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Lagoons and Coastal Wetlands in the Global Change Context: Impacts and Management Issues

Lagoons and Coastal Wetlands in the Global Change Context: Impacts and Management Issues

Selected papers of the International Conference "CoastWetChange", Venice, 26–28 April 2004

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LAGOONS AND COASTAL WETLANDS

Preface

Pierluigi Viaroli · Pierre Lasserre · Pierpaolo Campostrini

Lagoons and coastal wetlands are among the most common environments in the transitional zone located between terrestrial ecosystems and adjacent seas. Their persistence and ecosystem processes are controlled by complex interactions among stressors and fluxes of material between land, ocean and atmosphere. As a result, coastal zones are among the most changeable and vulnerable environments on Earth. Among other, natural factors that have the largest impact on coastal lagoons and wetlands are sea-level rise, precipitation and river runoff, and storminess (Crossland et al., 2005; Eisenreich, 2005). Natural stressors are interconnected in many ways and are often associated with human impact. In recent decades, most coastal ecosystems have experienced strong anthropogenic pressures, due to progressive human migration from continental areas. At present, nearly 40–50% of the population lives within 100 km of the coastline, including some of the world's largest cities (Crossland et al., 2005).

The impact of human activities on the variability of coastal systems is considerable, and usually leads to deterioration and losses of marine resources, standing stocks and coastal landscape. These pressures have dramatically increased in the last few decades and will continue and evolve, especially in developing countries. Therefore, lagoons and coastal wetlands are expected to be affected by growing modification, i.e. urbanisation, exploitation for aquaculture, marinas and tourism, as well as by large-scale climatic changes.

Most coastal lagoons and their watersheds are influenced by sea eustatism and are subjected to a natural subsidence that has been accelerated by marshland reclamation, groundwater and natural gas extraction. The combination of subsidence and sea-level rise may not be balanced by accretion of coastal wetlands, resulting in increased flooding and saltwater intrusion into freshwater wetlands. Furthermore, a rising sea level combined with more frequent storms and associated surges are likely to cause enhanced coastal erosion. Wetlands and barrier islands reduce storm surges and weaken their energy, to a greater extent than artificial sea defences.

An increased variety of land uses have contributed to increased changes in watershed

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structure and hydrographic networks. Overall, these alterations influence coastal wetlands and nearshore coastal waters through spatial dependent and time-lagged processes that control the delivery of nutrients and pollutants (Valiela et al., 1997).

Coastal lagoons and wetlands are recognised as highly unpredictable environments. There is evidence that within certain thresholds, marine communities and ecosystems are resilient to environmental changes and can buffer against external stresses. However, resilience and buffering capacities do not follow linear behaviour, but rather undergo sudden and exponential responses. Therefore, an increasing stress—e.g. by physical and chemical stressors—can result in rapid regime shifts and irreversible deterioration of the aquatic ecosystems. Assessments are further hampered by lack of historical time series, Venice lagoon, Wadden Sea and Chesapeake Bay being probably the only environments where this analysis has been attempted.

Coastal lagoons and wetlands have also a recognised human dimension, and they constitute an invaluable historical and cultural heritage, e.g. the lagoon of Venice or the smaller coastal lagoons scattered along the Mediterranean coast.

Over the last twenty years, the scientific community has taken an increasing interest in these important areas. Since the symposium organised in 1981 by UNESCO/SCOR Consultative Committee on coastal systems (Lasserre & Postma, 1982), several studies were published, focusing on hydrology, biology and ecological classification criteria, as well as on the coastal management and conservation strategies of coastal wetlands (Mitsch & Gosselink, 2000). In the last decade, the main research fields were functional ecology and biogeochemistry, in respect of ecosystem alterations and buffering capacity (see as an example Kjerfve, 1994; Caumette et al., 1996; Schramm & Nienhuis, 1996; Viaroli et al., 2005).

It is now urgent to identify the influence of global change, from regional (e.g. eutrophication, degradation, erosion and loss of natural habitats) and local impacts (e.g. urbanisation, contamination, and tourism activities). Among others, an important aspect lies in the conservation of distinctive elements of wetland biodiversity in a global context, as opposed to conservation targets framed from too narrow or arbitrary national and regional boundaries.

Identification of proxies and climate-sensitive keystone species having a large impact on the rest of the community needs to be achieved in a timely manner in order to develop appropriate monitoring programmes. The initiative of establishing an international Global Terrestrial Observing System (GTOS) and particularly its coastal module would be largely beneficial in improving the capacity for detecting and predicting the effect of global climate change on coastal systems (GTOS, 2005).

