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Predicting Sea-Level Rise and Infrastructure Effects on Coastal Wetlands

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Abstract

Climate change predictions for Australia include an accelerated sea-level rise, which challenges the survival of estuarine wetlands. Furthermore, coastal infrastructure poses an additional constraint on the adaptive capacity of these ecosystems. This paper presents results of wetland evolution based on hydroperiod and inundation depth experienced by vegetation, and computed using a hydrodynamic model. The application simulates the long-term evolution of a wetland on the Hunter Estuary heavily constricted by infrastructure that is undergoing the effects of predicted accelerated sea-level rise. The wetland presents a vegetation zonation sequence mudflats - mangrove - saltmarsh from the seaward margin, but is also affected by compartmentalization due to internal road embankments and culverts that effectively attenuates tidal inputs. Results of the model show that flow attenuation can play a major role in wetland hydrodynamics and that its effects can increase wetland vulnerability under climate change scenarios, particularly in situations where existing infrastructure affects the flow.

1. INTRODUCTION

Models of vegetation evolution on coastal wetlands responding to expected sea-level rise scenarios are common in landscape simulation studies and coastal management plans (Kirwan & Megonigal, 2013). These modelling tools consider that wetland vegetation depends on the prevailing hydrodynamic conditions based on empirical evidence collected both on saltmarsh (Morris et al., 2002) and mangrove studies (Crase et al., 2013). Accordingly, vegetation will establish itself and migrate landwards following the rising water levels. Some models consider that geomorphology will also be affected by these changes, with increased flow promoting erosion on tidal channels, and vegetation producing soil accretion on the tidal flats.

Vegetation preference to hydrodynamic conditions has been described as a function of local values of depth below mean high tide (D), tidal range, hydroperiod or elevation with respect to the tidal frame (D'Alpaos et al., 2007; Kirwan et al., 2010). Most of the relationships are site-specific and often times obtained via simplifications or proxies, so generalizations and extensions of the models outside of their validated domain generate great uncertainty. In addition, the hydrodynamic simulation of the flooding attenuation effects in current models is extremely simplified. A very common modelling simplification is to neglect flow attenuation mechanisms altogether by assuming that the water levels at a given time are the same over the entire wetland. Vegetation roughness in tidal flats reduces depth and maximum inundation extent but increases ponding, so it affects both inundation depth and hydroperiod. Local man-made flow restrictions in tidal flats and channels also contribute to flood attenuation in a similar way. Hydrodynamic attenuation effects due to levies, culverts and other man-made tidal modifications have not been considered in previous models.

2. METHODS

The simulation approach presented herein couples a hydrodynamic model with vegetation rules based on preference to hydrodynamic conditions (Rodríguez et al., 2017). It also includes soil accretion in vegetated areas for the long-term simulations. The hydrodynamic model solves the flow equations of continuity and momentum or energy at every point in the wetland to provide a continuous simulation of water levels. The model incorporates attenuation effects due to vegetation resistance using Manning's n coefficient, and due to man-made restrictions using discharge coefficients β. It then uses the time series of local water levels to compute inundation depths and hydroperiods required by the vegetation rules.

Vegetation establishment rules are defined based on spring tide conditions when inundation is more extreme. Hypoxia limits establishment for saltmarsh that has a typical height of 30 cm, so a maximum threshold value of 30 cm is set for D. For mangrove, a suitable hydroperiod range from 0.1 to 0.5 is defined given by limitations on oxygen availability and accumulation of phytotoxins in soils, which was selected based on data from our site and also from Crase et al. (2013). For long-term simulations in which vegetation is allowed to change and evolve, once the vegetation cover is determined by the rules a new run of the hydrodynamic model is performed on the modified domain.

