Wetlands Ecology and Management 12: 333–342, 2004.
© 2004 Kluwer Academic Publishers. Printed in the Netherlands.

Consolidation and volumetric soil-water content of salt marsh soils following habitat modification for mosquito control

M.J. Breitfuss[1,3,*] and R.M. Connolly[2]
[1]Australian School of Environmental Studies, Griffith University, Brisbane, 4111 Queensland, Australia; [2]School of Environmental and Applied Sciences, Griffith University, Gold Coast, Queensland, Australia; [3]Current address: Queensland Institute of Medical Research, The Bancroft Centre, PO Royal Brisbane Hospital, 300 Herston Road, Herston, 4029 Queensland, Australia; *Author for correspondence (e-mail: markb@qimr.edu.au; phone: +61-7-3362-0352)

Received 24 September 2002; accepted in revised form 4 June 2003

Key words: Intertidal zone, Queensland, Runnelling, Tidal frequency

Abstract

The runnelling form of habitat modification for mosquito control in saltmarsh increases tidal frequency, and may affect soil properties such as volumetric soil-water content and consolidation. The effects of habitat modification on soil properties are in turn likely to affect ecological processes. Runnels constructed mechanically to a depth of no more than 0.3 m with smooth, spoon shaped edges linked isolated mosquito-breeding pools in the high marsh to the tidal source at the saltmarsh/mangrove interface. The physical design of runnels may result in a significant increase in the frequency of flooding tidal events that flush isolated mosquito-breeding pools. Impacts of the runnelling technique were determined at three marshes using two sampling protocols: (a) comparisons between modified and unmodified shores and (b) comparisons with lateral distance from a runnel. At one marsh, volumetric water content was significantly higher at runnelled than at unrunnelled sites after tides that only partly inundated the marsh, but this pattern was not found at the other marshes. Soil consolidation was greater further from the shore, but was not different between runnelled and unrunnelled shores. Measurements at different lateral distances from runnels demonstrated higher water content levels and lower consolidation up to 5 m from runnels and no effect further away. The varied responses to runnelling at different marshes may reflect specific site characteristics such as slope and hydraulic tidal forces. Remedial strategies for similar mosquito control techniques, based on habitat modification, should include dynamic classifications of saltmarshes.

Introduction

Intertidal ecosystems occur at the dynamic boundary between land and sea on all continental margins. Where there is a reduction in the wave size or wave energy on coastlines, such as those in the southern hemisphere which are protected by a mangrove boundary on the lowest region of the shore, saltmarsh may form the dominant plant community. Saltmarsh can exhibit both terrestrial and marine characteristics however, because saltmarsh occurs within the intertidal zone, the structuring forces responsible for its genesis and sustained development are marine-based and linked to rates of sedimentation and tidal frequency (Hughes et al. 1998; Le Hir et al. 2000; Hussein and Rabenhorst 2001a, b).

Soil-water content has been investigated as one of the main abiotic differences between terrestrial and marine systems because of its capacity to structure ecological communities. In terrestrial systems, soil-water content is driven by rain events and influenced by topographical (Aucan and Ridd 2000; Qiu et al. 2001; Shaman et al. 2002) and physical (Yoo et al. 1998; Yoo 2001; Schultz and Ruppel 2002; Schmalz et al. 2002) conditions. Marine systems such as saltmarsh are also influenced by topographical and physical factors but soil-water content is generally driven by tidal rather than rain events (Adam 1990).

The physical properties of saltmarsh sediments can limit the movement and residence of water within the soil column. In systems dominated by fine-textured soils, the effects of modifying sediment structure through some management practices are well-documented and known to directly impact both the biological (Porporato et al. 2002; Barzegar et al. 2003) and physical properties (Tan et al. 1998, 2002) of the soil body. The saltmarsh soils of southeast Queensland, Australia, are dominated by clay loams (Beckmann et al. 1987) and resemble these soil types, albeit with significant salt inputs, and are likely to respond to modifying management practices in a similar manner.

In recent studies of saltmarsh physical processes, analyses of spatial and temporal patterns of tidally-derived soil water have identified its importance for tidal marsh management and restoration. This is largely because of the relationship between substrate condition, tidal frequency and some biological processes (Flynn et al. 1999; de Jonge 2000). The frequency of tidal inundation of saltmarsh is primarily responsible for the distributions of epifaunal and infaunal species because it limits the availability of suitable habitat (Sagasti et al. 2001) and affects soil chemical factors (Hussein and Rabenhorst 2001b). Where the frequency of tidal inundation of saltmarsh is increased by sea level rise (Stolt and Rabenhorst 1991; Simas et al. 2001) or human habitat modification (Breitfuss 2001; Breitfuss et al. 2003), the impact on coastal ecosystems is caused in proportion to the degree of submergence experienced, resulting in altered community composition or sediment accretion rates (Vernberg 1993; Dyer et al. 2000). The investigation of impacts from altered tidal regimes on ecological systems is complex and difficult; simple, non-destructive measurement of soil water and soil mechanics (e.g., consolidation) may provide a basis for assessing a wider range of substrate conditions (Avnimelech et al. 2001; Zhang et al. 2001) and act as a proxy measure of ecological effects.

