Vegetation-Sediment-Flow Interactions in Estuarine Wetlands

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EXTENDED ABSTRACT

Coastal saltmarsh distribution in Australia appears to be following a global trend of decline. In the estuaries of NSW, saltmarsh is often squeezed between landward encroachment of mangrove forest and urban/industrial development of foreshore land. Efforts to maintain and rehabilitate saltmarsh are complicated by an incomplete understanding of the hydraulic drivers for estuarine vegetation distribution.

Our research is focused on the hydraulic and geomorphologic conditions required to sustain saltmarsh in a rehabilitated wetland, comprised of tidal creeks, mangrove forest, saltmarsh and tidal pools, in the Hunter estuary, NSW. The wetland is an important roost site for migratory shorebirds and is part of the Kooragang Wetlands, which are recognised as a wetland of international importance under the Ramsar Convention. The area is hydraulically complex, with a number of culverts and roads that compartmentalise flow.

At a local scale (of the order of m^2), vegetation morphology influences the flow field by creating drag, which acts to slow flow through friction losses. Modelling of these fine scale interactions is both numerically and theoretically demanding, requiring solution of the Reynolds-averaged Navier Stokes equations. An alternate approach is to develop a simplified hydrodynamic model of the wetland based primarily on water level. This method, which requires fewer input variables and considerably less computational effort, is appropriate for modelling wetlands where hydraulic controls (e.g. inlet configuration and internal culverts) affect the macro-scale flow field (of the order of ha) to a greater extent than local scale effects such as vegetation roughness.

A hydrodynamic model of the study area is required to investigate the effects of various flow control scenarios on habitat distribution. In order to determine the most efficient modelling approach, a statistical review of the sensitivity of the flow field to vegetation type, site location, hydroperiod, elevation, tidal range and suspended particulate matter (SPM) was undertaken. This included comparison of mean velocity and vegetation community, to identify whether vegetation morphology was a significant determinant of mean velocity at the community scale; comparison of mean velocity in each vegetation community at each site, to test whether vegetation morphology was important at the site scale; comparison of mean velocity at each site with distance from the Hunter River, to test the assumption that hydraulic controls drive mean velocity to a greater extent than surface roughness in attenuated wetlands; and multi-variate analysis of hydraulic and SPM variables to identify similarities between sites.

Data collection involved measurement of vegetation morphological characteristics; water level monitoring using pressure transducers; flow field measurement by acoustic Doppler velocimeters; and gravimetric analysis of suspended particulate matter.

The hydraulic configuration of flow conveyance conduits, such as culverts, in estuarine wetlands was found to be critical to the distribution of the velocity flow field, tidal range, hydroperiod and SPM. Due to the low topographic relief in tidal wetlands, even relatively minor changes in hydraulic control can effect rapid and dramatic changes to vegetation distribution.

In areas of tidal attenuation due to constructed flow conduits, vegetation morphology and inlet distance was found not to significantly affect mean velocity. In these areas, a simplified hydrodynamic modelling approach based on hydraulic control configuration, particularly invert level and discharge capacity, may be adopted. In areas of unattenuated flow, a more complex modelling approach is required to simulate the effect of vegetation on the flow field and sediment transport.

1. INTRODUCTION

In Australia, as elsewhere in the world, coastal ecosystems are under pressure from anthropogenic demand for natural resources. In the past, estuarine wetlands have been particularly susceptible to degradation as they were considered to be of little value. More recently, appreciation of the contribution made by estuarine wetlands to ecosystem services has led to an increasing effort to restore tidal flows to degraded wetlands. In the coastal zone of NSW, for example, tidal flows have been extensively modified for agriculture and urban development. Williams and Watford (1997) identified in excess of 4000 impediments to tidal flow in this zone, of which approximately 1600 have potential for estuarine wetland rehabilitation. Often, however, there is insufficient information to predict how wetlands will respond to the reintroduction of tidal flows and whether the resulting habitat distribution will achieve desired management outcomes.