3. RESULTS

3.1. Simulation of the initial vegetation distribution

The sub-tropical coastal wetland located in the Hunter estuary of SE Australia presented in Fig. 1a,b is used as a case study. The wetland flow is heavily controlled by infrastructure, which includes 10 active culverts and bridges over an area of 1.2 km2. Vegetation comprises mudflats, tidal pools, *A. marina* mangroves, *S. virginicus – S. quinqueflora* mixed saltmarsh and some remnants of pasture on the periphery (Fig. 1c). Values of n for the different substrates and of β for the culverts were obtained by calibration using measurements of water levels in several points in the wetland. Roughness n values of 0.3 and 0.5 were selected for unvegetated and vegetated substrates, respectively; n values of 0.035 were selected for channels and β was set at 0.8.

Results of the model are compared to an approach that does not consider flow attenuation in Figs 1d,e,f (full attenuation effects) and Figs 1g,h,I (no attenuation effects). Both simulations use as tidal input the 2004 hourly tidal records at a nearby gauging station.

The approach without considering the attenuation effects of infrastructure and vegetation is unable to reproduce the initial vegetation distribution. The new approach presented in this paper correctly predicts mangrove and saltmarsh extent.

3.2. Predictions under sea-level rise

In order to assess sea level rise effects, continuous simulations for 60 years are run with both models (Figs. 2 and 3). A 2 mm/year of wetland surface elevation gain is incorporated, due to the capability of vegetation communities to build up their own soil by trapping sediments or by accumulating organic matter (Howe et al., 2009). A sea-level rise rate of 8 mm/year is considered, which corresponds to the to the IPCC AR5 PCP8.5 scenario. This increase on water levels is added on an annual basis to the same 2004 hourly tidal records used in 3.1.

