E-proceedings of the 36th IAHR World Congress
28 June – 3 July, 2015, The Hague, the Netherlands

STORM SURGE ATTENUATION IN A LARGE INTERTIDAL MARSH: IMPACT OF MARSH GEOMORPHOLOGY

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ABSTRACT

The potential of coastal wetlands to reduce flood risks is becoming more recognized, while studies on the quantification of storm surge attenuation in marshes are scarce. Here, in-situ water level observations in a tidal marsh as well as 2D hydrodynamic modeling are used to study the influence of marsh geomorphology on tidal propagation and storm surge attenuation for varying hydrodynamic boundary conditions in Saeftinghe, a 3000ha tidal marsh along the Western Scheldt estuary (SW Netherlands). Water level measurements, conducted at different locations in and around a 4 km long marsh channel during several spring-to-neap cycles and a severe storm surge, show that damping or amplification of tides within the marsh area depends on the height of the tidal wave compared to the marsh platform elevation. Undermarsh tides, with peak water levels below the platform elevation, are slightly amplified along the converging marsh channels. Overmarsh tides with peak water levels above the marsh platform are mainly attenuated, with maximum attenuation rates of up to 5cm/km along marsh channels for tides that inundate the platform by 0.5-1.0m. A hydrodynamic model is set up with TELEMAC-2D to assess a wider range of peak water levels and include simulations with variations in the marsh geomorphology. The effect of marsh vegetation is herein implemented by increased bed roughness. Model results indicate that tides are only attenuated if the channel depth and width are small and the extent of the marsh platform is large, while tides are slightly amplified if the channel depth and width are large and the influence of the platform is less. The model results confirm the dependency of flood wave damping or amplification on the peak water level relative to the marsh platform elevation for all scenarios. Finally, model simulations show that storm surge attenuation can be limited by the marsh storage area, due to blockage or reflection against levees or other man-made structures that surround the marsh area.

Keywords: *salt-marsh; geomorphology; tidal propagation; storm surge attenuation*

1. INTRODUCTION

Nowadays, coastal and estuarine wetlands are increasingly valued for their role in mitigation of flood risks. They have the potential to reduce the height of both wind waves and storm surges through additional flow resistance exerted by the wetland vegetation. Because of this potential, coastal wetlands are starting to be implemented as naturally sustainable coastal defense systems (Temmerman et al., 2013). This calls for a better understanding of flood level reduction by wetlands, including tidal marshes. Here we focus on the effect of variations in marsh geomorphology, including platform elevation and geometrical properties of the channels that dissect the marsh platform, on peak water level reduction in a tidal marsh.

Few field studies are available in which storm surge attenuation in coastal wetlands is reported for specific hurricane events (McIvor et al., 2012). Previously observed attenuation rates vary between 4cm/km and 25cm/km of peak water level reduction. Nevertheless, studies on the quantification of storm surge attenuation by wetlands for varying hydrodynamic conditions are to our knowledge non-existent. In addition, numerical modeling efforts on storm surge attenuation in coastal wetlands do mainly exist of hind-casts of hurricane events (e.g. Wamsley et al., 2010; Zhang et al.,2012), although some numerical modeling studies focus more on generating generic insights in the physical processes. Modeling studies have for instance shown that storm surge attenuation in marshes varies with geomorphological properties such as channel density, surface roughness, channel depth and platform elevation (e.g. Loder et al., 2009). However, the latter studies use rough idealized schematizations of marshes, instead of using a more realistic marsh topography and channel network. In this study, we use hydrodynamic modeling and in-situ water level observations in a large tidal marsh to study the influence of marsh geomorphology on tidal propagation and storm surge attenuation within the marsh area for varying hydrodynamic boundary conditions. The studied area is the '*Verdronken Land van Saeftinghe*', a 3000 ha brackish tidal marsh along the Western Scheldt estuary (SW Netherlands). Two-third of Saeftinghe consists of vegetated tidal marshes, while the remaining parts are unvegetated intertidal flats and channels dissecting the marsh platform. Water level observations in Saeftinghe are used to identify effects of variations in the hydrodynamic forcing or spatial variations in geomorphological characteristics on tidal and storm surge propagation through the marsh. A hydrodynamic model is then calibrated based on these water level measurements. This hydrodynamic model is used to assess the impact of geomorphology on tidal propagation and storm surge attenuation for realistic marsh morphology and channel networks.

