COASTAL WETLAND REMEDIATION IN A CHANGING CLIMATE: PROCESS UNDERSTANDING AND APPLICATION

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Abstract

Following major floods in the 1950s widespread engineering works were undertaken in New South Wales (NSW) to construct flood levees and tidal floodgates. Once drained this land was cleared to establish broad-acre agriculture. This process has degraded the natural environment, resulted in extreme levels of acidity and disconnected the floodplain from tidal flushing. As a result of these outcomes, and in acknowledgement of the ecosystem services provided by natural landscapes, a large number of remediation projects are underway throughout NSW.

This paper details the challenges of restoring tidal wetlands in NSW and the paradigm shift necessary to incorporate climate change into the remediation process. The process of undertaking wetland remediation projects is detailed and various issues including timing, complexity, social implications and externalities are addressed. Issues associated with numerical modelling of wetland remediation projects are then addressed. Case studies are presented to highlight the intricacies of modelling remediation scenarios and to illustrate how various small inaccuracies can drastically limit modelling outcomes. Finally, the implications of climate change and sea level rise are discussed to highlight how the current scientific approach is flawed and why a paradigm shift in our scientific method is required.

Introduction

Major floods in the 1950s, encouraged the construction of flood levees, drainage canals and tidal floodgates in the tidal floodplain (Williams and Watford, 1997). Once drained, the land was cleared to establish broad-acre agriculture. This process has degraded the natural environment, resulted in extreme levels of acidity and disconnected the floodplain from tidal flushing (Glamore and Indraratna, 2003; Sammut et al., 1996; White et al., 1997). As a result of these outcomes, and in acknowledgement of the ecosystem services provided by natural wetland landscapes, tidal restoration (or re-inundation) projects are underway worldwide.

Restoring (or re-inundating) tidal wetlands typically involves a four stage process including:

1. Conceptual Planning
2. Design
3. On-ground works
4. Adaptive management

In the Conceptual Planning stage the existing site is assessed and a range of options are considered. In NSW the majority of sites are backwater off-channel low-lying areas that have been hydraulically disconnected from the main channel through a process of levee building, the construction of deep drains and the addition of tidal barrages or floodgates in one or several locations. Removing these impediments to flow ranges in sophistication from solely removing the tidal floodgates and allowing uncontrolled tidal inundation, to more complex methods of manipulating tidal amplitude via modified water control structures to ensure overbank flushing is limited. In locations where a historic or natural flow regime is desired, other on-ground methods include earthworks to contain inundation extents to a limited area or the complete removal of all structures (including levees, culverts, floodgates, drainage lines, etc) and associated earthworks to promote historic flushing patterns.

The extent of redesigning the natural landscape is commonly controlled by the aims of the project and the funds available. In NSW, most sites impacted by acid sulphate soils are being restored by manipulating the tidal amplitude and restoring tidal flushing within the existing drainage lines. Conversely, compensatory offset sites (for destroyed habitat elsewhere) typically aim to achieve full restoration of the site via large earthworks. Other common aims include the reconnecting of natural relict drainage canals to the adjacent waterway in order to reduce upstream flood levels (i.e. create a flood detention basin), large soil remediation projects (i.e. Sydney Olympic Park) or earthworks to improve local amenities.

Once the Conceptual Planning stage is complete, the Design stage applies the desired project aims to the existing landscape. Numerical models are increasingly being used to test the various on-ground redesign options and simulate tidal flushing across the site. During the design stage, hydraulic models (i.e. MIKE, TUFLOW, RMA, etc) are regularly employed to simulate:

- Surface water inundation extents and duration
- Flow through culverts and in/around structures
- The impact of restored flushing to adjoining landholders
- Catchment wide implications
- Water quality and sediment dynamics
- Implications of earthworks
- On-ground designs
- Climate change risks

While numerical models are increasingly being used during tidal wetland restoration studies, a number of limitations remain that should be viewed with caution. Indeed, in floodplain restoration projects hydraulic models should be used with caution because:

1. Due to the flat terrain a small vertical change in the water level can have a significant influence on the horizontal areal coverage;
2. The current understanding of eco-hydraulics in these environments is limited;
3. Restoration of tidal flushing to a site is a dynamic process that will significantly influence geomorphic form and onsite vegetation type;
4. Significant (and often non-linear) losses can occur to groundwater and external boundaries not well simulated in existing models;
5. The data collected to calibrate the model often contains error greater than required for design consideration;
6. Short-term onsite flushing trials provided limited understanding of the long-term onsite conditions;
7. The models do not effectively simulate the temporal changes in hydraulic conveyance;
8. Externalities, including positive feedback inputs to upstream and downstream boundary conditions, are seldom addressed;
9. The models typically simulate short temporal and spatial periods and rarely include the extreme tidal levels that drive ecosystem process;
10. The resolution or refinement of the model may be inappropriate to simulate the desired processes (i.e. poor ability to simulate the onsite stage/volume relationship and map the hydraulic connectivity);
11. The bed slope is often extremely low or even reversed (i.e. negative bed slope);
12. The models typically fail to consider how sea level rise will impact the entire boundary condition.

This paper discusses the implications of the above concerns when undertaking tidal wetland restoration projects and provides examples of numerical modelling studies where these aspects have been addressed. Overall, the paper aims to highlight key numerical modelling limitations and provide methods for improving future projects. To remain concise this paper focuses on concerns related to model resolution (Point 10 above), the evolving geomorphology and vegetation issues (Points 3, 6 and 7), the implications to upstream and downstream boundary conditions (Point 8), and sea level rise (Point 12).

Stage and Volume Relationships

Tidal wetland environments are typically low-lying terrains with limited topographic features. In these environments the natural ecosystem has developed extreme micro-topographic delineations where various species are separated by small variations in elevation. These changes in elevation, however, are directly related to hydroperiod which has shown to be a driver of saltmarsh and mangrove populations (Howe, 2008).

To accurately simulate the fine topographic features of tidal wetlands, numerical models are reliant on the accuracy of input data, namely topographic (i.e. LiDAR) data and water elevation information. LIDAR data in particular can suffer from a range of errors and biases if not ground-truthed. Dense phragmite stands, typical of brackish wetlands, are notorious for providing false LiDAR data readings which can result in elevation measurements in excess of 0.5 m.

The implications of incorrect elevation data are evident in Figure 1. In this figure the elevation of a potential tidal restoration site is depicted in 0.1 m intervals. As evident, a small change in water elevation between 0.4 and 0.5 m Australian Height Datum (AHD) at this site would result in a large increase in the areal extent of inundated land. In these circumstances it is recommended that a stringent error analysis is conducted on the available data and, where possible, significant ground-truthing of the LiDAR data is undertaken to assess the accuracy of the digital terrain model.