The international Conference ''CoastWetChange—Lagoons and Coastal Wetlands in the Global Change Context: Impacts and Management Issues'' was organized in Venice, 26–28 April 2004, at the initiative of UNESCO and CORILA, to provide an interdisciplinary forum to share knowledge and experience of recent developments in wetland science and global change. The aim was to identify gaps, problems and successes in the integration of global change issues into lagoon and coastal wetland management. Based upon current scientific evidence, climate change will create novel challenges for coastal and marine ecosystems that are already stressed from human development, land-use change, environmental pollution, habitat alteration and loss. Venice was an emblematic venue for this meeting. Included in the World Heritage List established by UNESCO under the World Heritage Convention, Venice and its lagoon are a unique place internationally recognized as a ''laboratory'' for sharing and improving innovative technologies, developing knowledge in science and culture and for providing opportunities for intellectual exchange.

Most of the papers contributed to the conference have been published earlier (Lasserre et al., 2005). This volume comprises of 13 selected papers, of which five are reviews and eight primary research papers. A group of review papers, Section 1, analyses the main ecological and hydrogeomorphic features of coastal wetlands, with respect to climate change, including changes in sea level. Two papers address the importance of lagoons and wetlands as sentinel ecosystems for coastal observations of global change, and on the significance of flooding and ecological risk assessment applied to specific and more general situations. Finally, the research papers (Section 2) highlight our present understanding of the recent evolution of lagoons and coastal wetlands, including population dynamics, community succession, biogeochemical processes and pollution, key biological elements and related indicators.

Not every author has chosen the state-of-the-art approach. Some have preferred to concentrate on, from their point of view, crucial problems, which need further elucidation. A few give a detailed analysis and synthesis of the human-induced changes and rehabilitation measures. These differences are probably significant for our knowledge today, which is patchy in both space and depth.

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LAGOONS AND COASTAL WETLANDS

Broad-scale modelling of coastal wetlands: what is required?

Loraine McFadden · Tom Spencer · Robert J. Nicholls

Abstract A Wetland Change Model has been developed to identify the vulnerability of coastal wetlands at broad spatial (regional to global (mean spatial resolution of 85 km)) and temporal scales (modelling period of 100 years). The model provides a dynamic and integrated assessment of wetland loss, and a means of estimating the transitions between different vegetated wetland types and open water under a range of scenarios of sea-level rise and changes in accommodation space from human intervention. This paper is an overview of key issues raised in the process of quantifying broad-scale vulnerabilities of coastal wetlands to forcing from sea-level rise discussing controlling factors of tidal range, sediment availability and accommodation space, identification of response lags and defining the threshold for wetland loss and transition.

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Introduction

Coastal zones are currently experiencing intense and sustained environmental pressures from a range of natural, semi-natural and anthropogenic drivers (Mitsch & Gosselink, 2000). Increased resource use, environmental protection and the incorporation of social and equity issues into decision-making must evolve in the context of physical and ecological systems which show multi-scale dynamics and considerable uncertainties in likely response to near future environmental change (Poff et al., 2002; Morris et al., 2002). Both short-term and geological records show that coastal wetlands are particularly sensitive to change within the coastal zone (Allen, 2000; Schwimmer & Pizzuto, 2000; French & Spencer, 2002). Given such sensitivities, changes in wetland extent, position and type can be expected as accelerated sea-level rise increases forcing on wetland systems. Specific wetland loss mechanisms may include a range of natural processes, including edge erosion and retreat; internal dissection by the expansion of creek networks and surface ponds; changes in inundation frequency, waterlogging and in situ vegetative and root decay, and also human modification of marsh topography, sedimentology, ecology and hydrology (Mendelssohn & Morris, 2000). Within these contexts, this paper presents a new broad-scale wetland model which focusses upon the impact of relative sea-level rise on wetlands within the coastal zone.

Improving on earlier broad-scale assessments of wetland vulnerability (Hoozemans et al., 1993; Nicholls et al., 1999) and underpinned by a greatly improved global wetlands database (Vafeidis et al., 2004), the Wetland Change Model (i) provides a dynamic and integrated assessment of regional to global patterns of coastal wetland vulnerability and wetland loss; (ii) determines the ecological sensitivity of different wetland types to environmental forcing and the likelihood of transition to other wetland types and (iii) permits the assessment of the relative importance of sea-level rise, sediment supply and coastal protection measures in affecting wetland vulnerability. This model represents one module within the DIVA integrated assessment model for coastal areas (Dynamic Interactive Vulnerability Assessment)—developed within the EU-funded DINAS-COAST Project (Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-Level Rise, www.dinas-coast.net). The DIVA tool has been designed to assess impact and vulnerability of the coastal zone to sea-level rise at regional to global scales and is driven by a set of internally consistent 'mid-term' (until 2100) scenarios of sea-level rise and socio-economic drivers of societal sensitivity to plausible impacts of accelerated sea-level rise and adaptive capacity (Hinkel & Klein, 2003). DIVA identifies coastal units that are particularly vulnerable to sea-level rise and adverse human interventions and allows for the evaluation of a range of response options (McFadden et al., in press).