The research presented in this paper is part of a larger interdisciplinary study on ecohydraulics and estuarine wetland rehabilitation focused on understanding the hydraulic and geomorphologic conditions required to sustain wetland habitat for migratory shorebirds in the Hunter estuary, NSW, Australia (Figure 1). Shorebird roost habitat within the estuary is currently under threat as, like similar habitat across the world, it is being squeezed between landward encroachment of mangroves and development of foreshore land for industrial and residential land uses (Adam 2002; Saintilan and Williams 2000; Wolanski et al. 2004).

This paper presents a statistical analysis of field measurements in order to assess vegetation-sediment-flow interactions in an estuarine wetland, focusing on the identification of the dominant processes in different areas of the wetland. This information is relevant for future data collection and model selection.

2. BACKGROUND

In a previous paper (Howe 2005), the effect of removing impediments to tidal flow on topography, suspended particulate matter (SPM), hydraulics and migratory shorebird roost habitat at a degraded wetland was examined. The study area (Figure 1) is an important roost site for migratory shorebirds and is part of the Kooragang Wetlands, which are recognised as wetlands of international importance under the Ramsar Convention. It is an 124 ha tidal sub-catchment with two defined inlets to the south arm of the Hunter River; one of which is an 0.45m diameter culvert and the other an 8.5m wide tidal channel (Figure 2). The tidal channel was created in 1995 by removal of two 0.5m diameter culverts. The area is hydraulically complex, with a number of culverts and roads that compartmentalise flow within the site. Elevation ranges from 3.4 metres above the Australian height datum (mAHD) to -1.2mAHD; however, topographic relief over most of the area is less than 0.5m.

Figure 1 – Location of the study area in the Hunter estuary, NSW, Australia (32°51’52”, 151° 42’15”)

This previous study showed that immediately upstream of the removed culverts an unattenuated tidal regime was established, which originated rapid and dramatic changes in vegetation and topography: shallow tidal pools fringed with saltmarsh were replaced by extensive areas of mangrove forest with developed tidal channels. The unattenuated compartment exhibited elevated mean velocity and turbulent kinetic energy, which led to increased entrainment of bed sediments, lowering of bed elevation and increased export of sediment. Deeper in the wetland, flow controls, including culverts and roads, maintained an attenuated tidal regime with insufficient energy for entrainment of bed sediments, which created an environment favourable for sediment deposition and marsh accretion.

It was also found that the increased tidal range and flow velocity in the unattenuated compartment were gradually eroding tidal channels between the wetland compartments, which appeared to alter hydraulic conditions sufficiently to allow mangrove encroachment deeper into the wetland. It was anticipated that, without intervention, much of the saltmarsh in the study area would be converted to mangroves by this process.

3. HYDRODYNAMIC MODELLING APPROACHES

The distribution of wetlands is driven by the water cycle (Mitsch and Gosselink 2000). Estuarine wetlands are characterized by unsteady, non-uniform, shallow water flow. The primary driving forces acting on this type of flow are (Vreugdenhil 1994): atmospheric pressure gradients, wind stresses, density gradients, radiation stresses and tidal stresses. Energy generated by these driving forces is dissipated principally by turbulence and friction with the roughness elements at the bed. Application of the principles of continuity and momentum are required to hydrodynamically model these systems.

Figure 2 – The study area showing inlets and areas compartmentalised by roads and culverts

At a local scale (of the order of m^2), vegetation morphology influences the flow field by creating drag, which acts to slow flow through friction losses. Although vegetation drag increases turbulence around vegetation stems at the individual stem scale (of the order of cm^2), the conversion of flow momentum to vegetation drag reduces the shear stress applied to the bed and therefore reduces SPM transport, for all but very low vegetation densities (Leonard and Reed 2002; Lopez and García 1997). Modelling of these fine scale interactions is both numerically and theoretically demanding, requiring solution of the Reynolds-averaged Navier Stokes equations (e.g. Bockelmann et al. 2004; Fischer-Antze et al. 2001; Wu et al. 2000), and a detailed understanding of the model input parameters, such as water elevation, bed slope, bed roughness, stream cross-sectional area etc. Furthermore, as the biological response to hydraulic manipulation may take in excess of 10 years to reach a dynamic equilibrium (Streever 1997; Warren et al. 2002), the computational effort required to model system hydrodynamics over this timeframe may be considerable.

