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The importance of groundwater and other ecohydrological impacts in the management of salt marsh plant communities

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Abstract

Salt marshes are characterized by the presence of plants tolerant of some degree of salinity, although freshwater inputs can also be a significant component of the ecosystem. Sources and routes of freshwater can include river flow into the estuary, groundwater flow along a defined aquifer or channel and diffuse seepage as well as rainfall. In addition both fresh and saltwater flows can be the agents of transport to and from the marsh itself of sediment, mineral nutrients, pollutants and particulate and dissolved organic carbon. A common feature of many valley salt marshes is the presence of seepages of freshwater, particularly along the edge of the upper marsh, local upwelling or flow through permeable soil layers within the marsh. They can often be distinguished by the presence of plant species not fully tolerant of seawater. The commonest is *Phragmites australis* which can be seen as isolated clumps marking localized freshwater seepages or more widespread in areas where the soil salinity is reduced by a generalized freshwater input. While surface and groundwater flow can provide necessary plant nutrients excessive nutrient loading can result in hyper-eutrophic conditions with major effects on the biodiversity of the flora and fauna. Groundwater flows can cause the transport of these nutrients over considerable distances necessitating the use of special techniques to determine their source. This study also showed that excessive nutrient levels could be transported through to near-shore sediments with possible effects on marine habitats. Generally, however, salt marshes can be regarded as sinks which control the eutrophication of coastal waters by removing excessive nutrients. More is known about groundwater dynamics in wet coastal grasslands, enabling the prediction of changes. The installation of extensive instrumentation at specific sites has enabled the development of numerical models to study the groundwater dynamics of the forest-marsh interface. The next major step will be to integrate these various models in such a way that for any given salt marsh the underlying ecological processes can be understood sufficiently to develop management techniques. It has been demonstrated that current measures may be inadequate to restore fully the ecological processes of a healthy robust estuary or to reinstate the full beneficial functions of the estuarine ecosystem. This shows that the successful management of estuaries and coastal waters requires an ecohydrology-based catchment-wide approach. This will require a change in thinking and in management concepts for all estuaries and coastal waters.

Keywords: Salt marsh; Groundwater; Ecohydrology; Habitat creation.

The salt marsh habitat

Salt marshes are characterized by the presence of plants tolerant of both immersion in water for varying periods and some degree of salinity, although freshwater inputs can also be a significant factor in many marshes. There are various sources and routes of freshwater into a salt marsh. These can include river flow into the estuary, groundwater flow along a defined aquifer or channel or diffuse seepage, and also directly as a result of rainfall on the marsh and through surface flow from adjacent slopes. However, in general terms little attention has been paid to freshwater inputs and impacts on salt marshes except from the point of view of the effects of rainfall on the acceleration of seed germination of many plant species and the effect of river flow on the overall salinity of the water body at particular points in an estuary.

It has been shown that saltwater flows can be the agents of transport to and from the marsh itself of sediment, mineral nutrients, pollutants and particulate or dissolved organic carbon (Hazelden and Boorman, 1999). It would seem probable that where there are freshwater flows in a salt marsh a similar effect may be expected. Additionally as excessive nutrient levels in an estuary (White *et al*., 2004) can affect the marsh plant communities it would seem likely that nutrients brought in by freshwater could have a similar impact.

Water routes in salt marshes

A common feature of many valley salt marshes is the presence of seepages of freshwater, particularly along the edges of the upper marsh and local upwelling or flow through permeable soil layers within the marsh. Affected areas can often be distinguished by the presence of plant species not fully tolerant of sea water. The commonest is *Phragmites australis* which can be seen as isolated clumps marking localized freshwater seepages or more widespread in areas where the soil salinity is reduced by a generalized freshwater input. In addition freshwater from adjacent agricultural land often drains onto salt marsh or into the creeks, bringing with it nutrients or pesticides.

Salt marshes are commonly developed on fine-textured sediments with the particle-size in the clay and fine silt range, and consequently the permeability of such soil might be expected to be low. An inspection of many salt marshes shows that this is a simplification of the true picture. At low tide, water is seen to seep from the sides of marsh creeks from a variety of fissures and holes in the otherwise slowly permeable marsh clays and silts. These more permeable layers can be either physical or biological in origin. Physically cracks and fissures develop when the soil dries out and the clay shrinks. Although these will close up on rewetting, they remain a permanent feature of the soil structure. In addition, coarse-textured horizons within the soil (perhaps sand and shell debris deposited during a storm) give rise to more permeable layers within the soil. More permeable layers, of biological origin, can result from the residual channels left after the death and decay of roots and other underground plant material. They also result from the burrowing activities of varied intertidal fauna, from crabs and molluscs through to the many different groups in the meso- and micro-fauna. Water movement paths are also created in the marsh soil by the burial of layers of organic matter such as are created when the autumn fall of leaf material is buried by high rates of accretion during equinoctial tides. These layers are quite persistent as they are sometimes visible a hundred millimeters below the surface which, in a marsh with a mean annual accretion rate of around 3mm, represents an age of the order of 30 years.