Following the aim of the DINAS-COAST Project, the Wetland Change Model transforms a dynamic assessment of wetland vulnerability into patterns of wetland loss and transition. It seeks to capture the broad-scale response of wetlands to sea-level rise, integrating key drivers of wetland behaviour including human impacts such as dike construction or wetland nourishment (increasing sediment supply). This paper discusses key concepts raised in the process of modelling broad-scale wetland behaviour, underlining the problems of analysis at such spatial scales. Future developments are also considered, especially how this type of approach could be linked to other broad-scale monitoring efforts.

Broad-scale modelling of wetland behaviour

Modelling broad-scale wetland response to sea-level rise is important from a number of perspectives. In the first instance it strengthens our understanding of the mechanisms which control the behaviour of the wetland system as a large-scale unit within the physical landscape. Identifying 'hotspots' of wetland loss and a broad-scale assessment of levels of wetland vulnerability enables coastal managers and national organisations to make decisions on the best use of limited resources (Hammar-Klose & Thieler, 2001). Such modelling forms a basis from which effective plans can be developed to manage wetland change. In addition to this spatial dimension, broad-scale modelling is important to our understanding of long-term trajectories of future marsh behaviour. Important feedback mechanisms at longer-time scales (e.g. elevation/accretion relationships) mean that short-term measurements cannot be simply extrapolated to identify behavioural trends within a medium- to long-term temporal framework.

The Global Vulnerability Assessment (or GVA) and its subsequent revision provided the first worldwide estimate of both socio-economic and ecological implications of accelerated sea-level rise (Hoozemans et al., 1993; Nicholls et al., 1999). Based on a range of simple assumptions concerning rates of sea-level rise, subsidence and the response of the wetlands to sea-level forcing, the GVA gives a first-order perspective on wetland loss rates. However, the datasets have incomplete coverage, only three wetland types are considered, and wetland losses are only controlled by tidal range and accommodation space. While most calculations were conducted at a national scale, only results aggregated to a regional or global level could be considered valid (Nicholls et al., 1999).

Mass-balance models that focus on vertical adjustment of wetlands given accelerated sea-level rise have identified a number of controls on wetland response to environmental forcing factors: e.g. Severn Estuary, UK (Allen, 1990); North Norfolk coast, UK; Hut Marsh, Scolt Head Island (French, 1993); Venice Lagoon (Day et al., 1999); and wetlands of Louisiana, USA (Koch et al., 1990). Useful as these analyses are in defining the envelope of response, they only give a one-dimensional view of wetland-sea-level rise relations. Complex patterns of sedimentation mean that such models may not accurately represent the true sediment volumes required to enable such systems to keep pace with sea-level rise (French et al., 1995). Other studies have considered, and in some cases modelled, the landward retreat of saltmarshes under present, and expected near-future, rates of sea-level rise. Thus, for example, open coasts marshes in Essex, England (Harmsworth & Long, 1986; Reed, 1988), the marshes of the eastern Scheldt, Netherlands (Oenema & DeLaune, 1988) and salt marshes in the Gulf of Gabes, Tunisia (Oueslati, 1992) have provided a range of information on erosion and accretion along seaward marsh margins. In addition, it has been argued that floristically-rich upper marshes will disappear under the landward retreat of enclosing barriers (French, 1993). Most detailed studies of wetland loss of the type outlined above are typically local and relatively short-term in nature. Whilst such studies can be a useful means of calibration for broad-scale analysis, there is the significant problem of upscaling observations to the regional scale and longer time periods appropriate to modelling the broad-scale response of the system (Mitsch & Day, 2004). These problems have been addressed by the development of Landscape Simulation Models which are proving effective in assessing both the present and expected near-future distributions of wetland habitat types, taking into account both vertical and horizontal adjustments. Such models use hydrologic sub-models to distribute fluxes of water, nutrients and sediments over a grid of several thousand individual cells. Each cell incorporates a sub-model for plant production and soil formation which, alongside the hydrologic sub-model, determines the vegetation community. With changing environmental conditions, each cell is repeatedly interrogated by a ‘habitat switcher’ which resets the vegetation community if certain thresholds to inundation, soil chemistry and salinity are exceeded. Mapping expected environmental change in the Mississippi delta has been achieved in this way (Reyes et al., 2000; Martin et al., 2002). However, the computation effort required for this type of modelling approach precludes its current use as a widespread broad-scale tool for wetland analysis.

