) and results for each management scenario are presented in Table 11. A summary about the performance of each variable under the four management scenarios is presented as follows.

3.5.1 FRESHWATER FLOODPLAIN

All scenarios produce an increase in *FWFP* with low likelihood of predictions. Management Scenario 2 provides the highest probability of sign determinacy (Pr = 0.52) and Management Scenario 3 the lowest (Pr = 0.47).

3.5.2 INVASIVE SPECIES

All scenarios produce an increase in *InvSp* with low likelihood of predictions. Again, Management Scenario 2 provides the highest probability of sign determinacy (Pr = 0.50) and Management Scenario 3 the lowest (Pr = 0.40).

3.5.3 INDIGENOUS CULTURE

All scenarios, but Management Scenario 1, produce an increase in *Cult*, where Management Scenario 2 has a low likelihood of prediction (Pr = 0.49), and Management Scenarios 2 and 3 have a moderate likelihood of prediction (Pr = 0.64 and 0.72, respectively). The predictions for Management Scenario 1 have the same probability of occurrence for increase and decrease in the variable (Pr = 0.39).

3.5.4 BUSH TUCKER

All scenarios produce an increase in *BT* with low likelihood of predictions. Management Scenario 3 provides the highest probability of sign determinacy (Pr = 0.44) and Management Scenario 4 the lowest (Pr = 0.40).

3.5.5 LOCAL INCOME AND BUSINESSES

All scenarios, but Management Scenario 1, show an increase in *LocInc.* Management Scenarios 2 and 3 have low likelihood of predictions (Pr = 0.45 and 0.53, respectively). Management Scenario 4 provides the highest probability of sign determinacy (moderate likelihood, Pr = 0.65). Management Scenario 1 shows a decrease in *LocInc* (Pr = 0.45).

3.5.6 TOURISM

Without further interventions (scenario 1) in the YW Adaptation SES, Tourism is expected to decrease (low probability) under climate change (Pr = 0.51), whereas Management Scenarios 2-4 show an increase in tourism with low likelihood of occurrence (MS2 and MS3, Pr = 0.42 and 0.47, respectively) and moderate likelihood of occurrence (MS4, Pr=0.63).

3.5.7 DIFFERENCES IN PERCEPTION

All scenarios, but Management Scenario 1, show an increase in *DiffPerc.* Management Scenario 2 has a low likelihood of prediction (Pr = 0.45). Management Scenarios 3 and 4 provide moderate and high likelihood of sign determinacy (Pr = 0.70 and 0.80, respectively). Management Scenario 1 shows a decrease in *DiffPerc* (Pr = 0.49). We assume that increase in *differences in perception* means a more equal inclusion of indigenous and non-indigenous values in the joint management arrangement.

3.5.8 UNMANAGED FIRES

All scenarios produce a decrease in *Fire* with low likelihood of predictions. Management Scenario 1 provides the highest probability of sign determinacy (Pr = 0.53) and Management Scenario 4 the lowest (Pr = 0.42).

3.5.9 SALTWATER INTRUSION

In the Management Scenarios with no 'barrier' (MS1 and MS3) the predictions are for no change in Saltwater Intrusion with low likelihood of occurrence (Pr=0.42 for both scenarios). Management scenarios 2 and 4 show a decrease in *SWI* through barriers with moderate likelihood of occurrence (Pr=0.69 for both MS).

3.5.10 SALTWATER SPECIES

Predictions for *SWSP* are similar to those for *SWI* given the direct link between these two variables. The predictions are for no change in *SWSP* with low likelihood of occurrence for MS1 and MS3 (Pr=0.42 for both scenarios). MS2 and MS4 show a decrease in *SWSP* with moderate likelihood of occurrence (Pr=0.69 for both MS).

3.5.11 BUSH TUCKER

Again, under climate change current abundance of *BT* is strongly related to *SWI*, hence model results suggest a decrease in *BT* in MS1 and MS3 (Pr=0.41 and 0.40, respectively), and an increase in *BT* in MS2 and MS4 (Pr=0.45 for both) through the use of barriers to protect freshwater species from *SWI.*

Table 11. Results of management scenarios in the Yellow Water Social Ecological System Adaptation model: Green high likelihood (Pr>0.8), Yellow moderate likelihood (0.6 > Pr < 0.8), Red low Likelihood (Pr < 0.6).

No	Variable Name	Management Scenario 1			Management Scenario 2			Management Scenario 3			Management Scenario 4		
		+	0	-	+	0	-	+	0	-	+	0	-
1	Freshwater Floodplain (FWFP)	0.47	0.27	0.26	0.52	0.24	0.24	0.47	0.27	0.27	0.51	0.24	0.24
2	Invasive Animals (ferals) and Plants (weeds) (InvSp)	0.40	0.27	0.33	0.50	0.25	0.25	0.40	0.27	0.33	0.50	0.25	0.25
3	Indigenous culture (Cult)	0.39	0.22	0.39	0.49	0.22	29.2	0.64	0.18 1	0.18	0.72	0.14	0.14
4	Hunting, fishing, and gathering (HunFish)	0.44	0.27	0.29	0.39	0.28	32.6	0.44	0.28	0.29	0.39	0.29	0.32

5	Local income and businesses (LocInc)	0.34	0.21	0.45	0.45	0.23	32.1	0.53	0.22	0.25	0.66	0.17	0.17
6	Tourism (Tour)	0.29	0.21	0.51	0.42	0.24	34.1	0.47	0.24	0.29	0.63	0.19	0.19
7	Differences in perception (DiffPerc)	0.36	0.16	0.49	0.45	0.18	36.9	0.70	0.15	0.15	0.80	0.10	0.10
8	Floodplain management (FPMgt)	0.53	0.24	0.24	0.42	0.29	0.29	0.53	0.24	0.23	0.42	0.29	0.29
9	"hot" unmanaged fires (Fire)	0.24	0.24	0.52	0.29	0.29	0.42	0.24	0.24	0.53	0.29	0.29	0.42
10	Saltwater intrusion (SWI)	0.29	0.42	0.29	0.15	0.15	0.69	0.29	0.42	0.29	0.15	0.15	0.7
11	Saltwater species (SWSP)	0.29	0.42	0.29	0.15	0.15	0.69	0.29	0.42	0.29	0.15	0.15	0.70
12	Bush Tucker (BT)	0.33	0.26	0.41	0.44	0.28	0.28	0.33	0.26	0.40	0.45	0.27	0.27

4 Discussion

4.1 Diagnostic framework

The long history of Aboriginal use and management of floodplain resources depicted in the diagnostic framework shows that such habitats are dynamic and that plants and animals have responded to sea level fluctuations differently in the last 10,000 years. Aboriginal communities in Northern Australia have adapted to such biophysical changes by increasing resilience through learning how species responded to changes, modifying resource use (e.g. from saltwater species to freshwater species and vice-versa), and looking for resources elsewhere. Given the history of aboriginal culture and governance, adaptation in Northern Australia is likely if effective mechanisms to support learning about changes in floodplains dynamics are in place. The time frame of inundation (mild saltwater inundation of floodplains by 2030 and more widespread inundation by 2070) will probably give time for people to adapt but it is important that this adaptation process start now. In the light of the diagnostic framework and governance attributes that support adaptive capacity, the climate change threat can provide the following opportunities for adaptation in Kakadu.

4.1.1 LEADERSHIP

Bringing together the Aboriginal nodal governance structure with the hierarchical governance of Parks through the joint management arrangement is sometimes challenging. High level decisions come from the Board of Management but decisions in specific areas such as Yellow Water and their implementation depend on local shared leadership, which brings the benefit of stronger commitments between land owners of different parts of the floodplain, but is also more prone to conflicts. Often Parks avoid conflicts (Woodward et al., 2010:24), but often conflicts are not necessarily negative if handled/facilitated in a constructive way. In shared leadership conflicts are acceptable and considered as an important and necessary ingredient. However, it is important that conflicts are dealt with in an environment of trust and collaboration so they can effectively encourage negotiation, creativity and innovation (Paulson et al., 2009). Opportunities exist in joint management to support aboriginal leaders to resolve conflict between themselves and with Parks when they do happen. Reinstating the paid Northern Land Council (NLC) position in the Park to facilitate the engagement process would help resolve conflicts that might arise in managing the Park. Such leaders can use more effectively the nodal structure of indigenous governance systems to better coordinate Bininj engagement and participation, and to identify priorities and information needed to adapt and/or take actions at the relevant scale. It is also valuable that Park leadership is available to discuss concerns from Bininj with regards to management of KNP, and be supportive of fostering indigenous leadership.

4.1.2 CROSS-SECTORAL COOPERATION AND COORDINATION

The combined indigenous and non-indigenous institutional framework set to manage Yellow Water (and KNP more broadly) clearly recognises Bininj as the rightful owners and managers of the Park (Director of National Parks, 2007). Aboriginal institutions have a longer history in managing floodplain resources but sometimes Bininj feel that indigenous institutions appear to be less favoured when dealing with overall Park management issues than the non-indigenous institutions (Palmer, 2004b). This is due to ontological differences in value-systems between Bininj and non-indigenous parties during negotiation and decision-making processes (Palmer, 2004b). These differences pose some challenges to climate adaptation, but history shows that these differences can be overcome. For example, there are successful stories in Yellow Water where the combination of aboriginal and non-aboriginal knowledge systems was used to generate useful information to manage fires and weeds in the floodplains (McGregor et al., 2010). This is certainly a positive outcome which shows the will of Bininj and non-indigenous researchers to share information and work together towards a common goal. Other challenges include the continuation of resources (economic and human) to maintain such initiatives.

4.1.3 EFFECTIVE INTEGRATION OF KNOWLEDGE AND INSIGHTS

Joint management offers the opportunity for knowledge sharing between Bininj and non-Bininj Park staff. Such integration is seen by stakeholders as complementary and not mutually exclusive (Woodward et al., 2010:42) and is most effective when Bininj staff work with non-indigenous rangers thus creating learning opportunities for both cultures and knowledge systems. However, there are issues related to effectively incorporating traditional knowledge and culture in Park management activities, which has and can lead to tensions such as in the case of feral animal management and effective integration of indigenous and non-indigenous knowledge (Robinson et al., 2005; Woodward et al., 2010). This certainly poses some challenges to climate adaptation. However, as shown in the workshops climate change may provide a point of convergence where both knowledge systems can be integrated to better prepare for existing and future changes in the floodplains associated with saltwater inundation due to sea level rise. For example through collaborative monitoring and learning of floodplain system dynamics.

4.1.4 LEARNING APPROACH TO NATURAL RESOURCES MANAGEMENT AND GOVERNANCE

Such an approach is important to more effectively navigate diverse contexts and reconcile multiple objectives (Fidelman et al., 2012). A critical and reflexive approach to NRM means that stakeholders learn from each other, from management actions and processes. This learning approach to management was an important outcome of the climate change workshop and should continue to be encouraged as identified in the actions identified by KNP managers to manage sea level rise. The legal framework of KNP ensures that there are regular reviews of governance and management procedures and also that policies are treated as experiments and may be changed when required. This constitutes an adaptive management framework, where values and management objectives are identified and agreed between stakeholders (via the Plan of management), and actions/policies can be trialled, monitored and communicated. The challenge is to operationalize adaptive management in the KNP context, i.e. institutionalise trialling policies, learn about their effects and adjust them when necessary. This was an important component that was discussed during the climate change workshops, where it was suggested that small-scale experiments with levees and use of saltwater to control weeds could be trialled. Such an operational adaptive management framework also requires the development of effective engagement protocols and deliberation processes to bring together Bininj and Parks toward the common perceived threat of sea level rise. Again, the NLC position at KNP should be re-instated as a way to support the engagement process and equitable discussions between Bininj and Park staff. The focus of these protocols should be on understanding and reconciling nodal and hierarchical governance systems and the relationships they have with social, cultural, economic and biophysical domains, which will influence their capacity to adapt.

4.1.5 HUMAN CAPACITY AND COORDINATED PARTICIPATION

Bininj are consulted about management actions and strategies that are taken in the Park. However, in some instances there seems to be little time for deliberation between Aboriginal leaders and between these leaders and Park staff and also on potential impacts of these actions on Bininj values (Palmer, 2004b; Woodward et al., 2010). Results from the climate change workshops demonstrated that the process for deliberation about decisions that impact directly on floodplain values should include more effective two-way communication of alternative actions and their potential impacts between Bininj and non-indigenous managers. Management processes in KNP should therefore be well communicated and open for discussions so that decisions are perceived by stakeholders as fair and equitable based on sound information and merit (Herrfahrdt-Pahle and Pahl-Wostl, 2012). Bridging organisations such as the NLC (part of KNP governance) operationalized through the NLC position at the Park (currently vacant) offer an equitable opportunity to bring together KNP managers and acknowledge their different knowledge systems and governance structures. Such organisation helps build or maintain reciprocity and trust. This enables knowledge coproduction, trust building, sense making, learning, vertical and horizontal collaboration, and conflict resolution (Berkes, 2009; Brondizio et al., 2009; Cash et al., 2002; Cash et al., 2006). These factors are relevant for a shared understanding about the issues affecting the Yellow Water SES and KNP more broadly and are thus important for climate adaptation. The NLC coordination position in KNP has been empty for a period of almost 1 year and the recent political decision to freeze recruitments in the Commonwealth public service poses further challenges for climate adaptation in KNP. The NLC constitutes an important component of a transparent framework to improve communication between co-managers in KNP. Such a transparent framework may also help identify whether or not the level of collaboration between Bininj and Park staff is adequate and how to make the engagement process between the two parties more effective.

4.2 Management Scenarios

Overall, the analysis of management actions in the YW Adaptation SES model indicate that increasing traditional *Floodplain Management* to control *Fire* and *invasive species* to enhance *freshwater floodplains* combined with a strategy to control saltwater intrusion (strategy 4) provide the most robust system outcomes with improved likelihood of sign determinacy when compared to scenarios 1-3. This shows that maintaining floodplains health via active inclusion of indigenous knowledge and adapting governance system to allow the incorporation of this knowledge is a key to adaptation.

The ways in which saltwater might be controlled involve physical interventions by the means of hard or soft barriers, which pose some risk in the context of limited system understanding and require social acceptability. Any use of barrier to control saltwater intrusion would be subject to further studies regarding the localised impacts of such barriers. During the workshop in July 2014, it was discussed that a hard barrier requires detailed hydrological studies, and discussions with land owners about implications of locating such large structure (approximately 3km wide, see Appendix C) to minimise (i) unintended consequences, such as the barrier reducing freshwater flow during the wet season, thus further inundating areas upstream, and (ii) conflicts over location and effects of barriers to landowners. The costs of such barrier in a remote area like Kakadu needs also to be carefully considered as investments should be around a few million dollars. Soft barriers have been constructed in Kakadu in the past (Ligtermoet and Jackson in prep.), mostly using earthen embankments. The idea about building up the land to favour mangroves to grow and getting Bininj involved from the beginning in the planning process was initially well received. There was a general agreement that setting up a monitoring program to identify and learn about possible changes caused by occasional saltwater inundation would be an ideal opportunity to get Bininj involved in management and adaptation via country activities and observations of change. Such monitoring program would be a key to assessing the need for physical intervention and in supporting any decisions to establish hard or soft barriers and to also assess if they are needed. Some Bininj mentioned that saltwater might be part of a natural floodplain dynamics over longer time frames (as it happened around 6,000 yrs ago) and that rather than disappear, floodplains will be substantially modified and Bininj can learn to use and manage the new resources that would be established. However, such capacity to adapt is strongly linked to indigenous governance and decision-making processes and their ability to access country and observe changes.

4.3 A reflection on the Kakadu management planning framework

The methodology we applied in Kakadu helped inform Bininj and Park staff about possible effects of sea level rise in floodplain biodiversity and cultural values. Because of our work locals are more aware about how sea level rise is expected to affect floodplain values and how this might impact in their daily activities. A key lesson for the researchers and stakeholders is that managing sea level rise effects should be put in the context of existing socio-ecological threats and challenges, including invasive species (weeds and feral animals), unmanaged fires and intergenerational knowledge transmission. Governance is also a fundamental aspect of adaptation to existing and future threats to Kakadu floodplains.

The feedback we received from workshop participants demonstrates that the approach we have developed is useful and practical as it helped stakeholders gain a better understanding about issues related to sea level rise and its potential impacts on Park values. However, attendance at the workshops varied and diminished towards the end of the project, especially attendance by Bininj. This was probably the result of two factors, namely poor advertisement of workshops to Bininj (especially the workshop held in July 2014) and over-consultation (i.e. consultation fatigue). In regards to future research in the Park, researchers should better coordinate consultation activities to avoid consultation fatigue. Also, we found that Bininj would benefit more through one to one or small group interactions with researchers rather than in collective and formal workshops/consultations. This less formal approach is probably more in tune with indigenous governance and is also recognised as an effective method to manage business organisation (Shaw, 2002). Such one-to-one or small group approach allows for greater flexibility in engaging with individuals: meeting on their terms (location and time); tailoring discussion to the interests of the individual and potentially creating a less-confrontational environment for discussion. While a one-on-one approach is more costly in terms of time and funding, it is also more likely to contribute to meaningful outcomes for Bininj.

5 Conclusion

Climate change may provide an opportunity to bring together indigenous and non-indigenous knowledge and governance systems to address a commonly perceived threat. New freshwater habitats for species displaced by saltwater inundation are likely to be created because saltwater might ‘push’ freshwater further upstream and these refuge areas provide an opportunity for adaptation via learning about changes. Mitigation works and adaptation strategies will be required to deal with sea level rise threats, but climate adaptation requires a learning approach – supported by monitoring programs – to manage and understand the consequences of saltwater inundation on floodplain values and also to measure their effectiveness. This learning approach is expected to create an environment of creativity and innovation that will provide further adaptive capacity to people in Kakadu to deal with the potential impacts associated with predicted sea level rise.

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Appendix A Literature Review for diagnostic framework

Social, economic, and political setting (S)			
S1 Economic development			
S2 Demographic trends			
S3 Political stability			
S4 Government resource policy			
S5 Market incentives			
S6 Media organisation			
Resource system (RS)	**Yellow Water floodplains located in a National Park**	**Governance system (GS)**	**Co-management**
RS1 Sector	Conservation	GS1 Government organisations	Parks Australia
RS2 Clarity of system boundaries	Boundaries and ownership of some land are still under negotiation	GS2 Nongovernment organisations	Northern Land Council
RS3 Size of resource system	Finite size (plant and animal populations within wetlands and floodplain boundaries) (McGregor et al., 2010)	GS3 Network structure	Indigenous governance are 'nodal network' where its members (nodes) are essentially autonomous units that are interconnected and interdependent (Smith, 2008)
RS4 Human-constructed facilities	**Parks infrastructure** - buildings (Director of National Parks, 2007:58) - roads) **Tourism infrastructure** – accommodation (Gagadju Lodge Cooinda) (BMT WBM, 2011:70; McGregor et al., 2010) **Roads and bridges** (Boustead, 2009:31; Director of National Parks, 2010; Hyder Consulting Pty Ltd, 2008) **Housing** (Director of National Parks, 2010; Hyder Consulting Pty Ltd, 2008)	GS4 Property rights system	Land is privately owned by Bininj and leased back to the Director of National Parks (Director of National Parks, 2007; Palmer, 2004)
RS5 Productivity of system	Renewable resources	GS5 Operational rules	Kinship and marriage systems, behavioural and gender norms, family values, religious beliefs and moral system, principles of land ownership, ceremony and ritual (Smith, 2008). In Bininj negotiations, attention is typically paid to

			the landowners' primary rights to speak for country and resources, while at the same time respectfully recognizing the perspective of others (Palmer, 2004). The Board of management meets every 3 months and generally makes high-level policy and strategic decisions about Park management. Park staff make day-to-day management decisions and exercise powers on behalf of the director in accordance with the management plan, Board decisions and the EPBC act and other legislation
RS6 Equilibrium properties		GS6 Collective-choice rules	
RS7 Predictability of system dynamics	Follow wet/dry cycle: Seasonal Inter-annual Inter-decadal	GS7 Constitutional rules	The Land Rights Act provides for the granting of land to Aboriginal Land Trusts for the benefit of the traditional Aboriginal owners and requires land granted in the Alligator Rivers Region to be leased to the Director of National Parks (Director of National Parks, 2007:7). The Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act) provides for the Park to be managed by the Director in conjunction with the Bininj through a Board of Management that has a majority of members who are nominated by Bininj. The EPBC Act requires the composition of the Board to be agreed between the Minister (who appoints Board members) and the Northern Land Council (Director of National Parks, 2007:7)
RS8 Storage characteristics		GS8 Monitoring and sanctioning processes	
RS9 Location			
Resource units (RU)	Plants and animals inhabiting floodplains (magpie geese, ducks, water lillies, yams, freshwater turtles, file snake, goana – among other species known as 'bush tucker') (Bayliss and Yeomans, 1990; Director of National Parks, 2007:77; McGregor et al., 2010)	**Users (U)**	Bininj Tourists(?)
RU1 Resource unit mobility	Mobile animals (fish waterbirds, turtles, pigs, buffaloes) that feed and	U1 Number of users	Small number of users (families)

	breed on floodplain vegetation and plants used by indigenous people (lillies, yams, etc) (Bayliss and Yeomans, 1990; Harris, 2012:74; McGregor et al., 2010; Palmer, 2004)	
RU2 Growth or replacement rate	Growth or replenishment rate of harvested species in Yellow Water depend on complex ecological processes related to rainfall and freshwater flow into the floodplains, occasional saltwater intrusion, fire regimes and management, abundance of grasses and invasive species (feral animals (e.g. buffaloes, pigs, horses) and weeds) (Bayliss and Yeomans, 1990; BMT WBM, 2011:12; Director of National Parks, 2007; Douglas and O'Connor, 2004; McGregor et al., 2010; Petty et al., 2005; Setterfield et al., in press; Skeat et al., 1996:161) Growth or replenishment rate of harvested species (e.g. magpie geese, barramandi, freshwater turtles and water lillies) depend on seasonal inundation of floodplains, as well as on the amount of saltwater that enters the floodplain. River shape tidal flow, vegetation cover or landform can facilitate the entry of salt water into freshwater areas, with flow on negative effects on vegetation and animals (Boustead, 2009:45-46; Director of National Parks, 2007:57). Fire is a major driver of plant and animal growth and abundance. It is a natural part of the floodplain landscape and a fundamental expression of Aboriginal knowledge of their local ecology and their connection to their environment. Indigenous people have used fire as a management tool to encourage the regrowth of desired grasses and clear access for thousands of years (Boustead, 2009:58-59; Director of National Parks, 2007:63-64; McGregor et al., 2010; Petty et al., 2007:5). Invasive species (weeds and feral animals) also affect growth and	U2 Socioeconomic attributes of users

