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# Understanding system disturbance and ecosystem services in restored saltmarshes: Integrating physical and biogeochemical processes

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ABSTRACT

Coastal saltmarsh ecosystems occupy only a small percentage of Earth's land surface, yet contribute a wide range of ecosystem services that have significant global economic and societal value. These environments currently face significant challenges associated with climate change, sea level rise, development and water quality deterioration and are consequently the focus of a range of management schemes. Increasingly, soft engineering techniques such as managed realignment (MR) are being employed to restore and recreate these environments, driven primarily by the need for habitat (re) creation and sustainable coastal flood defence. Such restoration schemes also have the potential to provide additional ecosystem services including climate regulation and waste processing. However, these sites have frequently been physically impacted by their previous land use and there is a lack of understanding of how this 'disturbance' impacts the delivery of ecosystem services or of the complex linkages between ecological, physical and biogeochemical processes in restored systems. Through the exploration of current data this paper determines that hydrological, geomorphological and hydrodynamic functioning of restored sites may be significantly impaired with respects to natural 'undisturbed' systems and that links between morphology, sediment structure, hydrology and solute transfer are poorly understood. This has consequences for the delivery of seeds, the provision of abiotic conditions suitable for plant growth, the development of microhabitats and the cycling of nutrients/contaminants and may impact the delivery of ecosystem services including biodiversity, climate regulation and waste processing. This calls for a change in our approach to research in these environments with a need for integrated, interdisciplinary studies over a range of spatial and temporal scales incorporating both intensive and extensive research design.



## 1. Introduction

Coastal and estuarine environments are faced with numerous challenges, including over-population and economic development, climate change and sea level rise, and water quality deterioration (Kennish, 2002). As a result, the sustainable management of these environments at national and local scales must reconcile regulatory compliance with the demands of a wide range of stakeholders. In addition, considerable emphasis is now being placed on the economic and societal value of the natural functioning of global ecosystems in terms of the flows of materials and energy from natural resources that constitute 'ecosystem services' (Costanza et al., 1997; Millennium Ecosystem Assessment, 2005a; Jones et al., 2011). This is reflected in legislative and policy frameworks for managing and conserving aquatic ecosystems (European Parliament and the Council of the European Union, 1992, 2000; European Academies Science Advisory Council, 2009; Lawton et al., 2010) and the 'ecosystem services' approach provides a common framework for evaluating coastal management options and communicating their consequences to diverse stakeholder groups (Granek et al., 2009).

Although inter-tidal environments such as saltmarshes and mud flats occupy a small percentage (4%) of Earth's total land area, they deliver a wide range of ecosystem services that have significant global value and contribute to national economies (Barbier et al., 2011); in the UK this has been estimated at £48 billion or 3.46% of the UK's national income (Jones et al., 2011). Ecosystem services associated with estuarine and marsh ecosystems at the global scale include: provisioning services such as food, fuel and fibre; regulating services such as nutrient cycling, atmospheric and climate regulation, waste processing, disease regulation and flood hazard regulation; and cultural services such as recreation, amenity and

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aesthetical values (Millennium Ecosystem Assessment, 2005; EFTEC et al., 2006; Costanza et al., 2008; Granek et al., 2009). For saltmarshes, by far the most important benefits are sea defence, immobilisation of pollutants and the provision of rare and unique habitats which support both nursery grounds for fish, and breeding/feeding grounds for birds (Jones et al., 2011). Yet, up to 50% of saltmarshes worldwide have been degraded by human activity and this is likely to have significant impact on critical ecosystem services (Barbier et al., 2011) and as a consequence saltmarshes are frequently the subject of a range of management, restoration, remediation and rehabilitation strategies (Elliott et al., 2007).