The Wetland Change Model presented within this paper seeks to engage with both levels of the current analysis of wetland performance identified above, identifying the key dynamics of wetland response emerging from small-scale analyses, and building a model which can then be tested, in part, against the modelling of changing wetland extent at the landscape scale. Fundamental to this characterisation is a conceptual model that defines the parameters that control wetland behaviour (Fig. 1). This paper examines the primary components of this conceptual model; in doing so, the challenges of broad-scale modelling are discussed.

Identifying environmental factors driving broad-scale wetland change

The DIVA Wetland Change Model, following earlier models, is based on the assumption that wetland response to external forcing such as sea-level rise involves both horizontal migration and vertical adjustment (Phillips, 1986; Nicholls et al., 1999; Allen, 2000). Vertical and horizontal changes may act independently of each other, but system behaviour must be considered as the synergistic response of both components. This integrated response of the system is modelled using three broad, yet critical, environmental forcing factors.

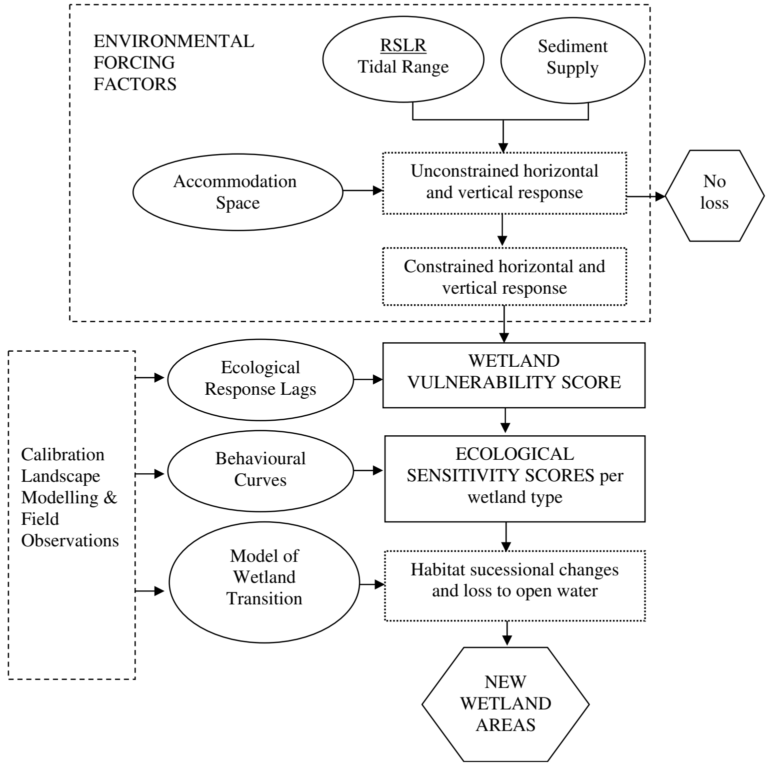

Fig. 1 Wetland Change Model

Ratio of relative sea-level rise to tidal range

A primary environmental forcing factor in driving vulnerability is the ratio of the rate of relative sea-level rise to tidal range. When sea-level rise is sudden and of high magnitude, as might result from sudden tectonic subsidence or high magnitude events such as tsunamis, a wetland may be completely submerged. Much more frequently, however, wetlands are subjected to slow rates of relative sea-level rise caused by eustatic factors and geological subsidence. Rather than submergence, the immediate impact of such gradual increases in sea level is a change in the nature of tidal flooding or hydroperiod (Reed, 1995). Hydroperiod is the cumulative inundation of surfaces due both to periodic flooding and to aperiodic tidal surge or high water levels associated with tidal surge or high river water flows and pulsed inputs of river sediments (Day et al., 1997). If wetlands are subject to a rise in relative sea-level without equal increases in elevation of the system, the duration and depth of tidal flooding will increase and communities can revert to a species composition typical of lower position in the tidal frame. In this situation tidal range is particularly significant in determining the vulnerability of the system to sea-level rise. It has been argued (Stevenson et al., 1986) that a wetland maintaining equilibrium under a large tidal range may have greater resilience towards the impacts of sea-level rise than a system existing within a narrower range of tidal fluctuation. As a result, modelling the combined impact of sea-level rise and tidal range is important in determining wetland response to sea-level forcing. Changes in storminess, direction of wave approach and tidal range are likely to accompany changes in mean sea level, but it is not possible to consider these effects in the current model framework.