	replenishment rates of important plants and animals. Weeds also alter the natural fire regime (Boustead, 2009:40-41; Douglas and O'Connor, 2004). Feral animals affect ecological relationships between plants and animals and also facilitate the dispersal of weeds (Director of National Parks, 2007:79; Skeat et al., 1996:161). Altered fire regimes and the spread of weeds and feral animals have influenced the composition of native plant and animal communities in the Park (Director of National Parks, 2007:67).		
RU3 Interaction among resource units	Connectivity within Yellow Water and between riverine, lacustrine and coastal waters (BMT WBM, 2011:17). Interaction between plant species (e.g. sedge *Eleocharis dulcis* and surrounding wild rice *Oryza* spp), which form preferred nesting and feeding grounds for magpie geese *Anseranus semipalmata* is influenced hydraulic connectivity (saltwater intrusion)(McGregor et al., 2010).	U3 History of use	Aboriginal people have been using and managing natural resources in the region for thousands of years. The Park was established in 1978 and since then it has been jointly managed by traditional land owners and Parks Australia (Boustead, 2009:40; Director of National Parks, 2007:67; McGregor et al., 2010)
RU4 Economic value	Magpie geese are an important source of food for Indigenous people. The value of wild harvested magpie goose is $20/bird (Boustead, 2009:42) The floodplains are a major focus of the tourism industry in Yellow Water and tourist visitations depend on good ecological conditions of floodplains (Prouse and Crawford, 2006:4). Tourism provides economic opportunities for jobs and local businesses (Director of National Parks, 2007:85; Harris, 2012:74; McGregor et al., 2010). The tourtist resort of Cooinda, next to Yellow Water floodplains was recorded as the most visited site of KNP and the floodplains constitute the main attraction for tourists (Tremblay, 2006	U4 Location	

	quoted in Boustead, 2009:31)		
RU5 Number of units		U5 Leadership/entrepreneurship	
RU6 Distinctive margins		U6 Norms/social capital	
RU7 Spatial and temporal distribution		U7 Knowledge of SES/mental models	
		U8 Importance of resource	Economic (subsistence), socio-cultural activities (Boustead, 2009:42; McGregor et al., 2010)
		U9 Technology used	
Interactions (I) -> outcomes (O)			
I1 Harvesting levels of diverse users	The tourism industry fears the loss of freshwater wetlands in Kakadu may reduce the appeal of Kakadu as a tourist destination and therefore lead to a drop in visitation (Boustead, 2009:13)	O1 Social performance measures	Satisfaction of indigenous people with the level of traditional knowledge that is used in Park management and implementation of management Plan (Director of National Parks, 2007:7,33)
			Satisfaction of Bininj with how well country in being looked after through management of fire, weeds and feral animals and how much involvement Bininj have in the design and implementation of management programs (Director of National Parks, 2007:63,76,79)
			Number of Bininj trained in modern management practices (i.e. modern Park Management Skills are transferred across to Bininj) (Director of National Parks, 2007:38)
			Number and type of capacity building initiatives provided for Bininj (including young aboriginals) (Director of National Parks, 2010:5)
			Level of satisfaction of stakeholders with the transparency and accountability of decision-making for the Park's management(Director of National Parks, 2007:33).
			Proportion of indigenous people working on land-related activities (e.g. fire management, land management, hunting, gathering, arts & crafts, bush tucker tours, hunting, feral and weed control etc.) (Director of National Parks, 2007:32,73,79)
I2 Information sharing among users	Through the board of management. Indigenous people are also employed in	O2 Ecological performance measures	Abundance of species of natural and cultural significance (Director of National Parks, 2007:68;

	the Park.		2010:6) Area of floodplain with acceptable levels of weeds (Director of National Parks, 2007:13) Area of floodplain damaged by feral animals (Director of National Parks, 2007:13; Petty et al., 2005) Proportion of floodplain area affected by unplanned or adverse fires (Director of National Parks, 2007:63)
I3 Deliberation process	Board of management is formalised around a western governance structure (Haynes, 2009:70)	O3 Externalities to other SESs	Climate change (rise in sea level, temperature and changes in fire regimes and cyclonic activities)
I4 Conflicts among users	Between indigenous families Between Bininj and Parks Between (the Aboriginal people of Kakadu National Park) Bininj and Park users (tourists, fishers) (Palmer, 2004)		
I5 Investment activities			
I6 Lobbying activities			
I7 Self-organising activities			
I8 Networking activities			
Related ecosystems (ECO): woodlands, estuaries, escarpments			
ECO1 Climate patterns	Monsoons (wet/dry cycle)		
ECO2 Pollution patterns			
ECO3 Flows into and out of focal SES	Tourists, migratory species (waterbirds)		

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Appendix B Report on consultations with Park staff to develop a management planning framework

Executive summary

Climate change seriously threatens Indigenous coastal communities in northern Australia because its impacts will exacerbate existing landscape-wide threats (e.g. para grass and aquatic weeds) to natural and cultural values that are inextricably connected. These cumulative impacts will substantially reduce opportunities for sustaining and developing future ecosystem-based livelihoods such as ecotourism. Hence, the socio-ecological impacts of a range of climate change scenarios need to be examined in combination with other existing pressures, and adaptation options developed and implemented before there are few or no options left.

The National Environmental Research Program (NERP) project 3.2 'Managing threats to floodplain biodiversity and cultural values on Kakadu National Park' has four components:

1. Indigenous values of floodplains (Griffith University)
2. Managing invasive aquatic grasses (Charles Darwin University)
3. Risk assessment of sea-level rise (CSIRO)
4. Management planning framework (CSIRO).

This document reports on a workshop held in the Bowali Centre in Kakadu on 3 December 2013 as part of components 3 and 4. These components have a strong participatory focus where researchers are guided by management needs from Kakadu National Park and Kakadu Traditional Owners (TO) Parks Australia and traditional landowners of Kakadu National Park to produce information that is relevant for its management. Workshop outcomes will be used to establish a framework to undertake an integrated environmental, social, cultural and economic risk assessment of sea-level rise on biodiversity and related ecosystem services of coastal floodplains. It will also consider the adaptive capacity of regional communities to respond.

The aims of the workshop were the following:

1. Provide updated saltwater inundation maps for four sea-level rise scenarios.
2. Introduce high-level management objectives for sea-level rise on Kakadu and associated performance indicators.
3. Undertake hands-on group sessions using maps and Google Earth to:
   - identify priority areas where it might be possible to mitigate for impacts of saltwater intrusion
   - discuss what actions may be taken to manage the impacts of saltwater inundation due to sea-level rise (in more detail during the afternoon session).
4. Evaluate workshop.

The workshop was divided in three parts. In the first part, researchers provided an update on sea-level rise models developed to understand which areas of Kakadu are likely to be affected by saltwater. The second part was a hands-on session where participants trialled some of the tools developed as part of the project, which included producing layers for saltwater inundation, bush tucker and vegetation that could be overlayed using Google Earth. The tool enabled users to select layers of interest and zoom-in on particular areas. At the same time, researchers also wanted to understand the needs of stakeholders in terms of priority areas, issues associated with saltwater inundation and possible actions that might help manage sea-level rise impacts.

During the workshop, the groups identified 14 priority areas. Yellow Water and Mamukala were mentioned by all groups as priorities for their importance for hunting (goose nesting area, water fowls and freshwater fish) and tourism. The groups identified 10 broad categories associated with saltwater inundation due to sea-level rise. Impacts on biodiversity/bush tucker and on tourism were mentioned by all groups and impacts on cultural sites and infrastructure were mentioned by two out of three groups. The groups identified 9 broad categories of actions to manage impacts of saltwater intrusion (Table 18). A large proportion of the actions (4) are associated with gathering information about particular issues and understanding ecological processes and potential impacts. Interestingly, two actions emphasised the importance of maintaining habitats in the present with acceptable levels of weeds/feral animals to facilitate the transition from freshwater habitats to saltwater ones, and also maintain the integrity of potential new freshwater habitats that might be created with sea-level rise. The three mitigation options identified involve constructing infrastructure (levee banks), moving or strengthening existing infrastructure and moving cultural/archaeological material. The results suggest that there was a lot of emphasis on trying to understanding potential effects of sea-level rise and how people and floodplains can adapt.

The third session was focused on group discussions to identify performance indicators for Kakadu National Park. The following indicators were considered by the group.

Cultural performance indicators and actions

Archaeological sites – need representative samples

No baseline information – More research of the floodplains needs to be done to get a better picture and understanding. Currently some floodplain archaeologiocal research is underway (Gabrielle).

Action – Map cultural/anthropological sites on the areas that may be inundated and ask Traditional Owners (TOs) to rank/prioritise them.

Economic indicators

Tourism numbers – Questionnaire to understand why and when they come to the Park to determine the reason for the visit (or not to visit), for example:

1. temperature
2. economic crisis
3. access (roads cut by inundation)
4. more waterbirds
5. more crocodiles.

Social indicators

1. Ability to access traditional areas – depends on season
2. Number of days that Traditional Owners (TO) are cut off from accessing hunting sites – will affect people economically as well as they will need to buy food
3. Information that is summarised and easily understood by TO

Part 1 Background and updates

Project background and update on sea-level rise simulations

1 Introduction

Climate change seriously threatens Indigenous coastal communities in northern Australia because such impacts will exacerbate existing landscape-wide threats (e.g. para grass and aquatic weeds) to natural and cultural values that are inextricably connected. These cumulative impacts will substantially reduce opportunities for sustaining and developing future ecosystem-based livelihoods such as ecotourism. Hence, the socio-ecological impacts of a range of climate change scenarios need to be examined in combination with other existing pressures, and adaptation options developed and implemented before there are few or no options left.

The National Environmental Research Program (NERP) project 3.2 'Managing threats to floodplain biodiversity and cultural values on Kakadu National Park has four components:

1. Indigenous values of floodplains (Griffith University)
2. Managing invasive aquatic grasses (Charles Darwin University)
3. Risk assessment of sea-level rise (CSIRO)
4. Management planning framework (CSIRO).

This document reports on a workshop held in the Bowali Centre in Kakadu on 3 December 2013 and with Kakadu Traditional Land Owners on 6 December 2013 focused on components 3 and 4. These components have a strong participatory focus where researchers are guided by management needs from Kakadu National Park and Traditional Owners (TO) of Kakadu National Park to produce information that is relevant for its management. Workshop outcomes will be used to establish a framework to undertake an integrated environmental, social, cultural and economic risk assessment of sea-level rise (SLR) on biodiversity and related ecosystem services of coastal floodplains. It will also consider the adaptive capacity of regional communities to respond.

1.1 Aims

The aims of the workshop were the following:

4. Provide updated saltwater inundation maps for four SLR scenarios.
5. Introduce high-level management objectives for SLR rise on Kakadu and associated performance indicators.
6. Undertake hands-on group sessions using maps and Google Earth to:
   - identify priority areas where it might be possible to mitigate for impacts of saltwater intrusion
   - discuss what actions may be taken to manage the impacts of saltwater inundation due to sea-level rise (in more detail during the afternoon session).
7. Evaluate workshop.

2 Overview of NERP project 3.2 'Managing threats to floodplain biodiversity and cultural values on Kakadu National Park'

For project component 3 'Risk assessment of sea-level rise', the coastal floodplains in Kakadu were mapped with LiDAR which provides information on terrain that we can use to understand where the saltwater will go. Kakadu floodplains are low lying (0.2–1.2m above mean high water), and therefore vulnerable to saltwater intrusion. Previous assessments (Bartolo *et al.* 2008) indicate that 72% of floodplains will be lost with a 1.1m SLR. However, these predictions were made based on coarse geographic information systems (GIS) analysis. LiDAR data collected in 2011 was used to construct a high resolution digital elevation model for better predictions using a hydrodynamic model for the dry season that shows where saltwater is likely to go with predicted SLR.

Component 4 develops a planning framework and supporting tools to help evaluate different management options using an adaptive management and participatory approach, where stakeholders have the opportunity to give their views on research.

2.1 Informal consultations in preparation for formal workshops in December 2013

On 23 November 2013, Peter B. and Leo D. went to Kakadu to discuss with Parks how to present information during the formal consultations in December 2013. They met with Kakadu National Park staff and Traditional Owners during informal sessions and showed draft SLR inundation maps with the outputs available at the time. The objective was to ask about GIS layers of interest to overlay SLR model outputs as well as feedback on colour schemes and overall presentation of maps and information.

A suggestion from the informal consultations was to use a freeware platform for visualisation, such as Google Earth, and make the data available so people can visualise outputs in their main areas of interest. Other layers of interest are turtle nesting, geese, vegetation (including weeds), tourism and recreational fishing. Another suggestion was to present SLR scenarios in pair-wise comparisons (e.g. present with each of the future scenarios only), instead of all scenarios together which creates confusion. In addition, discussions during formal consultations should focus on the 2030 time horizon but also refer to potential impacts beyond 2030 as a way to understand what is required to prepare for SLR. Finally, there was a suggestion that the research team should prepare kits with laminated maps to be left with rangers for discussion to generate ideas on management and adaptation after the formal consultations.

3 Update on sea-level rise simulations for present and future scenarios

The results of SLR model simulations were presented in hard-copy maps and Google Earth. The maps represent maximum inundation during a spring high tide in the dry season (December 2007). All scenarios presented are based on spring high tide plus SLR. Further refinements in the modelling are still necessary and expected to be finalised in January 2014, hence outputs are in draft form. Table 12 provides details of SLR scenarios used in the simulations.

Table 12. Sea-level rise (SLR) projections used in the models

Scenario	Present (2013)	2030	2070	2100
Years from 2013	0	17	57	87
SLR *	**0**	**0.14m**	**0.70m**	**1.1m**
Parks scenarios**	0	0.17m	0.50m	-

Based on high emissions scenario IPCC4 (2007)
* Used BMT WBM projections based on DCCEE advice (2011)
** Used projections based on Hyder (2008)

During the presentation, Steve W. said there was confusion with the colour schemes and transparency used in the maps; the transparency used in the layers confuses the visualisation as a new colour is created in the intersection between two layers. Peter B. replied saying that the colours can be easily changed based on advice from Parks. Steve suggested that the tool will be useful to look at SLR scenarios on layers separately.

The morning session finished with the presentation of a hierarchy showing high-level park objectives, high-level climate change objectives and performance indicators (Figure 13) to guide the next hands on session, which included a live demo facilitated by Peter B. on how to use Google Earth with the layers (SLR, vegetation, Bush Tucker) provided to Parks prior to the workshop to identify priority areas, issues associated with saltwater inundation due to sea level rise, and possible actions.

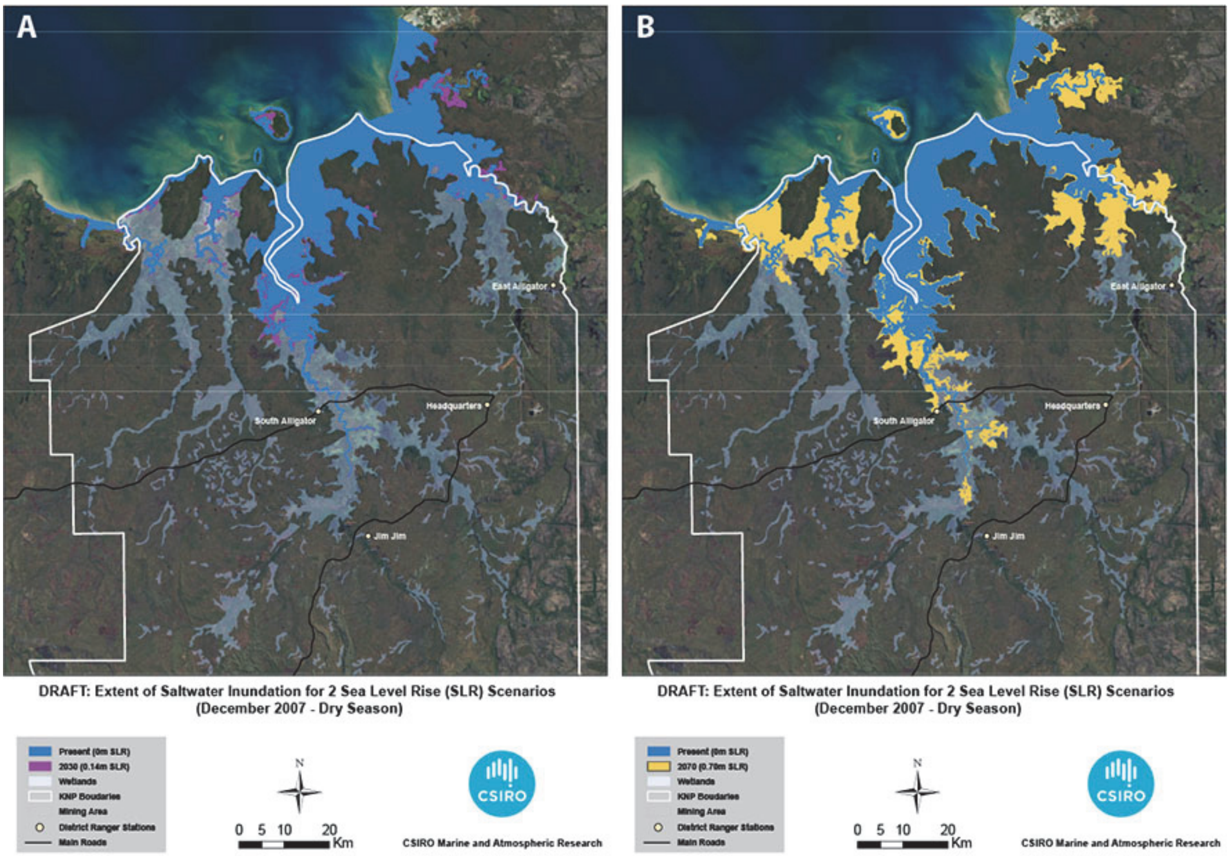


Figure 10. Maps of saltwater inundation for comparisons between A. Present (0m SLR) and 2030 (0.14m SLR), and B. Present and 2070 (0.7m SLR)

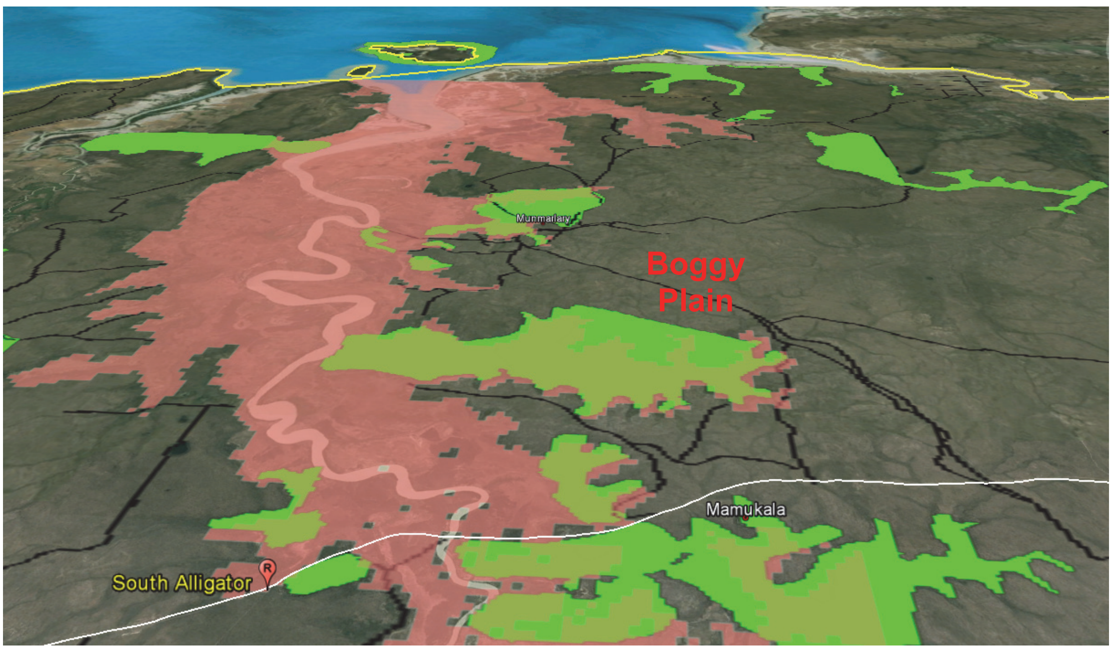


Figure 11. Map of saltwater inundation for 2100 (projected 1.1m) in red and bush-tucker areas in green, showing exposure of bush tucker to sea-level rise in red/green. Map was generated with Google Earth.

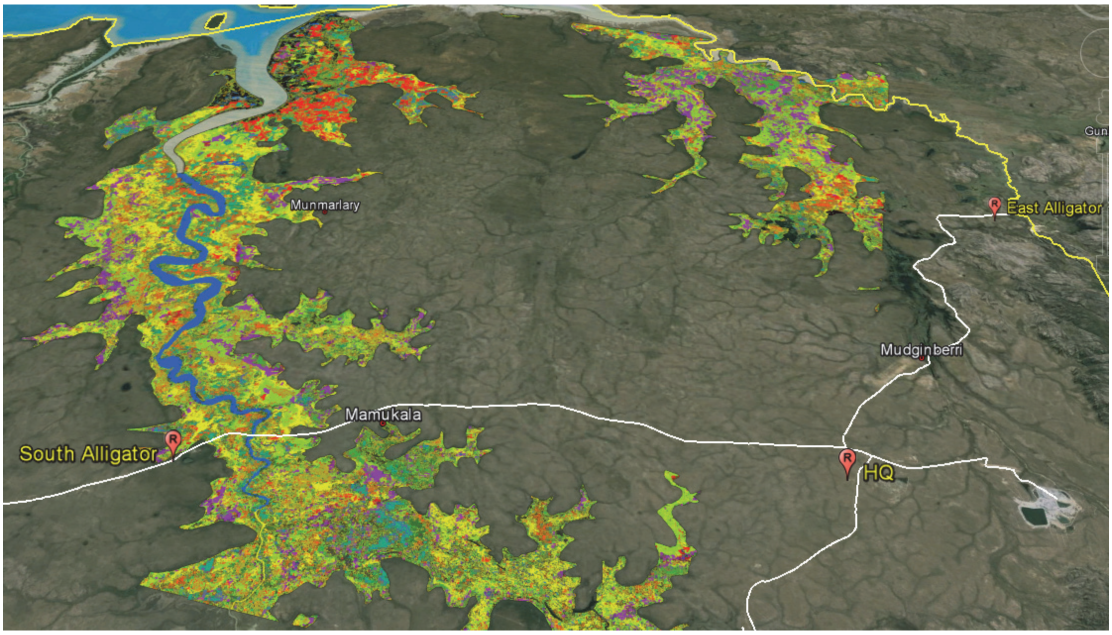


Figure 12. Floodplain vegetation (2010) displayed in Google Earth to demonstrate Google Earth capability to overlay weed and saltwater inundation maps to identify priority areas for vegetation/habitat management.

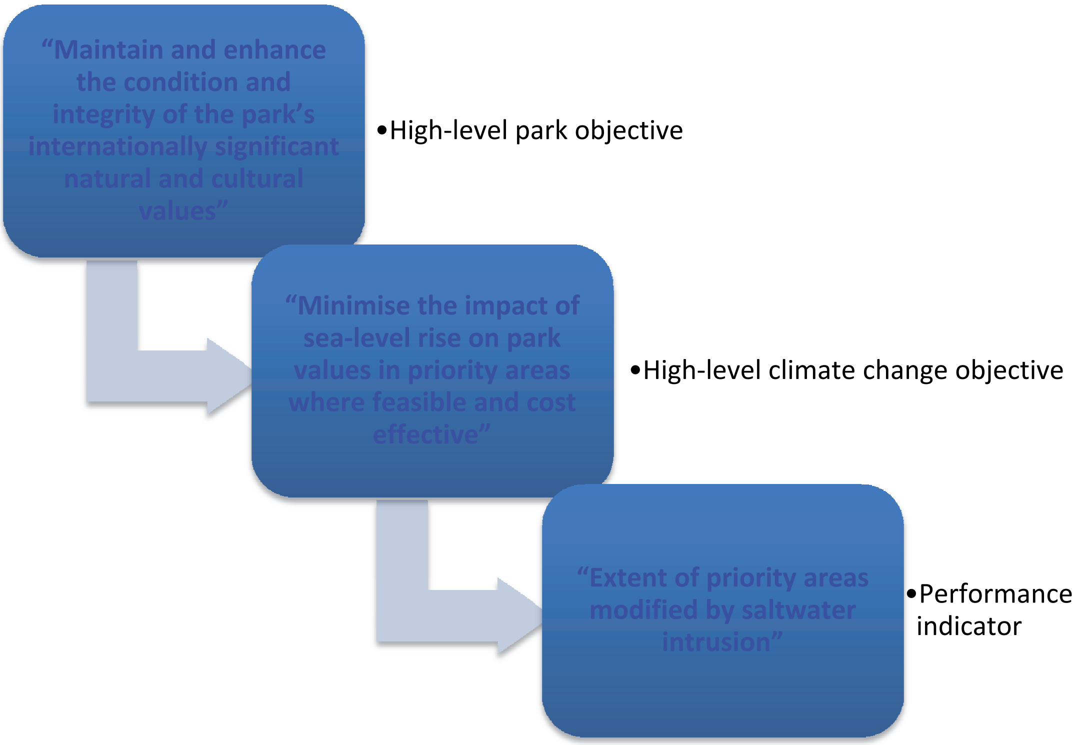


Figure 13. Examples of a high-level park objective, high-level climate change objective and performance indicator.

