Global and Planetary Change 92–93 (2012) 267–274

Contents lists available at SciVerse ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Coastal marsh die-off and reduced attenuation of coastal floods: A model analysis

Stijn Temmerman [a,*], Mindert B. De Vries [b], Tjeerd J. Bouma [c]

[a] Ecosystem Management Research Group, Department of Biology, University of Antwerp, Universiteitsplein 1, 2610 Antwerp, Belgium
[b] Deltares Delft Hydraulics, Rotterdamseweg 185, 2629 HD Delft, The Netherlands
[c] Royal Netherlands Institute for Sea Research (NIOZ Yerseke), POB 140, 4400 AC Yerseke, The Netherlands

ARTICLE INFO

Article history:
Received 24 October 2011
Accepted 5 June 2012
Available online 13 June 2012

Keywords:
coastal flooding
flood mitigation
salt marshes
ecosystem services
storm surge
sea level rise

ABSTRACT

Global climate change is expected to increase the risks of coastal flood disasters due to accelerating sea level rise and increasing intensity and frequency of storm surges. Coastal marsh vegetation is considered, on the one hand, to increase resistance to a landward propagating flood wave, such as a storm surge, and hence to protect against flood disasters. On the other hand, coastal marsh vegetation is dying off at several places around the world due to accelerating sea level rise. Here we present hydrodynamic model simulations of flood attenuation by a tidal marsh, with particular focus on the effects of spatial patterns of vegetation die-off. It is shown that a same percentage of marsh die-off but occurring as different spatial patterns of marsh break-up has largely different effects on flood attenuation. Patches of die-off that are directly connected to tidal channels have a much greater effect on increased landward flood propagation, while a same percentage of marsh die-off, but occurring at inner marsh locations disconnected from tidal channels, has only a minor effect. This implies that a random pattern of up to 50% of marsh die-off still provides a considerable flood attenuating effect. However with increasing percentage of random marsh die-off the flood attenuating effect decreases exponentially, since the chance for vegetation die-off occurring directly adjacent to tidal channels increases. This study demonstrates that tidal marsh die-off, which may increase with ongoing global change, is expected to have non-linear effects on reduced coastal protection against flood waves.

1. Introduction

Global climate change is expected to increase the risks and impact of coastal flooding in the coming century, through accelerating sea level rise (Meehl et al., 2005; Jevrejeva et al., 2010), increasing frequency and intensity of storm surges (Emanuel, 2005; Webster et al., 2005), and growing coastal populations (Nicholls and Cazenave, 2010). Today an estimated 10 million people experience coastal flooding each year, and this number could increase to 50 million by 2080 due to global change (Nicholls, 2004). Hence there is an urgent need for sustainable strategies to cope with the growing risks of coastal flooding.

Coastal wetland ecosystems, such as tidal marshes and mangroves, are increasingly identified as natural protective barriers against coastal flooding: their dense vegetations increase resistance to a landward propagating flood wave and hence reduce inland flood water levels (e.g., Costanza et al., 2008; Das and Vincent, 2009; Krauss et al., 2009; Wamsley et al., 2010). Vast areas of tidal marshes and mangroves naturally occur along low-lying coasts and in large deltas, which are exactly those places in the world that are most vulnerable to coastal flooding (Nicholls and Cazenave, 2010).

Human and natural pressure has led, however, to rapid global-scale degradation and loss of tidal marshes (ca. 50%) and mangrove ecosystems (ca. 35%) over the past two to three decades (Alongi, 2002; Millennium Ecosystem Assessment, 2005). Large-scale die-off of marsh vegetation may occur, with conversion into bare tidal flats or shallow water, as a consequence of processes such as marsh submergence by sea level rise (Baumann et al., 1984; Kearney et al., 2002; Marani et al., 2007; Kirwan et al., 2010) and herbivore grazing (e.g., Silliman et al., 2005). Hence the large-scale die-off of marsh vegetation may result in a drastic decrease of the protection provided by tidal marshes against coastal flooding. For that reason, extensive marsh conservation and restoration programs were proposed recently. For example, in the wake of the devastating hurricane Katrina surge that flooded New Orleans in 2005, about 2 billion U.S.$ have been nominated to restore 1000 s of acres of tidal marshes that previously submerged in the Mississippi deltaic area, with the intention to attenuate the landward propagation of storm surges caused by the passage of tropical cyclones (Stokstad, 2005; Day et al., 2007).