Sediment supply

The long-term stability of coastal wetlands is also determined by the ability of wetland surfaces to maintain relative position in the tidal frame, thus keeping pace with the rate of sea-level rise (French, 1993). Regional trends in sediment supply are difficult to estimate due to their localised and highly variable temporal behaviour. There are often multiple sources of fine sediments (including riverine, cliff and offshore sources) on low-lying coasts and it is frequently difficult to isolate the contribution of particular sources, to assess the relative importance of local versus long-distance fine sediment transport and to differentiate between primary sediment supply and the re-mobilisation of previously transported sediments. In developed regions, human influences on the natural supply of sediment may significantly affect the response of wetlands over the long term. The submergence of Mississippi wetlands is partly due to the nature of catchment land management practices over the last 200 years that have reduced the supply of sediment to the inter-distributary bays. Similarly, more locally, coastal protection works often modify sediment transport pathways and sediment circulation systems.

A number of physical and human parameters are used within DIVA Wetland Change model to assess the impact of varying sediment supply on wetland vulnerability (Fig. 2). However, given the complexities of impact and response between sediment supply and wetland change, a comprehensive analysis of this forcing factor is not possible at the broad scale. A number of constraints on the model exist. Estimating the supply of a specific sediment type such as sand, mud, organic or inorganic, for example, cannot adequately be considered, so that only fine-grained sediment appropriate to the wetlands being studied can be assessed. Whilst it is clear that below-ground processes play an important role in coastal wetland stability (Nyman et al., 1995), the volume of sediment accreting on a wetland surface is the primary determinant of system response within the model. Sediment supply from in situ accumulation of organic sediments (Cahoon & Reed, 1995; Middleton & McKee, 2001; Rooth et al., 2003) or from external, inorganic inputs (French & Spencer, 1993; Christiansen et al., 2000) or a combination of the two, are used to characterise the impact of the environmental forcing factor within the DIVA model.

Accommodation space

The third driving factor is lateral accommodation space: given sufficient sediment supply to the system, this parameter is a key factor in determining the horizontal migration responses of wetlands. Coastal geomorphology has a major impact on accommodation space, where areas of high relief with steep coastal gradients reduce or remove the capacity for landward migration. Landward margins that have been fixed through coastal defence structures also effectively reduce the accommodation space, preventing horizontal migration.

Summary of environmental forcing factors

The Wetland Change Model combines environmental forcing on both horizontal and vertical response to give an assessment of the vulnerability of the total wetland area (Fig. 1). The model incorporates a number of physical (e.g. tidal range and sediment supply) and socio-economic forcing factors (e.g. removal of accommodation space by building seawalls and dikes). It is multi-dimensional in its characterisation of wetland vulnerability. It extends and refines the range of parameters that have been used in previous global assessments by taking account of all the main drivers of wetland change at broad scales. The model further builds on this characterisation by including a weighting component for each forcing

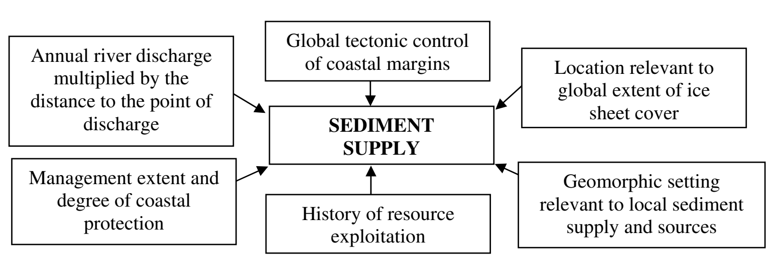

Fig. 2 Characterising sediment supply within the DIVA Wetland Change Model

Table 1 The global weighting component for the environmental forcing factors

Ratio of relative sea-level rise to tidal range	0.5
Sediment supply	0.3
Accommodation space	0.2

factor (Table 1). The relative weighting of the environmental forcing factors reflect the importance of the parameter and the confidence with which it can be estimated at the broad-scale. This weighting component facilitates a greater resolution of system variability, recognising that each environmental forcing factor may exert a variable influence on wetland response depending on regional conditions.

Wetland response timescales

The response of a wetland to environmental stresses is not necessarily immediate. Rather, it is likely to be due to a combination of current and previous ecological states. This time lag between a forcing event and its geomorphological and/or ecological expression is dependent on habitat type. As a key aspect of the behaviour of wetlands to sea-level forcing, it is important that appropriate wetland response timescales are considered within broad-scale analyses. Incorporating such ecological lag time within the Wetland Change Model involves two conceptual developments: (1) global coastal wetland typology and (2) establishing relative response times for each wetland type.