An alternate approach, which has been adopted more widely in the ecological literature (e.g. Boumans et al. 2002; Roman et al. 1995) is to develop a simplified hydrodynamic model of the wetland based primarily on water level. This method, which requires fewer input variables and considerably less computational effort, is appropriate for modelling wetlands where hydraulic controls (e.g. inlet configuration and internal culverts) affect the macro-scale flow field (of the order of ha) to a greater extent than local scale effects such as vegetation roughness.

4. RESEARCH AIMS

A hydrodynamic model of the study area is required to investigate the effects of various flow control scenarios on habitat distribution. In order to determine the most efficient modelling approach, a statistical review of the sensitivity of the flow field to vegetation type, site location, hydroperiod, elevation, tidal range and SPM was undertaken. This included comparison of mean velocity and vegetation community, to identify whether vegetation morphology was a significant determinant of mean velocity at the community scale; comparison of mean velocity in each vegetation community at each site, to test whether vegetation morphology was important at the site scale; comparison of mean velocity at each site with distance from the Hunter River, to test the assumption that hydraulic controls drive mean velocity to a greater extent than surface roughness in attenuated wetlands; and multi-variate analysis of hydraulic and SPM variables to identify similarities between sites.

5. METHODOLOGY

In this paper, flow characteristics are described by velocity and depth, vegetation by physical (morphological) measures and sediment by SPM concentrations. Flow velocities at discrete locations were measured using acoustic Doppler velocimeters deployed from 9 fixed transects (Figure 2). Two of these transects were located at the wetland inlets; the remaining seven were 8m transects located at the interface between vegetation communities and perpendicular to the community boundary. Two to six vertical velocity profiles were obtained from fixed positions along each transect. Water levels were recorded by pressure transducers located in each of the wetland compartments. Water level and topographic data were used to determine tidal range and hydroperiod at each of the transects.

SPM concentration was determined by gravimetric analysis of 1L bulk water samples collected during sampling at each transect. Due to the shallow water depth in vegetated areas, SPM samples were collected from only the deeper end of each transect. Velocity and SPM sampling was conducted monthly, generally on spring tides, over the period October 2004-March 2005. Sampling locations are shown in Figure 2.

Vegetation morphological characteristics were surveyed during August 2004 and March 2005 based on the five dominant morphological units in the wetland: *Sarcocornia quinqueflora*, *Sporobolus virginicus*, *Avicennia marina* pneumatophores, *A. marina* juveniles (<1.2m) and *A. marina* adults (>1.2m). The survey was conducted using nested quadrats depending on the scale of the morphological unit. A 25m^2 quadrat was used for *A. marina* adults, a 1m^2 for *A. marina* juveniles and pneumatophores and a 0.017 m^2 quadrat for the two saltmarsh species *Sa. quinqueflora* and *Sp. virginicus*. Vegetation distribution was surveyed by aerial photographic interpretation and ground-truthed by field survey.

One-way analyses of variance (ANOVA) on vegetation morphology and mean velocity were undertaken in order to ascertain if variability among vegetation communities was statistically significant. Regression analysis was undertaken to investigate the relationship between site mean velocity and distance from the Hunter River. Non-metric multi-dimensional scaling (nMDS) and similarity percentages (SIMPER) analysis of standardized, square root transformed data were conducted using PRIMER v5 multi-variate software (Clarke and Green 1988) to identify the key physical drivers for site similarity.

6. RESULTS

6.1. Vegetation Distribution & Morphology

Estuarine habitats in the study area were comprised of tidal creeks, mangrove forest, saltmarsh, and permanent tidal pools with an intertidal mudflat fringe. The tidal pools contained a range of micro- and macro-algae. Mangrove forest was characterised by dense, monospecific stands of the Grey Mangrove, *A. marina*. Pneumatophores within the mangrove forest were often covered with distinctive red algae. Saltmarsh was dominated by *Sa. quinqueflora* and *Sp. virginicus.*

The distribution of habitats was driven by elevation in areas of unattenuated tidal flow, with a gradient from tidal creeks at low elevation, followed upslope by mudflat, mangroves and saltmarsh. In areas of attenuated flow, the same habitat sequence occurred; however the sequence was shifted upslope by hydraulic controls and there were substantial areas of permanent tidal pools with a small tidal range (Howe 2005).