The runnelling method of mosquito control involves linking isolated mosquito-breeding pools located high on the saltmarsh shore to the tidal source at the saltmarsh/mangrove interface. Runnels are a permanent and cost-effective method of mosquito control and are usually constructed mechanically to a depth of less than 30 cm over a gradient of more than 1:1000 (Dale and Hulsman 1990; Owttrim and Dixon 2001). Runnels are usually three times wide as they are deep; in cross-section they have a smooth, spoon-shaped appearance. The depth of runnels enables transport of tides which would otherwise fail to breach the saltmarsh/mangrove interface and thus, can significantly increase the frequency of tidal inundation of mosquito-breeding pools (Breitfuss et al. 2003). This action disrupts the conditioning and developmental cycles of pest mosquitoes such as *Ochlerotatus vigilax* Skuse (a significant vector of arboviruses), reducing the density of adult mosquitoes. In addition, the effects of runnelling are reported to alter the distribution of surface-dwelling macroinvertebrates (Chapman et al. 1998) which require specific moisture gradients in which to burrow, feed and reproduce.

In this paper, we examine the effects of runnelling on two easily recorded measures of saltmarsh sediment, volumetric soil-water content and soil consolidation. These characteristics are implicated in a range of other soil features not dealt with directly in this paper but known to be important determinants of the patterns of wetting and drying of saltmarsh sediments following tidal inundation. Because runnels transport low-amplitude tides which would otherwise fail to flood the greater saltmarsh area, we expect volumetric soil-water content and soil consolidation to differ between the runnelled and unrunnelled areas as well as at specific lateral distances from the runnel.

Methods

Study sites

Three saltmarshes (Coomera, Tingalpa 1 and Tingalpa 2) within Moreton Bay, Queensland, Australia (153°15′E, 27°35′S), were sampled (Figure 1). All shores had a similar tidal range (~2.5 m) and height required for complete

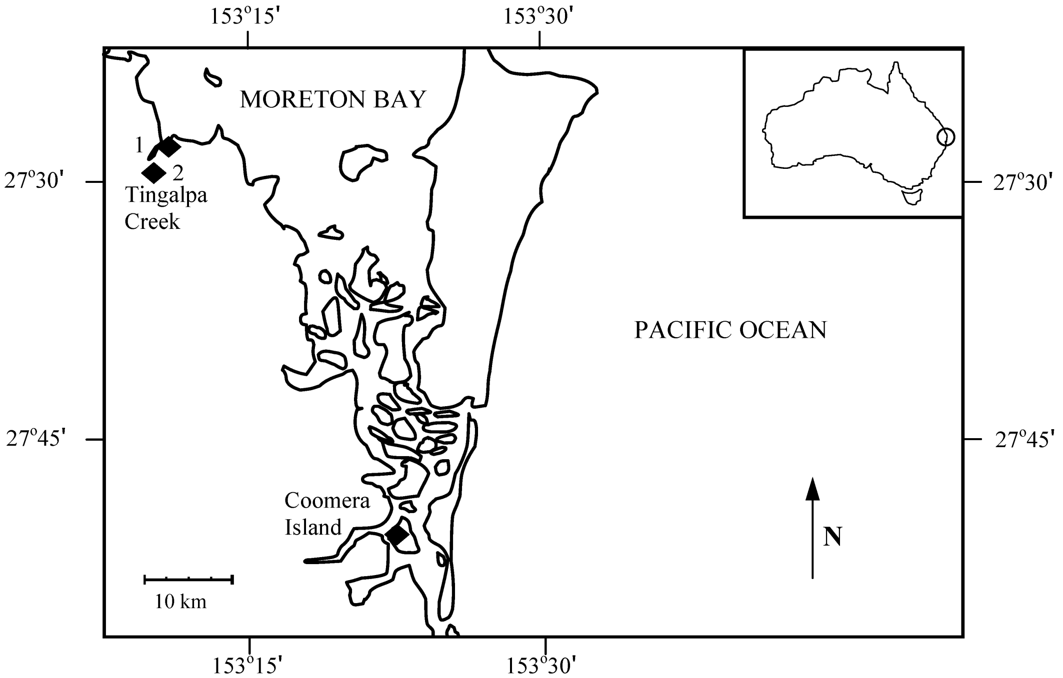

Figure 1. Location of saltmarsh sites (black diamonds) in southern Moreton Bay where samples were taken. All sites had been previously runnelled for mosquito control and were similar in terms of vegetation and tidal range.

inundation of the saltmarsh (>2.45 m). Sites were previously runnelled for mosquito control according to local drainage and topographic features (Owttrim and Dixon 2001), with the runnel beginning at the saltmarsh/mangrove interface low on the shore and extending at a right angle up the shore into the saltmarsh.

