# 3.2

# Eco-hydrology of estuarine wetlands

**Dr William Glamore**
Water Research Laboratory, School of Civil and Environmental Engineering,
University of New South Wales, Sydney
Australia

## Abstract

Eco-hydrology is an emerging field of science focused on how water volumes, water quality and hydro-dynamics influence onsite ecological attributes including species abundance, distribution and population dynamics. In urban and semi-urban landscapes the eco-hydrology of estuarine wetlands is often artificially manipulated due to site limitations, project restraints and/or desired project goals. In these circumstances estuarine wetland rehabilitation projects are typically undertaken using a 4-stage approach including: conceptual understanding, project planning/design, on-ground works and adaptive management. The conceptual understanding stage involves targeted field investigations to develop eco-hydrologic 'models' of the site under typical and extreme climatic conditions. The project planning/design stage aims to match the project outcomes with the site constraints. The on-ground works stage involves complex assessments of how the ecology will evolve based on small changes to the topography and hydrology. Finally, the adaptive management stage includes monitoring short and long-term hydrologic cycles to assess ecological impacts onsite. Computer modelling of eco-hydrologic processes is increasingly being used to simulate potential onsite outcomes at different stages of a wetland project. Examples are provided to highlight various applications of modelling tools under existing and future conditions at estuarine wetlands.

## Introduction

This chapter discusses the eco-hydrology of estuarine wetlands. In the context of this chapter, the term hydrology includes all of the water influencing a wetland. In estuarine wetlands this includes daily tidal movements, groundwater influences, upland inflows, riverine baseflows, flooding and evaporation. Eco-hydrology refers to the movement and volume of these waters in/around a tidal wetland and how they influence ecology (e.g. plant growth, fauna distribution, species abundance, etc.). There is a growing body of evidence that highlights the influence of hydrology on driving wetland ecology including aspects of hydroperiod (Miller and Zedler 2003; Snodgrass *et al*. 2001), saline dynamics (Middleton 1999; Glamore and Wasko 2007), sedimentation (Rogers *et al*. 2005; Cahoon *et al*. 2006; Rogers and Saintilan 2008) and climate change (Michener *et al*. 1997; Day *et al*. 2008; Granqvist *et al*. 2012).

This chapter is primarily focused on the eco-hydrology of estuarine wetland habitats during restoration or rehabilitation projects. Where useful, project examples are provided to highlight various concepts and applied techniques. The chapter covers three main aspects of estuarine wetland eco-hydrology namely:

1. The importance of selecting the ideal eco-hydrology regime for a estuarine wetland;
2. The eco-hydrologic issues to consider when undertaking wetland rehabilitation projects or managing large-scale estuarine wetlands; and
3. The engineering tools commonly used to simulate the eco-hydrology of an existing or proposed estuarine wetland.

## Site Limitations + Project Restraints = Engineering Solution

Wetland rehabilitation projects typically involve a proposed end goal (i.e. X hectares of salt marsh restored) and a proposed site location. In estuaries, proposed wetland rehabilitation sites have several characteristics in common, namely:

- The site was once subject to tidal flows;
- Tidal flushing has been restricted via earthworks (i.e. levees) and structures (i.e. culverts and tidal floodgates);
- The natural flow paths have been modified to include a hydraulically efficient ‘artificial’ drainage system with associated infrastructure; and
- The flora, fauna and topography have been affected by the altered drainage and flushing regime.

In addition to the above general site characteristics, most proposed wetland rehabilitation sites have several limitations which need to be considered. For instance, many sites have external boundary issues which may influence the onsite eco-hydrologic options. Importantly, these boundary conditions may include sensitive receivers, such as other environmental concerns, or cadastral boundaries (i.e. land boundaries) that cannot be impacted by the rehabilitation activities. The site may also have fundamental limitations in the quantity or quality of water which can be restored to the site.

The physical extent of the site may also impose eco-hydrologic limitations on the rehabilitation project. For instance, the wetland size or elevation may be insufficient to achieve the rehabilitation outcomes proposed. Alternatively, the proposed site may be degraded to an extent that limits an eco-hydrologic solution within the prescribed timeframe.

In addition to site limitations, there are several project restraints that may limit eco-hydrologic outcomes at an estuarine wetland. These restraints include financial restraints on either the funds available or the time period for the resources to be invested. With regards to time restraints, rehabilitation projects are typically short to medium term projects (say 1-10 years). It is worth noting that short to medium term projects (say up to 5 years) are unlikely to monitor eco-hydrologic characteristics such as geomorphology, changes to fauna distribution, sedimentation rates, response to climatic variability and other longer term response variables.

In combination, site limitations and project restraints imply that an ‘engineered’ eco-hydrologic solution is required (i.e. the site cannot be left to self-adjust back to some pre-existing ‘natural’ state). An eco-hydrologic solution is undertaken to overcome the site limitations by, for instance, limiting tidal flows (both tidal height and spatial flooding) to encourage the growth of a particular species. Eco-hydrologic solutions are also employed to overcome project restraints by, for instance, attempting to design a ‘mature’ estuarine wetland instead of allowing the site to geomorphically evolve towards maturity. The following discussion details common approaches for applying an eco-hydrologic solution to an estuarine wetland.

## Eco-Hydrologic Approaches and Wetland Rehabilitation Planning

In many estuarine wetlands the primary engineering solution is to modify the amount of water entering or moving across the wetland. This eco-hydrologic approach is often fundamental to achieving the projects objectives. Indeed, in estuarine wetlands around Australia this approach is being used to:

1. Ensure endangered ecological communities such as salt marsh habitat are created/maintained;
2. Ensure adjoining landholders are not negatively impacted by the rehabilitation activities (i.e. reduced drainage or flooding);
3. Adapt to climate change; and
4. Mitigate against acid sulphate soil drainage.

