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A Multi-Staged Management Strategy for Restoring Tidal Flushing

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Abstract
Tidal restoration/wetland rehabilitation projects are being undertaken throughout Australia without an integrated standardized approach. The lack of a comprehensive holistic management strategy can delay project outcomes or lead to piece-meal modifications that lack a full appreciation of the groundwater and surface water hydrodynamics. To overcome these limitations, this paper presents a tidal restoration/floodgate manipulation strategy that was developed from a four-year field study undertaken in southeastern NSW and subsequently applied at multiple field sites. An eight stage methodology is proposed to incorporate water quality, hydraulics, groundwater/saline intrusion, hydrology, field monitoring and flood design criteria. The strategy begins with a quantification of perceived outcomes for the study. Using these goals, the potential improvement in water quality are calculated using ion association models and field sampling techniques. The third stage quantifies the spatial flooding extent using GIS spatial analysis methods. The risks associated with saline intrusion into the sub-soil matrix are detailed using guidelines developed from calibrated numerical models and field data. The modified floodgate designs are also discussed. Finally, field-monitoring recommendations are given with specific emphasis on chemical speciation, data retrieval methods and quantification of mass flux levels. Tidal restoration should only be undertaken once every criterion has been addressed.

1 Introduction

In response to major flooding events during the 1940-50s, extensive flood mitigation works were commissioned across New South Wales to drain coastal wetlands and tidal swamps. During this period more than $50 Million was spent on the construction of flood mitigation drains, levee construction and the installation of related infrastructure (floodgates, tidal barrages, etc.). This development resulted in the permanent drainage of large tidal wetlands and the subsequent oxidation of hydric, sulfide bearing soils.

In response to the extensive floodplain drainage works, Walker (1972) warned that prolonged oxidation of the pyretic sediments would result in acidic pore water that could be subsequently drained into adjacent flood mitigation canals. Indeed, the combination of extensive coastal drainage works and acid sulfate soils has resulted in wide spread groundwater acidification, soil subsidence, and large 'acid reservoirs' which drain into downstream waterways with devastating impacts (Indraratna and Glamore, 2002). Furthermore, tidal floodgates, which restrict tidal flushing and limit fish passage, exacerbate acid production and transport (Glamore, 2004).

In efforts to rehabilitate tidal wetlands and reduce the impact of acid sulfate soils, restoration projects are being undertaken across NSW. Williams and Watford (1997) stated that >1035 floodgates currently exist which could be effectively modified to restore tidal flushing. With the large number of potential sites and sufficient scientific understanding, tidal restoration projects are currently being undertaken by various groups.

Restoring tidal flushing involves an interdisciplinary understanding of hydrodynamics, groundwater-surface water interactions, water quality/chemistry, ecology, estuarine dynamics and civil engineering hydraulics. Any restoration study should incorporate a staged approach that includes numerical forecasting of hydrologic and water quality conditions prior to on-ground works and allows landholders to assess potential changes *prior to* all major tasks. Failure to effectively restore tidal flushing can result in undue flooding, destruction of agriculture crops, salinity concerns, public mistrust, etc.

In response to (i) the environmental desire to restore tidal wetlands, (ii) the large number of tidal restoration projects, (iii) the lack of any existing methodology and (iv) the inter-disciplinary approach required, a systematic tidal restoration management strategy was designed. The strategy was initially developed and verified throughout a 3.5 year study, and subsequently applied to various sites. The development of this strategy is of particular importance considering that there are no current Australian methods to restore tidal flows and that previous studies (Sammut *et al.*, 1994; Blunden, 2000; and Glamore and Indraratna, 2004) have focused on individual components and not holistic methods.

This paper details the eight stage management strategy and its application at a monitored site in the Shoalhaven region of southeastern NSW. Tidal restoration works should not proceed unless each stage of the strategy is considered and approved.