At all sites, the uppermost layers of substratum (<9 cm deep) was of primary interest, being dominated by solonchaks which exhibit little profile development, are strongly saline and have a loamy/clayey texture (Beckmann et al. 1987). A review of previous analyses of the properties of these layers revealed little variation in terms of particle size (Law 1981) and no significant differences in samples were detected for pH, salinity and relative substrate moisture content (Dale and Hulsman 1990) at distances of between 10 and 50 m from the tidal source, up the saltmarsh shore. The presence of a fine, superficial silt layer (<1 cm deep) may reflect the low-energy nature of the sites in terms of sediment trapping and tidal flushing (Law 1981; Mwamba and Torres 2002).

Tidal waters flood the sites via either shallow inlets in the mangrove boundary, at the saltmarsh/mangrove interface, or through areas of slightly (<20 cm) lower elevation which support low-amplitude tidal transport. Saltmarshes of southeastern Queensland are naturally flat, with relative relief between the upper and lower regions of saltmarsh often being less than 0.5 m (Hulsman et al. 1989; Breitfuss et al. 2003). Complete and partial inundation of these marshes by tidal waters can be limited by a difference in predicted tidal height of only 10–15 cm.

Mosaics of salt-tolerant plants (primarily *Sporobolus virginicus* Bunge ex Ungen-Sternberg and *Sarcocornia quinqueflora* (L.) Kunth.) dominate the vegetation and develop on the thin silt deposits overlying solonchaks. On the seaward side of saltmarsh, *Avicennia marina* Forsk. forms a dominant structural component at the saltmarsh/mangrove interface. Mangrove transgression into saltmarsh is rare under natural flooding patterns but, propagule transport to saltmarsh is significantly increased by habitat modification for mosquito control (Breitfuss et al. 2003) and likely to result in the expansion of mangrove distribution within the intertidal zone.

Physical measurements

Volumetric soil-water content was measured with a ThetaProbe ML2x (Delta-T Devices, Cambridge) after a two-point specific soil calibration. The ThetaProbe device determines volumetric changes in the apparent dielectric constant of the soil medium. The output signal is converted into a DC voltage within a range that is virtually proportional to soil-moisture content (Gaskin and Miller 1996; Miller and Gaskin 1997), making it a useful tool for comparative purposes. Measures of soil-water content were extended to a depth of 6 cm (the length of the ThetaProbe prongs). Soil consolidation was measured using a Torvane (ELE International) shear strength device where strength (in kg $\cdot$ cm^2) was the force required to break a 25 cm^2 section of the soil surface to 1 cm depth. Both soil-water content and consolidation measures were restricted to the uppermost layer of sediment. This layer was believed to be of greatest ecological importance to surface grazing macroinvertebrates which compose the bulk of keystone fauna species on saltmarsh (Smith et al. 1991).

Physical measurements were taken daily during the spring tide period (3–4 days) approximately 1 h after ebbing of the predicted (Queensland Department of Transport 2001) highest high tide. A 1-h period was selected to allow the majority of surface water to drain from the substrate via macropores (generally crab burrows) and natural ebbing. It was then assumed that volumetric soil-water content and consolidation would reflect sediment conditions directly following tidal ebb, enabling post-high tide comparison between the runnelled and unrunnelled sites.

The highest high tides can be described in terms of saltmarsh inundation as either non-flood ($<$2.38 m) or flood ($>$2.45 m) events. Non-flood tides account for $\sim$16% of tidal events annually and reach only the saltmarsh/mangrove interface, flooding mangrove, while flood events account for $\sim$7% of tides and cover the entire mangrove and saltmarsh. The remaining 77% of tides are not considered in this paper as their predicted heights either flood mangrove but do not reach the saltmarsh/mangrove interface or are too low to flood mangrove.

Sampling protocols

For the first sampling protocol, two 50 m (made up by consecutive 10 $\times$ 10 m^2 plots) transects were established, one along the runnel and the other 20 m from and parallel to the runnel (Figure 2a). Within each plot, five randomly selected quadrats were selected from which five soil-water and one soil consolidation measurements were taken. For the second sampling protocol (Figure 2b), transects were located perpendicular to the runnel at distances of 0, 30 and 50 m up the shore. Sampling quadrats were situated along each transect at nine distances (from 0 to 20 m) from the runnel edge in both directions (see Figure 2b). Five soil-water and one soil consolidation measurements were taken within each quadrat.

Data analysis

Volumetric soil-water content and soil consolidation data from the first sampling protocol were analysed with three-way ANOVA where tide (flooding, non-flooding), distance from shore and treatment (runnelled or unrunnelled) were fixed factors. Measurements from the second protocol were analysed with three-way ANOVA where tide, distance from shore (here called shore height) and lateral distance from runnel edge were fixed factors. Data from both sides of the runnel were pooled prior to analysis of differences at lateral distance from the runnel. Tukey tests (HSD) were used to identify differences among means. Data from the three marshes were analysed separately.