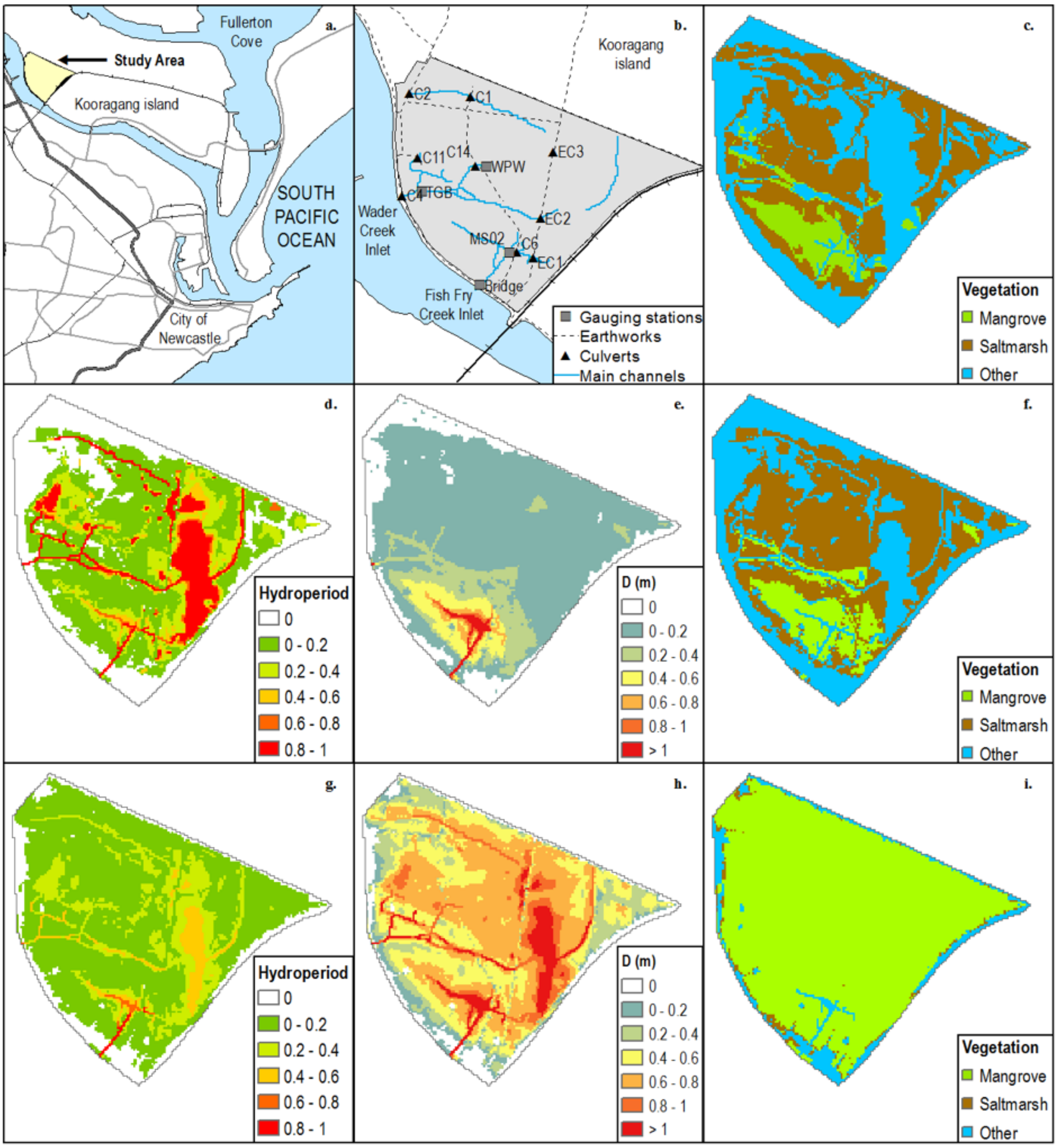

Figure 1 – Modelling initial conditions in a sub-tropical tidal wetland.

The model without attenuation effects predicts an initial vegetation distribution over most of the wetland dominated by mangrove (Fig 1i), with subsequent changes in hydroperiod and D that are gradual and follow the net difference between sea-level rise and accretion. That gradual change during the first 20 years produces conditions for mangrove establishment that squeezes saltmarsh into the high elevation areas (Fig.2c). After 40 years some mangrove areas in the lowest parts of the wetlands start to transition into mudflats and tidal pools due to increasing hydroperiods (Figs 2g-i).

When attenuation effects are considered the long term wetland evolution is totally different (Fig.3). Attenuation causes the uncoupling of the values of hydroperiod and D, which are noticeably correlated when the no attenuation approach is used.