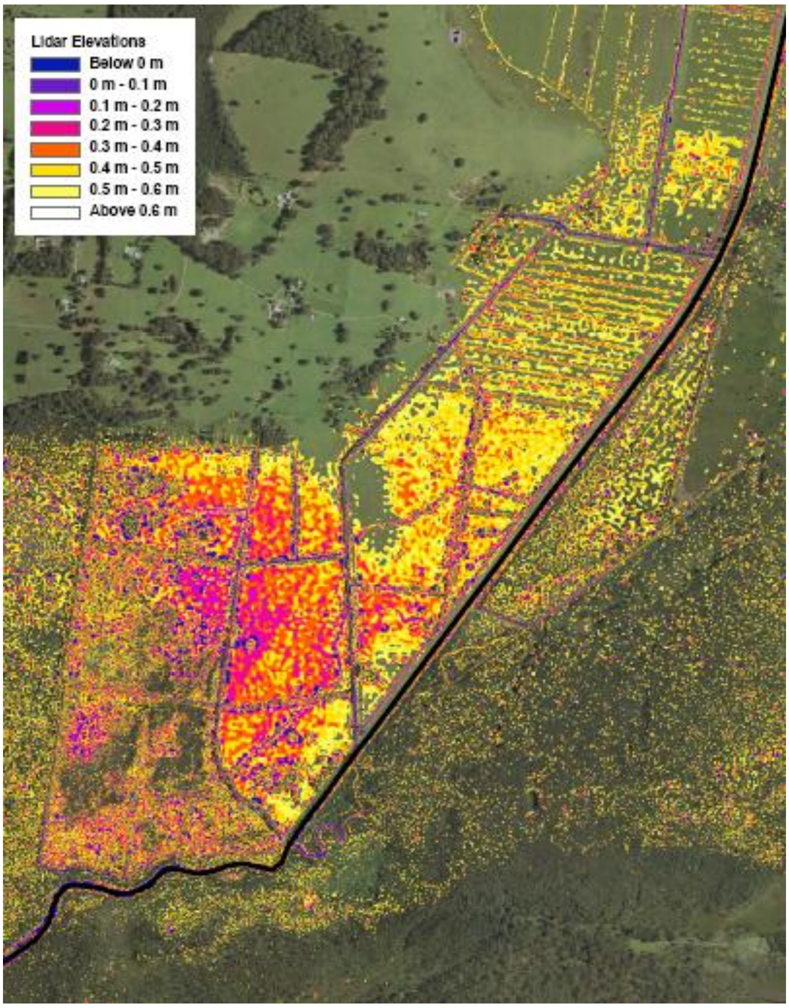


Figure 1. Digital terrain model with proposed tidal water level spatial extents (in m AHD).

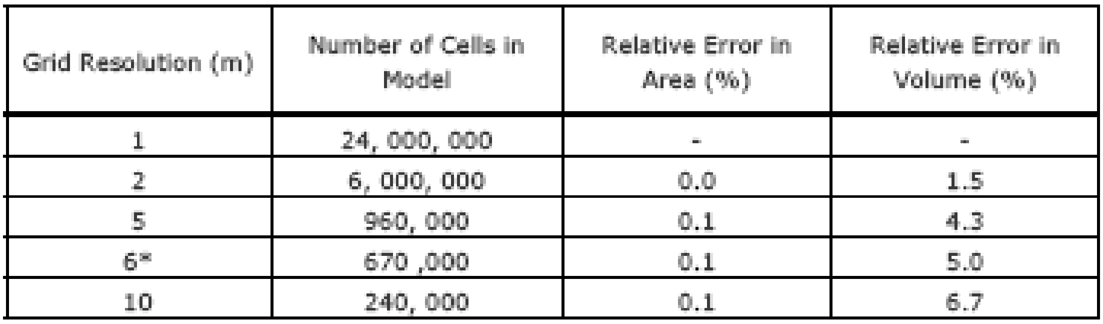
Spatial Resolution

While the spatial domain or extent of a numerical model is typically determined by the boundary conditions and study aims, the resolution of the model is a trade-off between several competing factors. In an ideal scenario the 2-dimensional (2-D) resolution of the overbank areas would be maintained at the highest resolution of the digital terrain model. In practice this would ensure that the micro-scale topographic features noted in Section 2 are well represented in the model. However, in large spatial models high levels of refinement can result in extreme numbers of elements which may reduce computational efficiencies and potentially over complicate model simulations. Therefore, it is common practice to make the model grid as coarse as possible, while ensuring that the overall volume and hydraulic features are preserved.

To ensure that the appropriate 2-D model resolution is maintained, a range of model checks are recommended. As shown in Table 1, a basic comparison between the highest level of grid resolution and a series of more coarse grids should be undertaken. This comparison should ensure that the relative error in area between grid resolutions remains unchanged despite any changes in the relative error in volume. The relative error in volume may change with increased grid resolution due to a loss in key topographic features as a larger area is interpolated for each grid. For the model tested in Table 1, a 5% relative error in volume was calculated between the 1 m grid versus the 6 m grid, which was deemed the maximum extent allowable for this study.