Well known eco-hydrologic estuarine wetland projects in New South Wales include the salt marsh re-creation project at Sydney Olympic Park (Laegdsraard 2006), the wetland re-creation projects within the Hunter Wetlands National Park (Haines 2013; Rodriguez and Howe 2013; Glamore 2013) and various acid sulphate soil wetland remediation projects such as the Big Swamp Wetland (Glamore *et al*. 2013) on the mid-north coast of NSW. These projects include large scale on-ground solutions including controlled tidal flushing to encourage the ideal eco-hydrologic conditions for a particular ecological outcome. Common to all of these projects has been a similar approach to detailed decision making including conceptual modelling, on-ground measurements, numerical modelling and long-term adaptive management.

There are typically 4 major stages in estuarine wetland rehabilitation projects, when eco-hydrology is the primary concern (Figure 3.2.1). In stage one (Figure 3.2.1a), eco-hydrologic information is obtained from targeted field investigations. Boundary (or forcing) conditions are commonly measured including tide data, upland inflows, groundwater flows, onsite drainage, etc. This information is then synthesized to develop a conceptual understanding of the existing site conditions.

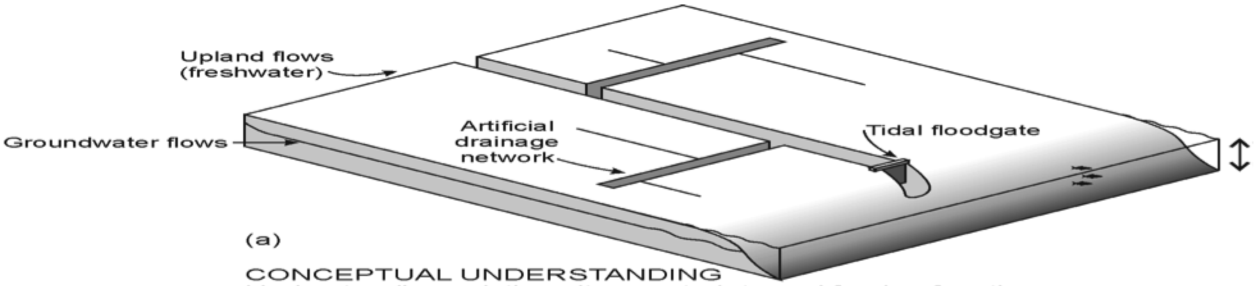
The second stage of most eco-hydrologic based wetland projects involves designing or planning rehabilitation outcomes for the site. The ideal outcomes are developed based on predetermined goals for the project (i.e. returning X species of migratory wading birds). These goals determine the desired eco-hydrologic characteristics for the site but are often limited by site and project restraints. To determine the final onsite approach the ideal scenario is then fitted to the actual site (Figure 3.2.1b) and an assessment of the likely outcomes can be developed. Eco-hydrologic modelling tools are often used at this point to (i) test the conceptual model and (ii) simulate the implications of the on-ground proposals.

The third stage of an eco-hydrologic wetland project is largely focused on the on-ground works. This includes applying the final design to the site using purpose built machinery (Figure 3.2.1c). In estuarine wetlands the on-ground works need to be undertaken with extreme care as a small change in the vertical height of the landscape can have a large impact on the amount of land inundated (and thus the likely habitat that forms onsite). For instance a small change in the inundation depth or frequency can result in a proposed saltmarsh site altering to a mangrove wetland. These changes in on-ground works may determine whether the end goals are achieved (e.g. encourage migratory wading birds).

The final stage of a typical estuarine wetland rehabilitation project is focused on adaptive management based on onsite monitoring (Figure 3.2.1d). This involves monitoring the eco-hydrologic conditions across the site and determining if the desired outcomes are being reached. Importantly, sufficient adaptability should be designed into the wetland so that the eco-hydrologic conditions can be adaptively managed onsite. This will ensure that any unforeseen changes in the upstream, downstream, groundwater or climatic conditions can be managed effectively. Understanding the spatial and temporal characteristics of the wetland (e.g. the time required for mangrove forests to reach maturity) is vital in determining the level of adaptive management required onsite but additional research is required to link eco-hydrology with on-ground response patterns.

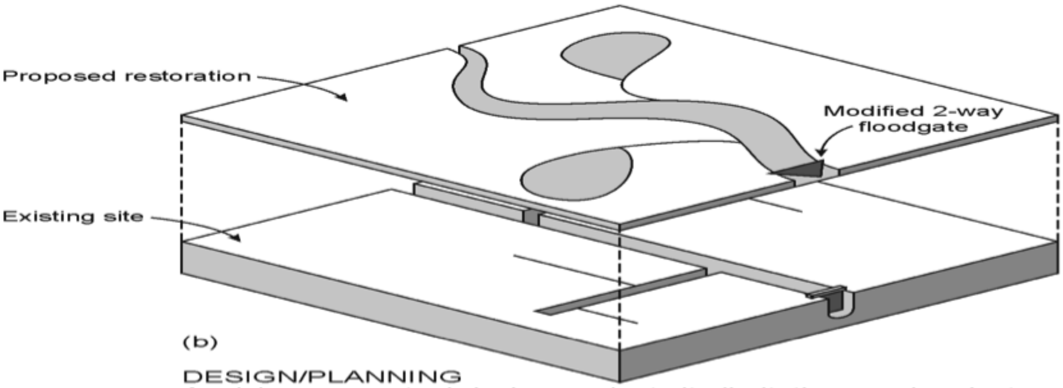
## Eco-Hydrologic Assessment Models

In this section a range of engineering tools to assess wetland eco-hydrology are presented. For clarity, the discussion begins with an explanation of how engineering tools are commonly incorporated within the initial ‘Conceptual Phase’ of a



