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Modelling the effects of typhoons on morphological changes in the Estuary of Beinan, Taiwan

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ABSTRACT

On average, Taiwan is subjected to three or four typhoon invasions each year. As a typhoon approaches, strong ocean waves from the sea, which are accompanied by flash floods on land, can considerably change the morphology of estuaries. Thus, knowing the effect of typhoons is important for coastal management. This study uses simulations and field surveys to analyze the processes of sediment transport near the Beinan Estuary in southeastern Taiwan. A model that is based on Eulerian and Lagrangian methods is used to simulate sediment transport from fluvial flows, waves, and currents. Typhoons of various intensities, different types of fluvial hydrographs, and seasonal effects are used to study their effects on the bathymetry. The relationships among the fluvial sediments, the wave loads, and the evolution of the estuary are derived from the results. The results indicate that the morphology of the Beinan Estuary is governed by typhoon events and that the process of erosion, transport, and deposition of sediment are short. The amount of fluvial sediments that is required to cause changes in the estuary is determined based on these results, and this estimate can be used for erosion protection in the future.

1. Introduction

Estuaries form transition zones between rivers and the seas and thus are subjected to complex hydrodynamic processes. These environments require special attention because of their social, economic, and ecological importance. The morphology of an estuary is governed by both natural and anthropogenic factors. Natural factors include river discharges, sediment sources, tides, and wave forcing; anthropogenic factors include activities such as channel dredging, land reclamation, sea walls, or riverbank protection (Cook et al., 2007; Dalrymple et al., 2012; Guo et al., 2012; Natesan et al., 2014; Yamada et al., 2012). Montagna et al. (2013) noted that the interactions among the climate, continental geology, and tidal regime make estuaries unique and different. Dalrymple et al. (1992) used three natural factors to describe an estuary. Other definitions and classifications for estuaries have been presented in the past; however, none seems to cover all the characteristics of estuaries (Perillo, 1995; Simenstad and Yanagi, 2012). Because most of the base flows in the rivers of Taiwan are almost reduced to trickles during the dry season, the estuaries in Taiwan can be categorized as '*intermittent estuaries*' (Perillo, 1995).

With the increase in coastal threats, the interests of the scientific community in solving the problems of estuaries/coasts have also increased in the past decades. The comprehensive references that were recently published by Wolanski and McLusky (2012) confirmed these interests. Numerical models with various degrees of sophistication have been developed, and measurements have been conducted either on site or through remote sensing. Uncles (2002) (see also Hardisty, 2007; Prandle, 2009) reviewed the progress in analyzing the physical processes of estuaries.

Generally, numerical models are used for one of two purposes, namely, either to predict the evolution of estuarine/coastal morphodynamics (Bernardes, 2005; Dastgheib, 2012; Guo, 2014) or to evaluate possible changes that are caused by human activities (Gelfort et al., 2010). Numerical models for coastal processes have progressed substantially over the past several decades. Models are now available that cover the full spectrum of dominating factors, such as tidal currents, waves, wave-induced currents, and sediment transport. These models can be used in more complicated situations and provide more flexibility in considering a variety of loads that act on the seabed. Huan et al. (2010) used the wave, flow, and mud transport modules of Mike 21 by DHI to simulate the sediment transport in the Bach Dang Estuary, Vietnam. Mud transport under both fair and stormy weather conditions was modelled with reasonable results. A numerical model called CCHE2D-Coast was applied by Ding et al. (2013) to evaluate the Touchien Estuary, western Taiwan. The hydrodynamic and morphodynamic responses to waves, tides and river flows were modelled. The results were used to propose flood prevention and erosion protection for the estuary.

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Fluvial sediments were assumed to have the same grain size distribution as those in the shelf zone in the above-mentioned models. This scheme has an inherent drawback in that sediments that are carried by large flows from a river during a flood can have grain size distributions that differ markedly from those in the coastal area. Larger grain sizes settle down closer to the river mouth, whereas finer sediments are transported farther into the sea and distributed more or less evenly around the coast. Geleynse et al. (2010) showed that the formation of sandbars near the river mouth is related to the internal sedimentary composition and stream flow. The adjacent shoreline is undisturbed with distance from the river mouth. Thus, the morphology near an estuary has different evolutionary patterns than the adjacent coasts.

A Lagrangian morphodynamic model can solve this problem much more precisely by tracking the fluvial sediment that is deposited in the coastal region. Black et al. (1999) noted that a Lagrangian model assigns mass to particles of a precisely known position, and mass conservation is always guaranteed. Soulsby et al. (2007) (see also Huthnance et al., 2008) used Lagrangian models to assess the effect of changing estuarine morphology in the UK on flooding risk and habitats. Different types of scenarios were tested for future management. The accuracy in modelling changes in the bathymetries near estuaries can be enhanced by using both Eulerian and Lagrangian methods.