Steve W. mentioned that he received an updated weeds map which seems different (worse) than the one Peter B. showed. He also mentioned that it will be good to have information on the frequency of inundation and those species that might be advantaged by more frequent inundation by saltwater. Peter B. said that these are important questions that we also want to answer. Steve W. also asked if modeling extreme weather events was part of this project. Peter B. replied by saying that this will be a separate project which he is trying to set up.

Part 2 Hands-on session

Identifying priority areas, issues and actions






4 Hands-on session to identify priority areas, issues associated with saltwater inundation due to sea-level rise and actions

After the live demo presented by Peter B. of Google Earth and GIS layers prepared for the workshop, participants were divided in groups, where each group had a computer set up with Google Earth and the sea level rise inundation layers, bush tucker layers. Peter B. and Leo D. worked closely with groups and individuals to show Google Earth capabilities and provide support on technical issues. Groups were asked to use Google Earth and hard copies of maps to:

8. Give comments on presentation

Given high-level objectives (Parks and Climate Change) they were asked to answer the following questions and write their answers on maps and butcher's paper:

9. What are the areas that might be impacted by saltwater (Priority Areas, focus is the 2070 scenario)
10. How do they think these areas will be affected (What is the issue)?
11. What kind of management actions will be required to minimise impact of sea level rise on Park values?

The groups were the following:

Group 1	**Group 2**	**Group 3**
Steve (scribe)	Louise (scribe)	Mary (scribe)
David	Anne	Jacqui
Calvin	Gabrielle	Jenny
Fred		

At the end of the session, each group presented their main findings and the summary from each group is provided below (for original butcher's paper pictures refer to Appendix A).

4.1 Summary from Group 1

Table 13. Priority areas, issues and actions to manage impacts of saltwater intrusion in the Park – Group 1 (refer to Figure 5 for priority area codes).

Area code	Priority area	What is the issue	Actions to manage impacts of saltwater intrusion	Type of action
1	Field Island	Loss of turtle nesting areas Migratory waders	Don't know – do they just move up the dune?	Information
2	North Pt Kapalga	Biodiversity: goose nesting/feeding areas, all waterfowl (ducks), freshwater fish	Only two places where the saltwater can come in – consider using levees – either through planting or constructing physical barriers.	Mitigation: hard-engineering solution (levee) and soft solution (planting trees to create levee)

Area code	Priority area	What is the issue	Actions to manage impacts of saltwater intrusion	Type of action
		Hunting area for long-necked turtle and file snake Loss of rice grass and water chestnut Impact on cultural sites (middens/ occupation sites)	Saltwater may help control *Mimosa* and *Hymenachne*	Adaptation
3	Diddygeegee	Biodiversity: goose nesting/feeding areas, all waterfowl (ducks), freshwater fish Hunting area for long-necked turtle and file snake Loss of rice grass and water chestnut Impact on cultural sites (middens/ occupation sites)	Only one place where salt water can come in – consider using levees – either through planting or constructing physical barriers. If levees are used they need to control water outflow	Mitigation: hard-engineering solution (levee) and soft solution (planting trees to create levee)
4	Magela	Need to find out more about putting in levees – where does the water go? Biodiversity: goose nesting/feeding areas, all waterfowl (ducks), freshwater fish Hunting area for long-necked turtle and file snake Loss of rice grass and water chestnut Impact on cultural sites (middens/occupation sites)	Could build a levee bank from Binjil Binjil to Anmurridgurr – consider using levees – either through planting or constructing physical barriers. Need to start early.	Mitigation: hard-engineering solution (levee) and soft solution (planting trees to create levee)
5	Boatshed area Kapalga	Need to find out more about putting in levees – where does the water go? Biodiversity: goose nesting/feeding areas, all waterfowl (ducks), freshwater fish Hunting area for long-necked turtle Loss of rice grass and water chestnut Impact on cultural sites (middens/occupation sites)	Numerous salt arms – difficult to protect all areas, could save patches	N/A
6	Boggy Plain	Need to find out more about putting in levees – where does the water go? Biodiversity: goose nesting/feeding areas, all waterfowl (ducks), freshwater fish	Could protect by putting a levee across front of floodplain – not a great distance so possibly achievable - seriously consider protecting.	Mitigation: hard-engineering solution (levee) and soft solutions (planting to create levees)

Area code	Priority area	What is the issue	Actions to manage impacts of saltwater intrusion	Type of action
		Hunting area for long-necked turtle and file snake Loss of rice grass and water chestnut Impact on cultural sites (middens/occupation sites)		
7	Mamukala	Geese Floodplain biodiversity: goose nesting/feeding areas, all waterfowl (ducks), freshwater fish Tourism Good waterfowl area Important hunting areas	Could protect bird-hide area Water needs to run out -–need environmentally friendly design of levees - some sort of way of letting water and wildlife out Need input from engineer to work out what is feasible	Mitigation: hard-engineering solution (levee) and soft solutions (planting to create levees)
8	Goose camp	Geese Floodplain biodiversity: goose nesting/feeding areas, all waterfowl (ducks), freshwater fish Tourism Good waterfowl area Important hunting areas	Too big, difficult to protect	N/A
9	Yellow Waters	Geese Floodplain biodiversity: goose nesting/feeding areas, all waterfowl (ducks), freshwater fish Tourism – especially important Good waterfowl area Important hunting areas	Need to try to protect but difficult because of amount of low country. Putting a huge levee bank will just move water to other areas. Salt water could kill *Salvinia*	Mitigation: hard-engineering solution (levee) and soft solutions (planting to create levees)
10	Coastal area	Loss of middens Cultural areas – occupation sites	?	N/A

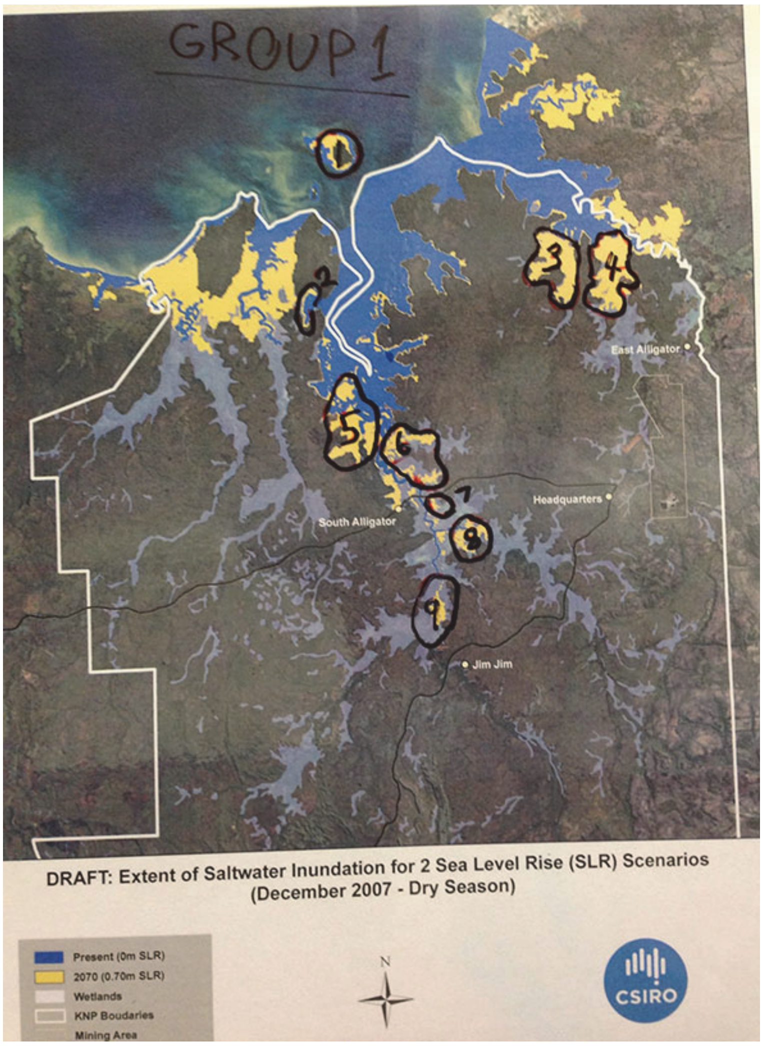


Figure 14. Priority areas identified by Group 1

4.2 Summary from group 2

Group 2 focused on areas along the South Alligator River only, but did not identify these on maps.

Table 14. Priority areas, issues and actions to manage impacts of saltwater intrusion in the Park – Group 2

Priority area	What is the issue	Actions to manage impacts of saltwater intrusion	Type of action
Yellow Waters (hunting, tourism, potential to do something, waterbirds)	Loss of freshwater habitat and impact on native plants and animals (biodiversity and hunting) and tourism	Reduce impact of feral animals and weeds to reduce other stresses on country especially buffalo. Focus should be on priority areas based on less inundation and more bush tucker.	Indirect
		Model where new and/or increased freshwater areas might be to inform planning for future (also for all infrastructure).	Information
		Monitor species populations.	Information
		Select refuge areas vs. areas that are likely to be lost and focus on management of refuge areas.	Information
Mamukala (hunting, tourism, waterbirds, river access by car currently)	Loss of freshwater habitat and impact on native plants and animals (biodiversity and hunting) and tourism	Reduce impact of feral animals and weeds to reduce other stress on country especially buffalo. Focus should be on priority areas based on less inundation and more bush tucker.	Indirect
		Model where new and/or increased freshwater areas might be to inform planning for future (also for all infrastructures).	Information
		Monitor species populations.	Information
		Select refuge areas vs. areas that are likely to be lost and focus on management of refuge areas.	Information
West Alligator River	Has been protected to date but predicted for huge inundation	? Open up for fishing in exchange for some other areas.	Adaptation
South Alligator floodplain	Archaeological material under water	Consult with TOs on relocation and/or removal of material.	Mitigation
	Cultural sites under water (including burial sites)		
Settlements and infrastructure	Loss of homes and infrastructure	Map all outstations and/or infrastructure etc. to indicate when they will be inundated on the model.	Information
	Cost of repairs etc. (e.g. Patonga Homestead/Mudginberri which also has historical value)	Consideration of what to do with any outstations, tourism infrastructure, etc.	Information
		Move?	Adaptation
		Strengthen?	Mitigation
		Evacuation plans?	

4.3 Summary from Group 3

Table 15. Priority areas, issues and actions to manage impacts of saltwater intrusion in the Park – Group 3 (refer to Figure 6 for priority areas codes)

Area code	Priority area	What is the issue	Actions to manage impacts of saltwater intrusion	Type of action
1	Magella/Nankeen	Weeds: What is the outcome on the research for para grass? Effects of saltwater on turtles, fish, paperbarks	Conduct more research to evaluate the effects of saltwater on short- and long-necked turtles, magpie geese, freshwater fish species and paperbark species.	Information
2 & 3	Munmalary and surrounds	New freshwater areas forming	N/A	N/A
4	Boggy Plain		N/A	N/A
5	Mamukala	Inundation of bird platform for tourists	Raise the bird platform higher (infrastructure).	Mitigation
6	Yellow Waters (birds, freshwater species, water lilies, freshwater mussels)	Inundation of boat ramp by saltwater	Reassess and move the boat ramp to Home Billabong.	Mitigation
		Inundation of Warradjan cultural centre	Relocate to higher ground.	Mitigation
		Will the birds move?	Tag birds and monitor their movements in response to saltwater impacts.	Information

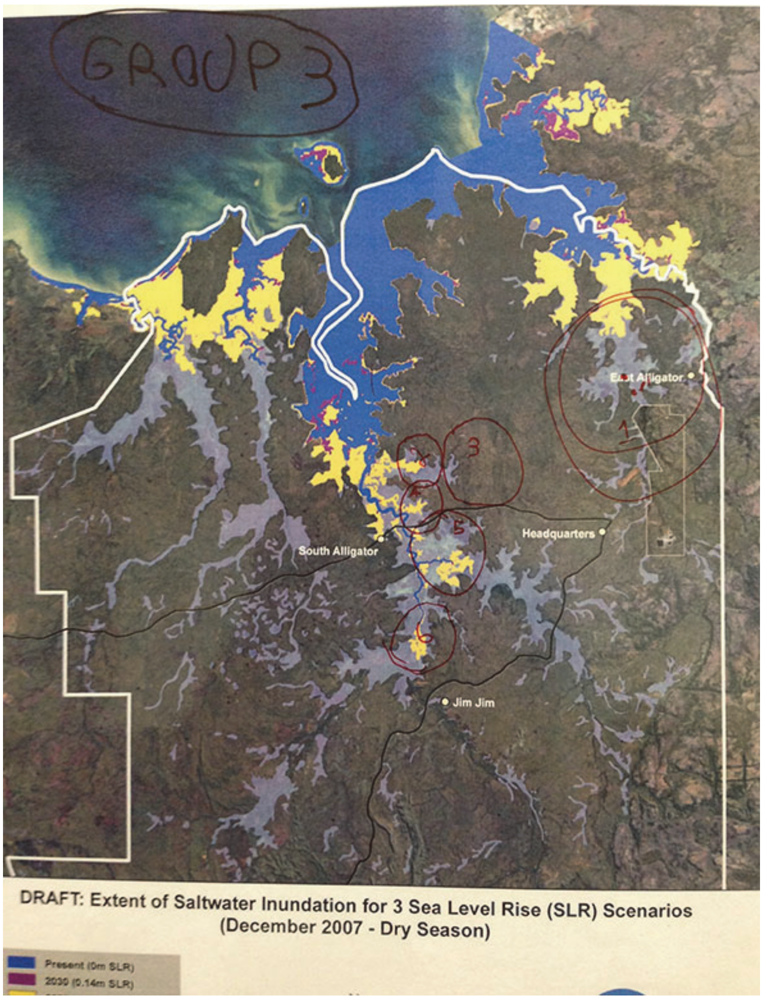


Figure 15. Priority areas identified by Group 3

5 Results

5.1 Priority areas

During the workshop, the groups identified the following 14 priority areas (Table 16). Yellow Water and Mamukala were mentioned by all groups as priorities for their importance for hunting (goose nesting area, waterfowl and freshwater fish) and tourism.

Table 16. Priority areas mentioned by groups

	Priority area	Mentioned by groups
1	Yellow Waters	1, 2, 3
2	Mamukala	1, 2, 3
3	Boggy Plain	1, 3
4	Magela	1, 3
5	Field Island	1
6	North Pt Kapalga	1
7	Diddygeegee	1
8	Munmalary	3
9	Boat shed area Kapalga	1
10	Goose camp	1
11	West Alligator River	2
12	South Alligator floodplain	2
13	Settlements and infrastructure	2
14	Coastal area	1

5.2 Issues associated with saltwater inundation due to sea-level rise

The groups identified 10 broad categories of issues associated with saltwater inundation due to SLR (Table 17). All three groups mentioned impacts on biodiversity/bush tucker and on tourism and two of the groups mentioned impacts on cultural sites and infrastructure.

Table 17. Broad categories of issues associated with saltwater inundation due to sea-level rise (SLR) identified by groups

	Identified issue associated with saltwater inundation due to SLR	Mentioned by groups
1	Impact on biodiversity/bush tucker (plants and animals)	1, 2, 3
2	Impact on tourism	1, 2, 3
3	Impact on cultural sites (middens, occupation sites, archaeological sites)	1, 2
4	Loss of homes and infrastructure and associated costs to repair	2, 3
5	Impact on migratory waders	1
6	Loss of turtle nesting areas	1

7	Impact on freshwater habitats	2
8	Weeds	3
9	New freshwater habitats being created	3
10	Loss of dunes – middens	1

5.3 Potential actions to manage impacts of saltwater intrusion

The groups identified nine broad categories of actions to manage impacts of saltwater intrusion (Table 18). Most of them (four) are associated with gathering information about particular issues and understanding potential impacts. Interestingly, two actions (5 and 9), which emphasise the role of maintaining habitats with acceptable levels of weeds/feral animals to facilitate the transition from freshwater habitats to saltwater ones, also maintain the integrity of potential new freshwater habitats that might be created with SLR. The three mitigation options identified involve constructing infrastructure (levee banks), moving or strengthening existing infrastructure and moving cultural/archaeological material. The results suggest significant emphasis on trying to understand potential effects of SLR and how people, their management of floodplains, plants and animals can adapt.

Table 18. Potential actions to manage saltwater intrusion identified by groups

	Actions to manage impacts of saltwater intrusion	**Type of action**	**Group**
1	Conduct research and monitoring to evaluate the effects of saltwater on turtles, magpie geese, freshwater fish and paperbark species.	Information	2, 3
2	Raise and/or move infrastructure.	Mitigation	2, 3
3	Gather information on nesting behaviour of turtles.	Information	1
4	Install levees by planting or constructing physical barriers.	Mitigation	1
5	Recognise that saltwater may help control weeds (e.g. *Mimosa*, *Salvinia*, and *Hymenachne*).	Adaptation	1
6	Consult with TOs on relocation and/or removal of cultural and archaeological material.	Mitigation	2
7	Map and evaluate impacts on infrastructure (e.g. consider what to do with outstations, tourism infrastructure).	Information	2
8	Identify and prioritise refuge areas vs. areas that are likely to be lost and focus on management of refuge areas.	Information	2
9	Reduce impact of feral animals and weeds to reduce other stresses on country, especially buffalo. Focus should be on priority areas based on less inundation and more bush tucker.	Indirect action (adaptation)	2

Part 3 Afternoon session

Discussion on possible performance indicators for Parks Australia

6 Information session: Presentation on stakeholder-driven project to develop management objectives and actions in the Great Barrier Reef

Leo D. presented work he is doing on the inshore Great Barrier Reef (GBR), which uses a stakeholder-driven approach to elicit management objectives, actions and indicators to provide Parks Australia with some examples. This followed up on a suggestion to select one of the actions proposed in the morning session and have a more-focused discussion on ecological, economic, cultural and social indicators for Kakadu National Park.

In the GBR project, the researchers asked participants to 'time travel' 20+ years into the future and answer the question: What *operational management objective(s)* would you use to reach your high level objective?

Examples of objectives to protect natural and cultural values:

1. **Environmental** – maintain/enhance biodiversity and habitats
2. **Cultural** – maintain/enhance access to bush tucker
3. **Social** – increase resilience of communities to adapt and respond to change
4. **Economic** – maintain/enhance livelihoods derived from park values, especially Indigenous livelihoods.

Performance indicators are critical in assessing whether or not management objectives are achieved. We asked the group: What *performance indicator(s)* would you monitor to determine whether or not you had reached your management objective(s)?

Steve W.: We want to investigate engineering options that mimic nature (natural flow) – best technology for levees. What organisms and species have the ability to move from saltwater to freshwater and vice versa?

Leo D.: If you built a levee, what would be important to monitor to see if it is working?

Steve W.: Examples of indicators include the following:

- mangroves
- *Melaleuca*
- salinity
- a control site
- magpie geese
- land reclamation
- water flow
- Mary River – provides useful lessons learnt about costs of levees
- abundance of key species – freshwater turtles, magpie geese, plants.

Peter: Monitoring program for saltwater inundation – would it be a good contribution from the NERP project?

Other examples of indicators provided by the group are outlined below.

6.1 Cultural performance indicators and actions

Archaeological sites:

1. need representative samples
2. no baseline information – More research of the floodplains needs to be done to get a better picture and understanding. Currently some floodplain archaeologiocal research is underway (Gabrielle).

Action: Map cultural/anthropological site on the areas that may be inundated and ask TOs to rank/ prioritise them.

6.2 Economic indicators

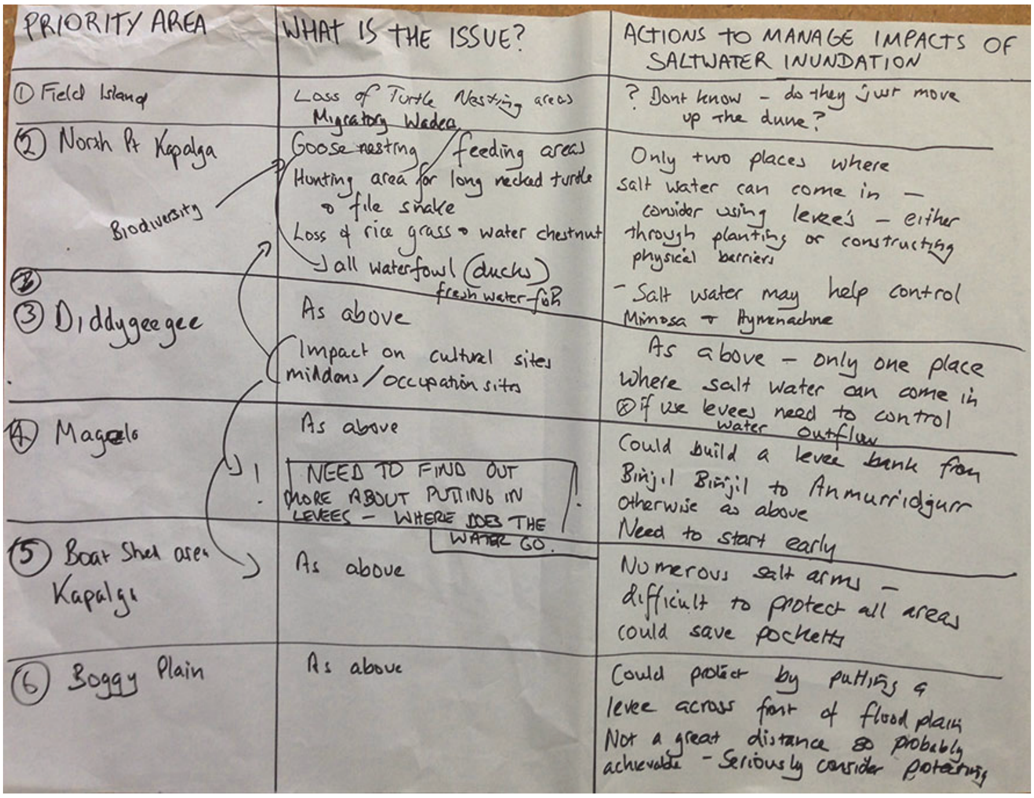
Tourism numbers: questionnaire to understand why and when they come to the park to determine the reason for the visit (or not to visit), for example:

1. temperature
2. economic crisis
3. access (roads cut by inundation)
4. more waterbirds
5. more crocodiles.