In addition to ensuring that the spatial resolution (i.e. area and volume) of the 2-D model is adequate for testing, the model resolution should also be tested to ensure that the natural hydraulic linkages are maintained. As shown in Figure 2, two different grid resolutions (which yield similar relative error in volume) have varying levels of hydraulic connectivity with the 10 m grid (Figure 2b) depicting large gaps in drainage channels. Failure to thoroughly consider the connectivity of hydraulic features as represented in the 2-D spatial extent can result in inaccurate hydroperiod calculations (and potentially inaccurate ecosystem predictions).

Table 1 Example grid resolution tests to ensure appropriate 2-D model resolution



Grid Resolution (m)	Number of Cells in Model	Relative Error in Area (%)	Relative Error in Volume (%)
1	24, 000, 000	-	-
2	6, 000, 000	0.0	1.5
5	960, 000	0.1	4.3
6*	670 ,000	0.1	5.0
10	240, 000	0.1	6.7

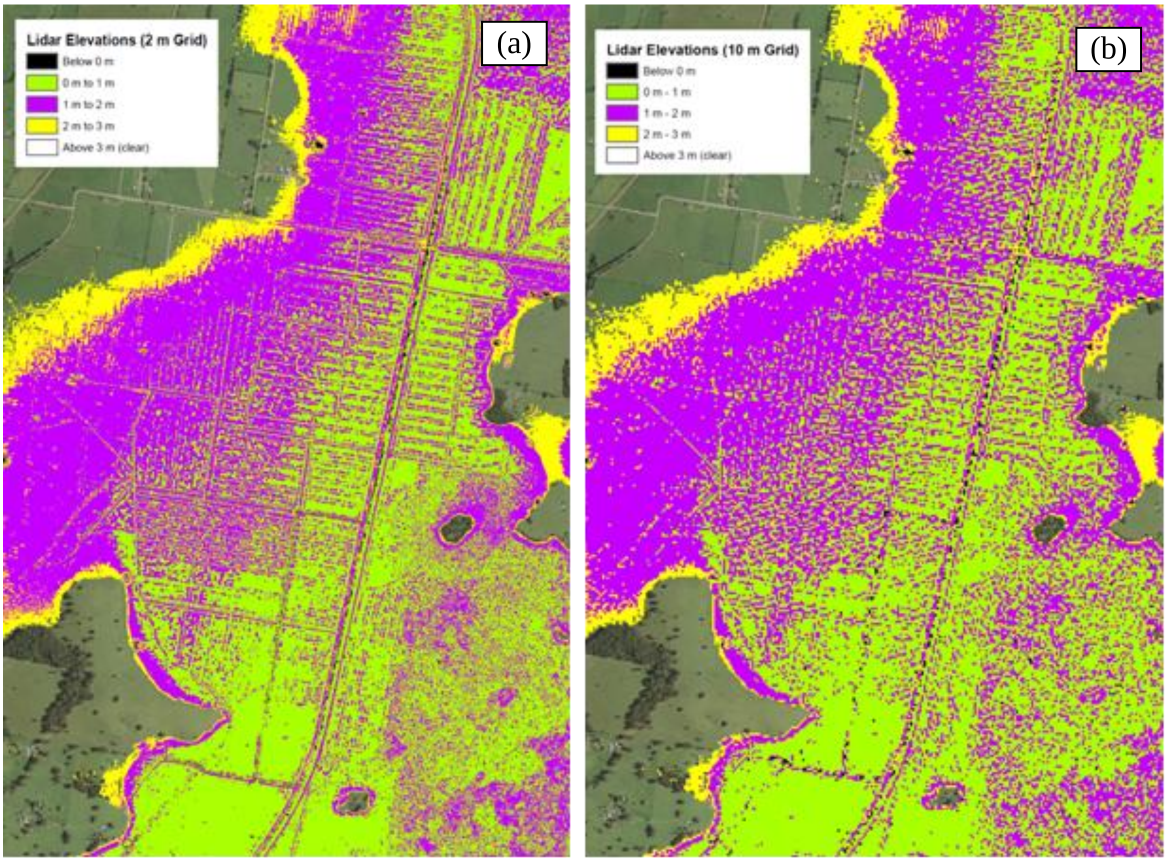


Figure 2. 2m (a) versus 10m (b) resolution grids for an area proposed for tidal wetland restoration

Geomorphic and Vegetation Dynamics

The above discussion highlights the importance of ensuring the base model accurately represents the initial conditions and that the input data accurately represents the on-ground conditions. This section discusses the importance of considering the dynamic nature of the site after tidal flushing has been restored. Of particular importance are the geomorphic and vegetation changes that will occur after the site has been restored and the issues associated with using short-term trials to calibrate numerical models.