Results

Runnelled versus unrunnelled transects

Runnelling affected volumetric soil-water content and soil consolidation but not at all three marshes. Other factors also affected these soil properties. At Coomera, soil-water values at the runnelled transect after a non-flooding tide were as high as those after a flooding tide. At the unrunnelled transect

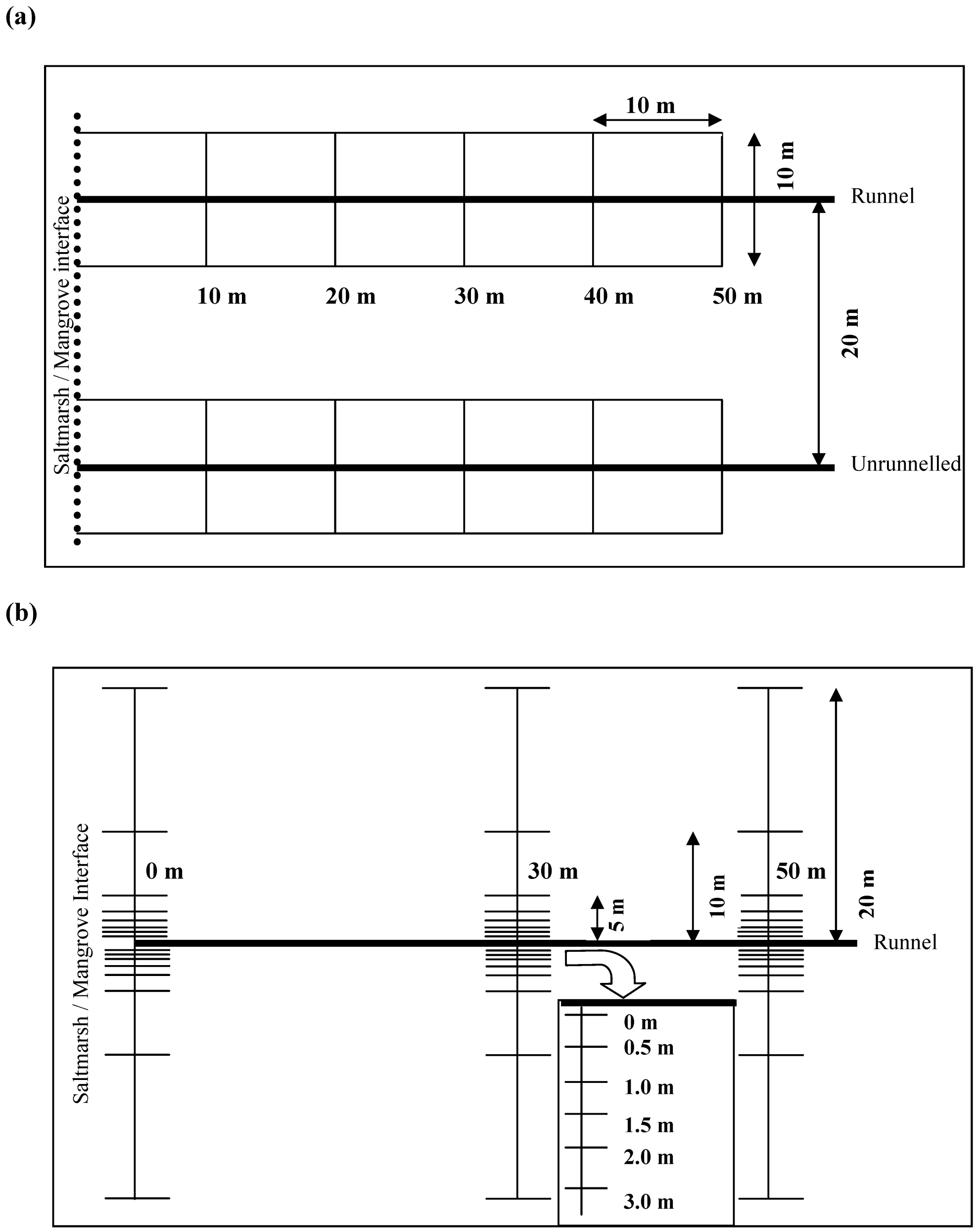

Figure 2. Sampling design and plot dimensions for (a) first sampling protocol comparing runnelled and unrunnelled transects (b) second sampling protocol showing lateral spread of sample points from the runnel edge at three shore heights.

soil-water values were lower after the non-flooding tide (Figure 3), and this was supported by significant interaction between tide and treatment shown in Table 1.

The soil-water values at Tingalpa 1 were higher after flooding tides at runnelled and unrunnelled transects, but there was no interaction between tide and treatment, indicating that the runnel did not affect soil-water content. Volumetric soil-water content values at Tingalpa 2 were not significantly affected by treatment, tide or distance up the shore.

Soil consolidation values at Coomera were higher after non-flooding than flooding tides, and increased with distance up the shore (Figure 4,

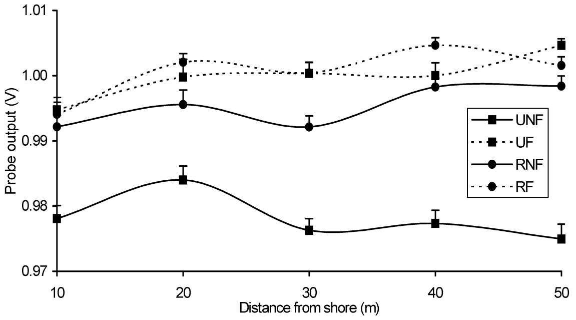

Figure 3. Mean soil-water content (+SE) at Coomera saltmarsh along runnelled (R) and unrunnelled (U) transects after flooding (F) and non-flooding (NF) tides.