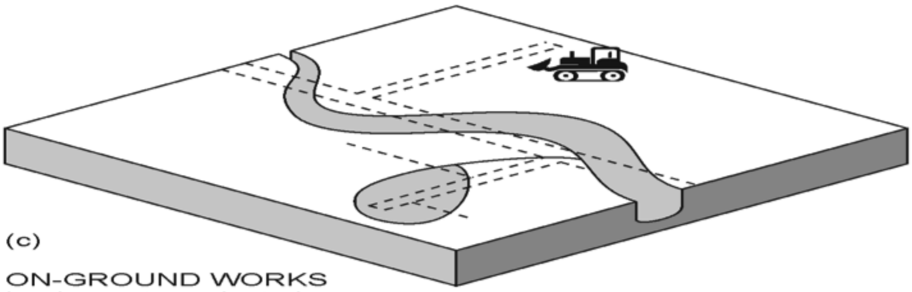
(a)

CONCEPTUAL UNDERSTANDING
Understanding existing site constraints and forcing functions
(numerical modelling)



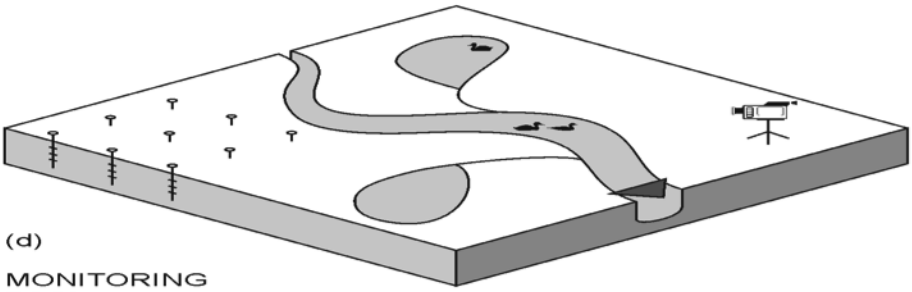
(b)

DESIGN/PLANNING
Applying conceptual design against site limitations and project restraints
(floodgate design criteria)



(c)

ON-GROUND WORKS
Implements project plan
(modified gate design)



(d)

MONITORING
BACI programme
(importance of mass flux and imaging techniques)

**Figure 3.2.1.** Eco-hydrologic approach to estuarine wetland rehabilitation projects.

rehabilitation project (Figure 3.2.1). The discussion then proceeds to how different engineering concepts can be applied during subsequent phases of project planning including the Design/Planning, On-ground and Adaptive Management phases discussed above.

At most estuarine wetlands, the fundamental controlling factor underlying the biological, ecological and geomorphic conditions is hydrology. Indeed, a wetland project has limited chance of succeeding unless the correct eco-hydrologic or flushing regime is established. This section examines the key engineering issues to consider in the initial 'Concept Phase' of a rehabilitation project. Where appropriate, recent advances in eco-hydraulic techniques are discussed.

Understanding the existing site hydrology, and developing a conceptual hydrologic flushing regime for a nominated wetland, requires a thorough understanding of the eco-hydrologic forcing functions. For most wetlands the forcing functions include external boundary conditions; largely the adjacent tidal boundary and any upland inflows. Groundwater inflows may also be an important internal forcing function, however, the overall contribution of groundwater flows to the site hydrology is typically limited in meso- and macro-tidal settings.

In estuarine environments the primary component of the site's hydrology is the tide. Calculating the influence of the tide on the wetland's water balance is often one of the most difficult tasks during the project's conceptual phase. Often limited information is available on the tidal amplitude, phasing, prism, constituents, channel roughness, salinity dynamics, etc. Further, detailed topographic information, including spot survey data, is required to assess how the incoming tide will disperse across the wetland (i.e. resulting in a stage-height relationship for the site).

With limited information, wetland managers are often tasked with the responsibility of restoring a wetland to achieve a desired outcome. The paucity of physical data (i.e. tidal information, survey levels, etc.) is often compounded by the desire to implement a biological outcome. Indeed, in many cases no information is available on the hydroperiods and salinity regimes required to establish a certain species of flora or fauna. To overcome these limitations, simulation models of a wetland's eco-hydrology prior to and proceeding tidal restoration works are developed. These models simulate the movement of water within the environment via algorithms that represent fundamental physical principles and include site specific data and various assumptions.

## Eco-hydraulic Modelling Approaches

Various modelling packages are commercially available to simulate eco-hydrological processes. These models range from simple elevation models to complex 3-Dimensional time-transient computer simulation models. Though often overlooked, physical models can also be useful to understand hydraulic issues such as tidal flow through or around complex structures where the fundamental physics are unknown or where traditional equations are not applicable (i.e. complex flow through long culverts).

Digital elevation models are a simple numerical modelling tool that should only be applied in areas where flow would not be restricted by time or space. In these models, high resolution survey data is input into spatial mapping software. The mapping software, such as ArcGIS or MapInfo, can then interpolate between available data points to create a surface layer. Once an elevation model has been developed, spatial analyst tools are used to calculate the lateral extent of flooding that may occur under different tidal flushing regimes. For instance, overland flooding areas can be determined based on water levels or via breaches in levees.

An example of a digital elevation model used to determine the impact of restoring a wetland is shown in Figure 3.2.2. In this example, extensive LiDAR data was used to develop a 3-Dimensional contour map of the floodplain using ArcGIS. Various water levels were then applied using the spatial analyst tool to determine the extent of tidal flushing under neap and spring tide levels. The digital elevation technique (or bucket model) could be applied to this site as the proposed area for tidal restoration has limited upland inflows (i.e. simple hydrology), was relatively small (approximately 1000 m and no loss of momentum), and did not contain any significant flow retarding structures (i.e. no hydraulic concerns).