For most rehabilitation modelling projects the overland flooding dynamics are calibrated against the existing vegetation onsite. However, recent on-ground research (Granqvist et al., 2012) at a large restored tidal wetland site has indicated that the vegetation quickly adapts to the new flushing dynamics resulting in changes to the onsite flow dynamics. An example of these vegetation changes between 2010 and 2012 is provided in Figure 3. Based on more than 10,000 images taken of this site combined with detailed onsite overland flooding measurements, it is strongly advised that both the existing and forecasted vegetation communities are simulated onsite using hydroperiod calculations.

In addition to dynamic vegetation conditions, numerical models of overbank tidal flushing should consider the dynamic nature of the geomorphic conditions. Establishing tidal flushing increases the tidal prism, and related critical shear velocities, which leads to expansion of the channel's cross sectional area. Williams et al. (1997) provides a useful description of how the channel top width, bottom width and cross-sectional area will change based on the tidal prism or the wetland area.

Due to the dynamic vegetation and geomorphic nature of restoring tidal wetland sites, it is strongly advised that any data obtained from re-flooding trials is viewed with caution. Short-term trials are unlikely to simulate how the restored site will function with time for the above reasons as well as initial losses to groundwater, changes in channel sinuosity and upstream/downstream boundary changes likely to occur (discussed further above).