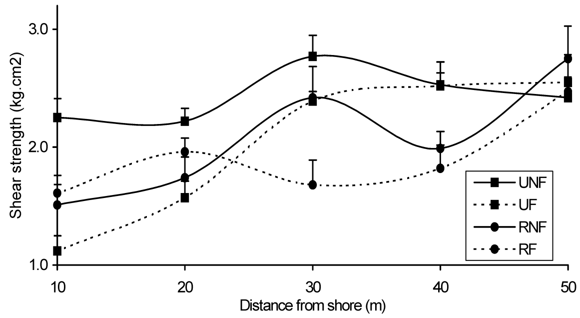

Figure 4. Mean soil consolidation (+SE) at Coomera saltmarsh along runnelled (R) and unrunnelled (U) transects after flooding (F) and non-flooding (NF) tides.

Table 1. Summary of three-way ANOVA results for soil-water content and soil consolidation at runnelled and unrunnelled transects. Only significant results are shown. Tukey results are shown where significant factor has greater than two levels.

Marsh	Factor	df	*P*	Tukey
Soil-water content				
Coomera	Tide	1	***	
	Treatment	1	*	
	Treatment*tide	1	*	
Tingalpa 1	Tide	1	*	
Soil consolidation				
Coomera	Tide	1	***	
	Distance	4	*	10 < 50
Tingalpa 1	Distance	4	*	10 < 50

Table 1), but there was no significant effect of treatment nor any interaction between tide and treatment. Soil consolidation values also increased with distance up the shore at Tingalpa 1 but were not significantly affected by any other factor. Soil consolidation values at Tingalpa 2 were not significantly affected by any measured factors.

Lateral distance from the runnel edge

Runnelling influenced soil-water content and soil consolidation but not at all sites, shore heights or lateral distances from the runnel edge. At Tingalpa 2, at 50 m up the shore, soil-water at lateral distances further than 5 m from the runnel edge tended to be lower after non-flooding tides whereas within 5 m of the runnel soil-water was as high as after flooding tides (Figure 5).

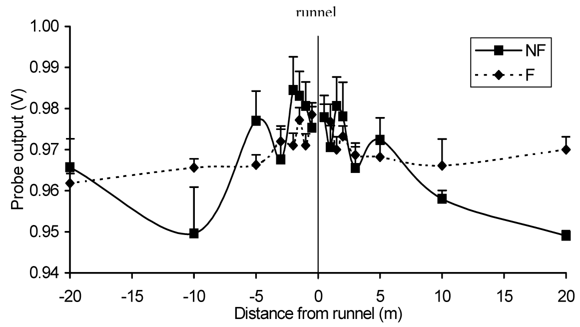

Figure 5. Mean soil water content (+SE) at Tingalpa 2 saltmarsh along lateral transects, radiating from a runnel, at 50 m shore height after flooding (F) and non-flooding (NF) tides.

Table 2. Summary of three-way ANOVA results for soil-water content and soil consolidation at distances from the runnel edge. Only significant results are shown. Tukey results are shown where significant factor has greater than two levels.

Marsh	Factor	df	*P*	Tukey
Soil-water content				
Coomera	Shore height	2	*	30 > 0, 50
Tingalpa 1	Tide	1	***	
Tingalpa 2	Shore height	2	***	0 < 30, 50
Soil consolidation				
Coomera	Shore height	2	***	0 < 30, 50
Tingalpa 1	Shore height	2	***	0 < 30, 50
Tingalpa 2	Shore height	2	***	0 < 30 < 50
	Distance from runnel	7	**	0.5, 5.0 < 10, 20

At Tingalpa 1, soil-water was significantly higher after flood events over the three shore heights (Table 2). This pattern was not found at either Coomera or Tingalpa 2 which both recorded

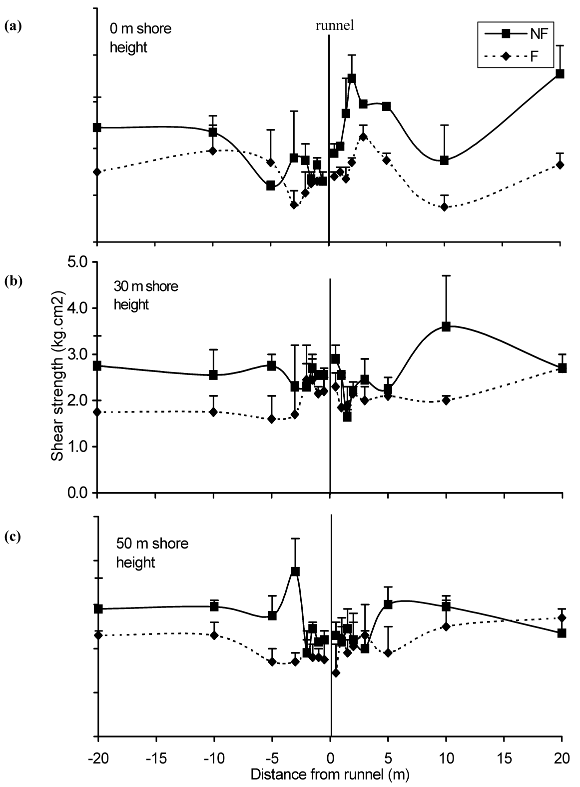

Figure 6. Mean soil consolidation (+SE) at Coomera saltmarsh along lateral transects, radiating from a runnel, at three shore heights after flooding (F) and non-flooding (NF) tides (a) 0, (b) 30 and (c) 50 m from shore.