2. OBSERVATIONS

In-situ water level measurements were conducted in and around a 4km long main channel in the Saeftinghe marsh at the locations shown in Figure 1. The measurements were used to quantify amplification and attenuation of peak water levels on the salt marsh scale for varying hydrodynamic conditions. The field measurements included several spring-to-neap cycles and a severe storm surge that induced peak water levels at tidal stations in the Western Scheldt estuary corresponding to a 1/8-1/20y^{-1} exceedance probability[i].

Our observations indicate that tides that do not inundate the marsh platform are slightly amplified along the converging salt marsh channels, while overmarsh tides with peak water levels above mean platform elevation are mainly damped. Depending on the height of the tide, observed attenuation rates reach a maximum of 4cm/km over the full 4km marsh transect (location 8 to 1) for tides that inundate the platform by 0.5-1.0m, while for lower or higher tides the attenuation rate decreases. Moreover, during the highest recorded storm tide with a peak water level of 1.8m above mean platform elevation, no attenuation was measured at all. Depending on the location within the marsh, attenuation rates reach maximum values of 2cm/km along outer marsh transects where the channel width ranges from 200m to 500m and the influence of the marsh platform is relatively small (between location 8 and 10). Along inner marsh transects where the channel width converges to about 4-8m and the extent of the platform is large, attenuation rates up to 5 cm/km are observed (from location 10 to 1 and 3). The highest attenuation rates of up to 70cm/km are found over relatively short distances of 50-100m on the vegetated marsh platform for tides that inundate the platform by ~0.3m, due to additional energy loss caused by the marsh vegetation (e.g. between locations 3 and 4; 3 and 5).