The digital elevation model results shown in Figure 3.2.2 had a significant impact on the outcomes of the wetland design process. As depicted, restoration of the full tidal limits would have resulted in overland flooding of private landholders, which was not an acceptable outcome for this study. However, if the tidal waters were restricted in height then the outcomes were achievable. Based

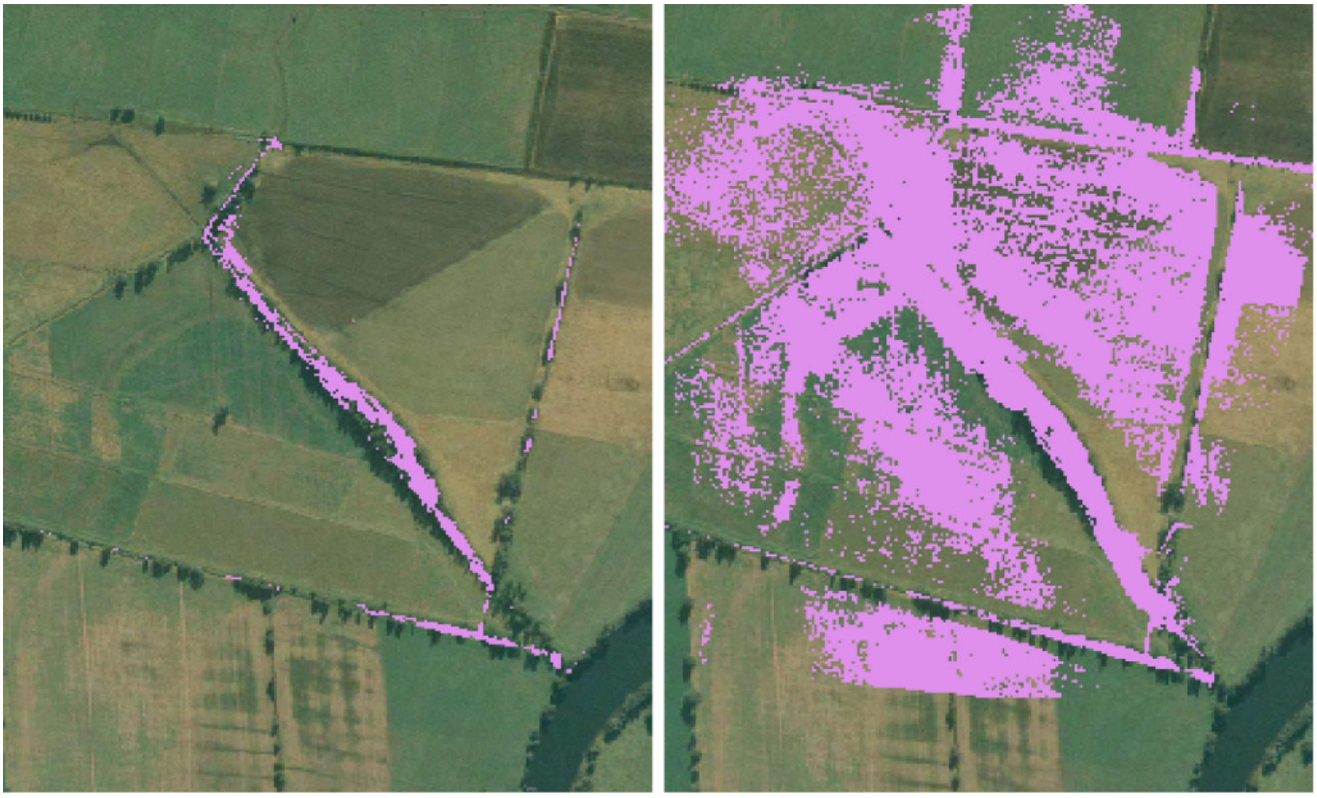


**Figure 3.2.2.** Example of geo-spatial modelling approach depicting (a) muted and (b) full tidal inundation at a potential estuarine wetland.

on these results, a structure was developed and installed that was able to restrict (or mute) the tidal flows to the desired levels.

In the above example the preferred outcome required a reduced tidal exchange to limit overland inundation on adjoining properties. However, the primary rationale for restoring tidal flushing to this site was to improve the existing water quality (which was acidic) by flushing the system with tidal waters rich in buffering agents (i.e. carbonate and bicarbonate ions). As the initial objective of the project was to improve water quality through mixing, and the digital elevation modelling indicated that less water was available than previously anticipated, water quality models (or ion association mixing models) were employed to determine if the proposed flushing regime would be sufficient to offset the poor water quality (i.e. would the environmental outcomes of the proposed project still be achieved with less water).

Ion association models, such as PHREEQC, can be used in conjunction with digital elevation models to assess the potential changes to water quality when restoring or creating wetlands (Glamore and Indraratna 2004). In the example detailed above, the digital elevation model indicated that instead of full tidal flushing (which would have resulted in 200% mixing of tidal water with in-situ water), the reduced or muted tidal flushing regime would result in a 80% mixing ratio between tidal water and in-situ water. In these circumstances, ion association models can be used to determine the water quality impact of the proposed rehabilitation scenario. The results from these simulations can be subsequently applied to assess eco-hydrologic outcomes onsite.

As shown in Figure 3.2.2, the geo-spatial bucket model indicated that the reduced wetland size (due to the muted tidal flushing regime) would result in significantly less improvements in water quality. However, the improvements in water quality were still deemed sufficient to justify proceeding with the on-ground modifications. Conversely, in other locations the water quality modelling has indicated that the proposed changes were not sufficient to justify capital expenditures. Regardless of the outcome, the ability to simulate the final result prior to implementing costly on-ground works is a significant advantage provided by these tools during the design phase of the project.