6.3 Social indicators

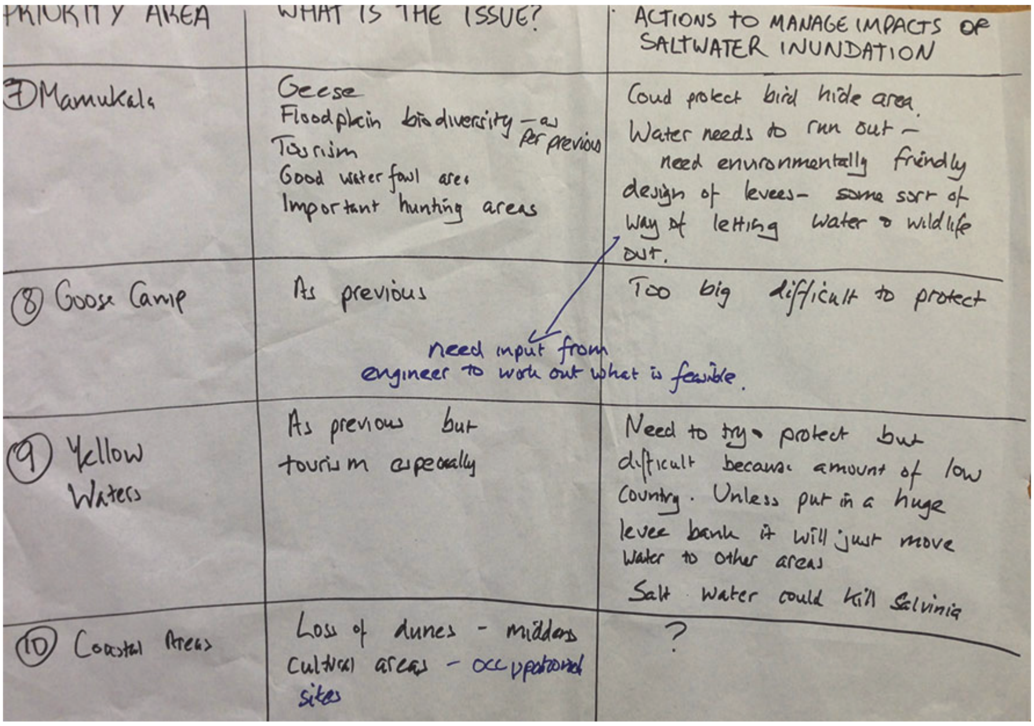
1. ability to access traditional areas – depends on season
2. number of days that TOs are cut off from accessing hunting sites – will affect people economically as well as they will need to buy food
3. information that is summarised and easily understood by TOs.

Appendix 1. Original butcher's paper from each group



PRIORITY AREA	WHAT IS THE ISSUE?	ACTIONS TO MANAGE IMPACTS OF SALTWATER INUNDATION
① Field Island	Loss of Turtle Nesting areas Migratory Wader	? Dont know – do they just move up the dune?
② North Pt Kapalga Biodiversity	Goose nesting / feeding areas Hunting area for long necked turtle & file snake Loss of rice grass & water chestnut all waterfowl (ducks) fresh water fish	Only two places where salt water can come in – consider using levee's – either through planting or constructing physical barriers – Salt water may help control Mimosa & Hymenachne
③ Diddygeegee	As above Impact on cultural sites middens / occupation sites	As above – only one place where salt water can come in ® if use levees need to control water outflow
④ Magela	As above NEED TO FIND OUT MORE ABOUT PUTTING IN LEVEES – WHERE DOES THE WATER GO.	Could build a levee bank from Binjil Binjil to Anmurridjurr Otherwise as above Need to start early
⑤ Boat Shed area Kapalga	As above	Numerous salt arms – difficult to protect all areas could save pockets
⑥ Boggy Plain	As above	Could protect by putting a levee across front of flood plain Not a great distance so probably achievable – Seriously consider protecting

Figure 16. Summary from Group 1A



PRIORITY AREA	WHAT IS THE ISSUE?	ACTIONS TO MANAGE IMPACTS OF SALTWATER INUNDATION
⑦ Mamukala	Geese Floodplain biodiversity – as per previous Tourism Good water fowl area Important hunting areas	Could protect bird hide area. Water needs to run out – need environmentally friendly design of levees – some sort of way of letting water & wildlife out.
⑧ Goose Camp	As previous need input from engineer to work out what is feasible.	Too big difficult to protect
⑨ Yellow Waters	As previous but tourism especially	Need to try & protect but difficult because amount of low country. Unless put in a huge levee bank it will just move water to other areas Salt water could kill Salvinia
⑩ Coastal Areas	Loss of dunes – middens cultural areas – occupational sites	?

Figure 17. Summary from Group 1B

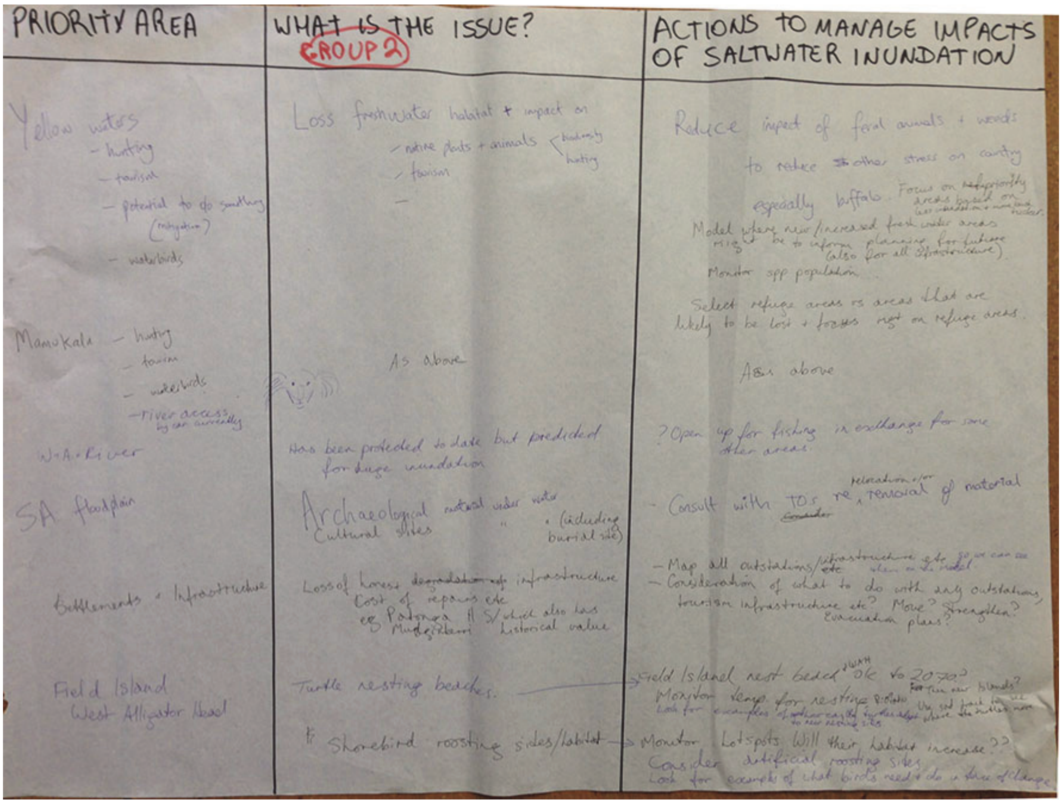


Figure 18. Summary from Group 2.

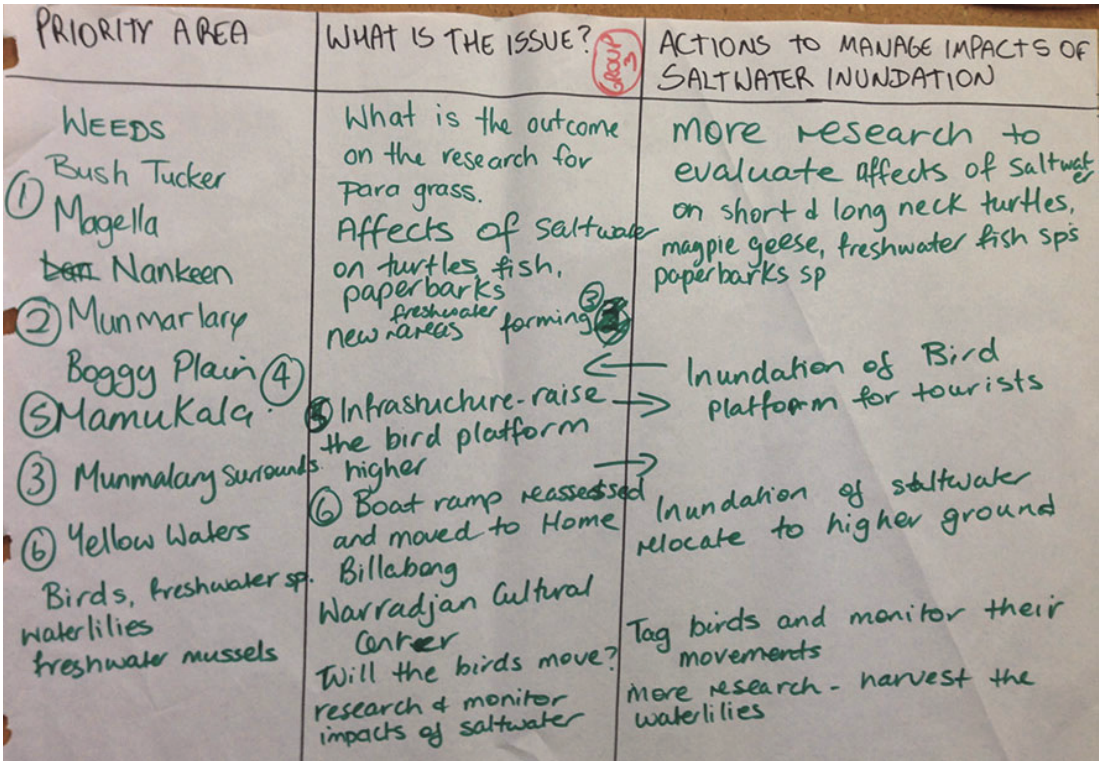


Figure 19. Summary from Group 3

Appendix C Sea Level Rise Booklet

National Environmental Research Program

NORTHERN AUSTRALIA HUB

Improving biodiversity conservation in northern Australia

Sea level rise in Kakadu National Park - DRAFT

How will it affect me and the plants and animals?

The National Environmental Research Program

Australia's biodiversity is unique and important and brings many social, environmental and economic benefits. The Australian Government is funding the Northern Australia Hub to research biodiversity across northern Australia. The region is under threat from weeds, feral animals, rising sea levels and more intensive development of its land and water resources.

We are working closely with Indigenous people because they own and manage large parts of northern Australia, and have extensive knowledge about the environment. This knowledge can be used to complement western science. Good engagement with Indigenous people brings major benefits for the research outcomes, the people involved and the environment.

Why have we made this booklet?

In December 2013 we held a workshop for Kakadu Traditional Owners to talk about the potential impacts of sea level rise on country, and possible management solutions to deal with it. Some people who attended the workshop said that they would like us to print the information in a booklet so that they can show the booklet to other people living in Kakadu and to talk with them about this topic. This booklet is a draft, and comments and suggestions on how to make it better are welcome.

Why are we looking at sea level rise in Kakadu?

Scientists believe that climate is changing and sea levels are rising. This is because more and more people are clearing the land and burning fuels for power and transport. These activities are changing the atmosphere and making the world warmer. Warmer temperatures are causing sea levels to rise, and more extreme weather like floods, cyclones and very hot days.

People are starting to notice these changes. Over the past 20 years, sea levels in northern Australia have risen from between 7 and 11mm each year. There is strong agreement that we need to understand as much as possible about the effects of climate change in Kakadu National Park.

Currently weeds and feral pigs are recognised as the biggest threats to floodplain health in Kakadu, and efforts are being made to deal with them. Sea level rise is a future threat. It will bring saltwater onto freshwater floodplains, changing the environment.

Understanding how sea level rise might push saltwater inland is important because the tides in northern Australia are big and the floodplains in Kakadu are flat.

Even a small rise in sea level might push saltwater onto large areas of freshwater floodplains, which might kill wildlife and plants.

Sea levels are rising slowly, so we have time to think about how we can manage saltwater entering the floodplains and how this may change the environment and bush tucker areas.

Who is involved in this project?

Researchers from CSIRO, Charles Darwin University, Griffith University and eriss are working with Bininj and Parks staff to estimate how much of the floodplain might be covered by saltwater in the future, and how this might change the environment.

Bininj have already provided information about how this may affect plants, animals, places and important cultural practices. We are working with Bininj and Parks to understand how this information can be used to manage country and which areas to prioritise.

Floodplains had saltwater species before

Scientists believe that Kakadu's floodplains were under saltwater before. Thousands of years ago sea levels were higher, bringing animals like barramundi, mullet and saltwater crocodiles to the areas that we now know as freshwater floodplains. Rock art on Kakadu floodplains show saltwater animals in the floodplains. Scientists think this could be how freshwater floodplains would look in the future if sea levels rise again.

Extent of saltwater inundation in a flat environment with small increase in sea level

Estuarine species represented in rock art, which shows that existing freshwater areas were previously covered by saltwater, which brought species like bream and mullet further up in the river.

How were the freshwater floodplains formed?

Eight thousand years ago sea levels began to get lower. Over time the animals and plants on the floodplains changed from the ones that can live with salt, like mangroves and crabs, to freshwater species like red lilies, water chestnut and magpie geese.

The floodplains have been freshwater for around 1,500 years. Rock art from this period shows that the new freshwater floodplains brought new bush tucker, like water lilies and magpie geese, which are still used by Bininj today.

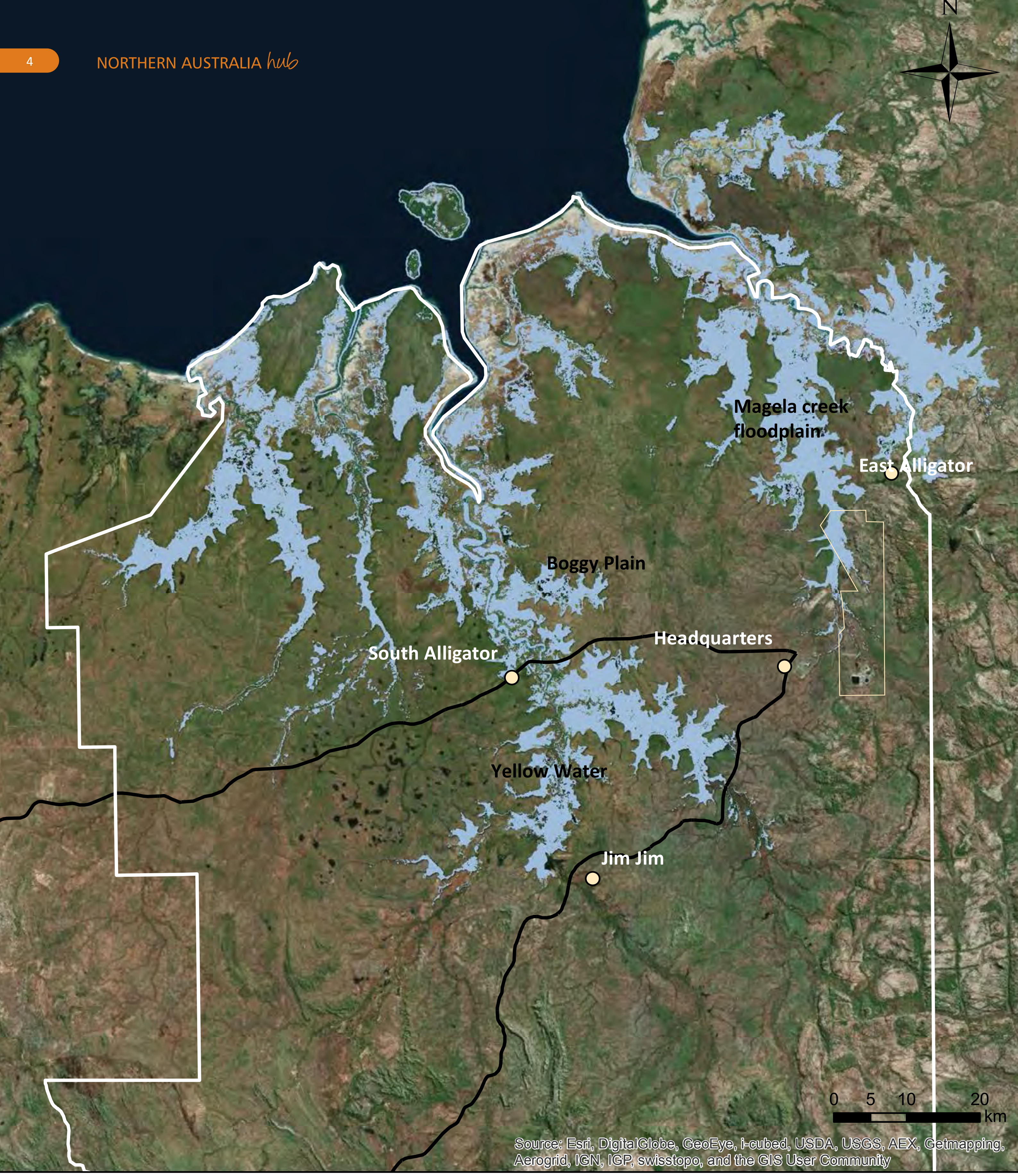
How do the floodplains work?

Floodplains are fully covered by freshwater during Gudjewg (the wet season), and almost completely dry during Gurrung (the dry season). Plants and animals need the floodplains to be covered by freshwater during Gudjewg to live.

Throughout Gudjewg the rains bring freshwater into the catchments and main rivers of Kakadu (Wildman, West, South, and East Alligator). This freshwater spills out onto the floodplains and flows through the main river channels to the sea. It pushes the saltwater at the mouth of the river back and no saltwater comes onto the floodplain, even when the tides are high.

Throughout Gurrung there is almost no rainfall and saltwater can travel to the upper reaches of Kakadu's rivers. In the South Alligator River, saltwater can travel as far up as Yellow Water during high tides. It enters floodplain areas through narrow channels during high tides, and normally stays in these channels. Saltwater plants like mangroves grow in these areas.

Saltwater only reaches freshwater plants in very high tides (king tides), which happen about twice a year around December and July. Some Bininj notice when saltwater enters the floodplains. It changes the smell, colour and feel of the water. People say they can feel saltwater as it stings cuts on their skin. Some people have told us stories about their efforts to stop the saltwater, like building small barrages.



Alligator River Region Flood Extent - March 2010

Alligator River Region Flood extent- March 2010

Kakadu National Park boundaries

Mining area

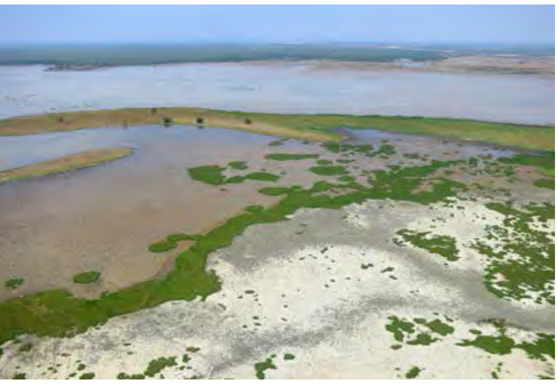
District ranger stations

Main roads

This is an example of areas that flood in the wet season now.

Source: Doug Ward / Griffith University

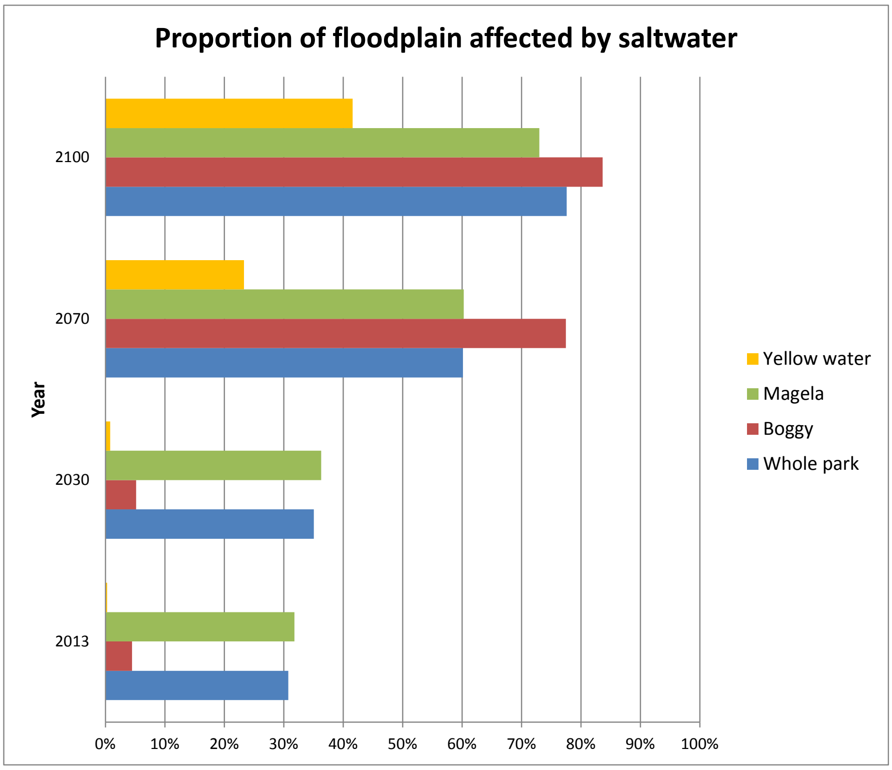
Ward, D. P., A. Petty, S. A. Setterfield, M. M. Douglas, K. Ferdinands, S. K. Hamilton and S. Phinn (2014). Floodplain inundation and vegetation dynamics in the Alligator Rivers region (Kakadu) of northern Australia assessed using optical and radar remote sensing. Remote Sensing of Environment 147: 43-55.

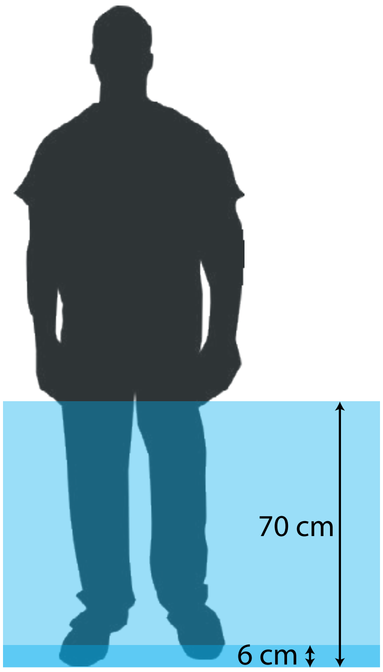


What will sea level rise do to the floodplains?

In the last 20 years sea levels have risen quickly – about 6cm (see Figure) . This is probably the reason that Bininj have seen saltwater coming to areas like Gina .

In the next 50 years sea levels may rise up to 70cm more. Our maps show that this amount of sea level rise could change the floodplains a lot. Freshwater areas may become saltwater country even during Gudjewg. Because the sea level will be higher cyclones won't need to be very strong to bring saltwater further onto the floodplains.