The eight stages of the strategy include:

1. Determine Objectives
2. Hydrologic Criteria
3. Water Quality Criteria
4. Ecological Criteria
5. Saline Intrusion Risk
6. Marine Infrastructure
7. Environmental Design Concerns
8. Monitoring Program

2 Area descriptions

A site was chosen which represents typical conditions found throughout low-lying tidal floodplains in mid-latitude eastern Australia. Located along Broughton Creek, a left bank tributary of the Shoalhaven River, the site has a maximum elevation of 2.0 m AHD and is underlain with acid sulphate soils (approximately 0.6-1.0 m below surface). Extensive airborne laser scanning and subsequent groundtruthing was undertaken to obtain accurate topographical maps of the region.

As with most drained sites in the region, the selected site is dissected by a 3 m deep flood mitigation drain which cuts through the acid sulfate soil layer and has been engineered to allow drainage of the backswamp region. Two tidal floodgates, installed at drain/creek junction, maintained the upstream drain water level at low tide and restrict tidal flushing. The two adjoining floodgates are 2 x 2 m in size and are top hinged (allowing drainage via hydrostatic head).

To monitor the field site and provide sufficient information for the restoration works, a series of *in situ* continuous monitoring sensors were installed in the surface water (upstream and downstream of the floodgate) and at logarithmic spacing intervals in the groundwater. Each sensor (a total of 9) monitored hourly pH, electrical conductivity, water level, dissolved oxygen, and temperature. Grab sampling was undertaken at other sites of concern (Figure 1).

The site was located approximately 10.2 kms upstream of the Shoalhaven River and 19 kms from the mouth of the Shoalhaven River. Median tidal fluctuations at the site were 0.9 m and creek water quality fluctuated with tidal flushing (median pH = 6.7, electrical conductivity ranges from 0.22-27.21 mS/cm, DO = 7.2) Conversely, water levels in the drain were consistently near low tide levels (-0.25 m AHD) and water quality was typical of acid sulfate soils (median pH = 4.5, electrical conductivity = 3.5 mS/cm, DO = 5.1 ppm). Additional information on the field site can be found at Glamore (2004).

3 Techniques

Due to the consistently poor water quality discharging from the site and the perceived potential for environmental improvements, the site was selected for tidal restoration. The eight stages of the management strategy were applied to the site. A description of the project is described below.

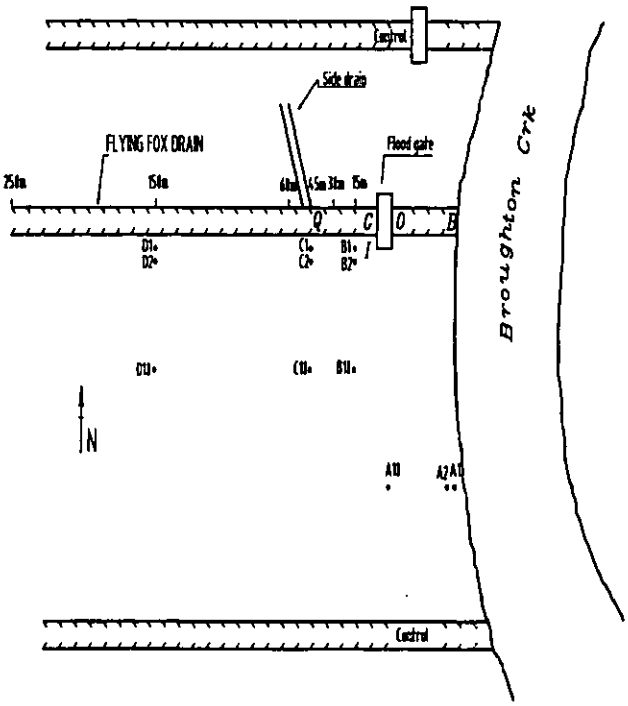

Figure 1. Study Site Layout and Sampling Sites (Note that Q, G, O, B and I are continuously monitoring sensors).

3.1 Determine objectives

Prior to commencing any on-ground works it is of the utmost importance to determine the aims and objectives of the study. In tidal restoration studies these objectives should be quantifiable outcomes including both ecological, water quality, hydrology and floodgate concerns.