differences in soil-water contents between shore heights, rather than tidal events (Table 2). For Coomera, soil-water measurements 30 m up the shore were significantly higher than the 0 and 50 m levels. At Tingalpa 2, soil-water content from 0 m shore height was significantly higher than either the 30 or 50 m positions.

Tidal inundation influenced soil consolidation measures, with significantly higher levels after non-flooding tides at Coomera than after flooding events (Table 2). Specifically, soil consolidation at all shore heights was higher at lateral distances greater than 5 m from the runnel edge after non-flooding tides, but were as low as those after flooding tides within 5 m of the edge (Figure 6). At Tingalpa 2, soil consolidation values differed significantly (Table 2) at lateral distances between 0.5 and 5.0 m and those taken further (10 and 20 m) from the runnel.

Discussion

Patterns of soil-water content and soil consolidation varied between the marshes, reflecting different substrate responses to tidal events and the presence of runnels. At the Coomera marsh, the runnel had the effect of increasing wetting on non-flooding tides to the levels measured after flooding tides, but this did not occur at other marshes. The effects of runnelling on both soil-water content and soil consolidation were localised, affecting the soil properties for up to 5 m either side of the runnel but having little impact beyond that distance. Given the similarity of soil physical structure at the sites sampled, the different patterns at the three marshes might be explained by biological consolidation, tidal forces and physical slope of the shore.

The most striking anomaly, illustrated by data from the Coomera marsh, is that soil consolidation increased with distance up the shore but it was not matched by a decrease in soil-water content. This lack of relationship between soil-water content and consolidation conflicts with results of other studies that examined similar soil properties (Nearing et al. 1991; Zhang et al. 2001) and reported that soil-water directly affects consolidation. One explanation for the lack of relationship between soil-water and consolidation in the marshes studied here is biological consolidation. Vegetation on the Coomera and Tingalpa 1 saltmarshes is dominated by grasses high on the marsh and halophytic herbs in lower parts. Soil consolidation measurements could be influenced by additional soil resistance attributable to higher root-mat densities of the fibrous-rooted grasses (Ringold 1979) higher on the shore. The influence of substrate biological factors on soil consolidation could be further confounded by built-up detritus layers in densely vegetated higher marsh sites (Smith-White 1988). Furthermore, these saltmarsh plant communities themselves are almost certainly influenced by soil conditions (Clarke and Hannon 1967; Gallagher 1979).

Alternatively, the lack of relationship between soil-water content and consolidation may be explained by physical processes which regulate tidal movement via surface and sub-surface mechanisms. Tidal forcing is a physical action of hydraulic head force through estuarine sediments when tides rise and results in surface soil saturation (Howes and Goehringer 1994). Hughes et al. (1998) analysed aquifer response to tidal forcing in saltmarsh wetlands of the lower Hunter River estuary in Australia and observed uniform forcing of porewater through saturated sediments over the length of a 36 m transect. At the three marshes surveyed in this study, little variation in soil-water content was detected over 50 m runnelled and unrunnelled transects after flooding tides. However, volumetric soil-water content was significantly lower along the unrunnelled transect at Coomera after non-flooding tides. In this case, the runnel may provide additional moisture resources for the deeper-acting hydraulic head, resulting in 'flood-like' soil-water levels measured in the top 6 cm of substrate. This supports observations by Dale et al. (1993) of increased soil moisture in and around runnels during tidal events that would not normally flood saltmarsh. However, the process was evidently not facilitated by runnels at Tingalpa 1 or Tingalpa 2 marshes, highlighting the variability of runnelling effects (and presumably deep-acting hydrological processes) among different marshes.

In addition to the sub-surface hydraulic forces and biological factors already discussed, tidal asymmetry and shore slope may provide further explanation for the variation in soil-water content and soil consolidation measured at the three sites. Aucan and Ridd (2000) examined flood and ebb tide movements across mangrove and saltmarsh systems in north Queensland, Australia. They report that the slope of tidal currents exiting up-shore areas, relative to the slope of the marsh surface, was an important determinant of water movement. In systems dominated by a higher water slope than surface slope (as in systems with large expanses of flat saltmarsh bordering mangrove), drying would occur more rapidly closer to the tidal source. This causes large volumes of water to become perched high on the marsh on the ebbing tide, restricting drainage to small channels (Aucan and Ridd 2000). The degree to which ebbing tidal waters perch depends on the slope characteristics of the marsh, and the effects of runnelling therefore might also vary among marshes with different slopes. For example, runnels aid transport of ebb tides from Coomera marsh so, volumetric soil water content is higher closer to the runnel edge than beyond during both flooding and non-flooding tides. A similar mechanism may also occur at Tingalpa 2 where soil consolidation close to the runnel was always different than at lateral distances greater than 5 m. The relationship between volumetric soil-water content and consolidation expected from previous work (Nearing et al. 1991; Zhang et al. 2001) was more evident in data from the second sampling protocol than the first. This might be an indication that in areas close to the runnel (within 5 m), where the runnel is having a greater impact, the effects of soil-water content on consolidation outweigh other factors (biological or physical) that are more important away from runnels. In effect, the presence of a runnel may exacerbate the influence of deeper sediment processes (such as tidal forcing and hydraulic head forces) that are reflected at the sediment surface.