Thus within a marsh developed on mainly fine material there is a wide range of potential routes for water movements. In addition there are a significant number of marshes based on coarse silts and sands where water movements are not nearly as restricted. In such marshes water flows and the associated fluxes are likely to be considerably enhanced in comparison with those in more typical marshes.

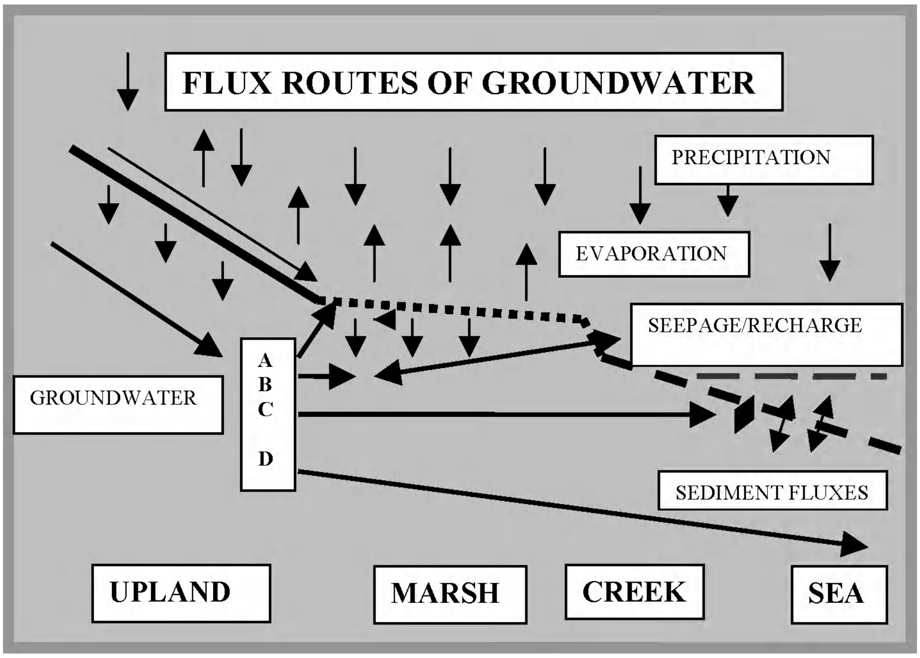

Fig. 1. Diagrammatic representation of the principal routes of water flow in a typical salt marsh. Specific groundwater routes:- A – seepage at junction between marsh and higher ground; B – horizontal percolation outwards through marsh soils and recharge during tidal immersion; C – seepage below main marsh layers; D – seepage through subsoil/ underlying strata below the marsh.

While there is much variation in the precise details of the water flow routes in the marsh it is the major routes that should be of most concern and these are summarised in Fig. 1. The two major driving forces are the flow of groundwater from the higher ground (‘upland’) adjoining the marsh and the bidirectional flow from the tidal waters on the seaward side of the marsh. There is also the direct impact of rainfall on to the marsh surface. All three of these have a more or less visible effect on the side of the marsh which they directly impact (the landward edge, the seaward edge and the top surface respectively), but within the body of the marsh there are complex interactions at various points depending on the magnitude and timing of each of them. The magnitude of local water movements will depend on differentials in the pore water pressure as well as the hydraulic conductivity of the sediments at a particular point in the marsh.

The dynamics of porewater nutrients has not so far been studied in great detail in salt marshes but it is clear from work on the porewater of an intertidal sand flat that nutrient concentration gradients can generate diffusive fluxes to and from the deeper sediments and that the increased oxygenation during emersion affected nitrification and nitrate reduction rates (Kuwae *et al.,* 2003). Microbial nitrate reduction occurred in the deeper subsurface sediments and this process was supported by the downward diffusive flux of nitrate from the surface sediment. It might be expected that in the less porous salt marsh soils similar processes might occur at a slower rate, however, even in the more porous sandy sediments both the soil water content and the levels of the water table changes little during immersion suggesting that porosity was not a particularly important controlling factor.

Hydrological impacts on salt marshes

While surface and groundwater flow can provide necessary plant nutrients excessive nutrient loading can result in hyper-eutrophic conditions with major effects on the biodiversity. It has been shown that groundwater flows can cause the transport of these nutrients over considerable distances (Mayer *et al*., 2000). This study also showed that excessive nutrient levels could be transported through to near-shore sediments with possible effects on marine habitats. This is an extreme situation and more generally salt marshes can be regarded as sinks which control the eutrophication of coastal waters by removing excessive nutrients from the system (Teal and Howes, 2000).