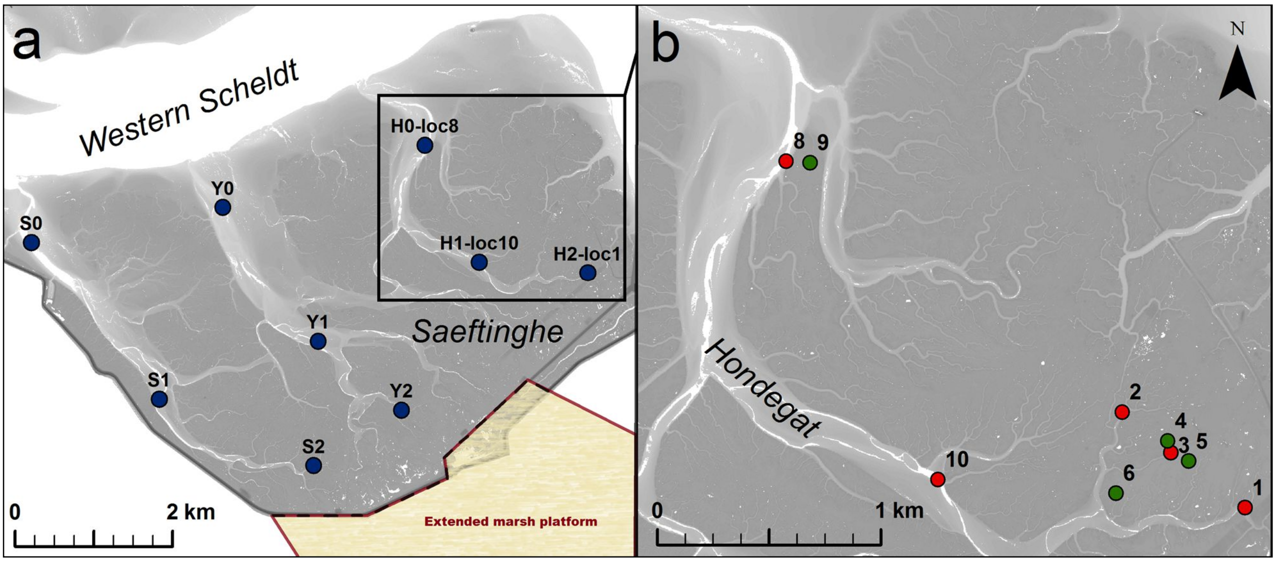

Figure 1. Study area in the Saeftinghe marsh showing (a) the locations of the transects used in the analysis of the model results and the platform area that is added in some simulations, and (b) the measurement locations of the water level observations in the intertidal channel system (red dots) and on the marsh platform (green dots).

3. NUMERICAL MODEL

A hydrodynamic model is set up for the Scheldt estuary and adjacent intertidal area of Saeftinghe with TELEMAC-2D, a two-dimensional model that solves the depth-averaged Navier-Stokes equations for continuity and momentum simultaneously (Hervouet, 2007). The model comprises the entire Scheldt estuary from its mouth at the North Sea up to its most upstream tidal reaches and tidal tributaries. The estuary model (without Saeftinghe) contains approximately 42.000 nodes with mesh sizes ranging from approximately 150-200m in the downstream part to about 10-50m in the upstream tributaries. At the study area of the intertidal area of Saeftinghe, the mesh is locally refined to 6-20m to include the marsh channel network and geomorphology, leading to a total number of nodes of about 130.000. The effect of marsh vegetation is implemented by increased bed roughness. For simplicity all vegetation classes are represented by a single bottom friction coefficient. Calibration of the part of the model that covers the study area was done by tuning Manning's bottom friction coefficients for unvegetated (n=0.01) and vegetated (n=0.08) parts of the marsh and by tuning the spatially and temporally constant velocity diffusivity coefficient (ν=0.5 m^2/s) which is implemented in TELEMAC-2D. The model was calibrated on a spring-neap cycle of in-situ water level observations described above. In addition, in-situ water level measurements of the two storm surge tides have been added to the calibration to verify the model performance for storm tides, which is of particular interest in this study.

Simulated peak water levels are compared with the field measurements for all locations in the marsh channel network. Peak water levels at the marsh edge (loc. 8) are simulated with a mean error (ME) of -0.03m and mean absolute error (MAE) of 0.04m, which is a similar accuracy as in nearby tidal stations in the estuary. Halfway the main channel (loc. 10), the ME and MAE are +0.02m and 0.02m respectively. At the inner marsh locations (1, 2 and 3), situated at the end of the main channel and narrower side-channels, values for ME range from 0.00m to +0.05m and values for MAE range from 0.04m to 0.07m. Furthermore, the model performance is assessed for the amplification and attenuation rates of overmarsh tides specifically. Between the marsh edge (loc. 8) and the location halfway the main channel (loc. 10), the ME for amplification or attenuation rates is +1.4cm/km for overmarsh tides. From the middle of the main channel towards the end of the main channel and side-channel (i.e. loc. 10 to 1 and loc. 10 to 3), ME values are -0.5cm/km and +0.7cm/km respectively. Verification for the two storm surge tides shows that the model slightly underestimates the maximum measured peak water level reduction during the second highest storm tide (-6.7cm instead of -7.9cm reduction). For the highest storm tide, during which no attenuation was present in the observations, the model results do not show attenuation either. All in all, the TELEMAC-2D model is capable of representing the observed peak water levels and the variations in attenuation rates between the inner and outer marsh transects that are present in our observations fairly well. Ultimately, the model is used to assess the impact of specific geomorphological scenarios to attenuation rates on the salt marsh scale.