For this study several objectives were determined prior to the study:

1. *Hydrology*- sufficient freeboard should be maintained within the drain to restrict overtopping of the levee banks.
2. *Water Quality*- Drain water quality should be maintained within ANZECC (2000) guidelines for pH, dissolved oxygen, soluble iron and aluminium.
3. *Ecological*- exotic weeds should be combated, fish passage restored and mosquito breeding conditions removed.
4. *Agriculture*- groundwater salinity levels should be maintained within ANZECC (2000) guidelines at least 10 m from the drain and 1 m from the surface.
5. *Floodgate*- the modified floodgate should restrict overtopping, allow for remote control via telemetry, and be controlled by water quality and water levels.

It was determined that *all* objectives had to be reached in order to progress with the study. Each objective was readdressed after the conclusion of every stage.

3.2 Hydrologic criteria

Drain hydrology was assessed to determine if sufficient tidal water could be permitted within the drain without causing flooding of the surrounding agricultural paddocks. Tidal analysis was first performed to determine the mean high water springs and mean high water level. This information was then combined with the topographic map layers in an ArcGIS framework to determine the maximum quantity of water permitted within the drain.

Using the spatial analyst tool in ArcGIS, water levels were manipulated to determine the optimal drain levels which maximized the quantity of water while providing sufficient freeboard. As depicted in Figure 2, the optimal water level in the drain was calculated to be 0.91 m AHD. This equates to a 58% increase in drain water levels during peak tidal periods.

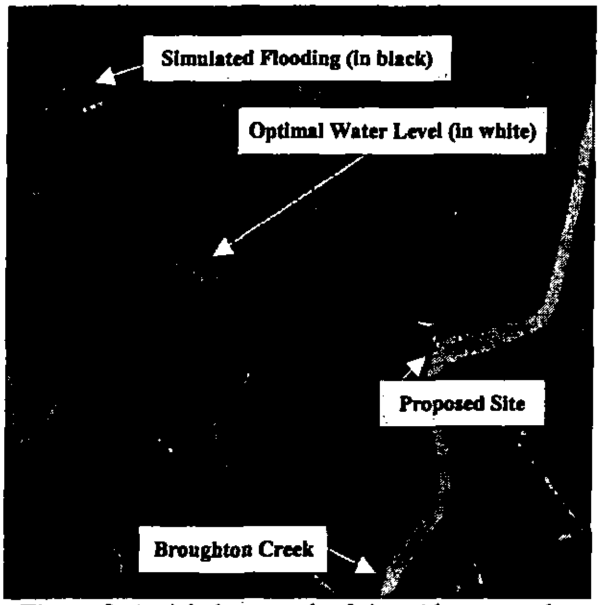

Figure 2. Aerial photograph of site with proposed drain water elevations (optimal elevation shown in white, overtopping shown in black).

The outcome of the hydrologic assessment implied that tidal restoration could be allowed within the drain during most tidal phases but that water levels would need to be controlled (via the floodgate) on king tides.

3.3 Water Quality criteria

Water quality was assessed to determine whether tidal flushing would increase drain water pH and DO, while decreasing soluble iron and aluminium concentrations. Baseline concentrations of both drain and river samples were determined by weekly grab samples at various sites (analysed using standard laboratory methods) over 14 months. Creek water samples indicated that the salinity regime fluctuated depending on inflows and that the creek typically recovered to 5 mS/cm within 7-14 days depending on rainfall. As described above, drain water was typical of acid sulfate soils and, due to the floodgates, the water was often stagnant.

To simulate the impact of restoring tidal flushing, lowly ionic and highly ionic creek water was mixed in proportion with acidic drain water. Samples were mixed using standard laboratory titration methods in ratios of 0.1:1, 0.25:1, 0.5:1, 0.75:1, 0.9:1, 1:1, 1.25:1, 1.5:1 and 2:1 of drain water to creek water. During and at the end of each titration, samples were analysed for pH, DO, EC, soluble iron and soluble aluminium.