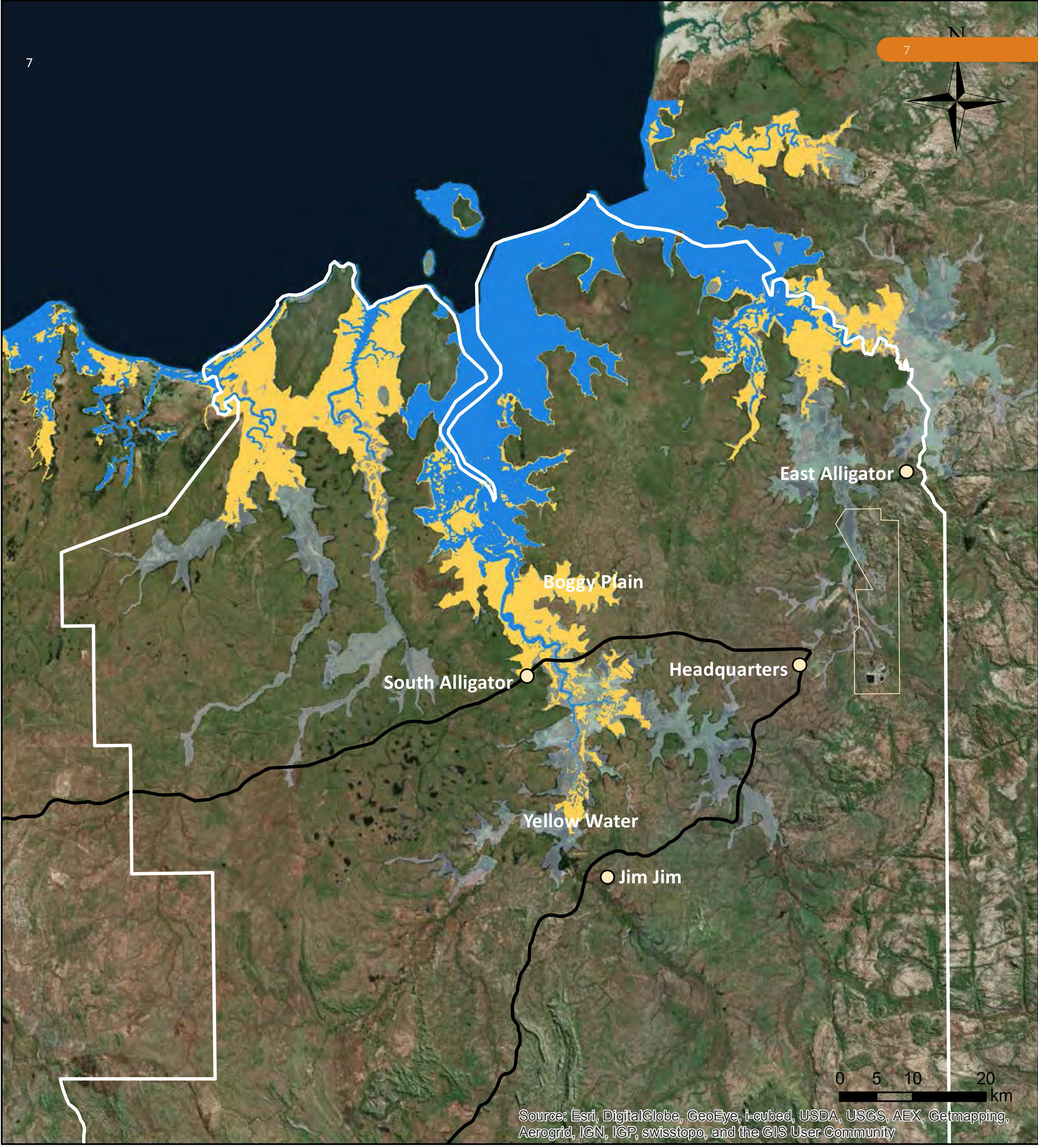


This photo shows loodplain channels (about 1.5m wide) covered by saltwater during high tides in dry season. Only salt-tolerant species like the mangroves in the background can grow in these areas (Photo: Leo Dutra).

DRAFT: Extent of Saltwater Inundation for the Present Sea Level (October 2013 - Dry Season)

2013 (0m SLR)
Kakadu National Park boundaries
Mining area
District ranger stations
Main roads

This shows the areas that are affected by saltwater now.



DRAFT: Extent of Saltwater Inundation Predicted for 2070 compared to 2013

2013 (0m SLR)
2070 (0.70m SLR)
Alligator River Region Floodplains
Kakadu National Park boundaries
Mining area
District ranger stations

CSIRO

Yellow shows the areas that could be affected by saltwater two generations from now. Blue is showing areas currently affected.

Sea level rise may change hunting and fishing sites

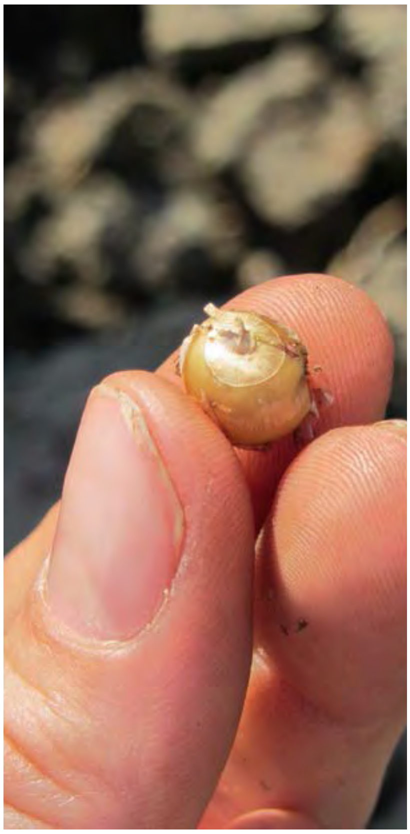
Sea level rise might be hard for us to notice over a few years but over many generations it may bring saltwater to freshwater places where Bininj now hunt and fish. It could be harder to go to these places because the tracks might be underwater and people will need to find other ways to go hunting and fishing.


Photo: CSIRO

How will plants be affected?

When floodplains get covered by saltwater the plants that live and grow there could change. At first, some plants like red lilies might die and others might grow. Some saltwater every now and then can help plants like water chestnut to grow better, which is also good for magpie geese. But when saltwater becomes deeper these plants will go, and more saltwater plants like mangroves may take their place.


Photo: CSIRO



Water chestnut should do well with a bit of saltwater in the beginning, but should go when saltwater becomes deeper.


Photo: CSIRO

All paper barks at the edges of the floodplains should go as they cannot live in saltwater.


Photo: CSIRO


Photo: CSIRO

How will animals be affected?

Sea level rise may change the shape of rivers and creeks, and new saltwater plants will bring different animals.

- Turtles might move.
- Magpie geese might lose their nesting areas.
- Magpie geese and whistling ducks could be affected as they depend on freshwater plants.
- File snakes could be affected, because they like to be in the paper barks.
- There might be more barramundi because they like saltwater.
- There might be less black bream because they only live in freshwater.
- New freshwater floodplains might be created as saltwater pushes the freshwater into new areas. But these won't be as big as the existing freshwater floodplains because the terrain means there aren't other large flat areas where the freshwater can go.
- As the saltwater area increases, there will be more saltwater crocodiles.

How can we respond?

Bininj and Parks staff think that saltwater from sea level rise will change freshwater places but it may also create new freshwater areas. Keeping the floodplains healthy by controlling weeds and pigs will make it easier for freshwater plants to survive in the new freshwater places.

There are different types of barriers that could also be suitable to protect some areas from too much saltwater. A barrage is another name for a barrier.

Can we build something to protect an area from saltwater?

There are different types of barriers that can be used to prevent saltwater from coming on to freshwater floodplains. Some of them have been used in the Mary River. We looked at two options that may help protect some floodplains:

1. A hard barrier that stops saltwater entering the floodplains during Gurrung (the dry season) and allows freshwater to flow during Gudjewg (the wet season).
2. A soft barrier to protect the coast and encourage mangroves to grow.

Hard barriers are built with concrete and large pipes to allow freshwater to flow during Gudjewg but to stop saltwater from coming in. They can be very good at stopping saltwater and are strong enough for areas where there is high water flow or lots of erosion. They can protect high value land and property during times of flood.

One problem with hard barriers is that they block the river and floodplain and can make it hard for fish, other animals and boats to move between the floodplains and the estuary. It is possible to build a special ramp in the barrier to help fish move past, but some fish might still be affected.

Hard barriers are also very expensive to build and are not suitable to protect all areas. There are also expensive ongoing costs to maintain them.

Soft barriers build the land up naturally by slowing the water, trapping sediments and allowing mangroves to grow.

They can be built with fallen trees, timber poles, bamboo matting and fish nets. Soft barriers will not work at all in areas where the water flows and waves are too strong.

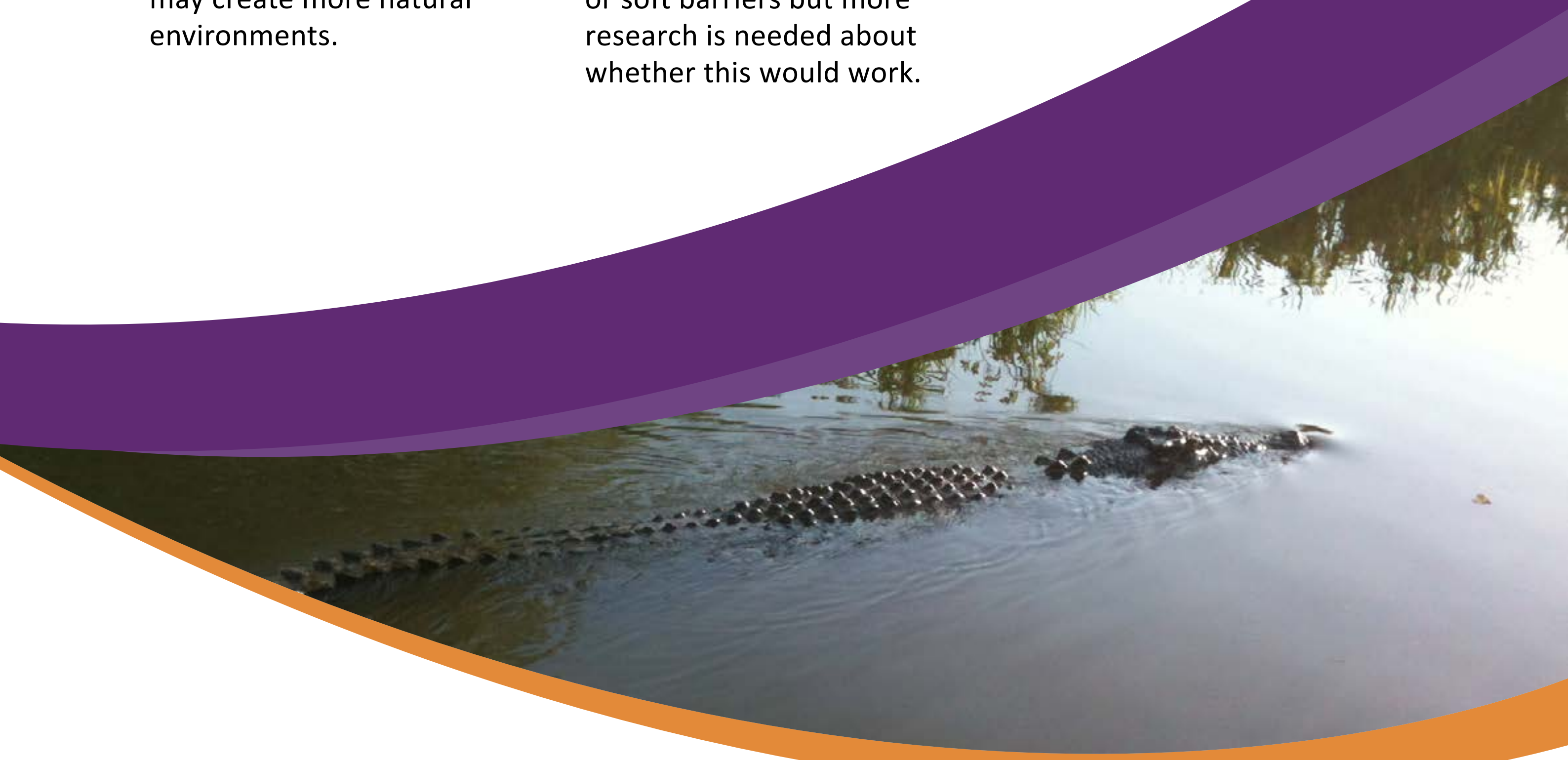
Soft barriers and healthy mangroves could help stop saltwater from sea level rise spreading across some parts of the floodplains. Soft barriers are not as strong as hard barriers in storms. They still cost a lot to build and maintain, but they are much cheaper than hard barriers. Using a soft barrier may create more natural environments.

These types of barriers don't work as quickly as hard barriers because it takes years for natural material to build up and trap sediments, and even longer for healthy mangroves forests to grow. It could take more than 10 years for a soft barrier to work properly and saltwater might still come past the barrier.

Yellow Water is a very important area to many people. Some people have asked if there is a way to protect it. It may be possible with a either a hard or soft barriers but more research is needed about whether this would work.

Further information:

Leo Dutra and Peter Bayliss - CSIRO
Email:Peter.Bayliss@csiro.au Phone: 0427 139 171



National Environmental Research Program

NORTHERN AUSTRALIA HUB

Improving biodiversity conservation in northern Australia

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Photos provided by Northern Australia NERP hub communications section (Carli Piltz), unless otherwise specified.

CSIRO CHARLES DARWIN UNIVERSITY Griffith UNIVERSITY National Environmental Research Program

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Phone: **08 8946 7085**

Appendix D Report on functional design of levee to protect Yellow Water from sea level rise (including brief with specifications and memo commenting on barrier proposal)

Brief describing the problem:

Yellow Water is located at the South Alligator River and is one of the floodplains within Kakadu National Park and includes World Heritage and Ramsar-listed wetlands (seasonal river-floodplains) that support a variety of freshwater plants and animals used by local Indigenous people. Indigenous culture and biodiversity values are also highly important for the tourism industry, which brings important economic benefits via indigenous businesses and jobs. Predicted sea level rise associated with climate change is expected to affect Yellow Water via saltwater inundation of (a) freshwater ecosystems, (b) cultural sites and (c) infrastructure (e.g. housing, roads, tourist facilities) with flow on effects on indigenous livelihoods.

The construction of levy banks has the potential to protect biodiversity and indigenous values in Yellow Water from saltwater intrusion so the floodplain can continue to provide ecosystem goods and services for future generations. We would like to assess the feasibility of protecting biodiversity, cultural and economic (indigenous businesses and jobs) values in Yellow Water via the construction of a levy bank that stops saltwater intrusion associated with predicted sea level rise in the floodplain during the dry season and allows the freshwater to flow during the wet season so habitat connectivity is maintained. Designing such a levy bank also involves the choice of a suitable location and costs associated with its construction and maintenance. This information is critical to Park managers to make an assessment of its feasibility and plan for adaptation options given the predicted sea level rise for this century.

The following data is available:

- Digital Elevation Model: LiDAR
- Outputs from a hydraulic model for 4 sea level rise (SLR) scenarios (Present (0m SLR, 2030 (0.14m SLR), 2070 (0.70m SLR), 2100 (1.1m SLR). Model was run during the dry season for a period of 8 days in 15-minute time steps. Highest tidal input was 3.39m (AHD) at the mouth of the South Alligator River.
- Mean water level at the South Alligator River during a typical dry season (October 2005) is 0.66m (AHD), Maximum tide 3.75m (AHD) and Minimum water level is -1.86m (AHD).
- There are a number of tidal and rainfall gauge stations (water level/flow and rainfall from NT government and rainfall from the Bureau of Meteorology) in the South Alligator River (see table below).

Table 19 Gauge stations from NT government (NRETAS)

StationID	StatioLocation	Agency	Lat	Long	Lat/Long Datum	Elevation (m)(AHD)	Catchment Area (km^2)	Attributes	Frequency	Commence	Cease
G8200045	South Alligator River At El Sherana	NRETAS					1300			19580818	
G8200005	South Alligator Plain	NRETAS									
G8200041	South Alligator at Arnhem Highway	NRETAS	-12.6485	132.5178	GDA94	32.691	10132	cumecs/ML/Day	Daily/Monthly	19690803	20110120
G8200044	Goodparla Creek at Coirwong Gorge	NRETAS					161				
G8200111	Jim Jim Creek At Oenpelli Road Crossing	NRETAS					0			19601111	19800926
G8200112	Nourlangie Creek At Kakadu Highway	NRETAS	-12.8184	132.7410	GDA94	32.713	2220	cumecs/ML/Day	Daily/Monthly	19601111	20061101

Yellow Water Information

Geomorphological Dynamics and Evolution of the South Alligator Tidal River and Plains. Woodroffe, Chappell, Thom and Wallensky, 1986

- South Alligator River has a catchment area of 9000 km^2.
- Tidal influence up to 105 km up the river.
- Annual flows in the wet season are 400-700 m^3/s.
- From Figure 2, catchment at Yellow Water approximately half of the total catchment.
- 275 mm of rainfall in March with 33% runoff
- This would give and average flow at Yellow Water of 150 m^2/s for the month of March, calculated as follows:
  9000 km^2/2*100 ha*10000m^2*0.275 m*0.33/31 d*24 Hr*60 min*60 sec
- Figure 7 gives a band of 3000-5000 m^3/s for a 1% event for the total catchment.
- In 2.2 Tidal Behaviour there is some discussion of flood recording at Arnhem Highway. This is downstream of Yellow Water and about 80% 0f the catchment flows through. A flood of March 1984 was recorded to have a flow of 800 m^3/s, but 300-500 m^3/s was said to be receding tide. This is around 70 km inland, where river width is shown as 500 m and mean tide flows are said to be 1000 m^3/s.
- Figures 16 and 19 indicate that river width and tidal flows drop off quickly upstream of the Arnhem Highway, with width down to 100 m at 85 km inland and tidal flow down to 150 m^3/s at this point.
- Figure 17 shows a tidal range of 3.3 m some 63 km inland with the spring tide. The river is 500 m wide at this point.

Estimations from the above information:

It appears that cross section information and the tidal range is not available at the downstream end of Yellow Water where it is suggested that some form of barrier could be built. Any barrier would need to exclude salt laden tidal flow but allow flows from upstream through in a way close to the existing flow regime. A flood gated barrier may be able to do this, but some form of fish ladder is likely to be required.

Assuming a river width of 100 m and tidal range of 3 m, a preliminary sizing of culverts and a weir was undertaken, assuming a total height from low tide to high tide of about 3 metres. Pipes or culverts 2.44 m high with the top of bank about 0.6 m above the overt was assumed.

Based on the catchment at Yellow Water being about half the total catchment the annual wet season flows were calculated to be about 275 m^3/s, using the average between 400 to 700 m^3/s and half the catchment area ((400+700)/2*2=275). Similarly the Q_{100} flow was estimated to be 2000 m^3/s ((3000+5000)/2*2=2000).

Using a Levee Downstream of Yellow Water

As set out above, based on limited information a level 3 m high with culverts 2.44 m high was adopted.

Culverts

a) Pipes 2.44 m diameter

Initially, pipe culverts were tried, using 2.44 m culverts with about 600 mm gap between meant 33 culverts could be placed, and with minimal head loss these would only pass about 200 m^3/s.

Allowing for a head loss of about 0.25 m the 33 pipes would pass the 275 m^3/s assumed as an annual flow.

Allowing for a head loss of 0.5 m the number of 2.44 m diameter pipes could be reduced to 25.

b) Box Culverts 2.44 by 2.44 m

Large box culverts can be more expensive to lay as they need a base slab. This can be offset to some extent as they achieve a greater area within a set width, and link slabs can be used between the boxes to cut costs. (Using link slabs works best with an uneven number of openings so that the two outside ones can be full culverts, with link slabs on every second opening in between.

The most openings that could be put in the 100 m of river width would be about 37. Using this number of culverts to pass the 275 m^3/s would give a head loss of 0.13 m.

Using 27 openings to pass the same flow would increase head loss to 0.25 m.

Using 23 openings to pass the same flow would increase head loss to 0.35 m.

Using 19 openings to pass the same flow would increase head loss to 0.5 m.

c) Weir Flow in Bigger Events

Once the capacity of the culverts is exceeded water will start to overtop the embankment and it would be desirable to keep depths and velocities over the weir to a minimum to limit the risk of failure.

Flow to be passed in the 100 year event is the 2000 m^3/s, although some of this will go through the culverts. With no level information it is not known how long the levee will be, and it could be shorter than calculated below if surface levels match top of levee level at some point offset from the waterway.

If flood depth over the weir could be kept to 0.5 m, weir flow would be about 0.7 $m^3/s/m$ and a weir some 2.8 km long would be needed.

With a flood depth over the weir of 1 m, weir flow would be about 2 $m^3/s/m$ and a weir some 1 km long would be needed.

Discussion

- The weir/levee and culvert arrangement with floodgates will be expensive and could be prone to failure.
- Maintenance would be a minor issue with debris blocking the floodgates, but this would not be critical as they would still reduce salt intrusion.
- Detailed modeling of the effects of salt intrusion is recommended before any decision is made on building a hard engineered structure.
- Modelling should also look at how long any high tide induced salt intrusion would stay in Yellow Water and whether this would be detrimental to flora.
- If some barrier is required, something more natural at a lower level-say vegetated bars at normal water level as in a wetland-should also be modeled.

Keith Boniface
Melbourne Water

Appendix E Climate Change Review

Climate Change Scenarios for Kakadu Risks to Floodplains Project

Leo X.C. Dutra and Peter Bayliss

01 July 2013

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Contents

Tables

Acknowledgments

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Executive summary

Kakadu National Park (KNP) in north tropical Australia will most likely face rapid rates of sea level rise and changes in rainfall regimes due to predicted changes in climate (Director of National Parks, 2010; CSIRO, 2007; Hyder Consulting, 2008). These changes will adversely impact on its unique habitats and biodiversity with flow on effects on the people who depend on ecosystem goods and services for socio-cultural activities, subsistence and income. Predicted sea level rise will intensify current land- and seascape hazards to natural and cultural values.

A Management Strategy Evaluation (MSE) approach and modelling framework are currently being developed to undertake an integrated assessment of potential effects of sea level rise effects on environmental, cultural, economic and environmental values of KNP. A critical requirement of the Kakadu MSE is the definition of which future scenarios will be explored in the simulation models because there is limited time, computation capacity and funding to simulate and visualise all the possible range of scenarios predicted for the future (see IPCC, 2007; CSIRO, 2007, 2013; Commonwealth of Australia, 2009). Due to development time and costs associated with the development of the hydrodynamic component of the Kakadu MSE it will be possible to explore only four scenarios: the present scenario and three future scenarios, correspondent to years 2030, 2070 and 2100.

The objective of this review is to provide the most updated climate change predictions for the Northern Territory (and Kakadu more specifically) as the basis to select present and future scenarios for simulation in the Kakadu MSE. A natural candidate for the scenarios is the latest predictions from the Intergovernmental Panel on Climate Change (IPCC), Fourth Assessment Report (AR4) (IPCC, 2007) and the regional downscaled IPCC models developed by CSIRO (CSIRO, 2007, 2012), reviews and assessments.

The review included new information from the literature–especially on the sea level rise and extreme weather events– and from personal exchange between the authors of this report and CSIRO scientists working on the forthcoming Fifth IPCC assessment. This update on sea level rise predictions is a major contribution of the present report as in recent times there has been considerable improvements in the knowledge about ice dynamics and contributions to future sea level rise, although uncertainties remain large.

The criteria used to select the climate scenarios for the Kakadu MSE are the following:

1) Use updated credible information (IPCC, published peer reviewed documents (e.g. journal articles).
2) Use regionalised predictions (Australia, Northern Territory, Alligator Rivers Region)
3) When possible, use scenarios previously applied in assessments that complied with 1 and 2, to improve the knowledge base on particular scenarios, and use the wealth of knowledge and data generated in these studies, thus maximising the investments on model development and data gathering.