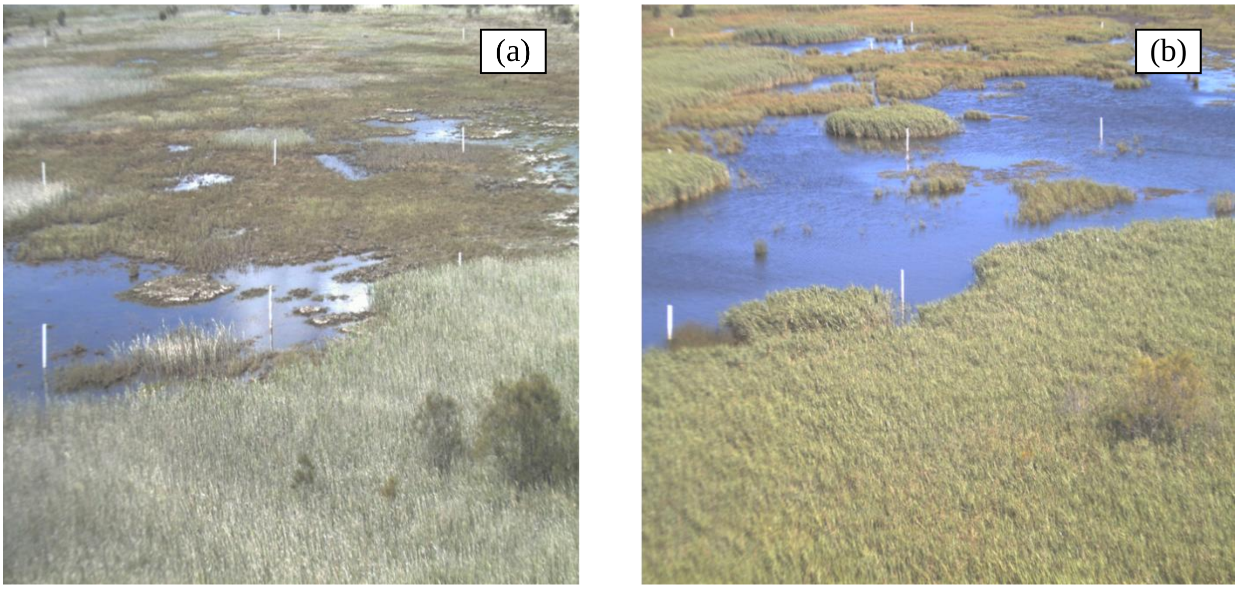


Figure 4 Elevated images taken from a tidal restored site in 2010 (a) and 2012 (b).

Feedback Hydraulics

Recent research (Ruprecht et al., 2012) suggests that for many estuaries in NSW the cross-sectional area of open channels are yet to reach full maturity (i.e. still expanding) or equilibrium. This is likely due to altered entrance conditions (i.e. fixed breakwaters) which have been imposed over the past century combined with dredging at the river mouth, recent sea level rise and changes to channel conveyance. The implication of this dynamic downstream boundary condition is one important factor worth considering in the design of any tidal wetland restoration project.

In addition to the dynamic nature of open channels, Williams et al. (1997) showed that restoration of tidal flows to a restored site increases the downstream cross-sectional area (including top and bottom widths). The extent of the change is directly proportional to the tidal prism and the restored wetland area, with larger sites having a greater influence downstream. Therefore, numerical models that simulate overland tidal dynamics should take into consideration the resulting impact on downstream channels and the likely impact this would have on increased tidal range and potentially salinity transport.

Based on the findings of Williams et al. (1997) in San Francisco, USA and Ruprecht et al. (2012) in Newcastle, Australia, hydraulic simulations were undertaken to assess the changes to the downstream channel area from the creation of tidal ponds in the Hunter River, NSW. As shown in Figure 5, cross sections for three locations were measured onsite and used within a RORB hydraulic model as reference locations. The model results indicate that the wetland creation project would significantly expand of the downstream channel. This is particularly important as the channel expansion may undermine bridge foundations and result in increased maximum tidal levels. As the site is specifically designed as a migratory wading bird refuge, increases in tidal range are likely to affect the project aims.