Geographic variation in vegetation zonation has traditionally been used to form the basis for coastal wetland classifications, generally for establishing resource inventories and the identification of sites of particular conservation value. The refinement of this approach has been to use numerical techniques to establish differences in habitat type, e.g. on Argentinean marshes (Cantero et al., 1998) and on the Mississippi River deltaic plain (Visser et al., 1998). Such arguments have to some extent been driven by the Clementsian theory of deterministic, unidirectional change in ecosystem development (Clements, 1916) where plants are the primary drivers in trapping and binding sediments in intertidal environments and through determining elevation change, further control plant succession (and see Chapman, 1959 for a saltmarsh example). However, it is now clear that this is only one model for coastal classification, largely restricted to low-lying coasts with abundant sediment supply. Broader classifications for coastal mangroves for instance, have identified multiple categories for mangrove forests (Woodroffe, 1990) where geomorphical setting and the process environment differentiate between types. Such broad findings are also supported by research on the morphodynamics of tidally-dominated saltmarshes (Reed & French, 2001). The key to a robust classification of coastal types is therefore to establish the physical contexts within which different wetland types are found. This means that for the assessment of wetland vulnerability, a morphological classification (Woodroffe, 2002) into wetland settings and their structural/physical characteristics is of more value. Taking this view, six broad wetland types were identified as the basis of transition and loss within the Wetland Change Model (Table 2).

Building on this classification, various response times associated with each wetland type were determined. Table 3 outlines the continuum of response times which define ecological lag effects within the model. Many saltmarsh plant species, for example, can tolerate a wide range of inundation frequencies (and the variations in physical

Table 2 The classification of wetland type used within the Wetland Change Model

1. Coastal forested wetlands
2. Freshwater marsh
3. Saltmarsh
4. Mangrove
5. Unvegetated sediment > mean high water springs (sabkas)
6. Unvegetated sediment < mean high water springs (mud and sand flats)

Table 3 Relative response lags within the Wetland Change Model

Coastal forested wetlands	Highest response lag
Mangrove	↑
Freshmarsh/Saltmarsh	
Unvegetated sediment	Lowest response lag

and chemical soil characteristics which accompany them) and can rapidly colonise a range of new tidal habitats. By comparison, coastal forest tolerances are typically lower and colonisation of new habitat is difficult. For this habitat type, response will be strongly influenced by previous conditions, until a threshold point is reached when the system may collapse catastrophically (Cahoon et al., 2003). The relative response times of each wetland type were based on expert judgement combined with field observations. Incorporating response lag into the model transforms the assessment of the vulnerability of the total wetland area into a value of the ecological sensitivity of the six wetland types to sea-level rise (Fig. 1).

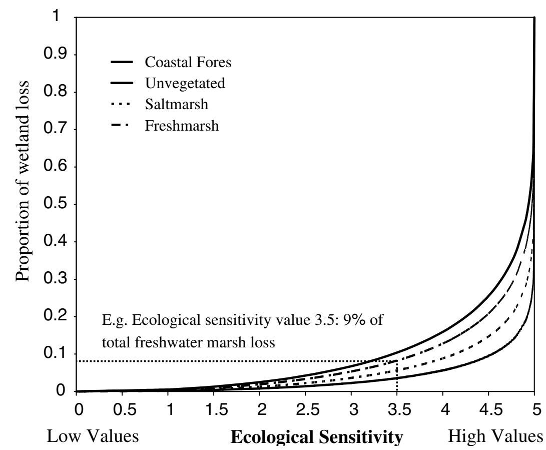

Fig. 3 Wetland loss, and wetland types as a proportion of total wetland loss, with changing wetland sensitivity (see text for explanation of ecological sensitivity)

Differentiation of wetland loss by wetland type

Existing large-scale models of wetland response to accelerated sea-level rise generally deal with the conversion of vegetated surfaces to open water and thus generate statistics on total loss of wetland area, e.g. GVA and subsequent revisions (Nicholls et al., 1999). Such models are most appropriate where local rates of relative sea-level rise are high, such as in subsiding, sediment-starved deltaic environments. However, under more moderate rates of sea-level rise and an adequate sediment supply ecosystem change may be (i) slower than predicted and (ii) involve change stepped across wetland types rather than simple loss, as ecological tolerances are exceeded in turn. The Wetland Change Model assesses both net wetland losses (due to conversion to open water) and transitions to other wetland types due to sea-level rise.