The proposed scenarios for MSE simulations (2030, 2070 and 2100) and intermediary intervals (2050) are presented in

Table 1. Climate change scenarios chosen by the project team for MSE simulations and visualisation. Note that only the 2030 and 2100 scenarios will be used in the actual simulations. Highlighted in grey are the climate change attributes selected for simulation in the Kakadu MSE (only for years 2030, 3070 and 2100)

Climate Change Attributes	Present	2030	2050	2070	2100
Sea Level Rise	0	0.143m		0.7m	1.1m
Temperature (mean annual)	Max. 34.2°C Min. 21.9°C	+1°C	+2 °C	+3°C	+3 °C
Temperature (mean Early Wet)	33 °C	+1°C	+2 °C	+3°C	+3 °C
Temperature (mean Late Wet)	33 °C	+1°C	+2 °C	+3°C	+3 °C
Temperature (mean Early Dry)	30 °C	+1°C	+2 °C	+3°C	+3 °C
Temperature (mean Late Dry)	30 °C	+1°C	+2 °C	+3°C	+3 °C
Rainfall (annual)	1,077mm	0%	0%	0%	0%
Rainfall (Early Wet)	691mm	0%	0%	+1%	+1%
Rainfall (Late Wet)	267mm	0%	0%	0%	+1%
Rainfall (Early Dry)	6mm	-4%	-2%	-13%	-14%
Rainfall (Late Dry)	113mm	-5%	-5%	-15%	-12%
Average annual areal potential evapotranspiration	2200mm	+3%		+10%	+10%
Extreme Events (wind speed in cyclones)	5-6m storm surge at Junction Bay related to cyclone Monica in April 2006	10% increase in cyclone intensity (wind speed), represented as an increase in 0.15m to the storm surge associated with Monica plus the 0.143m SLR	10% increase in cyclone intensity (wind speed), represented as an increase in 0.15m to the storm surge associated with Monica plus the 0.143m SLR	20% increase in intensity (wind speed), represented as an increase in 0.1m to the storm surge associated with Monica plus the 0.7m SLR	20% increase in intensity (wind speed), represented as an increase in 0.1m to the storm surge associated with Monica plus the 1.1m SLR

1 Introduction

Kakadu National Park (KNP) in north tropical Australia will most likely face rapid rates of sea level rise and changes in rainfall regimes due to predicted changes in climate (Director of National Parks, 2010; CSIRO, 2007; Hyder Consulting, 2008). These changes will adversely impact on its unique habitats and biodiversity with flow on effects on the people who depend on ecosystem goods and services for socio-cultural activities, subsistence and income. Predicted sea level rise is uncertain but will intensify current land- and seascape hazards to natural and cultural values.

Management Strategy Evaluation (MSE) is one framework that can be used to support planning and management in KNP. It has been applied to support natural resource management by allowing the comparison of social, environmental and economic trade-offs associated with alternative management decisions. The framework has also been successful also in improving communication and collaboration between stakeholders (Bunnefeld et al., 2011; Dutra et al., 2010; Dichmont et al., 2006; McDonald et al., 2006; Smith, 1994).

An MSE framework is currently being developed to undertake an integrated assessment of potential effects of sea level rise effects on environmentl, cultural, economic and environmental values of KNP. A critical requirement of the Kakadu MSE is the definition of which future scenarios will be explored in the modelling framework because there is limited time, computation capacity and funding to simulate and visualise all the possible range of scenarios (see IPCC, 2007; CSIRO, 2007, 2013; Commonwealth of Australia, 2009). Due to development time and costs associated with the development of the hydrodynamic component of the Kakadu MSE it will be possible to explore the present scenario and three future scenarios, correspondent to years 2030, 2070 and 2100.

The objective of this review is to provide the most updated climate change predictions for the Northern Territory (and Kakadu more specifically) as the basis to select present and future scenarios for simulation in the Kakadu MSE. A natural candidate for the scenarios is the latest predictions from the Intergovernmental Panel on Climate Change (IPCC), Fourth Assessment Report (AR4) (IPCC, 2007) and the regional downscaled IPCC models developed by CSIRO (CSIRO, 2007, 2012) and reviews, such as Garnaud (2008), and assessments, such as Commonwealth of Australia (2009) and Short and Woodroffe (2009). More regionalised studies focusing in the Northern Territory or Kakadu were also considered. For example, the KNP Climate Change Strategy (Director of National Parks, 2010 and predictions from Hyder Consulting, 2008) and the report titled “Kakadu: vulnerability and climate change impacts” (BMT WBM, 2011).

The review included new information from the literature–especially on the sea level rise and extreme weather events– and from personal exchange between the authors of this report and CSIRO scientists working on the forthcoming Fifth IPCC assessment. This update is a major contribution of the present report as since the IPCC, CSIRO and Hyder Consulting reports there has been considerable improvements in the knowledge about ice dynamics and contributions to future sea level rise, although uncertainties remain large.

2 Methods

The criteria used to select the climate scenarios for the Kakadu MSE are the following:

1) Use updated credible information (IPCC, published peer reviewed documents (e.g. journal articles).
2) Use regionalised predictions (Australia, Northern Territory, Alligator Rivers Region)
3) When possible, use scenarios previously applied in assessments that complied with 1 and 2, to improve the knowledge base on particular scenarios, and use the wealth of knowledge and data generated in these studies, thus maximising the investments on model development and data gathering.

A specific objective of the review was to update information on SLR and storm surges as since 2007 there has been a wealth of studies on the topics of ice dynamics and melting and storm surges were available. As a result, the predictions presented in this report draw substantially on the IPCC Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2007). The information from global assessments was complemented with other regional and/or more detailed local information, such as CSIRO (2007, 2012), Garnaut (2008), Hyder Consulting Pty Ltd (2008), BMT WBM (2011), Commonwealth of Australia (2009) and Short and Woodroffe (2009) and other studies presented in Appendix A.

Projections for differing emissions scenarios generally do not strongly diverge in the coming two to three decades, but uncertainty in the sign of change is relatively large over this time frame because climate change signals are expected to be relatively small compared to natural climate variability (IPCC, 2012). Therefore, we decided to adopt high-end emission scenarios (A1B for 2030 and A1FI for 2070 and 2100). The choice was based on evidence that current global CO_2 emissions are at the high end of IPCC emission scenarios (between scenarios A1B and A1FI), which would lead to a global-mean warming of 4.2-5.0^{o}C by the year 2100 (CSIRO, 2013). The description for this scenario is as follows (from CSIRO, 2007):

The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Scenario A1FI includes fossil intensive energy sources and scenario A1B represents a future with a balance across fossil and non-fossil energy sources.

The climate change factors covered in the review (Appendix A) are the following: sea level rise, temperature (annual, seasonal and extremes, such as number of hot days (>35oC)), average rainfall (annual and seasonal), rainfall patterns (annual and seasonal), relative humidity (annual), potential evapotranspiration (mean annual), evaporation (seasonal), extreme weather events (cyclonic activity), CO2 concentrations, and trade and monsoonal winds. For comparison purposes the temporal scale we covered in the review are pre-historical (Pleistocene and Holocene evidences of past climate changes and impacts), historical (also referred to as baseline (mostly covering the 20th century) and projections up to 2100 AD (CSIRO, 2007). In addition to the literature review we also requested updated information to scientists at CSIRO involved in the forthcoming IPCC AR5 both at global and regional (downscale to Australia) levels. In our review we investigated the effects of each climate change factor with regards to its physical, ecological and human (residents and visitors) impacts, as well as potential indicators and mitigation and adaptation options. This information will also be useful in the construction of future ecological and human models that will be part of the Kakadu MSE.

As part of the review, the authors of the report also contacted CSIRO scientists involved in the next IPCC AR5 assessment (sue in September 2013) with the objective of assessing whether or not there would be major changes in predictions in the forthcoming assessment.

An initial draft document of predictions and scenarios was circulated for comments and also discussed with researchers from the northern NERP (National Environmental Research program) project titled “Threats to coastal floodplains in Kakadu National Park” during a workshop held in Darwin from 25-28 February 2013.

3 Selected climate change scenarios

3.1 The forthcoming IPCC AR5

There is a range of groups from CSIRO currently working on updated climate projections as part of the Coupled Model Inter-comparison Project Phase 5 (CMIP5). The model results from CMIP5 will be included in the next IPCC AR5 report due in September 2013 (Dr Beth Ebert, pers. Comm. 15/01/2013). However, the synthesized information about new modelling results that will be included in the forthcoming IPCC CMIP5 report is not yet available. Some model runs have been performed by CSIRO scientists who are in the process of analysing the data. So far, there are no unexpected changes in atmospheric quantities when compared to CMIP3 (Dr Jonas Bhend (CSIRO), pers. comm. 18/01/2013). Information for sea level rise, storminess, and wave climate was requested to Dr Penny Wheeton, Dr Michael Grose and Dr John Church, but as for the 05/02/2013 no further information was received.

Initial analysis of global climate models (GCM) as part of CMIP5/AR5 does not show major changes in the projections for Australia but results of downscaled models should be available by end of March 2013 for global 50 km results for 6 global GCMs and 2 representative concentration pathways (RCP) (a high and low scenario) (Jack Katzfey, pers. Comm. 25/01/2013).

3.2 Scenarios for MSE model simulations in Kakadu

A copy of the draft climate change scenarios review (this document) was sent to the project team prior to a workshop held in Darwin on February 24-28 2013. During the workshop the project team decided to use the most likely scenarios from IPCC AR4 for 2030 and 2100 and also to look at intermediary time intervals when possible (e.g. 2050, 2070). This was possible for all but the SLR scenarios, as “most likely” scenarios for SLR are not available for two reasons (Meehl et al., 2007:820): (1) the observational constraint on sea level rise projections is weaker (compared to temperature for example), because records are shorter and subject to more uncertainty; and (2) the current scientific understanding leaves poorly known uncertainties in the methods used to make projections for sea ice. Due to the lack of “most likely” SLR scenarios we decided to adopt updated predictions from high emission scenarios. For storm surges the project team suggested the simulation of a known event, such as cyclone Monica in 2006, as it provides a “known” example that some residents and managers of KNP could related to their experiences. The proposed scenarios for MSE simulations (2030, 2070 and 2100) and intermediary intervals (2050) are presented in

Table 2. Climate change scenarios chosen by the project team for MSE simulations and visualisation. Note that only the 2030 and 2100 scenarios will be used in the actual simulations. Highlighted in grey are the climate change attributes selected for simulation in the Kakadu MSE (only for years 2030, 3070 and 2100)

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Appendix A Literature Review on climate change projections

Sea Level Rise

A useful review on the causes of contemporary regional sea level changes is discussed by Stammer et al. (2013) and the reader can refer to this reference for details on sea level dynamics. The range of sea level rise predictions for the 21st century varied between, 0.03m (2030) to 2m (2100) (Table 3), reaching up to 5-7m if ice sheets of Greenland and West Antarctica melt completely (Steffen and Hughes, 2013) and even with some authors suggesting a 9m rise in sea level (Foster and Rohling, 2013). Pre-historical data supports the 2m range of sea level rise predictions where Rohling et al. (2008) found mean global temperatures 2^{o}C warmer than present during Pleistocene, which is comparable to future projections of climate change (see predictions on the section "Temperature" below). Under these conditions the rate of sea level rise was 1.6m/century. Climate records from the end of the last interglacial period, also showed that when the northern hemisphere ice sheets disintegrated, sea-level rise peaked at a rate of 4 m/century. This indicates that substantially higher rates of sea-level rise than those predicted by the IPCC have occurred historically and these changes are within the temperature predictions for the next century (Church et al., 2008; Garnaut, 2008). As a result, there remains considerable uncertainty about the magnitude of global sea level rise that will eventuate by the end of the century. In addition to the uncertainty around the behaviour of the polar ice sheets, a fundamental source of uncertainty is the rate at which greenhouse gases will be emitted by human activities through the rest of the century (Steffen and Hughes, 2013).

Global sea level rise is projected by the IPCC AR4 to be between 0.18-0.59 m by 2100, with a possible additional contribution from ice sheets of 0.1 m to 0.2 m (CSIRO, 2007; IPCC, 2007). There are large uncertainties around the contribution of ice sheets to global sea level (see Bamber and Aspinall, 2013; Foster and Rohling, 2013; Steffen and Hughes, 2013), with some authors (e.g. Carlson et al., 2008; Commonwealth of Australia, 2009; Short and Woodroffe, 2009) suggesting that the IPCC AR4 projections should be considered "minimum" even without ice sheet dynamics. The arguments for higher sea levels for 2100 than those predicted by the IPC are the following:

1. Predictions of the rate of sea level rise from the Greenland Ice Sheet (GIS) by the end of this century in the IPCC AR4 A1B scenario are 6–40 times smaller than the estimated rate of the Laurentide Ice Sheet (LIS) mass loss in the early Holocene. Given the similar summer surface air temperature responses for these two periods, and the geologic evidence for rapid early Holocene LIS retreat, current projections of GIS melt rates for the coming century may be only minimum estimates even without considering positive feedbacks from ice-sheet dynamics (Carlson et al., 2008).
2. Observations also point to higher sea level rise than that predicted by the IPCC (2007). For example, Shepherd et al. (2012) observed an increasing contribution of the Greenland and Antarctic ice sheets to sea-level rise, where Greenland contributed 0.2 to 0.4mm per year to sea level rise between 1992 and 2009, and increased to 0.4 to 0.7mm per year for the period between 2002 to 2009 (ACE CRC, 2012). Also, rates of sea level rise observed from a tidal gauge in Darwin (NT) between 1990 and 2011 was 8.6mm/year (NTC, 2011), thus supporting the global trends in accelerating sea level rise described above. Church and White (2011) also observed an accelerating sea level trend in the last decades of 2.8 – 3.2mm per year for the period between 1993 and 2009.
3. Another factor that supports the argument of higher sea levels by the end of the 21st century than the high-end predictions of the IPCC (2007) is the thermal inertia in both the oceans and the larger polar ice sheets (Steffen and Hughes, 2013; Meehl et al., 2012). This means that even if humans manage to reduce emissions, there will be a time period where temperature would still continue to

rise, leading to continuation in melting ice. In particular, increase in temperature could lead to the crossing of a threshold for the Greenland ice sheet later this century, leading to the decay of much of the ice sheet (Lenton et al., 2008) and consequent increase in the rate of rise of sea level (Steffen and Hughes, 2013).

The combined scientific observations and modelling evidence for Australia are pointing to changes in the climate system at the upper end of projections in the 2007 IPCC AR4 report (CSIRO, 2007; IPCC, 2007), or even above it, where mid-range of predictions from several authors generally converge above 1m (Rahmstorf, 2007a, 2007b; Short and Woodroffe, 2009; Commonwealth of Australia, 2009; Vermeer and Rahmstorf, 2009; Jevrejeva et al., 2010; Rahmstorf et al., 2012; Schaeffer et al., 2012; Grinsted et al., 2009).

PHYSICAL IMPACTS

Predicting sea level rise is complex as global variations can be large relative to mean sea level and will occur as a result of variations in wind change, changes in atmospheric pressure and oceanic circulation, and associated differences in water density and rates of thermal expansion (IPCC, 2007; 2012). In addition, if rapid melting of ice sheets occurs it would lead to non-uniform rates of sea level rise across the globe due to adjustments in the Earth's gravitational field (IPCC, 2012; CSIRO, 2007; Carlson et al., 2008). On some coastlines, higher mean sea levels may alter the astronomical tidal range and the evolution of storm surges, and increase the wave height in the surf zones. As well as gradual increases in mean sea level that contribute to extreme impacts from transient extreme sea levels, rapid changes in sea level arising from, for example, collapse of ice shelves could be considered to be an extreme event with the potential to contribute to extreme impacts in the future. However, knowledge about the likelihood of such changes occurring is limited and so does not allow an adequate assessment at this time (IPCC, 2012).

Coastal floodplains in Kakadu are extremely vulnerable to climate change impacts, such as sea level rise and storm surges, because they are just 0.2 – 1.2m above mean high water level (Hyder Consulting Pty Ltd, 2008; Bayliss et al., 1997). The physical impacts in the Park associated with sea level rise include increased coastal erosion, saltwater intrusion into floodplains and groundwater, and increased severity of storm-surge events (Church et al., 2008; Hyder Consulting Pty Ltd, 2008). Above-average ocean water recorded between 1954-2000 suggest that future projections of sea level rise will also increase the extension of tidal influences along former and existing stream channels, also affecting the expansion of small tidal creeks and mudflats, leading to the formation of new tidal creeks, and accretion of sediment on the floodplain adjacent to, and at the end of, tidal channels (Winn et al., 2006). Increased tidal exchange and salinisation, as well as potentially large changes in salinity structure on major rivers and streams due to increased tidal exchange are also expected (Cobb et al., 2007).

The effectiveness of dams and levees across tidal channels of the South and East Alligator Rivers to prevent saltwater intrusion is an evident management option. However, its efficacy is questionable because, as indicated above, tributary (gully scour) and distributary (depositional fans) in the headwaters of tidal creeks indicate that some creeks are eroding salt flats and lowering the land surface whereas others are depositing sediments and raising it. The geography of deposition versus erosion is unknown but thought to be related to floodplain adjustment to relative change in sea level at an inter-decadal scale (Cobb et al., 2007).

ECOLOGICAL IMPACTS

Higher seas will affect ecological values via displacement of existing habitats (e.g. *Melaleuca* wetlands) with encroaching habitats (e.g. mangroves, mudflats and saline wetlands) and increase in the area of salt tolerant meadows. Alteration of structure and composition of existing freshwater plant and animal species as well as shifts in the spatial zoning of coastal and floodplain ecosystems are also expected (Bayliss et al., 1997; Hyder Consulting Pty Ltd, 2008; Director of National Parks, 2010). Higher seas recorded between 1950-2000 led to scour and die-back within stands of *Melaleuca* spp. forests, expansion of mangroves and tidal creeks (Cobb et al., 2007). Projected increases in sea level will also cause the adjustment of zonation of nearshore environments and sandy beaches in response to shoreline recession and erosion (Winn et al., 2006). Saltwater intrusion will negatively affect waterbird population that depend on freshwater habitats (Traill et al., 2009).

HUMAN IMPACTS

Human impacts associated with rising seas include contamination of ground water with salt water with impacts on irrigation and agriculture, as well as on potable water supplies. Sea level rise will also cause negative impacts on infrastructure through inundation (e.g. roads, bridges, houses) (Hyder Consulting Pty Ltd, 2008; Director of National Parks, 2010). Higher seas may also inundate and/or restrict access to sacred/cultural/hunting/tourism sites, and is also likely to impact on flowering and fruiting of the distribution and abundance of traditional food sources (e.g. magpie geese, water lilies, fish, turtles and crocodiles) and alter the bush tucker which, in turn, may limit traditional hunting and gathering activities (Director of National Parks, 2010). The impacts of SLR on indigenous social and cultural values is a potential source of conflicts between indigenous groups due to customary land tenures issues associated with land inundation and possible relocation and access to resources (Jackson et al., 2008).

Climate change may provide some opportunities for indigenous communities in KNP through participation in carbon trading programs and employment opportunities in monitoring the impacts of climate change and undertaking remedial and mitigation activities (Director of National Parks, 2010).

CHOICE OF SEA LEVEL SCENARIOS

Based on the literature review, we selected the following sea level rise scenarios for the Kakadu MSE simulations:

1. 0.143m for 2030
2. 0.70m for 2070
3. 1.1m for 2100

The value of 0.143m for 2030 was provided to BMT WBM for the report "Kakadu: vulnerability and climate change impacts" by the Department of Climate Change and Energy Efficiency (DCCEE) and is within the range suggested by CSIRO (2007) 0.03 to 0.17m. The BMT WBM (2011) report was Kakadu-specific, commissioned by the DCCEE and recently published (2011), hence our decision to use their scenario. Associaed with these scenarios is the

The BMT WBM report also used the 0.7m in their 2070 scenario, which includes the ice contribution as suggested in the CSIRO (2007) and IPCC (2007) reports, hence our decision to use 0.7m for this scenario. The value for 2070 (0.50m) from Hyder Consulting (2008) used in the Kakadu Climate Change Strategy (Director of National Parks, 2010) did not consider the melting ice contribution to sea level rise, which only recently have received more attention in SLR predictions.

Predictions for 2100 were not presented by the Kakadu Climate Change Strategy nor in the BMT WBM report. Our decision to adopt the 1.1m was based on the fact that several authors, including the IPCC, suggest that there is large uncertainty and knowledge gaps on the dynamics of ice melting. Several authors (refer to Table 3) suggest that the high-end projection provided by the IPCC (2007) of 0.8m (0.59 SLR + 0.2m melting ice) by 2100 should be considered "minimum". In a study published in 2009 for the coast of Australia, Short and Woodroffe (2009) proposed the range of SLR to be between 0.75 – 1.9m by 2100, with 1.1m as the mid range of projections. The Commonwealth of Australia (2009) also recognised this value, hence our decision to adopt the 1.1m value in the 2100 scenario.

Table 3. Range of sea level predictions sourced from the literature.

Time Scale	Predicted or observed changes	Spatial Scale	Potential Indicator	Mitigation / Adaptation	References
2030	+0.17m	Kakadu National Park	Salinity and amphibians	Barrages	Hyder Consulting Pty Ltd, 2008; Bayliss et al., 1997; Church et al., 2008
2030	+0.143m	Kakadu National Park			BMT WBM, 2011
2030	+0.17m	Kakadu National Park			Hyder Consulting Pty Ltd, 2008; Director of National Parks, 2010
2030	+0.03m – 0.17m	Global			CSIRO, 2007
2030	+0.2m (±0.1m)				Bayliss et al., 1997
2070	+0.50m	Kakadu National Park			Hyder Consulting Pty Ltd, 2008; Director of National Parks, 2010
2070	+0.70m	Kakadu National Park			BMT WBM, 2011
2070	+0.07m – 0.49m (does not include ice contribution)	Global			CSIRO, 2007
2100	Contribution of ice sheets only using an expert panel: 0.29m (median) 0.84m (95th percentile)	Global			Bamber and Aspinall, 2013
2100	+0.5m (0.25m – 0.8m)				Bayliss et al., 1997
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
2100	Accelerating sea level rise	Global			Church and White, 2006; Gehrels and Woodworth, 2013
2100	0.75-1.9m (1.1m as the mid range of the projection)	Australian coast			Short and Woodroffe, 2009; Commonwealth of Australia, 2009
2100	Cumulative sea level rise of 0.25m due only to melting ice	Global			Spada et al. 2013
2100	>9m (68% confidence, using geological evidence): results imply that a long-term 2 °C warming [CO2 between 400 and 450	Global			Foster and Rohling, 2013

Time Scale	Predicted or observed changes	Spatial Scale	Potential Indicator	Mitigation / Adaptation	References
	ppm] would mean acceptance of likely long-term sea-level rise by more than 9 m above the present.				
2100	1m with unmitigated emissions 0.8m (with a reduction in emissions to hold warming below 2^{o}C) and 1.025	Global			Schaeffer et al., 2012
2100	0.8m-1.3m	Global			Grinsted et al., 2009
1950-2000	above average ocean-water levels	Kakadu National Park (East Alligator River; 15km from Point Farewell)	*Melaleuca spp. Forests*, Mangrove forests, area of saline mudflats,		Winn et al., 2006
124k - 119k yr BP	1.6m per century	Global			Rohling et al., 2008
1950 - 1991	Changes in the distribution of mangroves, Maeleleuca spp and tidal channels in the ARR from 1950-2000	Alligator Rivers Region and streams debouching into the Southern waters of Van Diemen's Gulf		Dams, levees and buffers across tidal channels. (Traill et al., 2009)	Cobb et al., 2007; Traill et al., 2009
1980-1999	+0.18m	Global	Sea Level		IPCC, 2007
2090-2099	+0.59m (+0.1 to 0.2m due to ice melting)	Global	Sea Level		IPCC, 2007
1961-2003	Rate of sea level rise was 1.8 mm per year	Global			CSIRO, 2007; Church, 2006
1993-2003	Rate of sea level rise was 3.0 mm per year	Global			CSIRO, 2007; Church, 2006
1993-2003	Rate of sea level rise was 3.0 mm per year	Global		Some recent fluctuations in the rate of sea-level rise are linked to short-term cooling caused by the injection of aerosols into the stratosphere from volcanic events, for example Mt Agung in Bali	Church and White, 2011
1990 - 2011	Rise in sea level of 8.6 mm/year	Darwin			NTC, 2011
1900-1999	Rate of sea level rise was 1.2mm per year	Australia			Church, 2006; Church, 2006
1993-2011	Rate of sea level rise of 3mm per year in	Global			Dean and Houston, 2013

Time Scale	Predicted or observed changes	Spatial Scale	Potential Indicator	Mitigation / Adaptation	References
	the 1990				
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 (A1FI)	0.26m - 0.59m; central estimate 0.43m + 0.1 – 0.2 from ice sheets	Global			CSIRO, 2007

Mean Annual and Seasonal Temperatures

Mean monthly temperatures in KNP range from 21.9^{o}C to 34.2^{o}C, where the coolest months are in the dry season (June to November) (Hyder Consulting Pty Ltd, 2008). Increase in annual mean temperature in the KNP region is predicted to be +1.3°C (±0.6°C) by 2030 and +4°C (±1.7°C) by 2070 (Hyder Consulting Pty Ltd, 2008). For Darwin the IPCC AR4 predicts increase in median values of 1^{o}C by 2030(A1B) and 3.2^{o}C by 2070 (A1F1). The predictions for 2100 (for the broad Northern Region of Australia north of 30^{o}S) ranges from 2.8^{o}C to 3.5^{o}C (3.0^{o}C as the median value) (Christensen et al., 2007) (

Table 4). In addition to increase in the average annual temperature, it is expected that changes in seasonal temperature patterns will also occur as well as an increase in the number of hot days (35°C) (

Table 4).