In general, the impacts of runnels were site-specific with no general trends apparent at all of the marshes. In this study, we expected similar impacts from habitat modification at saltmarshes selected on the basis of *a priori* soil, topographical and tidal characteristics. However, given the variability in patterns recorded, even at unrunnelled transects, authorities concerned with managing impacts from physical methods of mosquito control should base remedial strategies on dynamic saltmarsh classifications.

Acknowledgements

We thank M. Mortimer for support, Redland Shire Council for access to the Tingalpa sites, and the Queensland EPA for equipment and field assistance. This research was supported by ARC grant C19906833 to P. Dale and R. Connolly and conducted through Griffith University.

References

Adam P. 1990. Saltmarsh Ecology. Cambridge University Press, Cambridge.

Aucan J. and Ridd P.V. 2000. Tidal asymmetry in creeks surrounded by saltflats and mangroves with small swamp slopes. Wetlands Ecology and Management 8: 223–231.

Avnimelech Y., Ritvo G., Meijer L.E. and Kochba M. 2001. Water content, organic carbon and dry bulk density in flooded sediments. Agricultural Engineering 25: 25–33.

Barzegar A.R., Asoodar M.A., Khadish A., Hashemi A.M. and Herbert S.J. 2003. Soil physical characteristics and chickpea

yield responses to tillage treatments. Soil and Tillage Research 1774: 1–9.
Beckmann G.G., Hubble G.D. and Thompson C.H. 1987. The Soil Landscapes of Brisbane and Southeastern Environs. CSIRO, Soils and Land Use Series No. 60.
Breitfuss M.J. 2001. Predicting the effects of runnelling on non-target saltmarsh resources. Arbovirus Research in Australia 8: 23–29.
Breitfuss M.J., Connolly R.M. and Dale P.E.R. 2003. Mangrove distribution and mosquito control: transport of *Avicennia marina* propagules by mosquito-control runnels in southeast Queensland saltmarshes. Estuarine Coastal and Shelf Science 56: 573–579.
Chapman H.F., Dale P.E.R. and Key B.H. 1998. A method for assessing the effects of runneling on salt marsh grapsid crab populations. Journal of the American Mosquito Control Association 14: 61–68.
Clarke L.D. and Hannon N.J. 1967. The mangrove swamp and salt marsh communities of the Sydney district. I. Vegetation, soils and climate. Journal of Ecology 55: 753–771.
Dale P.E.R., Dale P.T., Hulsman K. and Kay B.H. 1993. Runnelling to control saltmarsh mosquitoes: long-term efficacy and environmental impacts. Journal of the American Mosquito Control Association 9: 174–181.
Dale P.E.R. and Hulsman K. 1990. A critical review of saltmarsh management methods for mosquito control. Review in Aquatic Science 3: 281–311.
De Jonge V.N. 2000. Importance of temporal and spatial scales in applying biological and physical process knowledge in coastal management, an example for the Ems estuary. Continental Shelf Research 20: 1655–1686.
Dyer K.R., Christie M.C. and Wright E.W. 2000. The classification of intertidal mudflats. Continental Shelf Research 20: 1039–1060.
Flynn K.M., Mendelssohn I.A. and Wilsey B.J. 1999. The effect of water level management on the soils and vegetation of two coastal Louisiana marshes. Wetlands Ecology and Management 7: 193–218.
Gallagher J.L. 1979. Growth and element compositional responses of *Sporobolus virginicus* (L.) Kunth to substrate salinity and nitrogen. American Midland Naturalist 102: 68–75.
Gaskin G.J. and Miller J.D. 1996. Measurement of soil water content using a simplified impedance measuring technique. Journal of Agricultural Research 63: 153–160.
Howes B.L. and Goehringer D.D. 1994. Porewater drainage and dissolved organic carbon and nutrient losses through the intertidal creekbanks of a New England salt marsh. Marine Ecology Progress Series 114: 289–301.
Hughes C.E., Binning P. and Willgoose G.R. 1998. Characterisation of the hydrology of an estuarine wetland. Journal of Hydrology 211: 34–49.
Hulsman K., Dale P.E.R. and Kay B.H. 1989. The runnelling method of habitat modification: an environment-focused tool for salt marsh mosquito management. Journal of the American Mosquito Control Association 5(2): 226–234.
Hussein A.H. and Rabenhorst M.C. 2001a. Tidal inundation of transgressive coastal areas: pedogenesis of salinization and alkalinization. Soil Science Society of America Journal 65: 536–544.
Hussein A.H. and Rabenhorst M.C. 2001b. Modelling the impact of tidal inundation on submerging coastal landscapes of the Chesapeake Bay. Soil Science Society of America Journal 65: 932–941.