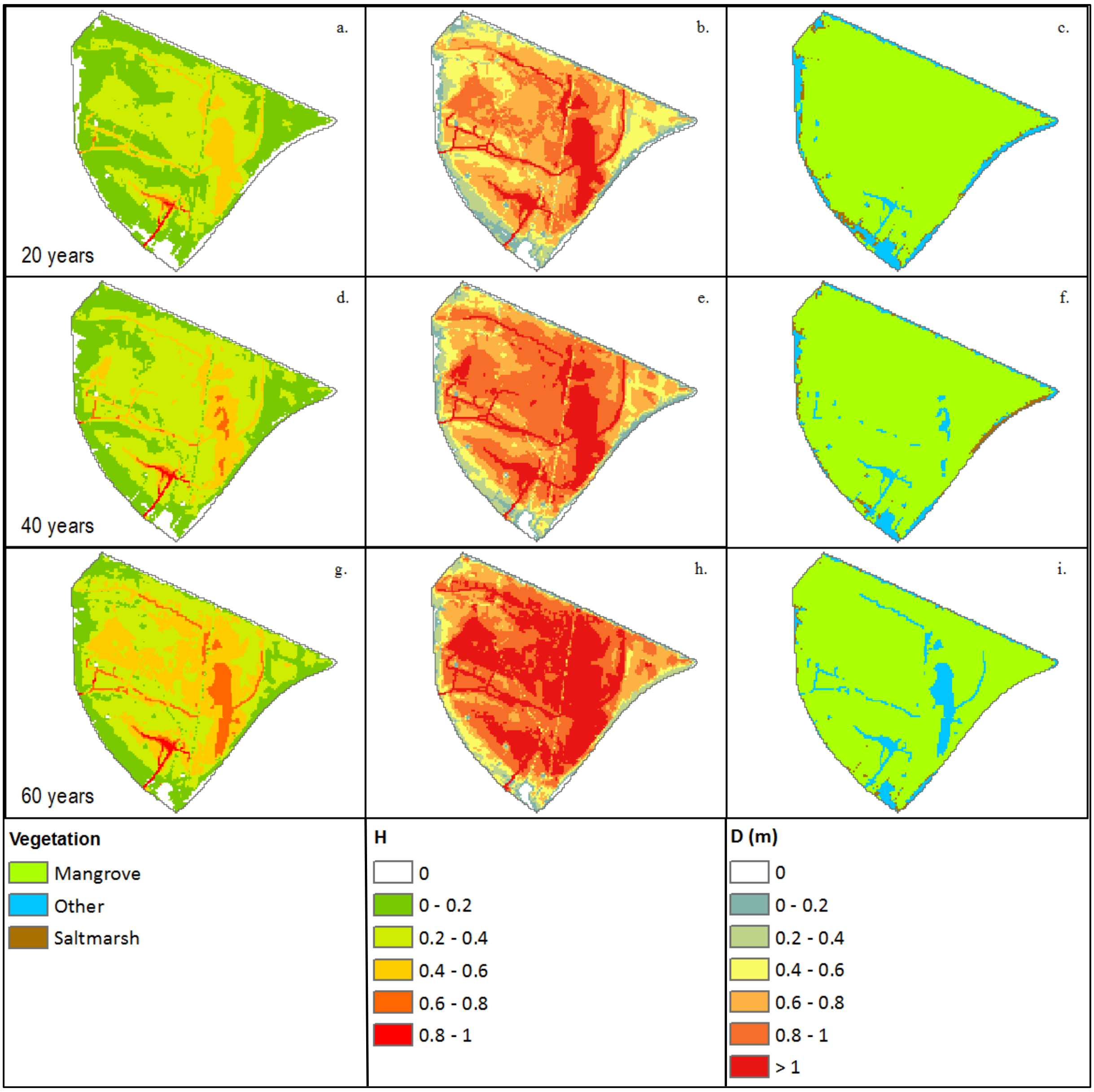

Figure 2 – Predictions without infrastructure and vegetation effects.

As a result of sea level rise, mangrove is adversely affected by the increasing hydroperiods, while saltmarsh is displaced by mangrove and by the increasing depths. During the first 20 years there is a minor migration to higher ground in both mangrove and saltmarsh communities as a result of increasing depths and hydroperiods (Fig 3a,b,c), which compensates vegetation losses due to the increase in the size of tidal pools. The next two snapshots at 40 and 60 years show more pronounced vegetation losses due to an increase in permanently inundated areas that have long hydroperiods (Fig 3e,h) and are also becoming deeper (Fig.3d,g). The distribution of vegetation consists of mangroves fringing a large central tidal pool with remnant saltmarsh on the periphery, which agrees with the typical pattern observed in sub-tropical wetlands. After 60 years the wetland area has been reduced to ½ of the original extent, a major feature that was not captured by the previous model.