An increasingly widespread coastal management approach across Europe and the USA that has the potential to restore saltmarshes and deliver these ecosystem services is Managed Realignment (MR), which is the deliberate removal of a coastal flood defence to allow the tidal inundation of a previously protected low-lying coastal area. Such schemes encompass a range of soft engineering techniques whereby floodwalls or embankments may be breached, removed or lowered (Rupp-Armstrong et al., 2008). Through engineered modifications, both the elevation and hydroperiod of these sites can be controlled by either excavation or sediment re-charge, or by using sluice gates and pumps to control cycles, rates and periods of tidal inundation to enhance the conditions required for specific habitat development (ABPmer, 2010). In Europe and the USA, there are at least 150 MR schemes (or similar) (ABPmer, 2009, 2010) driven by legislative requirements under the EU Habitats and Birds Directives (European Parliament and the Council of the European Union, 1992, 2009) and the Clean Water Act (Committee on Mitigating Wetland Losses, 2001) for habitat (re) creation for either conservation or compensation purposes (Rupp-Armstrong et al., 2008; ABPmer, 2010) and sustainable coastal flood defence. In addition to habitat restoration and coastal defence these schemes have the potential to offer additional ecosystem services including improvements to surface water quality through nutrient and contaminant storage and denitrification, and carbon sequestration (Williams and Orr, 2002; Andrews et al., 2006; Environment Agency, 2007; Shepherd et al., 2007) and therefore have the potential to help EU member states meet their obligations for improving chemical water quality and ecological status under the Water Framework Directive (European Parliament and the Council of the European Union, 2000; Environment Agency, 2010). Despite this, there has been little focus on quantifying the full range of ecosystem services delivered by saltmarsh restoration schemes. Although many restoration schemes are deemed successful and result in environmental enhancements (ABPmer, 2010), there is building evidence to suggest that in restored sites vegetation colonisation may often be poorer/slower than expected, that fewer microhabitats develop, and that restored sites may be less effective at sequestering organic carbon, with higher emissions of the greenhouse gases $CO_2$ and $N_2O$ and high variability in denitrification rates (Kenny et al., 2004; Elsey-Quirk et al., 2009; Blackwell et al., 2010; Garbutt, 2010; Mossman et al., 2012). This indicates that these restoration sites may not be maximising the delivery of regulating services including nutrient cycling, atmospheric and climate regulation and waste processing, or provisioning services such as wild species diversity.

There is a pressing need for saltmarsh restoration as the maintenance of coastal defences becomes economically unviable and as more space is required for the accommodation of tidal floodwaters and habitat recreation, yet technical, financial and cultural constraints to the further provision of restoration and MR in particular persist (Parrott and Burningham, 2008). Demonstrating not only that current practices result in environmental enhancement, but also that they result in fully functioning ecosystems and maximise the delivery of the full range of potential ecosystem services is crucial in supporting the future expansion of MR and other restoration schemes. Fully functioning ecosystems must be underpinned by the effective rehabilitation and long-term sustainability of inextricably linked ecological, biogeochemical and physical processes (Viles et al., 2008). For restored coastal saltmarshes, associations between vegetation patterns and geomorphic characteristics are broadly understood and already considered within both design and monitoring protocols (e.g. Neckles et al., 2002; Callaway and Zelder, 2004). However, there remains very little understanding of the long-term physical (hydrogeomorphological and hydrodynamic) and biogeochemical functioning of restored sites, the interactions between physical, biogeochemical and biological processes (Townend, 2010) and the impacts this may have on ecosystem service delivery. In addition, many of these restored sites will have been subjected to external system impacts or physical 'disturbances' (cf. Viles et al., 2008) associated with their former land use (drainage, urbanisation or agriculture) and/or restoration technique and there is no understanding of how this might affect ecosystem functioning and the potential delivery of ecosystem services in these systems.

This paper first assesses the availability of physical and biogeochemical process data for restored saltmarshes on which we currently base our understanding of ecosystem functioning. Secondly, we examine the impact of disturbance on physical and biogeochemical processes and hence delivery of ecosystem services, focussing on the diversity and development of saltmarsh vegetation. Finally, we consider how such knowledge may initiate a step-change in our approaches to research (and potentially management) in these systems. This complements recent calls within the wider biogeomorphology literature for improved theoretical understanding of complex and non-linear relationships between ecological and geomorphological systems within a range of terrestrial and aquatic environments and over various spatio-temporal scales to inform practical environmental management (Viles et al., 2008; Reinhardt et al., 2010; Rice et al., 2010).

## 2. Data availability

Current understanding of both the functioning of restored saltmarshes and quantification of the ecosystem services that they deliver is derived from pre- and post-project monitoring data. However, the usefulness of these data is limited and although a wide range of monitoring variables are recommended (including sediment erosion/accretion, surface water flow and hydrodynamics, physical and chemical sediment characteristics, vegetation, birds and fish (Leggett et al., 2004; Environment Agency, 2010)) no standard protocols exist, making comparison of data at both local and regional scales difficult (Neckles et al., 2002). In addition, long-term monitoring data sets are rare due to cost and partly because restoration techniques, such as MR, are relatively new management practices. Consequently, although habitat development may take place quite quickly (e.g. Morgan and Short, 2002; Thom et al., 2002; Byers and Chmura, 2007) these sites are often considered immature in terms of the development of wider ecosystem functioning (Kentula, 2000). An additional obstacle to generating an improved understanding of system functioning is associated with a reluctance to focus on, and report, the less successful aspects of restoration. For example, in a review of MR monitoring activities across Europe (ABPmer, 2010) many projects were identified as either being moderately or highly successful with vegetation development identified as poorer than expected for just two out of 51 projects reviewed. However, a lack of detail on project effectiveness may partly result from the fact that any perceived 'failure' can compromise both future funding and stakeholder confidence, but it also reflects a general acceptance that schemes achieving any