However, even with the most advanced computational techniques, not all the mechanisms that are involved in coastal and estuarine processes can be considered in detail. This concept is true irrespective of the degree of sophistication of the numerical model. Furthermore, numerical errors may accumulate in the evolving morphology, rendering the validity of long-term simulations uncertain (Ding and Wang, 2008; Huthnance et al., 2007). Kristensen et al. (2013) noted that a 2D model is only suitable for short- to medium-term simulations. One reason is that the computation can be time consuming. Another reason is that an accumulation of errors can eventually lead to erroneous results. A 2D model may not yield realistic results if drastic morphological changes occur.

Measured data are required to realistically model the evolution of shorelines. These data either serve as input for the model or are used to check the outputs. Splinter et al. (2013) noted the need for data sets with high quality and adequate duration. Frequent field surveys were proposed to enhance the accuracy of estimating shoreline evolution. Ideally, field surveys should be frequent and cover as large a region as possible but quite often are limited in both number and extent because of financial reasons. Large-scale field measurements appear only scarcely in the literature. Data of sediment in suspension, currents, waves, sea level, sediment size, and bedforms have been measured in recent years (Black et al., 1999; Bolaños and Souza, 2010). All these data are very helpful to improve both our understanding of the relevant mechanisms and the numerical modelling techniques.

The northwestern Pacific region is a basin with active tropical storms. The coasts in this region are under constant threat during the typhoon season. However, relatively few literatures have examined the effects of severe weather on sandy beaches (Bouchette et al., 2013). As noted by many researchers, the effect of typhoons on sandy beaches or estuaries is '*strikingly distinct from what occurs in systems forced by more moderated wind/wave forcing*' (Campmas et al., 2014; Meulé et al., 2013). The base flows of most rivers in Taiwan are very low during dry seasons, which is not the case for severe weather, such as torrential rain during wet seasons or typhoon invasions. In these circumstances, substantial amounts of water can flow down from inland areas. This sediment-laden flow is eventually discharged into the sea. With strong waves coming from the sea, the conditions can become very complex. Therefore, knowing the possible effects of torrential rain and/or typhoons on the coasts is very important.

In this paper, an integrated model is used to study the possible effects of severe weather on the morphology of the Beinan Estuary, Taiwan. Both seasonal weather and typhoon invasions are considered. The calculated results compare favorably with data from field surveys. A 'first-order estimate' of the amount of fluvial sediments to cause erosion/accretion is proposed according to these results.

2. Study domain

2.1. Geographical background

The Central Mountain Range is located on the eastern side of Taiwan and extends from north to south, which causes all the rivers in eastern Taiwan to have short lengths, steep slopes, and high flow rates. Outflows from these rivers on ordinary days are typically small, and the sediments mostly consist of fine materials. Their effects on the coastal morphology are therefore of no importance. However, large amounts of water may discharge from these rivers on severe weather days, especially during the summer and autumn seasons, when torrential rainstorms or typhoons affect Taiwan. Under these circumstances, high-speed, sediment-laden river outflows, which are occasionally combined with waves from the sea, can severely affect the estuarine morphology.

The study area covers the coastal region of the Beinan Estuary (latitude=22°45′53.70″ N; longitude=121°10′38.04″ E) in Taidong County in southeastern Taiwan. Fig. 1(a) shows the geographic location of Taiwan, and Fig. 1(b) shows where the measuring stations are marked in the Beinan Estuary. The estuary is fan shaped with adjacent beaches on each side, and the widths of the beaches decrease away from the estuary. Sandbars at the river mouth remain intact for some time before they are breached and reshaped by streamflow during a flood, which indicates that the sediment supply to the delta front almost entirely originates from typhoons/flood events; therefore, severe weather may greatly affect the morphology of the estuary.

Only six bathymetric surveys were conducted in the past decade because of financial constraints. Three surveys were conducted in 2005, and one survey was conducted in 2006 as part of a construction project. No major incidents were known to have occurred, so field surveys were conducted once every three or four years. Changes in the bathymetry between 2009 and 2014 in this area are shown in Fig. 2. In this figure, areas of accretion are marked in blue and areas of erosion are marked in red. Substantial erosion has clearly occurred near the Beinan Estuary. However, whether an underlying trend of erosion exists or if this erosion was a result of severe weather events that have occurred during these years is not clear. The coast may be subjected to severe ocean climates because it is facing the Pacific Ocean and lies along the tracks of typhoons. The four surveys in 2005 and 2006 covered all four seasons, so their data were used as basic information for this study. In the following sections, we clarify the use of these data through numerical modelling. These results can be used as a reference for future erosion protection measures.

2.2. Hydrological background

The Beinan River is 84.35 km long with a catchment of 1,603.21 km^2. Its headwaters have an elevation of approximately 3295 m. The hydrological gauging station nearest to the river mouth is located at a distance of 4.5 km from the river mouth and is positioned on the Taidong Bridge. This station is operated by the Water Resource Agency (WRA). Hourly discharge data from 1950 to 2014 are available. The annual mean river discharge is 93.09 m^3/s. The observed hourly mean discharge varied from 0 m^3/s under drought conditions to 12,800 m^3/s during the Typhoon Nora flood in 1973. Monthly mean discharges also have a wide distribution and vary from 17.53 m^3/s in February to 229.66 m^3/s in September. The data show that the river flow has different characteristics during the dry and wet seasons.