Table 1 shows the mean height, diameter and stem density of the five dominant vegetation morphological units in the study area. ANOVA indicated a significant difference in the diameter, height and density ($P<0.05$) of all morphological units, except the height of the two saltmarsh species ($P=0.421$), and height of *Sa. quinqueflora* and *A. marina* pneumatophores ($P=0.179$).

Table 1 – Morphological characteristics of dominant vegetation species

Morphologic Unit	Height (m)	Dia. at 10cm (mm)	Density (stems /m^2)	Vegetation Type
Sarcocornia quinqueflora	0.201 (0.01)	2.0 (0.08)	3428 (368)	Saltmarsh
Sporobolus virginicus	0.223 (0.01)	0.9 (0.04)	8255 (560)	Saltmarsh
A. marina pneum.	0.176 (0.01)	6.1 (0.27)	78.0 (21.4)	Mangrove
A. marina juvenile	0.518 (0.04)	11.5 (1.4)	4.87 (1.85)	Mangrove
A. marina adult	2.213 (0.13)	77.7 (9.05)	0.83 (0.34)	Mangrove

Note. Standard error in brackets

6.2. Flow Velocities

Velocity profiles obtained from each vertical location along each transect were depth integrated to obtain mean resultant velocities. These results were then pooled in two ways: by site and by vegetation community, to determine whether a detailed hydrodynamic model was warranted for all compartments in the wetland (i.e. whether surface roughness or hydraulic controls were driving mean velocity distribution). Regression analysis was also undertaken to investigate the relationship between mean velocity and distance from the Hunter River inlets.

ANOVA for log-transformed depth-averaged velocity data from each of the dominant vegetation communities in the study area (Table 2) indicated a significant difference between the vegetation groups ($F=30.9$, $P<0.001$). Tukeys honestly significant test identified that the significance was driven by creek velocity, with no significant difference in the mean velocities of the other vegetation communities.

In order to ascertain whether this lack of differentiation at the vegetation community scale was a result of averaging procedures across sites, ANOVA of the velocity field in different habitats within the same transect was undertaken (Table 3).

Table 2 – Mean velocity by vegetation community

Vegetation Community	Mean Velocity (cm/s)
Saltmarsh[a]	0.926 (0.15)
Mangrove[a]	1.610 (0.42)
Mudflat[a]	1.575 (0.36)
Creek[b]	25.279 (5.80)

Notes. Standard error in brackets, ANOVA indicated group b was significantly different from group a (F=30.88, P<0.001)

These results indicated a significant difference (P<0.1) in mean velocity at sites where flow is channelised (sites 3, 4 and 8), but the results were less conclusive for sites where vegetation fringes tidal pools (sites 6, 7 and 9). There was a significant difference (P=0.055) between mudflat and saltmarsh flow rates at site 7; however at this site saltmarsh mean velocity (1.51cm/s) was greater than mudflat mean velocity (0.52cm/s). There was also a significant difference (P=0.031) between mudflat mean velocity (1.50cm/s) and mangrove mean velocity (0.45cm/s) at site 9. There was no significant difference between the mean velocities for vegetation communities at the remainder of the sites.

Table 3 – Comparison of mean velocity by transect and vegetation community

Site[1]	F Value and (Level of Significance)				
	CK-SM	CK-MA	MA-SM	MF-SM	MF-MA
3	6.37 (0.022)	-	-	-	-
4	3.57 (0.091)	3.76 (0.081)	0.00 (0.993)	-	-
6	-	-	-	1.86 (0.231)	-
7	-	-	-	5.67 (0.055)	-
8	4.96 (0.053)	2.59 (0.133)	0.80 (0.387)	-	-
9	-	-	-	-	5.74 (0.031)

1 Sites 1 & 2 were excluded from the analysis as only one vegetation type (creek) was present, site 5 excluded as too few samples for pairwise analysis CK = creek, SM = saltmarsh, MF= mudflat, MA=mangrove. Shaded cells are significantly different (P=0.1).