4. RESULTS AND DISCUSSION

The model results of simulations with varying geomorphological scenarios are discussed for a limited number of transects (see Fig. 1 for transect locations) that are representative for the trends that were observed from the simulations. Model simulations are performed in which the marsh platform and channel intertidal elevation in Saeftinghe are independently lowered or raised within the same order of magnitude as changes in channel and platform elevation that occurred during the last decades (Wang & Temmerman, 2013). The channel elevation is lowered by 0.9m or raised by 0.7m. The platform elevation is raised and lowered by 0.4m. Besides, a simulation is performed in which the extent of the marsh platform is increased by removing the levee on the south side of Saeftinghe and extending the marsh platform by several kilometers. With this simulation, it is possible to assess the effect of restrictions in storage area on storm surge attenuation, as the presence of levees might be a limiting factor for storm surge attenuation for larger surge events (Resio & Westerink, 2008). All performed model simulations consist of a series of peak water levels and storm tides, ranging from regular tides to severe storm surges.

The influence of the elevation of the marsh platform on the maximum attenuation rate is little. Maximum attenuation rates are all within the range of 6 to 7cm/km for platform elevations that have been either lowered or raised by 0.4m (Fig. 2). However, the model results show that the platform elevation determines which tides are attenuated, as attenuation only occurs for overmarsh tides that inundate the marsh platform up to about 1m, and attenuation rates are highest for overmarsh tides that are approximately 0.9 to 1.1m above the mean marsh platform elevation. For higher or lower tides, the attenuation rates are decreasing, which is in accordance with the field observations. The latter is not valid for the simulation in which the marsh platform is extended, as attenuation rates do not significantly decrease for higher tides in this simulation. The effect of limitations in storage area on the marsh platform is assessed by extending the platform by 5km behind the Y- and S-transects. Results of this simulation indicate that the storage area was indeed a limiting factor for attenuation of especially higher tides (Fig. 2). As the platform storage area is extended, attenuation rates do not or barely decrease with increasing height of flood events and amplification does not occur for higher storm tides. Besides, the simulation in which the levee has been moved by 5km shows an apparent maximum attenuation rate of 10cm/km for tides higher than 4.5m NAP.

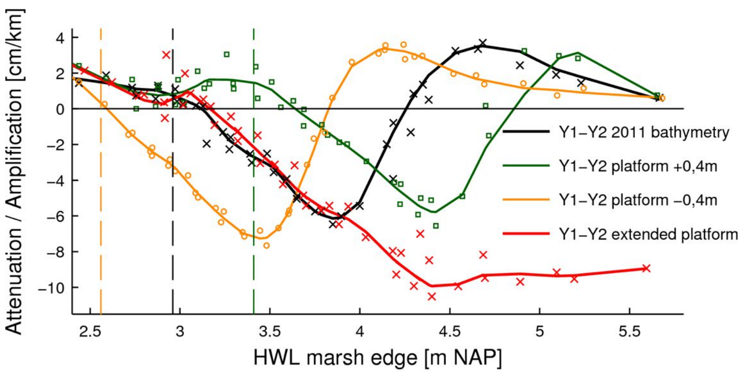

Figure 2. Modeled attenuation and amplification rates of tides with different high water levels (in m NAP, NAP being the Dutch ordnance level, close to mean sea level) over the Y1-Y2 transect (see Fig. 1 for location of the transect) for varying platform elevations and for a simulation with an extended platform area. The markers represent individual tides and the lines are loess fits to the simulation results. The mean platform elevations for the different bathymetries are indicated with dashed vertical lines.