As well as affecting the concentrations and fluxes of nutrients, organic matter and sediment associated with a salt marsh, the hydrology of the marsh can also affect the physical conditions within a marsh. It has been shown that variability in evapotranspiration and tidal flooding can affect the soil volume and consequently the precise level of the surface of the marsh (Paquette *et al*., 2004). This effect is of primary importance in making accurate measurements of accretion/erosion in marsh development. Such measurements are crucial both in the study of salt marsh processes and in the monitoring of success in salt marsh creation. Undetected changes in marsh levels could also have significant consequences for physical and biological processes on the surface of the marsh; in particular on the patterns of seed dispersal and germination and thus the subsequent resultant patterns of plant colonization.

The discussion so far has related to salt marshes in temperate, relatively damp and cool, areas. In drier and warmer areas of the world the input of freshwater becomes of increasing importance to the salt marsh. In South Africa it has been shown that the salt marsh plants are only in active growth during the winter rainfall period (Bornman *et al*., 2002). During the dry season plants are dependant for their survival on access to saline groundwater. The occurrence of winter rainfall ensures the replenishment of the saline groundwater with freshwater both decreasing the depth of the water table and reducing its salinity thus facilitating plant growth.

Techniques for studying salt marsh hydrology

Groundwater flows, with the possibilities of their transporting nutrients over considerable distances, necessitate the use of special techniques to determine their source. In one study, involving the leakage of partially treated sewage, the molecular marker coprostanol was used to assess nutrient inputs to a marsh (Mayer *et al.*, 2000). Radio-isotopes have also been used to trace groundwater pathways. Routes and flux rates of submarine groundwater discharge in a Massachusetts salt marsh were determined using four radium isotopes (Charette *et al.*, 2003). These workers also showed that under drought conditions seawater-sediment interactions were important in delivery of certain dissolved substances to coastal waters. In another study in North Carolina the isotopic composition of dissolved inorganic carbon was used to define a component of the surface water-groundwater system (Gramling *et al.*, 2003). The work demonstrated that, when precipitation was low, artesian groundwater discharge accounted for virtually all the freshwater input to the marsh while in wet periods there was a negligible groundwater contribution.

Studies continue to collect long-term real-time data on the ecohydrology of salt marshes and to develop mathematical models to interpret the various processes involved (Crowe *et al.*, 2004). More is known about groundwater dynamics in wet coastal grasslands, enabling the prediction of changes (Mohrlok, 2002). Reeves and Fairborn (1996) installed extensive instrumentation to enable the development of a numerical model to study the groundwater dynamics of the forest-marsh interface. The next major step will be to integrate these various models, possibly through the use of a decision based support system, in such a way that for any given salt marsh the underlying ecological processes, including the magnitude and direction of the various fluxes, can be understood sufficiently to develop effective management techniques.

Groundwater and the implications for salt marsh management

The most direct effect of groundwater on salt marshes is the opportunity it offers for the transport of pollutants into the salt marsh ecosystem. Salt marshes adjacent to intensively used farm land can have significant concentrations of selective herbicides (Fletcher *et al.*, 2004). The transport was by both surface and sub-surface routes. While it was not possible to demonstrate a detectable effect on the vegetation the residual herbicide concentrations measured in this study were above the UK environmental safety guidelines.

The implications of groundwater quality for the management of salt marshes can also be inferred indirectly. Studies in Japan showed that the use of excessive fertilizer could affect the use of the water for irrigation (Fujiwara *et al.*, 2002). Seawater intrusion into the aquifer was also shown to be having an impact on water quality but the situation was complicated by the activity of cation exchange phenomena.

As well as the ionic transport of plant mineral nutrients there can be significant fluxes of dissolved inorganic carbon with significant contributions from the degradation of organic carbon (Cai *et al*., 2003). These studies showed that the groundwaters in the marsh in South Carolina are mixtures of sea water and freshwater and that the end-members are modified by the input of CO_2 from the degradation of organic matter. Furthermore the work demonstrated that there were significant groundwater fluxes of dissolved inorganic carbon from the land to the sea via the salt marshes.

Mention has already been made of the serious effects groundwater pollution can have on salt marshes but while efforts are being made to reduce the inputs of excessive nutrient levels as yet there has been little work on controlling groundwater pathways. However, in a situation where the reverse problem has occurred, that of saline intrusions in fresh groundwater, a degree of groundwater control has been achieved by modelling the discharge matrix and then by the selective drawdown through controlled pumping (Zhou *et al*., 2003).