Linking the relative ecological sensitivities of wetland types to rates of wetland loss and transitions given sea-level rise requires (i) the construction of a series of wetland response curves (Fig. 3) which define the behaviour of the system by modelling the proportion of wetland expected to convert to another type given increasing exposure of a region to sea-level rise; and (ii) a model of wetland transition where loss is distributed between the wetland transitional types (Fig. 4).

Given the lack of information on broad-scale wetland behaviour, in the first instance both the wetland response curves and the transitional model were based on provisional estimates of wetland loss derived from expert judgement. Two primary datasets were used for calibration: (i) forecasting of changing wetland and open water areas in the Barataria and Terrebonne basins of South East Louisiana, USA from a basis of historical data collected by the United States Fisheries and Wildlife Service (USFWS) (D.J. Reed, pers. comm., 2003) and (ii) predictions of wetland type transitions produced by large-scale landscape modelling in the same region (Reyes et al., 2000). The Reyes model was initialised with the 1956 USFWS habitat map for the two basins and the results of a 32-year simulation compared against the 1988 map of the region (Reyes et al., 2000). Simulated maps showed a goodness-of-fit of 75% using a multiple resolution fit algorithm. The model was then run to the year 2018 under a range of scenarios.

The rate of increase in open water is a useful and readily definable summary measure of wetland loss. Table 4 shows the increase in the proportion of open water for the period 2000–2060 for four US Gulf Coast administrative units, calculated within the DIVA Wetland Change Model using the highest level of modelled sea-level forcing (1.07 m, 1990–2100) available from

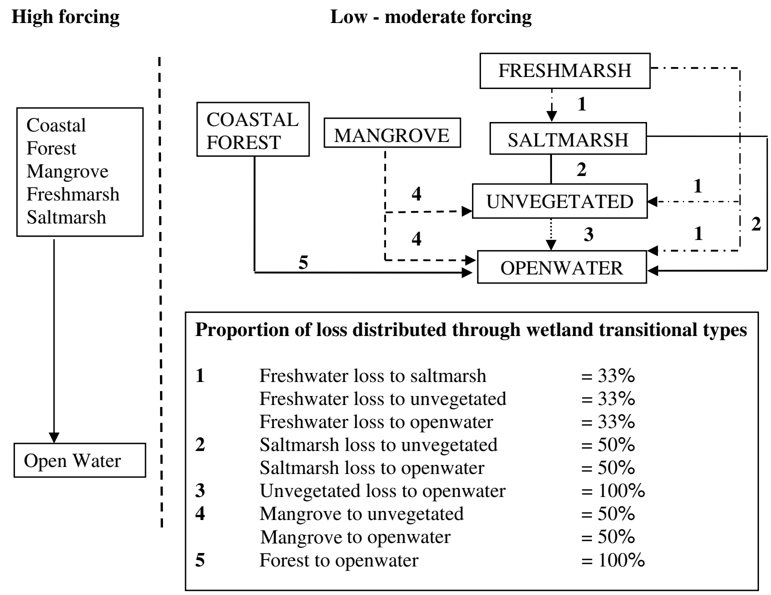

Fig. 4 Wetland loss and transitions between wetland types, to open water under sea-level rise: the Wetland Change Model

the Model. These data compare well with Reed's predictions of changes in the extent of open water in the Barataria and Terrebonne basins, with a similar timeframe and sea-level rise scenario.

The role of landscape modelling outputs (Reyes et al., 2000) within the DIVA calibration was two-fold. In the first instance, the results were used as a guide to the relative positions of the response curves within the envelope of vegetated wetland (Fig. 3). Outputs from the model were re-classified into the DINAS-COAST typology (Fig. 5) and basic trends in wetland loss were identified: the increase in open water at the expense of freshwater/brackish marsh and saltmarsh and the greater sensitivity of fresh marsh to sea-level forcing than saltmarsh within the basins. Less expected was the resilience of coastal forest which some authors (e.g. Conner & Day, 1988) have suggested might disappear from the Mississippi delta altogether, with continuous flooding preventing seedling establishment.