In locations where the transport of water across or through the wetland is important, hydrodynamic models are required. Hydrodynamic numerical models are used to simulate the

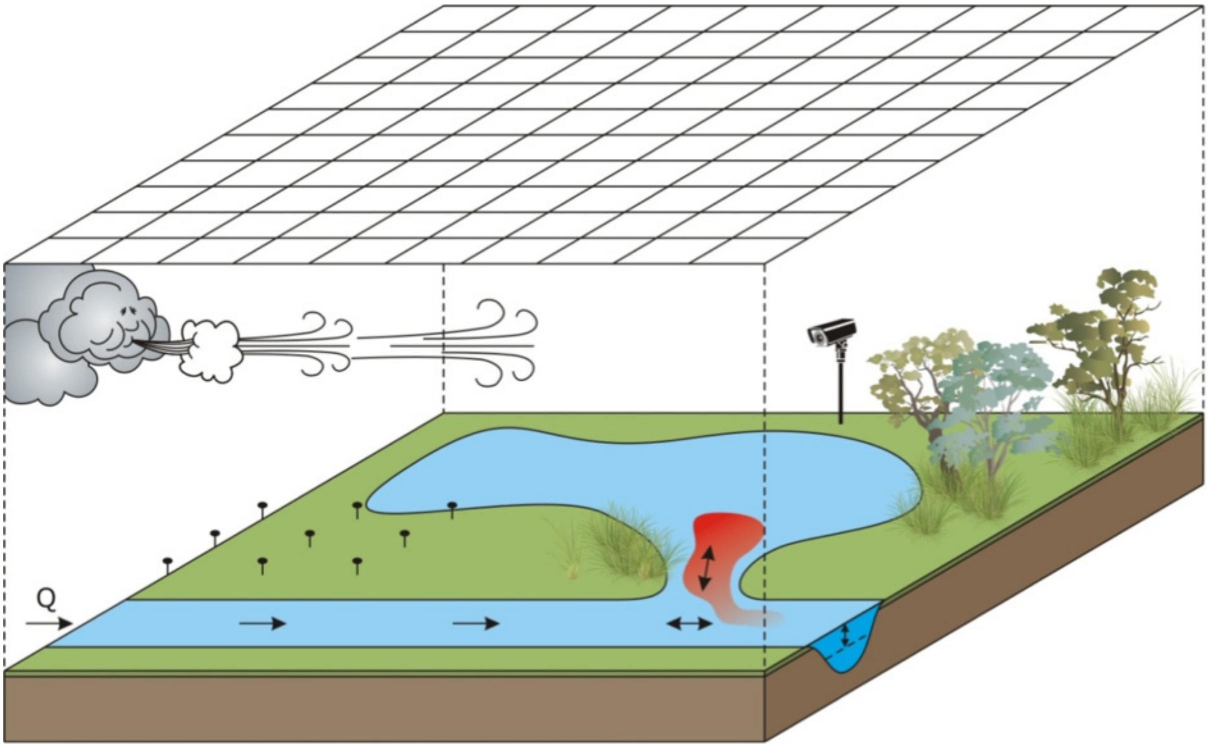


**Figure 3.2.3.** Depiction of a numerical computer grid being applied to an estuarine wetland. Computer models must simulate all relevant estuarine wetland physical processes into upland inflows, shallow inundation, tidal fluctuations and environmental influences.

transport of water in 1, 2, and/or 3-Dimensions through a range of forcing functions (i.e. boundary conditions), on-site data (site topography, bathymetry, water levels, channel roughness, etc.) and physics-based advection and momentum equations. In wetland projects, hydrodynamic models are typically calibrated to simulate the existing conditions and then used to simulate various on-ground options.

The ability of any model to simulate real world conditions is entirely reliant on the quality of data used to set-up, calibrate and verify the model (Figure 3.2.3). In wetland projects, numerical models are predominantly used to simulate overbank flow and shallow water flooding of relatively flat surfaces. Numerical models are particularly vulnerable in these cases as the model (i) relies on detailed topographic information to simulate overbank flows and (ii) has a series of marshing parameters that must be adjusted to maintain network integrity. As this chapter seeks to highlight eco-hydraulic approaches, other references are recommended for background information on numerical modelling techniques (James 1993; Warner *et al*. 2005). Nonetheless, engineering advice should be sought prior to undertaking complex numerical modelling of salt marsh environments.

Several innovative eco-hydraulic techniques have been developed in recent times to simulate wetland environments. Of particular interest are recent advances in combining broad acre water quality modelling with hydrodynamic simulations. In Australia, these advances have largely focused on examining estuary wide phenomena and using these results to determine the optimal location for rehabilitation works. Other examples include examining the role of sedimentation and wetland aggradation or the impact of sea level rise and future wetland extents. A detailed example of a hydrodynamic simulation model for an estuarine wetland is provided below.

## Case Study: Yarrahapinni Wetlands, NSW

**Project Aim:** Assess the optimal rehabilitation strategy for a degraded estuarine wetland with considerations for financial (ongound engineering) and site (upstream landholders and agriculture) constraints.

**Conceptual Understanding:** During the 1960s a series of levees were built across the tidal boundary of a large estuarine wetland to establish agricultural farmlands (Figure 1). Tidal floodgates were also installed in the levee to drain the wetland and lower the groundwater table. Over the following 50 years these on-ground works significantly reduced water quality (due to acid sulphate soils), dramatically decreased fish populations and provided limited agricultural gains.

A multi-stage plan was developed to restore the estuarine wetlands (Glamore and Timms 2009). Due to limited funds and site constraints, a computer model of the eco-hydrologic conditions was recommended to simulate tidal flushing options, assess the impacts to adjoining landholders and determine a staged series of on-ground works. The impact of future sea level rise was also simulated.