Regression analysis of the spatial distribution of mean velocity (Figure 3) indicated that there was an exponential decay relationship with distance from the river (R^2=0.76) for sites 1-3 in the unattenatued part of the wetland; however, there was no relationship (R^2=0.38) in mean velocity in the attenuated wetland compartment (sites 4-9), despite considerable differences in flow path length.

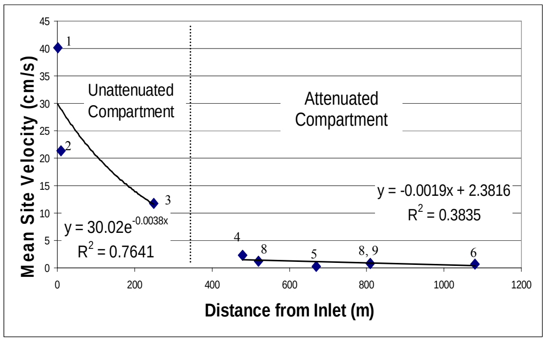

Figure 3 – Relationship between mean velocity by site and distance from the Hunter River

6.3. Physical Drivers for Site Similarities

To further investigate the site differences driving velocity distribution, analysis of SPM, transect elevation, hydroperiod and tidal range was undertaken, excluding vegetation (Table 4). Non-metric multi-dimensional scaling (nMDS) and similarity percentages (SIMPER) analysis of standardized, square root transformed data identified three groups of sites (similarity > 85%). The first group (sites 1, 2 and 3), characterized by high mean velocity and SPM concentrations, was located on tidal creeks close to the Hunter River (<250m), and was least affected by tidal attenuation (tidal range 0.84-1.66m).

Table 4 – Hydraulic variables and SPM concentrations at sampling stations

Site	Mean Velocity (cm/s)	SPM (mg/L)	Elevation (mAHD)	Tidal Range (m)	Hydro-period
1[a]	40.11	46.38	-1.03	1.66	1.000
2[a]	21.31	27.94	-0.17	0.84	1.000
3[a]	11.70	54.30	-0.30	1.21	0.694
4[b]	2.24	22.02	0.30	0.32	0.986
5[b]	0.30	28.11	0.37	0.27	0.999
6[c]	0.68	13.49	0.31	0.32	0.977
7[c]	0.76	17.70	0.30	0.33	0.978
8[c]	1.24	14.65	0.24	0.41	1.000
9[c]	0.84	15.36	0.15	0.38	1.000

a – group A sites, b – group B sites, c – Group C sites

The second group (sites 4 and 5), characterised by moderate SPM concentration, high elevation and extended hydroperiod, was comprised of saltmarsh sites on tidal creeks in the vicinity (<100m) of major internal culverts. The third group (sites 6-8 and 9), was generally comprised of open marsh sites with low SPM, high elevation, extended hydroperiod, small tidal range (~0.3m) and low mean velocity, with the exception of site 8, which had characteristics of both a tidal creek and an open marsh, depending on the tidal conditions. During low tides (<0.3m) flow was conveyed via the main creek channel, with overbank flow to the saltmarsh from north to south. On high tides

(>0.3m) flow also reached the site via an overland flow path from the south, which reduced mean velocity at the site.

7. DISCUSSION

7.1. Vegetation-Sediment-Flow Interactions

At a fine scale (~m^2), vegetation morphology is an important descriptor of the velocity field in estuarine wetlands, and is relevant to the consideration of small-scale ecosystem functions, particularly those affected by diffusion processes. Our results indicate that at the wetland scale (~ha) macro-effects such as tidal attenuation and hydraulic controls affect mean velocity to a greater extent than vegetation morphology, particularly in areas of attenuated flow.

Although the morphological characteristics of the dominant vegetation types in the study area were generally significantly different (Table 1), there was no significant difference between the spatially and temporally averaged mean velocities for mudflat, saltmarsh and mangrove substrates in the study area (Table 2). The difference between mean velocities in tidal creeks and other habitats may be better described by transition from in-channel flow to overland flow, rather than by transition from non-vegetated to vegetated substrate.