PHYSICAL IMPACTS

Higher temperatures will increase the probability of more intense and frequent fires in the future (Bowman et al., 2010; Christensen et al., 2007; Hyder Consulting Pty Ltd, 2008; Director of National Parks, 2010).

ECOLOGICAL IMPACTS

Rise in temperature will have a profound impact on the ecology of animals and plants (both aquatic and terrestrial species) in KNP. It is expected that higher temperatures will cause a decline in amphibian populations, local extirpations and range shifts of freshwater fish species, also promoting changes in sex ratios of reptile species such as the pig nose turtle, and salt- and fresh-water crocodiles (Director of National Parks, 2010). The effects of increased water temperatures are also indirect, via reducing dissolved oxygen concentrations and increasing fish metabolism causing an oxygen debt (by increasing demand and reducing supply) (Hyder Consulting Pty Ltd, 2008).

Rising temperatures are likely to lead to increased prevalence of parasites in birds, and may force shifts of bird distribution to higher elevation grounds (Zamora-Vilchis et al., 2012). Birds that experience limited temperature variation and have low basal metabolic rates will be the most prone to the physiological effects of warming temperatures and heat waves (Sekercioglu et al., 2012). A 3.5 °C surface warming by the year 2100 may result in 600–900 extinctions of land bird species, 89% of which occur in the tropics, due to habitat loss. Depending on the amount of future habitat loss, each degree of surface warming could lead to approximately 100–500 additional bird extinctions (Sekercioglu et al., 2012).

While monsoon rainforest trees can recover following a single fire, they are susceptible to recurrent fires and are therefore vulnerable to increases in fire frequency that will be more likely with predicted increases in temperature. Conversely the tolerance of savanna trees to fire is thought to explain why they dominate the monsoon tropical landscape despite having lower growth rates and assimilation rates compared to monsoon rainforest trees (Bowman et al., 2010).

HUMAN IMPACTS

It is expected that increases in average annual temperatures will also increase the incidence of vector-borne diseases, such as dengue (Earnest et al., 2012; Zamora-Vilchis et al., 2012). In Kakadu higher temperatures and extreme weather events may facilitate the spread and re-emergence of diseases such as malaria, encephalitis and meliodosis (Australian National University, 2009). Increase in average annual temperatures may also affect tourists' comfort, expectations and satisfaction and increase the incidence of heat stroke and heat stress in visitors and Park staff (Hyder Consulting Pty Ltd, 2008; Director of National Parks, 2010). Predicted higher temperatures will possibly change tourism seasons (tourists coming in periods that are not too hot) and along with the increase in the number of hot days it will also increase energy demand for cooling systems and cause negative impacts on livestock and crops (CSIRO, 2007; Director of National Parks, 2012).

CHOICE OF TEMPERATURE SCENARIOS

Based on the literature we selected the following scenarios for temperature:

1. An increase in 1^{o}C on mean annual temperature by 2030
2. An increase in 3^{o}C in mean annual temperature by 2070
3. An increase in 3^{o}C by 2100

The 2030 and 2070 scenarios are based on regional projections for Darwin from downscaled IPCC (2007) models made by CSIRO (2007). The median value for increase in temperature presented in a regional Australian assessment for 2100 (Christensen et al., 2007) is slightly lower (3.0^{o}C) than that provided for 2070 for Darwin (3.2^{o}C), but still within the range of predictions. Given the relative low difference in predictions and associated uncertainties we decided to use the same value of 3^{o}C for increase in temperature for both 2070 and 2100 temperature scenarios.

Table 4. Range of temperature (average annual, seasonal and number of hot days) predictions sourced from the literature.

Annual / Season	Time Scale	Predicted or observed changes	Spatial Scale	Potential Indicator	Mitigation / Adaptation	References
Annual	Baseline (1975 - 2004)	Max 34.2°C / Min 21.9°C	Kakadu National Park	Fish, amphibians, reptiles		Hyder Consulting Pty Ltd, 2008; Earnest et al., 2012
	2030	0.75°C - 1.0°C	Australia			CSIRO, 2007,

Annual / Season	Time Scale	Predicted or observed changes	Spatial Scale	Potential Indicator	Mitigation / Adaptation	References
						2012
	2050	1.2°C - 2.2°C	Australia			CSIRO, 2007, 2012
	2070	1.8°C - 3.4°C	Australia			CSIRO, 2007, 2012
	2030	+1.3°C (±0.6°C)	Kakadu National Park			Hyder Consulting Pty Ltd, 2008
	2070	+4°C (±1.7°C)	Kakadu National Park			Hyder Consulting Pty Ltd, 2008
	2100	+4°C (possible from 2060)	Global			Stafford-Smith et al., 2011
	2011-2030	+0.64°C - 0.69°C (±0.05°C)	Global	Surface Air Temperature		IPCC, 2007
	2046-2065	+1.3°C -1.8°C (±0.05°C)	Global	Surface Air Temperature		IPCC, 2007
	2090-2099	+1.8°C (1.1 to 2.9°C) to 4.0°C (2.4 to 6.4°C)	Global	Surface Air Temperature		IPCC, 2007
	2180-2199	+2.1°C -3.4°C (±0.05°C)	Global	Surface Air Temperature		IPCC, 2007
	2020	+0.1°C -1.0°C; central estimate 0.5°C	Australia (0-400km inland of coast)			Hennessy et al., 2007
	2050 (high emission)	+1.5°C (10p); + 2.0°C (50p); 3.0°C (90p)	Northern Territory			CSIRO, 2012
	2050	+0.3°C -2.7°C; central estimate 1.5°C	Australia (0-400km inland of coast)			Hennessy et al., 2007
	2080	+0.4°C -5.4°C; central estimate 2.9°C	Australia (0-400km inland of coast)			Hennessy et al., 2007
	2030	+0.4°C -2.0°C	Global (Stafford-Smith et al., 2011) and Australia (Christensen et al., 2007)			Christensen et al., 2007; Stafford-Smith et al., 2011
	2070	+1.0°C - 5.0°C	Australia			CSIRO, 2013
	2070	+1.0°C -6.0°C	Australia			Christensen et al., 2007
	2100	+3.0°C (median) range of 2.8°C to 3.5°C	Northern Australia, north of 30°S			Christensen et al., 2007
	2030 (A1B)	+0.7°C (10p); + 1.0°C (50p); 1.4°C (90p)	Darwin			CSIRO, 2007
	2070 (B1)	+1.2°C (10p); + 1.7°C (50p); 2.3°C (90p)	Darwin			CSIRO, 2007

Annual / Season	Time Scale	Predicted or observed changes	Spatial Scale	Potential Indicator	Mitigation / Adaptation	References
	2070 (A1F1)	+2.3°C (10p); + 3.2°C (50p); 4.4°C (90p)	Darwin			CSIRO, 2007
Early Wet (DJF)	1961-1990	30°C -33°C	KNP			Bureau of Meteorology, 2013c
	2030(A1B)	+0.7°C (10p); + 1.0°C (50p); 1.4°C (90p)	Darwin			CSIRO, 2007
	2050 (high emission)	+1.5°C (10p); + 2.0°C (50p); + 3.0 °C (90p)				CSIRO, 2012
	2070 (B1)	+1.1°C (10p); + 1.6°C (50p); 2.4°C (90p)	Darwin			CSIRO, 2007
	2070 (A1F1)	+2.1°C (10p); + 3.2°C (50p); 4.6°C (90p)	Darwin			CSIRO, 2007
	2100	+3.1°C (median) range of 2.6°C to 3.7°C	Northern Australia, north of 30°S			Christensen et al., 2007; Bowman et al., 2010
Late Wet (MAM)	1961-1990	30°C - 33°C	KNP			Bureau of Meteorology, 2013c
	2030(A1B)	+0.7°C (10p); + 1.0°C (50p); 1.5°C (90p)	Darwin			CSIRO, 2007
	2050 (high emission)	+1.5°C (10p); + 2.0°C (50p); 3.0°C (90p)	Northern Territory			CSIRO, 2012
	2070 (B1)	+1.1°C (10p); + 1.7°C (50p); 2.4°C (90p)	Darwin			CSIRO, 2007
	2070 (A1F1)	+2.2°C (10p); + 3.3°C (50p); 4.7°C (90p)	Darwin			CSIRO, 2007
	2100	+3.1°C (median) range of 2.7°C to 3.6°C	Northern Australia, north of 30°S			Christensen et al., 2007
Early Dry (JJA)	1961-1990	27°C -30°C				Bureau of Meteorology, 2013c
	2030(A1B)	+0.7°C (10p); + 1.0°C (50p); 1.4°C (90p)	Darwin			CSIRO, 2007
	2050 (high emission)	+1.5°C (10p); + 2.0°C (50p); 3.0°C (90p)	Northern Territory			CSIRO, 2012
	2070 (B1)	+1.1°C (10p); + 1.7°C (50p); 2.3°C (90p)	Darwin			CSIRO, 2007
	2070 (A1F1)	+2.2°C (10p); + 3.2°C (50p); 4.5°C (90p)	Darwin			CSIRO, 2007

Annual / Season	Time Scale	Predicted or observed changes	Spatial Scale	Potential Indicator	Mitigation / Adaptation	References
	2100	+3.0°C (median) range of 2.7°C to 3.3°C	Northern Australia, north of 30°S			Christensen et al., 2007
Late Dry (SON)	1961-1990	27°C-30°C	KNP			Bureau of Meteorology, 2013c
	2030(A1B)	+0.7°C (10p); + 1.0°C (50p); 1.4°C (90p)	Darwin			CSIRO, 2007
	2050 (high emission)	+1.5°C (10p); + 2.0°C (50p); 3.0°C (90p)	Northern Territory			CSIRO, 2012
	2070 (B1)	+1.2°C (10p); + 1.7°C (50p); 2.3°C (90p)	Darwin			CSIRO, 2007
	2070 (A1F1)	+2.3°C (10p); + 3.3°C (50p); 4.4°C (90p)	Darwin			CSIRO, 2007
	2100	+3.2°C (median) range from 3.0°C to 3.8°C	Northern Australia, north of 30°S			Christensen et al., 2007
	2100	Increase in temperature across seasons and annually			Conservation of upland tropical areas as they are currently a low-disease habitat (Zamora-Vilchis et al., 2012)	Christensen et al., 2007; Zamora-Vilchis et al., 2012; Sekercioglu et al., 2012
Annual number of hot days	Baseline (1975 - 2004)	11 days	Kakadu National Park			Hyder Consulting Pty Ltd, 2008
	2030	+62 days	Kakadu National Park			Hyder Consulting Pty Ltd, 2008
	2070	+295 days	Kakadu National Park			Hyder Consulting Pty Ltd, 2008
	1999 (current)	10.8 days	Darwin			CSIRO, 2007
	2030 (A1B)	27.9 (10p); 44 (50p); 68.8 (90p)	Darwin			CSIRO, 2007
	2070 (B1)	49 (10p); 89.4 (50p); 153.1 (90p)	Darwin			CSIRO, 2007
	2070 (A1F1)	140.6 (10p); 226.8 (50p); 308.3 (90p)	Darwin			CSIRO, 2007

Mean Annual and Seasonal Rainfall

The climate in Kakadu is monsoonal with a hot wet season from November to March accounting for 90% of the average annual rainfall (Hamilton and Gehrke, 2005) of 1,077mm (Hyder Consulting Pty Ltd, 2008). The hydrology of the Park is highly dependant on rainfall patterns, where several major rivers and associated floodplains inundate during the wet season. Floodplains can be underwater for periods of up to four months, where during the dry season they drain and water evaporates from the back swamps. As the water drops, the remaining water bodies become important refuge areas for animals and plants (Hyder Consulting Pty Ltd, 2008; McMahon et al., 1992).

There are contrasting predictions for the Kakadu region where Hyder Consulting Pty Ltd (2008) propose that by 2070 there will be extended dry periods and more frequent and intense rainfall periods, whereas Moise and Colman (2012) suggest a small mean change in the seasonal cycle of precipitation over tropical Australia, but with precipitation increase during March and April, resulting in prolonged wet seasons. Rainfall predictions are highly variable and uncertain (Bureau of Meteorology, 2013a), ranging from large decrease and increase in annual rainfall for the 21st century (Table 3). However, the regionalised predictions from CSIRO (2007) suggest "no change" for annual rainfall. Due to the high variability in current and future rainfall scenarios we present below possible effects of an increase or decrease of rainfall.

Changes in rainfall regimes are strongly associated with the occurrence of El-Niño events. It is expected that change in ocean temperature will affect the occurrence of El-Niño events, however the IPCC AR4 suggest that there is no evidence that El-Niño events will intensify in the future. There are nevertheless disagreements on future occurrences and intensity of El Niño events (Garnaut, 2008:98). For example, historical El-Niño like conditions have occurred in the last 1000 years, for periods of up to 160 years that influenced the inundation extent of floodplains in Kakadu as well as the habitats they support (Wasson and Bayliss, 2010) with similar findings elsewhere in the world (Martin et al., 1993).

PHYSICAL IMPACTS

Changes in rainfall will affect runoff and streamflow, in turn affecting delivery of sediments and nutrients to downstream habitats. Increased rainfall amount and intensity increases sediment transport rates but total loads will be highly variable and non-linear (Hancock, 2012). In terms of impact of increased rainfall and storms on sediment output, the more frequent returns of high intensity rainfall increases sediment output but average concentration may reduce as a result of the increased discharge (Hancock, 2012). Localised salinity changes associated with changes in rainfall regimes may occur in nearshore waters, particularly near stream mouths potentially affecting seagrasses and inshore biota. Changes in groundwater state of sandy beaches may contribute to rates of erosion (Cobb et al., 2007).

ECOLOGICAL IMPACTS

Periods of below average rainfall may increase the risk of local extinctions in several mammal species (Braithwaite and Muller, 1997) through negative affects on groundwater levels and vegetation productivity. Decrease in rainfall and associated hydrological cycles could increase the vulnerability of fish and amphibian populations to detrimental exposures of UV-B. The ecological impacts associated with an increase in rainfall, especially if the wet season is extended, will enhance both the spread and productivity of mangrove, saltflat and samphire communities, although increased storminess will inflict some damage on these vegetation communities (Hyder Consulting, 2008).

Increased rainfall will also promote mangrove levee destabilisation due to flooding, basal sapping of banks on tidal creek, and movement of the saline wedge in major rivers and streams. Some bird, fish and invertebrate communities dependent on these areas for foraging and habitat may be advantaged by an expansion in habitat range. Contrasting to Hyder Consulting Pty (2008), Traill et al. (2009) propose that extended periods of inundation associated with possible increases in annual rainfall will negatively affect habitats that support waterbirds. Data from the Simpson desert suggest that increases in the magnitude and frequency of extreme rainfall events are likely to drive changes in the populations of mammals through direct and indirect changes in predation pressure and wildfires (Greenville et al., 2012).

Nesting behaviour of the Australian freshwater turtles *Emydura macquarii* and *Chelodina expansa* is related to rainfall. A decrease in rainfall may adversely affect the reproduction of these animals. An increase in the number of El Niño events may have adverse effects on these two species by delaying nesting, making nesting construction more difficult, or making nests more conspicuous to predators (Bowen et al., 2005).

Alterations to the predictability or variability of the seasons in the region may interrupt life cycles and species population dynamics. In addition, changes in the availability of water may offset the ability of amphibian species to cope with climate warming. Limited dispersal ability may further increase the vulnerability of amphibians (and reptiles) to changes in climate (Hyder Consulting Pty Ltd, 2008). Winn et al. (2006) suggest that a decline in wet-season rainfall and flood events will most likely cause scour and die-back within stands of *Melaleuca* spp forests as recorded in the 1970s.

HUMAN IMPACTS

Hanigan et al. (2012) found an increased relative risk of suicide (associated with droughts) of 15% for rural males aged 30-49 year. In contrast, the risk of suicide for rural females aged >30 y declined with droughts.

As pointed out above, river flow regimes and wetlands in the NT are intrinsically dependant on rainfall and resident indigenous people in the region are “intimately connected to these landscapes via customary tenure, cosmological beliefs and a body of environmental knowledge accumulated over hundreds of generations of actively caring for country” (Jackson et al., 2008). Therefore, changes in rainfall are expected to impact on indigenous social and cultural values and may also be a potential source of conflicts between indigenous groups due to customary land tenures issues associated with land inundation and possible relocation, which is exacerbated by effects of higher seas.

CHOICE OF RAINFALL SCENARIOS

The literature suggests a “no change” in future mean annual rainfall for the KNP region (CSIRO, 2007, 2012, 2013). For this reason we decided to use no change in rainfall in all MSE scenarios (2030, 2070 and 2100).

Table 5. Range of rainfall (average annual and seasonal) predictions sourced from the literature.

Annual / Seasonal	Time Scale	Predicted or observed changes	Spatial Scale	Potential Indicator	References
Annual	Baseline (1975 - 2004)	1077mm	Kakadu National Park		Hyder Consulting Pty Ltd, 2008; Traill et al., 2009; Hancock, 2012
	2030	0% (±7%)	Kakadu National Park		Hyder Consulting Pty Ltd, 2008
	2070	0% (±23%)	Kakadu National Park		Hyder Consulting Pty Ltd, 2008
	2030 (A1B)	-7% (10p); 0 (50p); +6% (90p)	Darwin		CSIRO, 2007
	2050	-5% (10p); 0 (50p); +20% (90p)	Northern Territory		CSIRO, 2012
	2070 (B1)	-11% (10p); -1% (50p); +10% (90p)	Darwin		CSIRO, 2007
	2070 (A1F1)	-21% (10p); -1% (50p); +20% (90p)	Darwin		CSIRO, 2007
	2030	-10% - +5%	Northern Areas		CSIRO, 2007
	2050	-15% - +7.5%	Northern Areas		CSIRO, 2007, 2012
	2070	-30% - +20%	Northern Areas		CSIRO, 2007

Annual / Seasonal	Time Scale	Predicted or observed changes	Spatial Scale	Potential Indicator	References
	2100	uncertain	Northern Australia		Christensen et al., 2007
Early Wet Season (DJF)	Baseline (1975 - 2004)	691mm	Kakadu National Park	Amphibians and reptiles	Hyder Consulting Pty Ltd, 2008
	2030	0% (±7%)	Kakadu National Park		Hyder Consulting Pty Ltd, 2008; Moise and Colman, 2009
	2070	0% (±23%)	Kakadu National Park		Hyder Consulting Pty Ltd, 2008
	2030 (A1B)	-6% (10p); 0% (50p); +7% (90p)	Darwin		CSIRO, 2007
	2050 (high emissio n)	-10% (10p); 0 (50p); +20% (90p)	Northern Territory		CSIRO, 2012
	2070 (B1)	-10% (10p); 0% (50p); +11 (90p)	Darwin		CSIRO, 2007
	2070 (A1F1)	-18% (10p); +1% (50p); +21% (90p)	Darwin		CSIRO, 2007
	2100	1% (-8% - 8%)	Northern Australia, north of 30^{o}S		Christensen et al., 2007; Moise et al., 2012
Late Wet Seson (MAM)	Baseline (1975 - 2004)	267mm	Kakadu National Park		Hyder Consulting Pty Ltd, 2008
	2030	0% (±15%)	Kakadu National Park		Hyder Consulting Pty Ltd, 2008
	2070	0% (±45%)	Kakadu National Park		Hyder Consulting Pty Ltd, 2008
	2030 (A1B)	-11% (10p); 0% (50p); +11% (90p)	Darwin		CSIRO, 2007
	2050 (high emissio n)	-10% (10p); 0 (50p); +20% (90p)	Northern Territory		CSIRO, 2012
	2070 (B1)	-18% (10p); 0% (50p); +18% (90p)	Darwin		CSIRO, 2007
	2070 (A1F1)	-32% (10p); 0%(50p); +34% (90p)	Darwin		CSIRO, 2007)
	2100	1% (-12% to 15%)	Northern Australia, north of 30^{o}S		Christensen et al., 2007)
Early Dry Season (JJA)	Baseline (1975 - 2004)	6mm	Kakadu National Park		Hyder Consulting Pty Ltd, 2008
	2030	n/a	Kakadu National Park		Hyder Consulting Pty Ltd, 2008
	2070	n/a	Kakadu National Park		Hyder Consulting Pty Ltd, 2008
	2100	-14% (-20% to 3%)	Northern Australia, north of 30^{o}S		Christensen et al., 2007

Annual / Seasonal	Time Scale	Predicted or observed changes	Spatial Scale	Potential Indicator	References
	2030 (A1B)	-27% (10p); -4% (50p); +18% (90p)	Darwin		CSIRO, 2007
	2050 (high emission)	-20% (10p); -2% (50p); +30% (90p)	Northern Territory		CSIRO, 2012
	2070 (B1)	-41% (10p); -7% (50p); +31% (90p)	Darwin		CSIRO, 2007
	2070 (A1F1)	-63% (10p); -13% (50p); +59% (90p)	Darwin		CSIRO, 2007
Late Dry Season (SON)	Baseline (1975 - 2004)	113mm	Kakadu National Park		Hyder Consulting Pty Ltd, 2008
	2030	+4% (±19%)	Kakadu National Park		Hyder Consulting Pty Ltd, 2008
	2070	+11% (±57%)	Kakadu National Park		Hyder Consulting Pty Ltd, 2008
	2100	-12% (-32% - 2%)	Northern Australia, north of 30^{o}S		Christensen et al., 2007
	2030	Extended dry periods and more frequent and intense rainfall periods	Kakadu National Park		Hyder Consulting Pty Ltd, 2008
	2070	Extended dry periods and more frequent and intense rainfall periods	Kakadu National Park		Hyder Consulting Pty Ltd, 2008
	2030 (A1B)	-21%(10p); -5% (50p); +13%(90p)	Darwin		CSIRO, 2007
	2050 (high emissions)	-20% (10p); -5% (50p); +30% (90p)	Northern Territory		CSIRO, 2012
	2070 (B1)	-33%(10p); -8%(50p); +22%(90p)	Darwin		CSIRO, 2007
	2070 (A1F1)	-54%(10p); -15%(50p); +42%(90p)	Darwin		CSIRO, 2007
Wet season	1950-2000	Decline in wet-season rainfall and flood events after 1976-77	Kakadu National Park (East Alligator River; 15km from Point Farewell)		Winn et al., 2006

Relative humidity

The predicted changes in relative humidity in the Kakadu region show a trend to decrease this factor, although uncertainties are relatively high (Table 4). Relative humidity would have implications for evaporation rates, agriculture, building design, and human comfort and health (CSIRO, 2007:78).