Law J. 1981. The Hydrological Regime and Geomorphological Processes Operating within the Coomera Island Saltmarsh. Griffith University Internal Report, Brisbane, Queensland, Australia.
Le Hir P., Roberts W., Cazaillet O., Christie M., Bassoullet P. and Bacher C. 2000. Characterization of intertidal flat hydrodynamics. Continental Shelf Research 20: 1433–1459.
Miller J.D. and Gaskin G.J. 1997. The Development and Application of the ThetaProbe Soil Water Sensor. MLURI technical note.
Mwamba M.J. and Torres R. 2002. Rainfall effects on marsh sediment redistribution, North Inlet, South Carolina, USA. Marine Geology 189: 267–287.
Nearing M.A., Bradford J.M. and Parker S.C. 1991. Soil detachment by shallow flow at low slopes. Soil Science Society of America Journal 55: 339–344.
Owttrim A. and Dixon M. 2001. Local Government Runnelling Works for Saltmarsh Mosquito Control: Fish Habitat Code of Practice for use with Strategic Permits Issued Under Section 51 of the Fisheries Act 1994. Queensland Department of Primary Industries, Brisbane, Australia.
Porporato A., D'Odorico P., Laio F., Ridolfi L. and Rodriguez-Iturbe I. 2002. Ecohydrology of water-controlled ecosystems. Advances in Water Resources 25: 1335–1348.
Qiu Y., Fu B., Wang J. and Chen L. 2001. Soil moisture variation in relation to topography and land use in a hillslope catchment of the Loess Plateau, China. Journal of Hydrology 240: 243–263.
Queensland Department of Transport, 2001. The Official Tide Tables and Boating Safety Guide 2001. Queensland Department of Transport, Brisbane, Australia.
Ringold P. 1979. Burrowing, root mat density, and the distribution of fiddler crabs in the eastern United States. Journal of Experimental Marine Biology and Ecology 36: 11–21.
Sagasti A., Schaffne L.C. and Duffy J.E. 2001. Effects of periodic hypoxia on mortality, feeding and predation in an estuarine epifaunal community. Journal of Experimental Marine Biology and Ecology 258: 257–283.
Schmalz B., Lennartz B. and Wachsmuth D. 2002. Analyses of soil water content variations and GPR attribute distributions. Journal of Hydrology 267: 217–226.
Schultz G. and Ruppel C. 2002. Constraints on hydraulic parameters and implications for groundwater flux across the upland-estuary interface. Journal of Hydrology 260: 255–269.
Shaman J., Stieglitz M., Stark C., Le Blancq S. and Cane M. 2002. Using a dynamic hydrology model to predict mosquito abundances in flood and swamp water. Emerging Infectious Diseases 8: 6–13.
Simas T., Nunes J.P. and Ferreira J.G. 2001. Effects of global climate change on coastal salt marshes. Ecological Modelling 139: 1–15.
Smith T.I., Boto K.G., Frusher S. and Giddens R. 1991. Keystone species and mangrove forest dynamics: the influence of burrowing by crabs on soil nutrient status and forest productivity. Estuarine Coastal and Shelf Science 33: 419–432.

Smith-White A.R. 1988. *Sporobolus virginicus* (L.) Kunth in coastal Australia: the reproductive behaviour and the distribution of morphological types of chromosome races. Australian Journal of Botany 36: 23–39.

Stolt M.H. and Rabenhorst M.C. 1991. Micromorphology of argillic horizons in an upland/tidal marsh catena. Soil Science Society of America Journal 55: 443–450.

Tan C.S., Drury C.F., Gaynor J.D., Welacky T.W. and Reynolds W.D. 2002. Effect of tillage and water table control on evapotranspiration, surface runoff, tile drainage and soil water content under maize on a clay loam soil. Agricultural Water Management 54: 173–188.

Tan C.S., Drury C.F., Soultani M., van Wesenbeeck I.J., Ng H.Y.F., Gaynor J.D. and Welacky T.W. 1998. Effect of controlled drainage and tillage on soil structure and tile drainage nitrate loss at the field scale. Water Science and Technology 38: 103–110.

Vernberg F.J. 1993. Salt-marsh processes: a review. Environmental Toxicology and Chemistry 12: 2167–2195.

Yoo C. 2001. Sampling of soil moisture fields and related errors: implications to the optimal sampling design. Advances in Water Resources 24: 521–530.

Yoo C., Valdes J.B. and North G.R. 1998. Evaluation of the impact of rainfall on soil moisture variability. Advances in Water Resources 21: 375–384.

Zhang B., Zhao Q.G., Horn R. and Baumgartl T. 2001. Shear strength of surface soil as affected by soil bulk density and soil water content. Soil and Tillage Research 59: 97–106.