The results from the laboratory titration experiments were subsequently imported into an ion association program, PHREEQC, to calibrate the model output for simulating mixing of two waters. A mixing program was written and applied within the 1-dimensioinal open framework model to simulate chemical speciation and mixing over varying ionic conditions. The results from the program were then calibrated against the laboratory titration tests to evaluate the mixing of alkaline creek waters of varying ionic strengths with acidic drain water rich in aluminium and iron. The main inputs to the model were elemental ion concentrations and EC (i.e. salinity).

Results from the laboratory tests and subsequent modelling indicated that a significant improvement in water quality could be obtained within the drain following tidal restoration. Using the results from the spatial simulation it was shown that during mean high water events, creek water would mix with drain water at a ratio of approximately 0.6:1. Based on the model outputs this equated to an increase in drain water pH of more then one order of magnitude, and a 50% decrease in soluble iron and aluminium (Glamore and Indraratna, 2004).

The use of an ion association model as described above assists in forecasting the likely changes in water quality due to tidal restoration. At this site, it was determined that although tidal restoration would not restore water quality to ANZECC (2000) levels (objective #1), the significant improvements in pH, Al and Fe justified the capital expenditures. The modelling simulations also allowed for a quick estimation of potential mixing benefits at other sites downstream, which may have higher buffering levels (i.e. more ionic). Further investigations, however, indicated that this site suited all other relevant criteria.

3.4 Ecological Criteria

Several studies both overseas and in Australia (Pollard and Hannah, 1994, Sammut et al., 1996) have shown that restoring the tide improves both drain and creek ecology by controlling exotic weeds, restoring breeding grounds, providing vital salt water marsh wetlands and reducing mosquito breeding areas. In subtropical regions of Australia the impact of the Cape waterlily on reducing light penetration, dissolved oxygen levels and influencing drain hydrodynamics is well documented. In southeastern NSW, environmental conditions suit an acidophilic freshwater sedge, *Eleocharis equisetina.*

At the selected study site, *Eleocharis* was shown to infest the drain and completely cause a mono-specie culture. In addition to reducing the hydraulic efficiency of the drain, the weed infestation increased organic matter content. The decomposition of organic matter in conjunction with the acidic water and one-way floodgates enhanced the formation of mono-sulfidic black oozes (MBOs). Sullivan and Bush (2000) suggest weed accumulation and a high concentration of dissolved sulfate from previously oxidised pyrite provides an ideal environment for MBO deposition on the drain invert. Disturbing these sediments, via mechanical weed clearing or during floods, can induce secondary oxidation and increase drain and creek water acidity.

Pollard and Hannah (1994) suggest that one-way floodgates cause alienation of habitat areas, restrict fish passage and block larval transport, whereas Gibbs et al. (1997) found that the quantity of fish species significantly increased in drains with 'leaky' floodgates. At the study site, prior to tidal restoration only undesirable species such as exotic carp were found within the drainage network.

It was deduced that regular tidal flushing of brackish water would reduce weed growth, decrease MBO formation and improve the hydraulic efficiency of the drain. With regards to mobile species, it was determined that tidal flushing would increase the number of species assemblages within the drain system, reduce areas for mosquito larvae, and allow fish passage.

3.5 Saline Intrusion Risk

The two largest perceived threats of tidal restoration projects in agricultural regions are overtopping of saline waters onto productive agricultural paddocks and intrusion of saline tidal waters within the soil matrix. The overtopping concerns are dealt with in Stages Two and Six (hydrodynamic and marine infrastructure). This section addresses the groundwater salinity concerns.

Several studies have examined the physical nature of acid sulfate soils (Blunden 2000, Blunden and Indraratna., 2001). Potential acid sulfate soils are commonly dense massive Holocene clays with high moisture contents and low hydraulic conductivities. Once oxidised, the actual acid sulphate soils reduce in moisture content and allow oxygen transport via, typically vertical, macropores. The oxidation process, as well as the overbearing soil type (sand or peat), can significantly increase the hydraulic conductivity of the soil with reported K_{sat} values ranging from 0.001 to 30-40 m/day.