PHYSICAL IMPACTS

Lower relative humidity will affect water balance in the atmosphere, thus increasing evaporation rates. Relative humidity is a critical component to calculate the Maximum Fire Danger Index. A decrease in relative humidity will increase the probability of the incidence of fire (Bureau of Meteorology, 2013).

ECOLOGICAL IMPACTS

Relative humidity directly affects the water relations of plant and indirect affects leaf growth, photosynthesis, and pollination. When relative humidity is low, transpiration increases causing water deficits in the plant, which blocks the entry of the carbon dioxide that is critical for photosynthesis (TNAU Agritech Portal, 2013).

HUMAN IMPACTS

Increase in relative humidity can affect the incidence of respiratory infections and allergies. A decrease in relative humidity is beneficial to human health via reducing the survival and infectivity of infectious bacteria and viruses (Arundel et al., 1986).

DECISION ON HUMIDITY SCENARIO

Humidity is not a parameter considered in MSE models.

Table 6. Range of predictions for annual relative humidity changes sourced from the literature.

Time Scale	Predicted or observed changes	Spatial Scale	References
Baseline (1975 - 2004)	53%	Kakadu National Park / Monsoon rainforests	Hyder Consulting Pty Ltd, 2008
2030	-1.1% (±1.9%)	Kakadu National Park	Hyder Consulting Pty Ltd, 2008
2070	-3.4% (±5.7%)	Kakadu National Park	Hyder Consulting Pty Ltd, 2008
2030 (A1B)	-1% (10p); -0.5% (50p); 0% (90p)	Darwin	CSIRO, 2007
2070 (B1)	-1.7% (10p); -0.8% (50p); 0% (90p)	Darwin	CSIRO, 2007
2070 (A1FI)	-3.2% (10p); -1.5% (50p); +0.1% (90p)	Darwin	CSIRO, 2007

Potential Evapotranspiration

Evapotranspiration (ET) is the term used to describe the part of the water cycle which removes liquid water from an area with vegetation and into the atmosphere by the processes of both transpiration and evaporation (Bureau of Meteorology, 2001). Area Potential ET is the ET that would take place, if there was an unlimited water supply, from an area so large that the effects of any upwind boundary transitions are negligible and local variations are integrated to an areal average (Bureau of Meteorology, 2001).

Projections from the IPCC AR4 (IPCC, 2007) downscaled to Australia (CSIRO, 2007) suggest an overall increase in potential evapotranspiration. For Darwin the change by 2030 ranges from 2% to 5% increase, with the best estimate being a 3% increase. By 2070, the B1 scenario gives increases of 3% to 8% (best estimate of 5%), while the A1FI scenario gives increases of 7% to 15% (best estimate of 10%), where seasonal changes follow a similar trend (Table 5).

Evaporation is different from evapotranspiration as it refers to the amount of water which evaporates from an open pan called a Class A evaporation pan. The rate of evaporation depends on factors such as cloudiness, air temperature and wind speed. Measurements are made by the addition or subtraction of a known amount of water, which then tells us how much water has evaporated from the pan .

PHYSICAL IMPACTS

Along with rainfall, potential evapotranspiration will directly affect the residence time of water in Kakadu floodplains (period of inundation). The projected increase in potential evaporation suggests that under a future no change in rainfall the floodplains will drain quicker than present, however links with groundwater should also be considered.

ECOLOGICAL IMPACTS

Drier floodplains will most likely promote the decline in amphibian populations due to their dependence on moisture, but will also affect birds, plants and other animals that depend on the wet/dry floodplain cycle (Hyder Consulting Pty Ltd, 2008).

HUMAN IMPACTS

Due to the influence of potential evapotranspiration in the hydrological cycle on a regional scale, it is expected that increase in this factor will also affect crops and water supply, with consequences to human populations in Kakadu.

CHOICE OF POTENTIAL EVAPOTRANSPIRATION AND EVAPORATION SCENARIOS

We will adopt the annual areal PET corresponding to the KNP area provided by the Bureau of Meteorology (2001) of 2200mm/year as the present scenario. The PET scenarios for simulation are the following:

1. 2030: increase in PET of 3%
2. 2070: increase in PET of 10%
3. 2100: Increase in PET of 10%

We adopted median values from high emission scenarios from CSIRO (2007, 2012) for 2030 and 2070. Given

Table 7. Range of predictions for changes in annual and seasonal potential evapotranspiration and evaporation sourced from the literature.

Climate Change Factor	Annual / Season	Time Scale	Predicted or observed changes	Spatial Scale	References
Potential Evapotranspiration	Annual	Baseline (areal evapotranspiration) (1961-1990)	2200mm/year	Kakadu National Park	Bureau of Meteorology, 2001

		2030	+4% (±4%)	Kakadu National Park	Hyder Consulting Pty Ltd, 2008
		2070	+11% (±11%)	Kakadu National Park	Hyder Consulting Pty Ltd, 2008
		2030 (A1B)	+2% (10p); +3% (50p); +5% (90p)	Darwin	CSIRO, 2007
		2070 (B1)	+3% (10p); +5% (50p); +8% (90p)	Darwin	CSIRO, 2007
		2070 (A1FI)	+7% (10p); +10% (50p); +15% (90p)	Darwin	CSIRO, 2007
		2100	Drier climate	Australia	CSIRO, 2007
	Summer (DJF)	2030 (A1B)	+2% (10p); +4% (50p); +6% (90p)	Darwin	CSIRO, 2007
		2070 (B1)	+3%(10p); +6% (50p); +10% (90p)	Darwin	CSIRO, 2007
		2070 (A1FI)	+6% (10p); +11% (50p); +18% (90p)	Darwin	CSIRO, 2007
	Autumn (MAM)	2030 (A1B)	+2% (10p); +3% (50p); +5% (90p)	Darwin	CSIRO, 2007
		2070 (B1)	+3% (10p); +6% (50p); +8% (90p)	Darwin	CSIRO, 2007
		2070 (A1FI)	+7% (10p); +11% (50p); +16% (90p)	Darwin	CSIRO, 2007
	Winter (JJA)	2030 (A1B)	+1% (10p); +3% (50p); +5% (90p)	Darwin	CSIRO, 2007
		2070 (B1)	+1% (10p); +5% (50p); +9% (90p)	Darwin	CSIRO, 2007
		2070 (A1FI)	+2% (10p); +9% (50p); +17% (90p)	Darwin	CSIRO, 2007
	Spring (SON)	2030 (A1B)	+2% (10p); +3% (50p); +4% (90p)	Darwin	CSIRO, 2007
		2070 (B1)	+3% (10p); +5% (50p); +7% (90p)	Darwin	CSIRO, 2007
		2070 (A1FI)	+5% (10p); +9% (50p); +14% (90p)	Darwin	CSIRO, 2007
Average annual Evaporation	Daily	2100	0.1mm/day	Northern Australia	IPCC, 2007

Average Evaporation	Annual	1961-1990	2400mm/year	Kakadu National Park (Boggy Plain)	Bureau of Meteorology, 2013b
Average Evaporation	Daily Seasonal (May to September)	Current (no info on period)	5mm/day	Kakadu National Park (Boggy Plain)	Jolly, 2003

Extreme Weather Events

Extreme weather events refers to the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable. For simplicity, both extreme weather events and extreme climate events are referred to collectively as 'climate extremes' (IPCC, 2012). Examples of weather events are tropical cyclones and associated heavy rainfall and tidal surges. Future predictions suggest an increase in extreme weather events such as wind speeds in category 5 tropical cyclones and increase in intense precipitation events (Christensen et al., 2007; Hyder Consulting Pty Ltd, 2008; Nott, 2006). Storm surges associated with tropical cyclones have a significant impact on Kakadu's coastal floodplains. They are also expected to be exacerbated in the future (IPCC, 2012; BMT WBM, 2011).

Predicting cyclone behaviour is difficult because of limited data sets and questions about data reliability going back in time, with consistent data on cyclone intensity only available since the start of the modern satellite era in the early 1980s (Steffen and Hughes, 2013). Climate change influences in cyclones occurs in two ways (Steffen and Hughes, 2013; IPCC, 2012):

1) The formation of cyclones is affected by the vertical gradient in temperature through the atmosphere – that is, the difference in temperature near the Earth and the temperature higher up in the atmosphere – and by increasing surface ocean temperatures. Cyclones form more readily when there are very warm conditions at the ocean surface and the vertical gradient is strong.
2) Increasing sea surface temperature increases the intensity of cyclones, both in terms of maximum wind speeds and the intensity of rainfall.

At a global level there is generally low confidence in projections of changes in extreme winds because of the relatively few studies of projected extreme winds, and shortcomings in the simulation of these events (IPCC, 2012). An exception is mean tropical cyclone maximum wind speed, which is likely to increase, although increases may not occur in all ocean basins. It is likely that the global frequency of tropical cyclones will either decrease or remain essentially unchanged (IPCC, 2012). Studies for Australia suggest a similar trend of increase in intensity of cyclones (wind speed) (Steffen and Hughes, 2013; CSIRO, 2013; BMT WBM, 2011; CSIRO, 2007; Christensen et al., 2007; Cook and Goyens, 2008; Cook and Nicholls, 2009) and no change or decrease in frequency (general trend in Northern Territory) (CSIRO, 2007, 2013; BMT WBM, 2011). For the Kakadu region the predictions are for an increase of 10% in intensity by 2030 and an increase in intensity of 20% by 2070 (BMT WBM, 2011). More intense wind speed associated with cyclones represented an increase in storm tide. For example, at 2030 the projected increase in storm tide associated with an increase in 10% of intensity in wind speed adds an extra 150mm in present day storm tide (plus sea level rise) and at 2070 the projected increase in storm tide adds an extra 100mm in present day storm tides (plus sea level rise) (BMT WBM, 2011). This means that for a cyclone such as Monica, which reached the Alligators River Region in 2006 producing storm tides in the order of 6m, an increase in 10% in wind speed represents an additional 0.15m in storm tide for 2030 totalling 6.15m of storm tide plus 0.143m of SLR. A 20% increase in wind speed for 2070 represents an additional 0.1m of storm tide, thus totalling 6.1m of storm tide plus 0.7m in SLR. The reduced increase in storm tide at 2070 from that of 2030 projected from the modelling may be attributed to modelled variables such as increased water levels and the resultant decreased shoaling, and vegetation effects on waves, that can result in less surge (BMT WBM, 2011: xv). Globally, the IPCC (2012) suggest increase in wind speed towards the end of the century in the order of 2-11%.

Sea level rise will amplify the effects of storm surges associated with extreme weather events. As a rule of thumb a 0.1 m rise in sea level increases the frequency of flooding by about a factor of three. This effect is multiplicative so that even a relatively modest increase in mean sea level of 0.5 m will increase the frequency of flooding by a factor of roughly 300. This means that an event which presently only happens on average once every 100 years (the '100-year return event') will happen several times a year after sea level has risen by 0.5 m (ACE CRC, 2012).

PHYSICAL IMPACTS

The incidence of cyclones for very short-period (days) fluctuations associated with semidiurnal spring tidal cycles and surge events will promote greater rates of mixing downstream than upstream thus producing a greater increase in salinity that can eventually inundate the floodplains (Winn et al., 2006). This phenomenon can be intensified during king tides. However, an analysis made by Cobb et al. (2007) using data from extreme water level events from the 1959–1997 in Darwin shows that a strong majority of high water level events are associated with 'king tides', the highest astronomical tides plus local set-up, rather than tropical cyclones. This demonstrates that the chances of coincidence of getting storm surges on the top of high/king tides are relatively low but if they occur the consequences will be widespread, especially when considering sea level rise in a relative flat area such as Kakadu coastal floodplains.

Storm surges associated with cyclonic activity promote short term changes in flow patterns of tidal creeks (Cobb et al., 2007). These changes can also promote erosion of landforms (or cheniers) and depositing the coarser sediment from these landforms hundreds of metres further inland, thus creating new landforms. These natural levee banks could reach heights of 5-8m AHD (Australian Height Datum) depending on intensity of cyclone/surge (Cobb et al., 2007; Nott, 2006). The dynamic process of sediment erosion and deposition can influence local hydrodynamics with adverse consequences on freshwater habitats.

ECOLOGICAL IMPACTS

Nott (2006) suggests that certain vegetation types including large trees, such as *Eucalyptus porrecta*, will be particularly sensitive to high intensity cyclones and the accompanying destructive winds. Smaller shrubs, such as paperbark trees, are able to withstand the high destructive winds. Mangroves often sustain damage following cyclonic activity but can display considerable resilience and re-sprout readily following catastrophic weather events. The predicted increase in the intensity of tropical cyclones will also Increase the proportion of uprooted/snapped trees and defoliation with increase in peak of wind gusts (Cook and Goyens, 2008). In the case of Cyclone Monica, there is evidence of a 5-6m storm surge zone in Junction Bay (in NT) where trees were totally defoliated, snapped or uprooted (Nott, 2006).

Changes in turbidity associated with increased storm intensity and/or duration may affect seagrasses and inshore biota through light penetration and episodic erosion of sea grass banks. Intensity and duration of storms will also affect the balance of erosion versus deposition in nearshore environments and sandy beaches (Cobb et al., 2007). Increased storm intensity will also increase inundation period/extent of low-lying coastal mudflats inundated (Cobb et al., 2007).

HUMAN IMPACTS

The impacts of extreme weather events are associated with damages to infrastructure, public safety and agriculture associated with strong winds (Cook and Nicholls, 2009). Impacts from storm surges may be similar to the impacts described in the section "human impacts from sea level rise", which include inundation, destruction of infrastructure and access to socio-cultural and tourism sites. However, there are clear differences in time scales, where storm surges happen in hours/days with water receding in days/months, and SLR promotes more permanent changes in the mean sea level.

CHOICE OF EXTREME WEATHER SCENARIOS

We chose to simulate the effects of storm surges associated with cyclonic activities. For the current scenario the model will simulate the surge associated with cyclone Monica (2006), where a storm surge in the order of 5-6 m was recorded at Junction Bay. The future scenarios are the following:

1. 2030: An increase in 10% in wind intensity, represented as an increase in storm tide of 0.15m on top of the storm tide recorded for cyclone Monica (plus SLR of 0.143m)
2. 2070: An increase in 20% in wind intensity, represented as an additional 0.1m on top of the storm tide recorded generated by cyclone Monica (plus SLR of 0.7m).
3. 2100: Due to the absence of storm surge scenarios for KNP in 2100 we decided to adopt a similar scenario to 2070, but with the 2100 SLR scenario (1.1m).
4. For all scenarios: No change in frequency of cyclones.

Table 8. Range of predictions for changes in extreme weather events sourced from the literature.

Time Scale	Predicted or observed changes	Spatial Scale	Potential Indicator	Mitigation / Adaptation	References
1950 – 2000	Changes in the distribution of mangroves, Melaleuca spp and tidal channels	Alligator Rivers Region and streams debouching into Van Diemen's Gulf		Dams and levees (with varying success in preventing saltwater intrusion)	Cobb et al., 2007
2006	5-6m storm surge at Junction Bay related to cyclone Monica in April 2006	Junction Bay, NT			Commonwealth of Australia, 2013
2030	Increase in intensity by 10% and no increase in frequency	Kakadu National Park	At 2030 with a SLR of 143mm the projected increase in storm tide was an extra 150mm		BMT WBM, 2011
2030	Increase in extreme weather events such as category 5 tropical cyclones				Hyder Consulting Pty Ltd, 2008; Nott, 2006
2030	Increase in intensity of tropical cyclones (maximum wind speeds)				CSIRO, 2013
2070	Increase in intensity of 20% and no increase in frequency		At 2070 with a SLR of 700mm the projected		BMT WBM, 2011

			increase in storm tide was an extra 100mm	
2070	Increase in extreme weather events such as category 5 tropical cyclones			Hyder Consulting Pty Ltd, 2008
2070	Increase in intensity of tropical cyclones and decrease or no change in frequency			CSIRO, 2013
1950-2000	decline in intensity and frequency of tropical cyclones since 1950s and particularly since the mid-1980s.	Kakadu National Park (East Alligator River; 15km from Point Farewell)		Winn et al., 2006
2100	very likely Increase in intense precipitation events	Australia		Christensen et al., 2007
2100	likely increase in the proportion of the tropical cyclones in the more intense categories, but a possible decrease in the total number of cyclones.			CSIRO, 2007
2100	increase in the intensity of tropical cyclones		Trees (foliage, and damage (uprooting/snapping)	Christensen et al., 2007; Cook and Goyens, 2008; Cook and Nicholls, 2009
?	In the future we are likely to see more high-intensity cyclones and fewer low-intensity cyclones			Steffen and Hughes, 2013
-	The likelihood of storm surges are linked with rise in sea level. As a rule of thumb a 0.1 m rise in sea level increases the frequency of flooding by about a factor of three.	More frequent surges with sea level rise		ACE CRC, 2012

CO_2 Concentrations

As one of the main drivers of climate change, the prediction on future rises in atmospheric CO2 concentrations depends on the emission scenario. Effects of rise in CO2 concentrations in the atmosphere are beneficial to plants, but will adversely affect ecological relationships between native and invasive species in Kakadu. Increase in atmospheric CO2 will promote the build up of fuel during wet season due to expansion of rainforests with possible increase in the probability of more intense fires to happen.

PHYSICAL IMPACTS

Increased rainfall and atmospheric CO_2 will result in higher fuel loads building up in the wet season (Hyder Consulting Pty Ltd, 2008).

ECOLOGICAL IMPACTS

Hyder Consulting Pty Ltd (2008) proposes that rising CO2 concentration acts to increase photosynthesis, plant biomass and plant water-use efficiency in many plant species, thus alleviating water limitations and enhancing primary production. However, the differences among species in their responses to elevated CO2 should be considered as these will affect competitive interactions and thus community structure and composition. For example, invasive annual grasses may be relatively advantaged over native species, thus promoting increased invasion. Enhanced CO2 may also enhance the growth of woody shrubs, relative to grassy species, potentially leading to increase in fuel loads (and CO2 emissions) and therefore promotion of an accelerated fire cycle (Hyder Consulting Pty Ltd, 2008).

The expansion of monsoon rainforests is likely to occur with an increase in atmospheric CO2 concentration. Increases CO2 concentration can potentially overwhelm the negative feedback between fire and rainforest cover that is responsible for the meta-stability of monsoon rainforest boundaries (Bowman et al., 2010).

HUMAN IMPACTS

More intense fires may impact infrastructure and public safety.

CHOICE OF CARBON SCENARIOS

Carbon scenarios are not directly used in simulations, but a high carbon emission scenario from the IPCC (2007) was used as the base to select temperature, rainfall, potential evapotranspiration scenarios as discussed above.

Table 9. Range of predictions for changes in atmospheric CO_2 concentration sourced from the literature.

Time Scale	Predicted or observed changes	Spatial Scale	Reference
Baseline (1975 - 2004)	353ppm	Kakadu National Park / monsoon rainforests	Hyder Consulting Pty Ltd, 2008
2030	+165ppm	Kakadu National Park	Hyder Consulting Pty Ltd, 2008
2070	+365ppm	Kakadu National Park	Hyder Consulting Pty Ltd, 2008
1990	A1FI 7.2 GtC*[1]	Global	IPCC, 2001
2000	A1FI 7.97 GtC*[1]	Global	IPCC, 2001
2030	A1FI 16.19 GtC*[1]	Global	IPCC, 2001
2050	A1FI 23.90 GtC*[1]	Global	IPCC, 2001
2070	A1FI 27.28 GtC*[1]	Global	IPCC, 2001
2100	A1FI 28.24 GtC*[1]	Global	IPCC, 2001

*GtC: Gigatons of Carbon

[1] Emission scenarios used in both IPCC 3rd (IPCC, 2001) and 4th Assessments (IPCC, 2007)

Trade & Monsoonal Winds

Wind speed directly affect sea level via wave formation thus causing similar physical, environmental and human impacts as described for "extreme weather events" and "sea level rise".

PHYSICAL IMPACTS

N/A

ECOLOGICAL IMPACTS

Increase of wind speed will cause sediment movement potentially affecting freshwater basins, mudflats and wetlands (Cobb et al., 2007). An increase in the number of El Nino events may have adverse effects oil the two Australian species by delaying nesting, making nesting construction more difficult, or making nests more conspicuous to predators (Bowen et al., 2005)

HUMAN IMPACTS

N/A

CHOICE OF TRADE & MONSOONAL WIND SCENARIO

No scenario for this variable as selected as MSE models do not require such inputs.

Table 10. Range of predictions for changes in wind speed sourced from the literature.

Annual / Season	Time Scale	Predicted or observed changes	Spatial Scale	References
Annual	2030	Increase of up to 10% of the mean wind	Northern Australia, north of 30°S	Christensen et al., 2007
	2030 (A1B)	-1% (10p); +1% (50p); +2% (90p)	Darwin	CSIRO, 2007
	2070 (B1)	-2% (10p); +1% (50p); +4% (90p)	Darwin	CSIRO, 2007
	2070 (A1FI)	-4% (10p); +2% (50p); +7% (90p)	Darwin	CSIRO, 2007
Summer (DJF)	2030 (A1B)	-5% (10p); +1% (50p); +7% (90p)	Darwin	CSIRO, 2007
	2070 (B1)	-8% (10p); +2% (50p); +12% (90p)	Darwin	CSIRO, 2007
	2070 (A1FI)	-16% (10p); +3% (50p); +23% (90p)	Darwin	CSIRO, 2007
Autumn (MAM)	2030 (A1B)	-3% (10p); 0% (50p); +2% (90p)	Darwin	CSIRO, 2007
	2070 (B1)	-5% (10p); -1% (50p); +3% (90p)	Darwin	CSIRO, 2007
	2070 (A1FI)	-10% (10p); -12% (50p); +7% (90p)	Darwin	CSIRO, 2007
Winter (JJA)	2030 (A1B)	-2% (10p); 0% (50p); +2% (90p)	Darwin	CSIRO, 2007

	2070 (B1)	-4% (10p); 0% (50p); +4% (90p)	Darwin	CSIRO, 2007
	2070 (A1FI)	-7% (10p); 0% (50p); +7% (90p)	Darwin	CSIRO, 2007
Spring (SON)	2030 (A1B)	-1% (10p); +2% (50p); +5% (90p)	Darwin	CSIRO, 2007
	2070 (B1)	-1% (10p); +3% (50p); +9% (90p)	Darwin	CSIRO, 2007
	2070 (A1FI)	-2% (10p); +7% (50p); +17% (90p)	Darwin	CSIRO, 2007

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