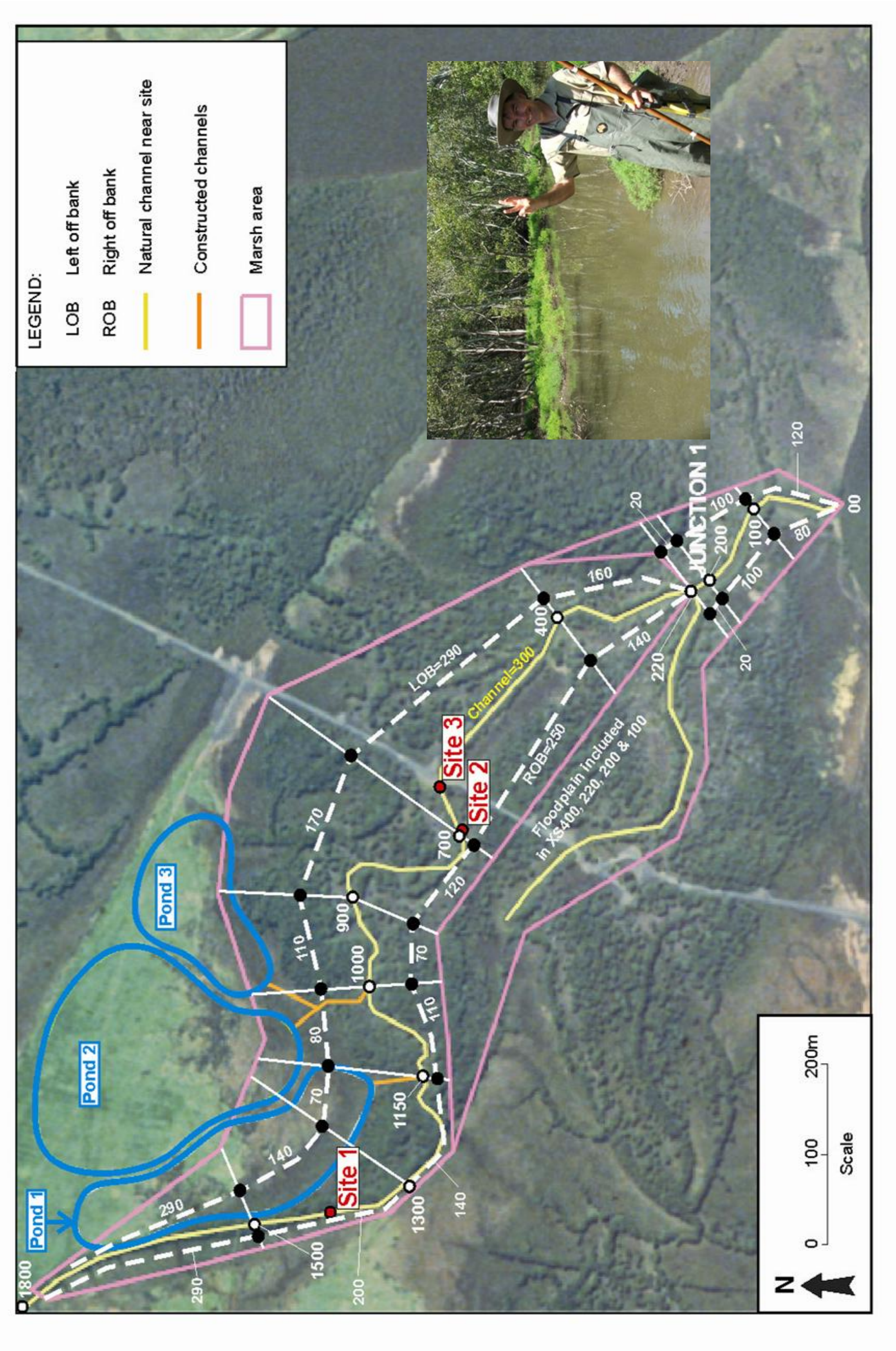


Figure 5. Model design to assess the impact of creating tidal ponds on downstream channel area including three reference sites.

Climate Change Considerations

In many estuarine sites across NSW, wetland restoration projects are being undertaken to encourage a particular ecosystem (such as salt marshes or mangroves) by maintaining a specified tidal range and hydroperiod. Numerical models are often used in these projects to optimise flushing dynamics and to assist in designing water control structures (culverts, levees, floodgates, etc). Once designed and the optimal tidal hydraulics achieved, these sites are typically left to naturally recover, a process which is likely to take decades (Moreno-Mateos et al., 2012).

While these types of wetland restoration projects are common throughout NSW, they often fail to consider the implications of forecasted sea level rise. Low-lying backswamps are likely to be strongly influenced with sea level rise particularly considering that levee banks surrounding the floodplains will be overtopped during king tides by 2050 (assuming 0.4m sea level rise) and by regular tidal flushing by 2100 (assuming 0.9m sea level rise). An example of sea level rise implications is shown in Figure 6, with acceptable depth increases occurring if restoration works are undertaken immediately (Figure 6a) but with unacceptable increases (to adjacent landholders) forecasted by 2050 (Figure 6b). It is also worth noting that the area and/or length of the tidal boundary condition should be considered when modelling sea level rise as the extent of inundation is likely to be different from existing conditions.