A conceptual model was developed based on extensive field data gathering. Cross-sections of the river channel, water levels, discharge data, vegetation surveys and extensive topographic data was obtained at multiple locations. Data analysis during wet and dry periods allowed for a detailed conceptual model to be constructed for the site. The conceptual model detailed the potential risks of reintroducing tidal flows across the wetland, including impacts to irrigation water quality, and highlighted a range of rehabilitation options.

**Design/Project Planning:** The field data and conceptual model were subsequently used to develop a numerical model of the wetland's eco-hydrology. Data was input into a detailed numerical grid to simulate tidal inundation across the site under a range of restoration stages including removing the tidal floodgates and various options of levee bank removal. Each restoration option was assessed to determine the like risk to upland agricultural, the eco-hydrological implications and the need for further infrastructure to limit saline intrusion. Detailed vegetation maps were integrated into the simulation results to depict how the aquatic vegetation would evolve during and following the rehabilitation program.

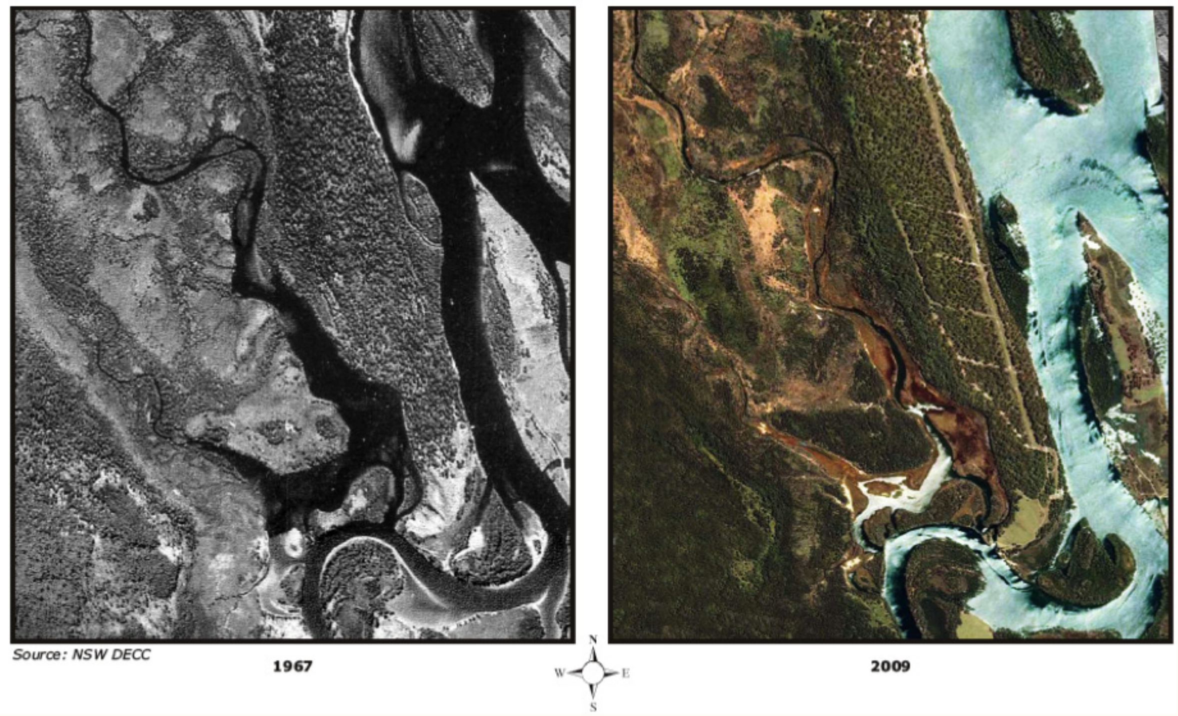

Source: NSW DECC

**Figure 1.** Yarrahapinni Wetland prior to and following drainage works.

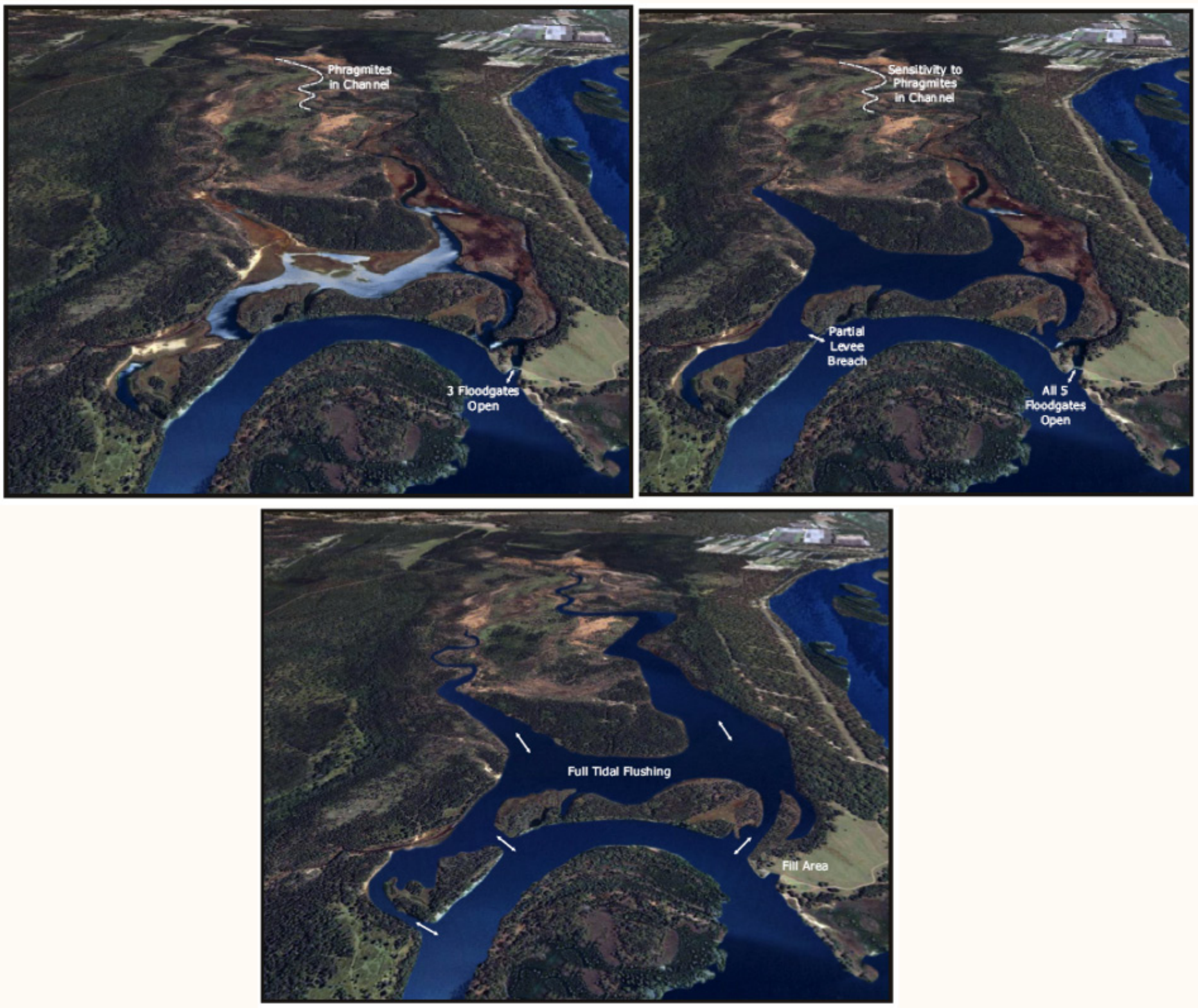


**Figure 2.** Various eco-hydrologic based restoration options for Yarrahapinni Wetland including (a) modification of tidal floodgates, (b) minor levee bank removal and (c) full tidal flushing.

**On-ground Outcomes:** Simulation results indicated that the estuarine wetland could be restored in a staged process with significant eco-hydrologic benefits (Figure 2). In addition to simulating the proposed impacts of tidal inundation to the vegetation communities, the modelling results were also used to determine the ideal length of the levee bank to remove. Minimising the extent of the levee bank removal is important to reduce on-ground works, however, a sufficiently wide gap in the levee bank is required to ensure that the water velocities entering the wetland are similar to background estuarine velocities. This is particularly important as the return of estuarine fish within the restored wetland is a major project goal.

**Adaptive Management:** Sea level rise scenarios were simulated to depict the impact of not undertaking onsite wetland rehabilitation works (Figure 3). These simulations indicated that the majority of the site will become inundated and be subject to a range of new eco-hydrologic pressures over the next 40 years. This will have a particular impact on vegetation communities and suggests that the existing infrastructure requires immediate attention. Targeted monitoring and continual adaptive management of the restored estuarine wetland will ensure that the site evolves in-line with the project goals.

Further details on this project can be found in Glamore *et al*. (2012).