Despite such plans, remarkably little scientific knowledge exists on the relationships between tidal marsh characteristics, such as the degree of marsh die-off, and their effects on the attenuation of a landward propagating flood wave. This lack of knowledge is largely attributed to the scarcity and heterogeneity of field measurements of extreme flood water levels within and behind large tidal wetlands. The relatively few field data that exist display a wide range of flood

* Corresponding author.
E-mail address: stijn.temmerman@ua.ac.be (S. Temmerman).

0921-8181/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.gloplacha.2012.06.001

attenuation rates, ranging from about 4 to 25 cm of flood level reduction per kilometer of tidal wetland (Lovelace, 1994; Krauss et al., 2009; Wamsley et al., 2010). This wide range suggests that the extent of flood level reduction is highly variable between specific wetland locations and between specific flood events.

Hydrodynamic modeling studies have recently enlarged our insights on the mitigating effect of coastal marshes on extreme floods during storm surges. Especially storm surge simulations for the U.S. Gulf coastal area, which were performed after the hurricane Katrina surge (2005), have demonstrated that enhanced friction by coastal marshes can slow down the landward propagation of storm surges, which increases peak water levels seaward of the marsh, and reduces peak water levels landward at rates that are within the values reported from observations (e.g., Resio and Westerink, 2008; Westerink et al., 2008; Wamsley et al., 2009). Model simulations further revealed that the attenuation rate is not constant but may strongly vary, depending on the specific geometry and bathymetry of the coastal zone, and on the intensity, duration, and track of the storm forcing (Wamsley et al., 2010). Moderate storm surges (with peak water depth 2 to 3 m above the marshes) are most effectively attenuated by coastal marshes, while extremely high storm surges (5 m and more) that continue longer may be so overwhelming that coastal marshes have a relatively smaller attenuating effect (Loder et al., 2009; Wamsley et al., 2010). Simulations further demonstrated that the attenuating effect decreases when degradation of coastal marsh vegetation is simulated (by using lower friction values), when a higher bed elevation in the coastal marsh zone is applied, and when straight wide channels are considered within the marsh (Loder et al., 2009; Wamsley et al., 2009, 2010).

While these modeling studies emphasized on simulating the physical processes that generate a storm surge for large coastal landscape settings (e.g., Loder et al., 2009; Wamsley et al., 2009, 2010), their maximum grid resolutions of approximately 200 m was too rough to account for the spatial complexity of vegetation patterns that are typical for tidal marshes. As a consequence vegetation die-off was simulated in the storm surge models as rather spatially homogenous over larger marsh areas (Wamsley et al., 2009), while field observations show that vegetation die-off is typically occurring on specific localized portions of the marsh platform, resulting in a heterogeneous break-up of the marsh vegetation by gradual emergence of bare patches (e.g., Kearney et al., 2002; Kearney and Rogers, 2010). Furthermore, vegetation die-off is generally considered to result in a local reduction of sediment deposition or even bed erosion, leading in the longer term to a decrease of the local bed elevation relative to rising sea level (e.g., Morris et al., 2002; Marani et al., 2007; Kirwan et al., 2010). In the present study we specifically address the high-resolution (20 m) effects of spatial patterns of vegetation die-off, with and without the combination of bed lowering, on the rate of flood attenuation.

Our choice for a high-resolution hydrodynamic model approach implied to simplify the hydrodynamic forcing, by simulating the propagation of an externally-forced sinusoidal flood wave over a tidal marsh. Hence it is not our intention to include the simulation of storm surge formation at the open ocean off-shore from coastal marshes, which would necessitate to include complex effects of wind friction, wave piling, and atmospheric pressure setup in generating the storm surge (e.g., Resio and Westerink, 2008; Westerink et al., 2008). An externally-applied flood wave, as simulated in the present study, can be considered as a reasonable approximation when focusing on high-resolution effects of spatial patterns of vegetation die-off on flood attenuation, as wind friction, wave piling, and atmospheric pressure setup are expected to have little effect once the flood wave travels through a tidal marsh.