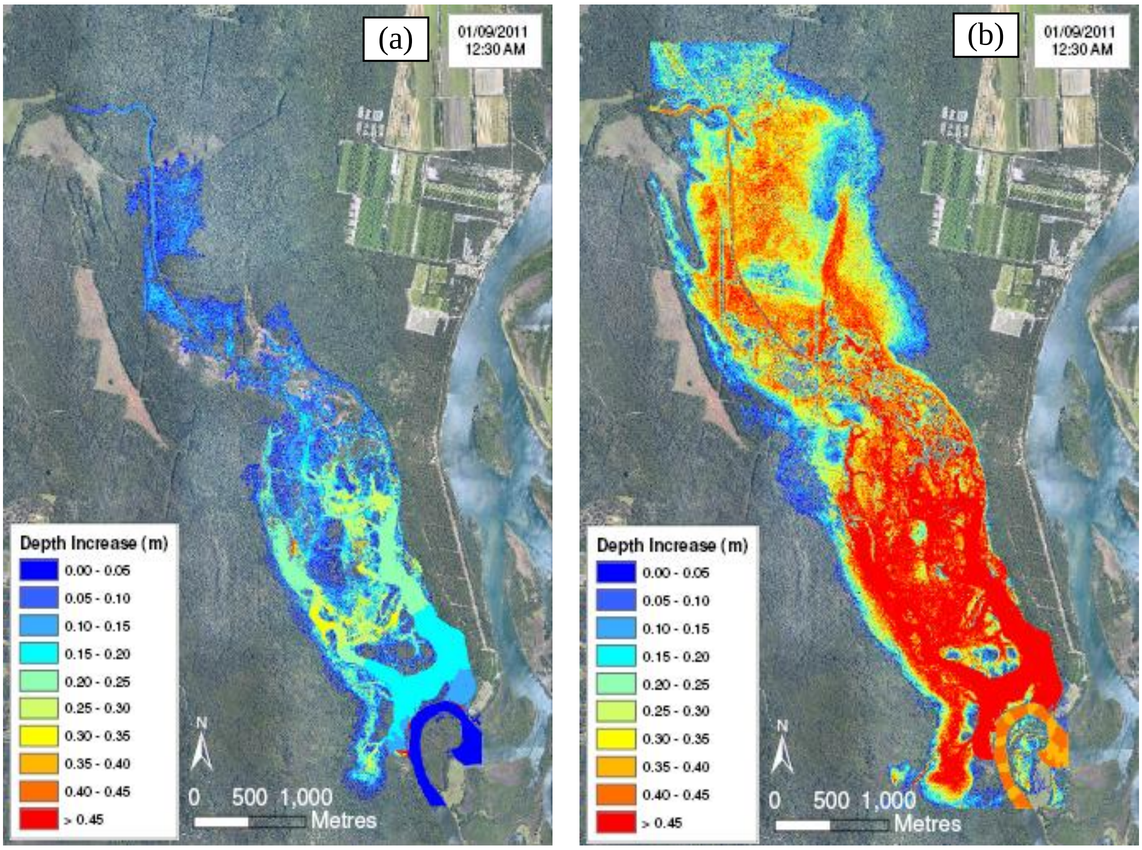


Figure 6. Forecasted (2050) (a) and existing (b) increases in water depth due to overland tidal flushing at a proposed wetland restoration site.

Summary

Numerical models are commonly being used to assist in the conceptual and design process of tidal wetland restoration projects. This paper highlights several issues associated with overbank and in-channel dynamics and provides detailed discussions around the key points of vertical accuracy, spatial resolution, geomorphic and vegetation dynamics, channel feedback hydraulics and climate change. Onsite examples are provided, where appropriate, to highlight recommended methods.

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