To determine the impact of restoring tidal flushing on the soil matrix a 3-Dimensional transient groundwater numerical model was developed. The model was run using the aforementioned multi-parameter sensors as boundary conditions, topography maps and extensive field data for material properties (unsaturated properties, vertical and lateral hydraulic conductivities, porosity, etc.). The model was calibrated and verified using hourly and weekly groundwater data collected over a 6 month period (Glamore, 2004).

Site specific results depict that even in a worse case scenario (no rainfall for 6 months, highly saline boundary conditions- Figure 3), groundwater salinity would be lower then ANZECC (2000) criteria at 10 m from the drain boundary and 1 m from the surface. Furthermore, rainfall of 50 mm over two days is sufficient to completely flush the saline contaminates from the soil. Based on this assessment it was determined that tidal restoration would comply with the design objectives. To provide further confirmation of the results, groundwater monitoring was maintained throughout the 3 year study.

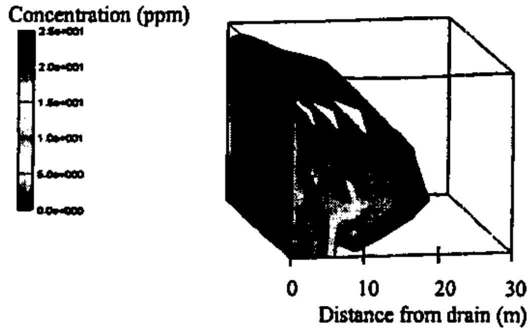

Figure 3. Saline intrusion under worse case scenario.

Sensitivity analysis from the calibrated model indicated that saline intrusion was most sensitive to changes in lateral saturated hydraulic conductivity.

3.6 Marine Infrastructure

Based on Stage 3 findings, increased tidal flushing equates to improved water quality. However, Stage 4 findings indicate that water levels need to be controlled to limit overtopping. Currently, no standardised modification codes to redesign flap gates have been developed and consequently, floodgate modifications are often undertaken *ad hoc* without proper considerations of engineering design concepts or hydraulic concerns. This section addresses the design and hydraulic issues regarding floodgate modifications, with particular reference to the multitude of concerns involved before floodgate modifications. An environmental controlled *SmartGate* system installed at the site is detailed.

Based on the water quality and overtopping concerns detailed above, as well as the stated objectives given in Section 3.1 (i.e. the modified floodgate should restrict overtopping, allow for remote control via telemetry, and be controlled by real time water quality and water levels), and working within the infrastructure and hydraulic considerations of the site, modifications of the floodgate structure were required to fall within strict operational guidelines.

Whereas the main objective in regards to water quality was to restore tidal flushing to the drainage system, floodgate modifications were restricted by other hydrodynamic, environmental and agricultural criteria. These criteria are applicable to all floodgate modifications and include:

1. Maintaining flood mitigation characteristics (i.e. not reducing hydraulic efficiency during storm events);
2. Control of maximum and minimum water levels;
3. Sufficient flexibility to trial several management strategies including optimising water levels (incremental control) and seasonal variations;
4. Low maintenance and comply with OH&S standards;
5. Long lasting, vandal resistant and reasonably costed;
6. Permits fish passage;
7. Ability to be implemented within existing infrastructure;
8. Easily transported and installed with potential for widespread application;
9. Designed to function and be controlled (either on site or remotely) during extreme events;
10. Limit the amount of time gate is closed (i.e. not allowing tidal flushing).

By applying the above criteria to several floodgate designs, using a management matrix approach, it was determined that no existing floodgates complied with all criteria. To overcome this deficiency, an environmentally controlled *SmartGate* system was designed, fabricated and installed at the field site. As described by Glamore and Indraratna (2004), the *SmartGate* system is designed to allow tidal flushing based on real time water level and water quality variables.

The *SmartGate* operates by uploading in stream sensor data at 10 minute intervals into a central network and then determining whether an aperture within a floodgate should be open or closed based on a series of predetermined trigger levels. The system fits within the existing infrastructure, is solar powered, easy to operate, can be incrementally controlled, is self-contained, permits fish passage, and can be remotely controlled using telemetry. As such, the system fits all the desired criteria and was installed at the field site.