The effect of channel geometry on attenuation of storm tides is significant. Model results show that maximum attenuation rates along the Y1-Y2 inner marsh transect vary between 4, 6 and 10cm/km for simulations in which the channel elevation is lowered by 0.9m, kept equal or raised by 0.7m resp. compared to the 2011 bathymetry (Fig. 3). The maximum attenuation over the inner marsh transects varies also between the S-, Y- and H-channels (see locations in Fig. 1). The highest attenuation rates of up to 10cm/km are simulated for the Y1-Y2 transect in the middle of the marsh, while the lowest maximum of 7cm/km is simulated for the S1-S2 transect where the extent of the marsh platform is less. It should be stated that we only present modeled attenuation rates calculated over transects of approximately 2km. If shorter parts of these transects are considered, much higher attenuation rates are found. However, here we focus on large scale geomorphological properties and therefore on large scale attenuation rates. Along the outer marsh transects, the channel is relatively deep and wide and the extent of the platform is very small compared to the channel width. Similarly to what was observed in the measurement series, the influence of the bed roughness then becomes smaller than the influence of channel convergence, leading to amplification (~2cm/km along the Y0-Y1 transect) instead of attenuation of peak water levels for all simulated high water levels. Only the results for the Y0-Y1 transect are shown in figure 3, but similar results were obtained for all three outer marsh sections.

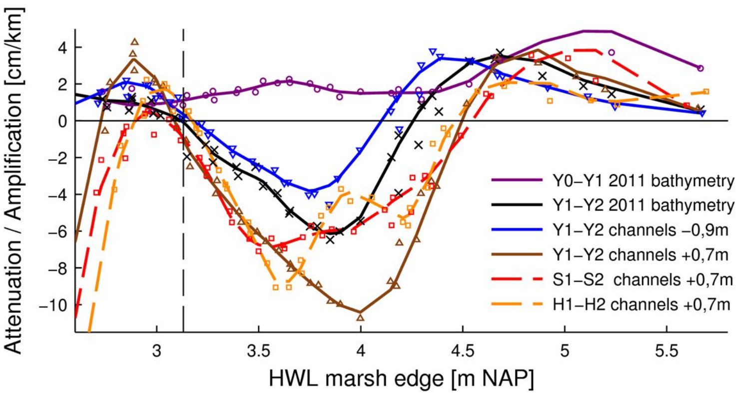

Figure 3. Modeled attenuation and amplification rates of tides with different high water levels over different transects (see location of transects in Fig. 1) and for varying channel elevations. The markers represent individual tides and the lines are loess fits to the simulation results. The mean platform elevation for the 2011 bathymetry is indicated with a dashed vertical line.

On the full marsh scale (S0-S2, Y0-Y2 and H0-H2), over a length of about 4km, modeled maximum attenuation rates vary between 0-2cm/km for the scenarios with deeper channels and up to 2-5cm/km for marshes with shallower channels. In simulations with an extended marsh platform, implying that the attenuation is not limited by the platform storage area, maximum attenuation rates on the marsh scale range from 2-3cm/km for scenarios with deeper channels to 4-6cm/km for scenarios with shallower channels. However, in the latter simulations attenuation does not decrease significantly with increasing high water levels, whereas the simulations with the regular bathymetry and including the presence of a levee show amplification for the highest tides.

In conclusion, we were able to validate a two-dimensional hydrodynamic model of tidal and storm tide propagation through an intertidal marsh based on in-situ water level observations. The model results allow to quantify the effects of specific features in the marsh geomorphology (i.e. platform and channel elevation, channel width) on attenuation rates for a realistic marsh geomorphology. Field observations indicate that the elevation of the marsh platform has a direct influence on the range of peak water levels that are attenuated. The model results confirm the dependency of flood wave damping or amplification on the peak water level relative to the marsh platform elevation for all scenarios. Secondly, the channel elevation has an impact on the amount of attenuation or amplification, as does the extent of the marsh platform compared to the channel width for overmarsh tides. Hence, marsh geomorphology and channel geometry have a definite impact on tidal propagation and storm surge attenuation in marshes.

ACKNOWLEDGMENTS

The authors would like to thank the Antwerp Port Authority for funding this research.

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[i] water level exceedance probabilities for tidal stations are obtained from Rijkswaterstaat (http://www.rijkswaterstaat.nl).