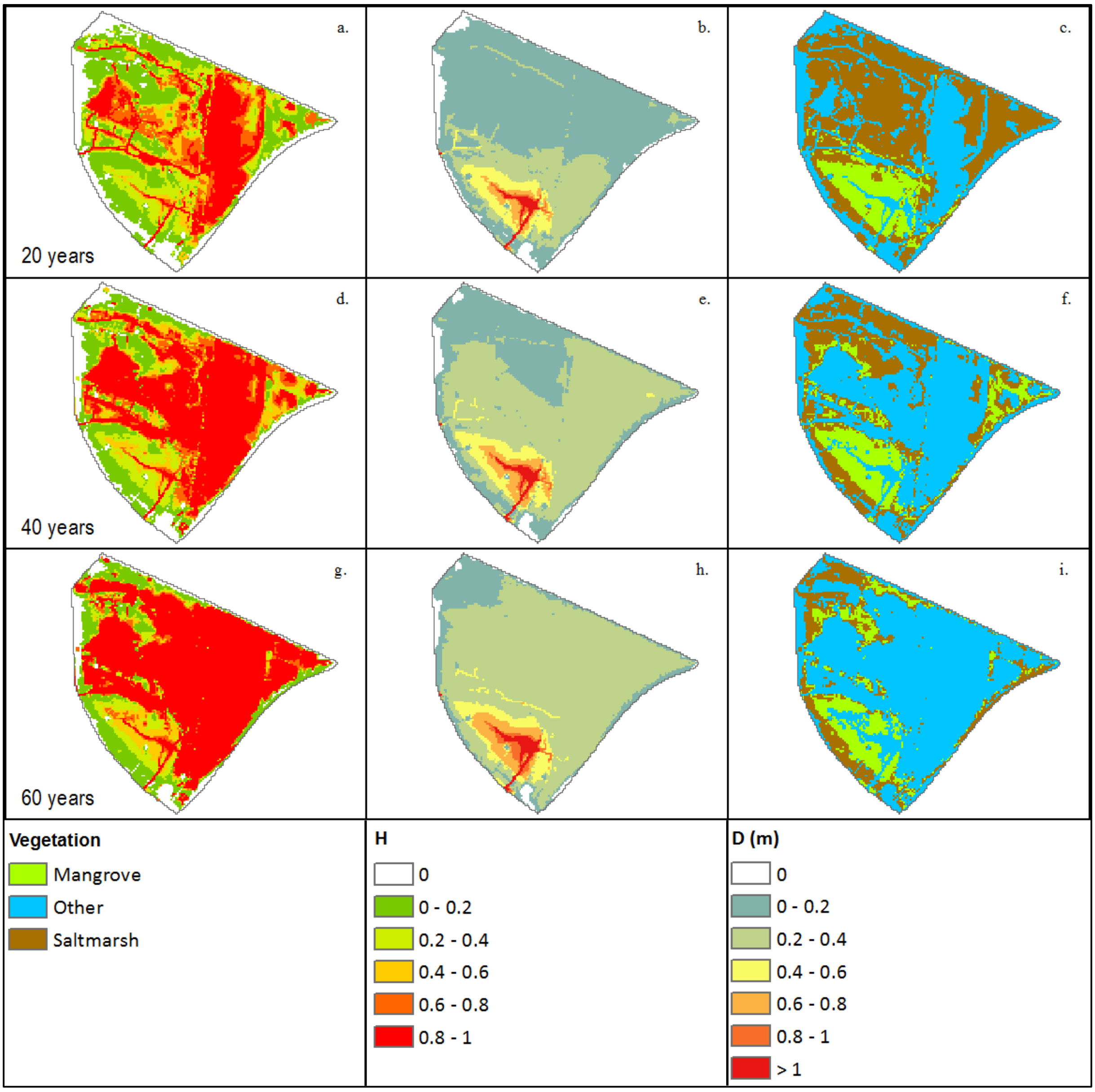

Figure 3 – Predictions with infrastructure and vegetation effects.

4. CONCLUSIONS

This paper shows an important underestimation of sea-level rise impacts predicted by commonly-used models on coastal wetlands when applied to systems with man-made flow restrictions. The reason for the underestimation is that flow attenuation effects due to vegetation, culverts, levies and bridges that distort the tidal wave are not considered.

Those attenuated flow conditions are captured, in terms of depth below mean high tide and hydroperiod, using a hydrodynamic model and are combined with vegetation establishment rules based on those hydrodynamic variables. Application of the new model to predict the observed vegetation distribution in a wetland in Australia with flow restrictions produced a remarkably good agreement, as opposed to the results of a simulation without considering flow attenuation.

Long term projections of sea-level rise considering attenuation effects show a much higher rate of wetland loss than previous estimates based on predictions of commonly-used models that do not consider attenuation effects. These results also have important implications for worldwide estimates of wetland loss under sea-level rise.

5. ACKNOWLEDGMENTS

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