The installed *SmartGate* was shown to effectively control water levels within the flood mitigation drain throughout the 2 year trial and was particularly useful during flooding periods when access to the site was limited. Furthermore, by allowing tidal flushing on every tide the *SmartGate* system maximised the extent and duration of the tidal flushing at the site. In comparison with other buoyancy gates driven solely by hydrostatic pressures, the *SmartGate's* critical advantages are that it can operate using multiple parameters including pH, salinity, temperature, dissolved oxygen, rainfall, and flow velocities to vary water elevation levels upstream or downstream of the floodgate. This is significant because improved water quality, and not water elevation, is the key objective in restoring tidal flushing.

3.7 Environmental Design Concerns

Once the above objectives have been met, key environmental concerns have to be finalised. These largely relate to the period immediately after the tide has been restored but prior to it establishing a tidal wetland environment. In this period, significant dieback will occur of freshwater and other low-lying species that have established within the drained area. Anticipating and controlling the dieback is of the utmost importance to water quality (DO, pH, BOD_5) and other factors (visual amenities, bank stability, etc).

In acid sulfate soil environments the dieback of freshwater species is of particular importance because the aquatic plants often act to stabilise the bed sediments. By killing the plants the detritus consumes oxygen and increases BOD, which may enhance MBO formations. Moreover, during high flow periods (floods) the sick or dead plants may be uprooted leaving the bed vulnerable to scour and secondary oxidation of MBOs. Therefore, prior to floodgate modifications consideration should be given to whether freshwater weeds should be removed by appropriate methods or whether, due to the site specific criteria, natural dieback is more effective.

At the proposed site it was determined that due to the large costs involved in artificial weed removal and the legal ramifications of clearing land which fell within the critically endangered and protected Golden Bell frog habitat, it would be prudent to allow natural processes to control the weeds. To quantify this impact an extensive post-modification monitoring program, as described in Section 3.8, was undertaken.

Additional environmental criteria which should be considered prior to restoring tidal floodgates include (i) OH&S criteria relating to site access, (ii) safety concerns for floodgate managers during flooding events, (iii) site security and (iv) protocols for triggering floodgate movements. It is also of the utmost importance to have landholder and community support throughout the project and to work with the landholders to obtain floodgate triggers which are suitable for heavy machinery (i.e.

soil saturation levels and trafficability) and certain crops.

3.8 Monitoring Program

As a final step prior to commencing on ground works, an extensive monitoring program should be set up to determine trends in surface and ground water quality, and water levels. Obviously any program would be site specific but as a minimum should focus pH, soluble iron, soluble aluminium (summed for total acidity), bicarbonate levels, dissolved oxygen and electrical conductivity. It is strongly recommended that where feasible *in situ* continuous sensors should be employed to measure fluctuations following rainfall and temporary floodgate closures.

The sampling routine established at the site, as described previously, was undertaken 1 year prior to tidal restoration and 2 years after tidal restoration.

3.9 Discussion and Conclusions

When all of the objectives have been addressed tidal restoration can proceed. Failure to reach an objective, may not necessarily require the study to be rejected, but should at the least require a reassessment of the objectives. In the selected study site, all of the stated objectives were achieved except for the water quality criteria. Discussion with the working group, however, indicated that the anticipated improvement in water quality was sufficient to warrant the study to proceed.

The presented method is a significant advance on current ad hoc and localised methods. Firstly, the method allows for the objectives to be tested and, in many cases, numerically simulated prior to floodgate modifications. This is particularly important on large wetland systems where significant investment is required and where the benefits of the restoration may not be quantifiable. Second, the presented stages are significant improvements on current labour intensive methods. For instance, use of the spatial analyst tools allows for low-lying overtopping points to be highlighted and for water levels to be determined. This is a major improvement on current sandbagging methods where the levee bank is lined with sandbags and the hazard spots determined by the level of water against the sandbags. Third, the method covers all aspects of restoring tidal flows and to save time several stages can be addressed concurrently.

4 Acknowledgements

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