The relation of the salt marsh and freshwater flows is often seen simply in terms of a stream or river flowing to the sea, through an area of salt marsh, and measurement of the incoming river flow will thus be considered to characterise the freshwater input. However, in practice salt marsh areas often have many freshwater inputs from a number of distinct areas with very different types of land cover and land use. Such was the case in a study of salt marshes in South Carolina where, through the development of a conceptual model, it was shown that the monitoring of creek headwaters could give early warning of possible harmful effects on tidal areas with serious implications both for conservation and economically important activities (Holland *et al*., 2004).

Hydrological aspects of salt marsh creation

The re-creation of salt marshes on land which was originally salt marsh would in the hydrological sense seem fairly straight forward. However, there can be problems caused by the changes that will have taken place to the sediment and soils while the land has been used for agriculture or grazing (Hazelden and Boorman, 2001). The most obvious physical change is the 'ripening' of the soil; this is the irreversible drying of the sediment by evapotranspiration during which the bulk density increases and porosity decreases. Soil structure, a semi-permanent network of cracks throughout the soils delineating soil 'peds', also develops, and the salt (NaCl) will have been leached from at least the upper layers of the soil. On some newly-created salt marshes the old agricultural soil is rapidly buried by the accumulation of new sediment, which provides a good medium for the germination and growth of salt marsh plants. However, where this does not happen, the establishment of salt marsh vegetation may be hindered in these dry, dense soils.

The physical properties of reclaimed marsh soils are little altered by the reversion of the land to salt marsh, and their burial by new sediment. However, the relatively dense subsurface layer will affect subsequent creek development. Drainage patterns established on a site prior to its reversion to salt marsh will, to a great extent, control those that subsequently become established.

In some sites salt marsh re-creation may be complicated by other factors. It has been shown that some grassland communities of saline areas are very much dependant on the up-welling of groundwater through a saline peat layer (Beyen and Meire, 2003). In order to compensate for the loss of such areas it was necessary to make detailed hydrological studies, albeit on a fairly local scale, to locate the relative rare occurrence of sites suitable for this type of habitat creation.

Even when there are no such special conditions for the re-creation of salt marsh the changes in the soil hydrological regime which occurred while the marsh was under agricultural use, and no longer subject to regular tidal flooding, are considerable. The effects of the changes in tidal level were limited to small changes in the level of the underlying water table (Blackwell *et al.*, 2004). Consequently there were major adjustments following the return of tidal flooding. Not only was there the direct effect of the immersion in saltwater but there were also a wide range of changes in both physical and chemical soil properties. Changes in soil water table resulted in the soil environment changed from an oxidising to a reducing environment. In the short term there were changes in soil pH, with the topsoil water becoming markedly acid. There were also large decreases in the rates of decomposition of organic matter. All of these effects have serious implications for the establishment of salt marsh vegetation and subsequent salt marsh management.

The sustainable long-term management of created salt marshes must be a key part of any such programme and there are a range of issues involved (Boorman and Hazelden, 2004). While the successful establishment of vegetation cover may only take a few years much longer time periods are needed before anything like full ecosystem function is achieved. A recent study of the rate of ecosystem development in created *Spartina alternifolia* marshes (Craft *et al.*, 2003) showed, while most of the functional ecological attributes have achieved equivalence to those in nearby natural marshes in 5 to 15 years, the levels of pools of organic carbon and nitrogen are still lower than in the natural marshes even 28 years after marsh creation. This work involved the study of a wide range of ecological processes and this may not always be possible when there is extensive marsh creation.

It is important however to note that simpler methods of assessment may give misleading results. Studies in a range of healthy and impaired salt marshes in Louisiana showed that the state of the above-ground biomass was not a good indicator of marsh health (Turner *et al.*, 2004). However, the work did show that marshes under stress have a reduced below-ground biomass which could be detected long before there was any detectable effect on the vegetation above-ground thus giving the possibility of applying appropriate management techniques.

Ecohydrology – the new approach

The case for salt marsh creation in order to compensate for lost or degraded marshes has been well made but at present the remedial measures suggested are considered to be inadequate to fully restore the ecological processes of a healthy robust estuary or to reinstate the full beneficial functions of the estuarine ecosystem (Wolanski *et al*., 2004). These authors consider that the successful management of estuaries and coastal waters requires an ecohydrology-based catchment-wide approach. This will necessitate changing present practices which are based on local administrative units and on the narrowly focused approaches of managers of specific activities (including fisheries, water resources and urban development). Without this change in thinking and in management concepts estuaries and coastal waters will continue to degrade whatever management plans are put in place.

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