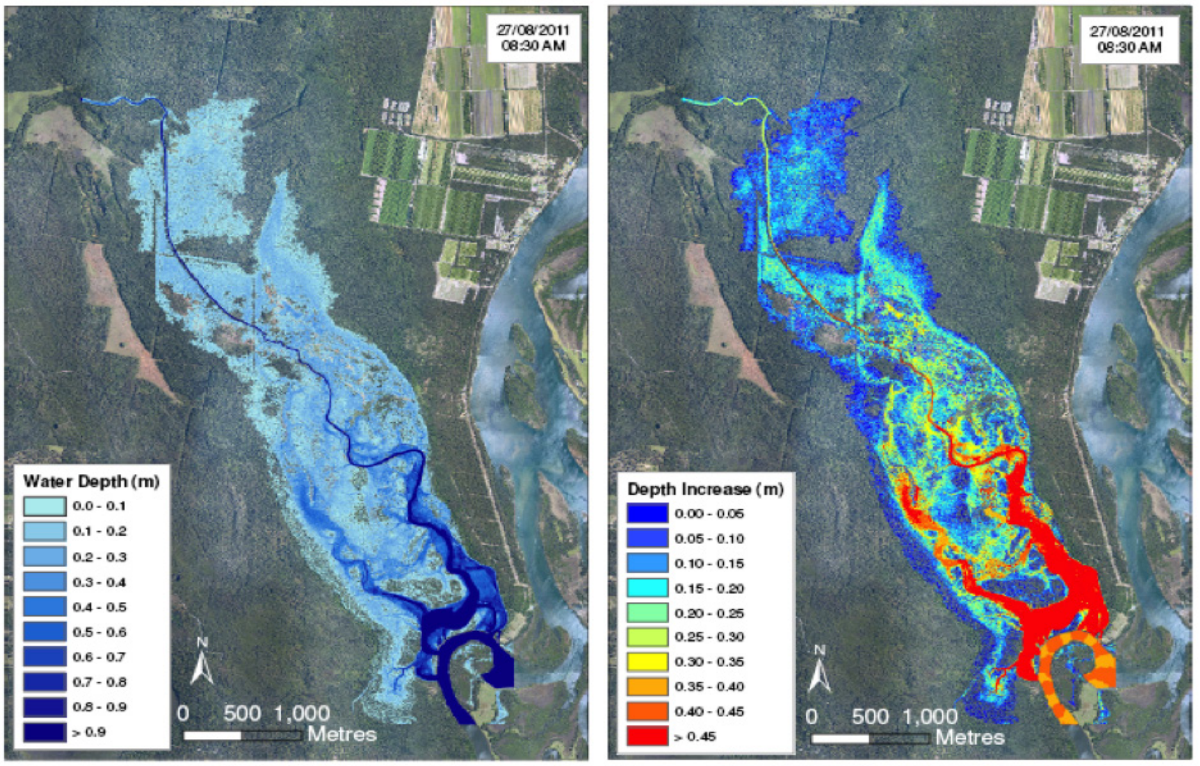


**Figure 3.** Eco-hydrologic simulations depicting the impact of sea level rise by 2050 to the Yarrahapinni Wetland.

## Summary

This chapter provides an overview of estuarine wetland eco-hydrology and issues pertaining to undertaking large wetland rehabilitation projects. The chapter emphasises that an eco-hydrologic solution is often required due to site and project restraints. Applying an eco-hydrologic approach within project restraints often results in an engineered on-ground solution (i.e. the site cannot natural adapt to some pre-existing state).

Applying an eco-hydrologic approach to an estuarine wetland is commonly undertaken in a 4 stage process. This includes (1) collecting information and developing a conceptual model of the eco-hydrologic conditions, (2) planning an optimal design developed around project goals, (3) undertaking detailed and careful on-ground works and (4) adaptively managing the onsite outcomes via targeted field investigations. During each stage numerical modelling techniques may be useful to simulate potential outcomes and in testing conceptual models.

A range of numerical modelling techniques and approaches are summarised to highlight various applications in assessing wetland eco-hydrology. These models range from simple geo-spatial ‘bucket’ models to complex multi-dimensional hydrodynamic simulation models. Case studies are provided to highlight different modelling approaches.

### References

Cahoon, D., Hensel, P., Spencer, T., Reed, D., McKee, K., *et al*. (2006). Coastal Wetland Vulnerability to Relative Sea-Level Rise: Wetland Elevation Trends and Process Controls. Ecological Studies. 190, Verhoeven, Beltman, Bobbink and Whigham (Eds). Springer-Verlag Berlin Heidelberg.

Day, J., Christian, R., Boesch, D., Yanez, A., Morris, J., *et al*. (2008). Consequences of Climate Change on the Ecogeomorphology of Coastal Wetlands. *Estuaries and Coasts* **31**, 477–491.

Glamore, W. (2012). Incorporating Innovative Engineering Solutions into Tidal Restoration Studies. In ‘Tidal Marsh Restoration: A Synthesis of Science and Management. The Science and Practice of Ecological Restoration’. pp. 277– 295. (Island Press).

Glamore, W., and Indraratna, B. (2004). A two stage decision support tool for restoring tidal flows to flood mitigation drains affected by acid sulphate soil: case study of Broughton Creek floodplain, New South Wales, Australia. *Australian Journal of Soil Research* **42**, 639–648.

Glamore, W., and Timms, W. (2009). Yarrahapinni Wetlands National Park Restoration Plan. Technical Report 2009/05 by University of New South Wales' Water Research Laboratory. April 2009.

Glamore, W., Wasko, C., and Smith, G. (2012). Rehabilitation of Yarrahapinni Wetlands National Park: Hydrodynamic Modelling of Tidal Inundation. Technical Report 2011/21 by University of New South Wales' Water Research Laboratory. August 2012.

Granqvist, L., Glamore, W., and Cox, R. (2012). Using Elevated Digital Images to map Tidal Hydraulics and Saltmarsh Evolution. In 'Proceedings of 2012 Hydrology and Water Resources Symposium. Sydney. November 8-12, 2012.'

Haines, P. (2013). Hydrological modelling of tidal re-inundation of an estuarine wetland in south-eastern Australia. *Ecological Engineering* **52**, 79–87.

James, A. (1993). 'An Introduction to Water Quality Modelling.' p. 311. (John Wiley and Sons Ltd.)

Laegdsgaard, P. (2006). Ecology, disturbance and restoration of coastal saltmarsh in Australia: a review. *Wetlands Ecology and Management* **14**, 379–399.

Middleton, B. (1999). 'Wetland Restoration, flood pulsing, and disturbance dynamics.' (John Wiley & Sons: USA.)

Miller, R., and Zedler, J. (2003). Responses of native and invasive wetland plants to hydroperiod and water depth. *Plant Ecology* **167** (1), 57–69.

Mitchener, W., Blood, E., Bildstein, L., Brinson, M., and Gardner, L. (1997). Climate Change, Hurricanes and Tropical Storms and Rising Sea Level in Coastal Wetlands. *Ecological Applications* **7**, 770–801.

Rodriguez, J., and Howe, A. (2013). Estuarine Wetland Ecohydraulics and Migratory Shorebird Habitat Restoration. In 'Ecohydraulics: An Integrated Approach'. (Wiley & Sons Ltd.)

Rogers, K., and Saintilan, N. (2008). Relationships between Surface Elevation and Groundwater in Mangrove Forests of Southeast Australia. *Journal of Coastal Research* **24** (Issue 1A), 63–69.

Rogers, K., Saintilan, N., and Cahoon, D. (2005). Surface elevation dynamics in a regenerating mangrove forest at Homebush Bay, Australia. *Wetlands Ecology and Management* **13**, 587–598.

Snodgrass, J., Komoroski, M., Bryan, L., and Burger, J. (2001). Relationships among Isolated Wetland Size, Hydroperiod and Amphibian Species Richness: Implications for Wetland Regulations. *Conservation Biology* **14** (2), 414–419.

Warner, J., Geyer, W., and Lerczak, J. (2005). Numerical Modelling of an Estuary: A comprehensive skill assessment. *Journal of Geophysical Research: Oceans* **110** (C5) CO5001.