As a first objective, we study the effect of different percentages of vegetation die-off, occurring as different spatial patterns of marsh break-up, on the amount of flood wave attenuation. As a second objective, we investigate the combined effect of patterns of vegetation die-off and local sediment bed lowering on flood wave attenuation. These two objectives are addressed by hydrodynamic model simulations of flood propagation through a tidal marsh.

2. Methods

2.1. Brief model description

Flood wave propagation through a tidal marsh was simulated using the DELFT3D-FLOW model. This hydrodynamic model computes flow characteristics, such as flow velocities and water level changes, over a two- or three-dimensional finite difference grid, based on the Shallow-Water equations (Hydraulics, 2003; Lesser et al., 2004). In previous studies the model has been calibrated and validated against field data on tidal water level changes and flow velocities in a Dutch tidal salt marsh (Temmerman et al., 2005, 2007). In the present study the model was applied in two-dimensional (2D) mode, in accordance with previous modeling studies assuming that three-dimensional effects on flood propagation through tidal marshes are of minor importance (Loder et al., 2009; Wamsley et al., 2009, 2010). When applied in 2D mode, friction is simulated using a roughness coefficient that is considered here to be representative for friction exerted by both the sediment bed surface and by the vegetation canopy. A Chezy-type roughness formulation is used, with the Chezy roughness coefficient, C, defined as $C = H^{1/6}.n^{-1}$, where H = water depth [m] and n = the Manning roughness coefficient [$m^{-1/3}.s$]. Hence the used friction factor is dependent on water depth and on a predefined Manning n-value, as in previous models for storm surge propagation through coastal marshes (Loder et al., 2009; Wamsley et al., 2009, 2010).

2.2. Model implementation

We performed simulations of flood wave propagation over a rectangular grid representing an idealized coastal zone of 2 km alongshore length and 200 km cross-shore length, of which 20 km of tidal marsh and 180 km of off-shore coastal zone (Fig. 1). The large off-shore zone was included in order to allow the simulation of inertia effects on the piling up of water levels against the seaward edge of the marsh zone, which was found to be a significant process in previous modeling studies of storm surge propagation over tidal marshes (Loder et al., 2009; Wamsley et al., 2009, 2010). Horizontal grid cells were 20 × 20 m within the marsh zone, while gradually larger grid cells (up to 1000 × 20 m) were used in off-shore direction. A time-step of three seconds was applied.

The off-shore bathymetry was schematized as a regular off-shore slope of 1:1000 (Fig. 1), in accordance with recent simulations (Loder et al., 2009) that were designed to be representative for storm surge mitigation by coastal marshes in Louisiana. The marsh zone was defined as a flat platform dissected by a branched network of tidal channels (Fig. 1A). The marsh platform had an elevation of 0.5 m above mean sea level (similar to Loder et al. (2009)). At the seaward marsh edge there is a step-change in elevation of 0.5 m (Fig. 1B), which is typically found at the transition from mature tidal marshes to the non-vegetated intertidal or subtidal zone (e.g., Fagherazzi et al., 2006). The channel network was extracted from aerial pictures from a Dutch salt marsh (Fig. 1A), and reveals a dendritic channel network that may be considered as typical for non-degraded tidal marshes (e.g., Fagherazzi et al., 1999). Channels smaller than the width of a grid cell (i.e., 20 m) were not represented in the model. The bathymetry within the channels was defined as a concave length profile (Fig. 1B). Based on empirical observations and model simulations on tidal channel morphologies (see De Swart and Zimmerman (2009) for a review), both concave and convex length profiles may be found depending on factors such as tidal forcing. Hence, as mentioned also in the next paragraph, the effect of a concave versus convex channel length profile was simulated as one of the model scenarios. The