Comparison of mean velocity in different vegetation communities in the same transect (Table 3) generally supported the aggregate findings that substrate roughness was not a significant contributor to mean velocity distribution. Anomalous results for sites 7 and 9 can be attributed to local flow conditions at these locations.

Multi-variate analysis (nMDS and SIMPER) identified three groups of sites (Table 4). Group A sites (1-3), were all located near the Hunter River and exhibit a semi-diurnal (M2) mesotidal lunar cycle with tidal ranges greater than 0.8m. In contrast, tidal range in the remaining sites was severely attenuated by hydraulic controls (~0.3 m) and driven by the fortnightly spring-neap tidal cycle. Tidal fluctuations in Group B and Group C sites were at elevations equivalent to the upper part of the tidal range of the Group A sites, indicating that hydraulic controls maintain permanent tidal pools that drive an ebb-dominated tidal asymmetry, with short, strong ebb currents and longer, weaker flood currents.

Whilst hydroperiod is a key driver for the distribution of wetland vegetation (Howe 2005; Warren et al. 2002), results indicate that velocity and SPM are also important descriptors of site similarity. The effect of artificial hydraulic controls (roads and culverts) is to reduce velocity, tidal range and SPM, and increase hydroperiod. The low velocity in the inner marsh favours sediment deposition and marsh accretion; however, hydraulic controls limit the capacity for SPM from the (river) catchment to be transported deep into the marsh, which may reduce sediment deposition to the extent that marsh accretion is unable to match substrate consolidation and sea level rise.

7.2. Implications for Wetland Modelling

The results discussed above represent the first six months of data collection in the study area, and have enabled refinement of the field work program to target the dominant hydraulic variables operating in various parts of the wetland (i.e. water level in the attenuated compartment and all variables in the unattenuated compartment). Further sampling and multi-variate statistical analysis (nMDS, multiple regression) will be undertaken to verify that the research findings can be applied over a wider range of hydraulic conditions and at greater temporal scales for vegetative change.

In the unattenuated compartment (sites 1-3), mean velocity and SPM data indicate that active sediment transport is occurring. The mechanisms by which sediment is entrained from the bed is a function of vegetation morphology, and a more complex hydrodynamic model is required to adequately simulate the physical processes driving vegetation distribution and sediment transport.

In estuarine wetland where tidal flows are attenuated by hydraulic controls (e.g. sites 4-9), field data collected at a limited number of sites (most importantly the flow conduits) can be extrapolated to the entire compartment, and a simplified approach to hydrodynamic modelling may be adopted based on water level fluctuations.

8. CONCLUSIONS

The hydraulic configuration of flow conveyance conduits in estuarine wetlands is critical to the distribution of the velocity flow field, tidal range, hydroperiod and SPM. Due to the low topographic relief in these wetlands, even relatively minor changes in hydraulic controls (particularly invert level and discharge capacity) can effect rapid and dramatic changes to vegetation distribution.

Analysis of field data collected from an estuarine wetland in the Hunter River indicates that in areas of tidal attenuation due to constructed flow conduits, vegetation morphology and inlet distance do not significantly affect mean velocity. In these areas, a simplified hydrodynamic modelling approach based on hydraulic control configuration, particularly invert level and discharge capacity, may be adopted, such as the Marsh Response to Hydrological Modification Model developed by Boumans et al. (2002). In areas of unattenuated flow, a full hydrodynamic modelling approach (e.g. RMA-2, STREMR or RBFVM) is required to simulate the effect of vegetation on the flow field and sediment transport.

In tidal wetlands, hydraulic drivers govern the distribution of estuarine habitats and an array of tools is available to model wetland hydrodynamics. Understanding the applicability of these tools can enhance sustainable ecological management of estuarine wetlands by identifying the level of hydraulic sampling and the complexity of hydrodynamic modelling required to adequately simulate potential habitat manipulation scenarios. This information can assist in the wise allocation of resources for maintenance of critical habitat and rehabilitation of degraded habitat, in order to sustain, for example, populations of migratory shorebirds.

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