The landscape modelling data also provides some calibration of the point at which the model of wetland transition changes from gradual transition between types to complete submergence (Fig. 4). With lower forcing, transitions to other wetland types reflect gradual changes as salinity levels increase and environmental thresholds are crossed. At the present time, the model distributes wetland loss in equal proportions through the

Table 4 DIVA predictions of wetland conversion to open water in 4 US Gulf Coast States compared with predicted wetland/open water transition data for two basins in the Mississippi Delta (from Reed, pers. comm., 2003)

	DIVA Wetland Change Model parameters				Reed (pers. comm., 2003)	
	DIVA Administrative Units (Digital Chart of the World, ESRI, 2002)				Barataria	Terrebonne
	Texas	Louisiana	Alabama	Florida		
Coastal slope	Low forcing	Low forcing	Low forcing	Low forcing		
Tidal range	Low forcing	Low forcing	Low forcing	Low forcing		
Sediment supply	Moderate–high forcing	Moderate–high forcing	Moderate–high forcing	Moderate–high forcing		
Increase in open water 2000–2060	37%	26%	26%	32%	35%	23%

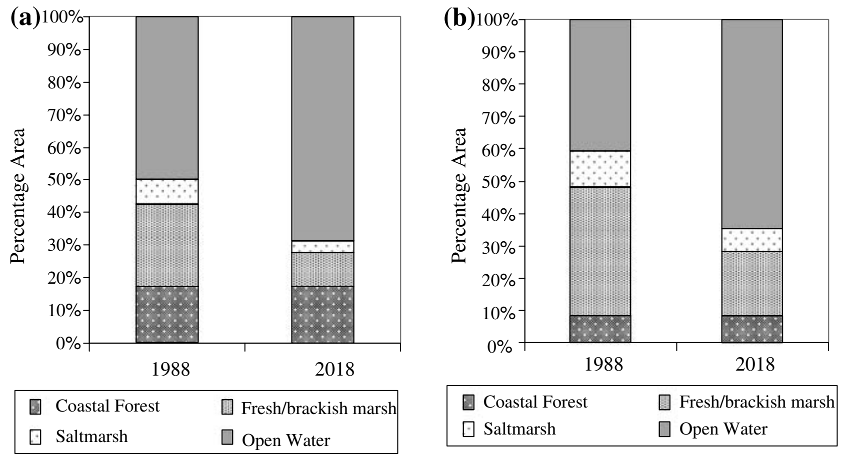

Fig. 5 Model outputs from Reyes et al. (2000) for the Barataria (a) and Terrebonne (b) basins, Mississippi delta, re-classified into the DINAS-COAST wetland typology

successive wetland types. However, under high levels of environmental forcing (high sea-level rise, low sediment supply and construction of barriers to horizontal wetland migration), the model converts all wetland losses to open water. The potential of the DIVA Wetland Change Model can be illustrated by the application of the model to another of the US Gulf Coast administrative units, the State of Florida (Fig. 6). The Model predicts an increase in open water from 2% in 2000 to 33% in 2060, largely at the expense of tidal flat environments but with some loss of saltmarsh and freshwater marsh. The resilience of coastal forest should be noted and that of mangrove forest, although as sea-level rise accelerates so mangrove areas begin to decrease.

The results from the DIVA Wetland Change Model appear commensurate with general estimates of global wetland losses given accelerated near-future sea-level rise. Nicholls et al. (1999), for example, have estimated that 22% of the world's wetlands could be lost by 2080 given a rise in global sea level of 38 cm. Table 5 shows the predicted loss of global wetlands over the time period 2000–2080 with low forcing scores for sediment supply and accommodation space under two sea-level rise scenarios. Although the model can predict regional to global vulnerability, a number of challenges remain, particularly when downscaling to regions where local effects may over-ride broad-scale controls. The development of more systematic national to regional scale assessments of wetland loss would further refine these estimates by contributing significantly to calibrating broad-scale models of the type presented here.

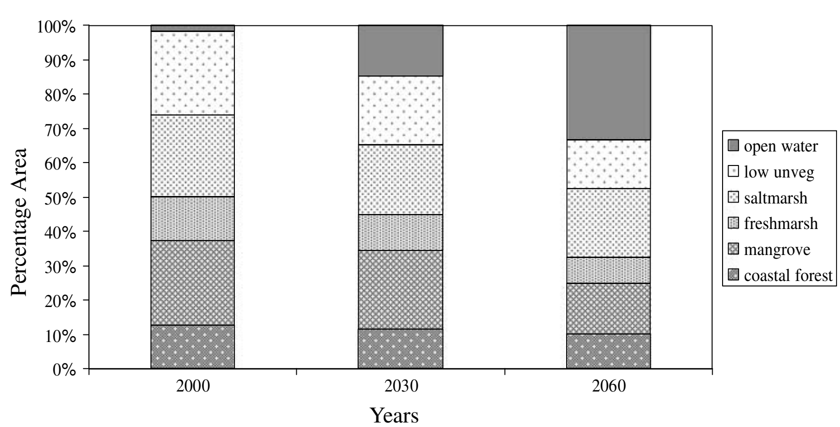

Fig. 6 Scenario of predicted wetland transitions 2000–2060 within the State of Florida, USA as predicted by the DIVA Wetland Change Model