Continental Shelf Research 49 (2012) 90–99

Contents lists available at ScienceDirect

Continental Shelf Research

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

Research papers

Modelling the equilibrium hypsometry of back-barrier tidal flats in the German Wadden Sea (southern North Sea)

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ARTICLE INFO

Article history:
Received 15 December 2010
Received in revised form
26 April 2011
Accepted 11 May 2011
Available online 27 May 2011

Keywords:
Hypsometry
Tidal flats
Back-barrier tidal basins
German Wadden Sea

ABSTRACT

Hypsometry is the distribution of volume or horizontal surface area with respect to elevation. Some observations show contradictory scale-dependent characteristics of tidal flat hypsometries in back-barrier tidal basin environments, and traditional theory explains the flattening hypsometry by relating concave-up hypsometries in low tidal range basins to the dominating influence of wind waves rather than tidal currents. In order to investigate these two problems, two series of numerical modelling exercises were carried out using schematized rectangular back-barrier tidal basins roughly corresponding to the tidal basins found in the German Wadden Sea. The results show that, in the equilibrium states of tidal basins, hypsometries of back-barrier tidal flats are dependent on the basin scale and tidal range. Thus, large basin areas and low tidal ranges favour strong concave-up hypsometries, whereas small basin areas and high tidal ranges favour less concave-up hypsometries. Because wind waves were excluded in the model, these relationships are purely associated with tidal-current action. In addition to the traditional theory, which emphasises the relative importance of wind waves, the flattening of hypsometric profile shapes can, therefore, also be interpreted as a response to the relative area of intertidal areas or channels in the tidal basins. Thus, if tidal channels have relatively large areas, the development of tidal flats between channels is markedly restrained, the tidal flats being prevented from growing upward to higher elevations. As a result, strong concave-up hypsometries are formed that are associated with relatively large areas of low tidal flats and small areas of high tidal flats. As basins with large areas and low tidal ranges have large relative channel areas, this results in pronounced concave-up hypsometries, and vice versa.

1. Introduction

Hypsometry is a concise and quantitative method to characterize and understand the morphological characteristics of the Earth's surface (Strahler, 1952; Emery, 1979; Walcott and Summerfield, 2008). In mountainous areas, the hypsometry of fluvial drainage basins has been shown to be sensitive to tectonic, lithologic, and climatic factors, which, in turn, make it a useful proxy for these external factors (Masek et al., 1994; Perez-Pena et al., 2009; Jansen et al., 2010). By analogy, hypsometry is a sensitive morphological parameter of tidal basins and tidal flats, being not only related to hydrodynamics and morphodynamics (Boon and Byrne, 1981; Eiser and Kjerfve, 1986; Marciano et al., 2005; Toffolon and Crosato, 2007; Moore et al., 2009) but having also been shown to be useful in ecological and environmental contexts (Kirby, 2000; Oertel, 2001; Sanderson and Coade, 2010). For example, Wang et al. (2002) addressed the relationship between hypsometry and tidal asymmetry, and Oertel (2001) suggested that hypsometry has a strong influence on wetland health. The types of sediment occupied on these tidal basin systems are diverse, covering sand (Wang et al., 2002; Toffolon and Crosato, 2007), fine sand and silt (Moore et al., 2009), mud–sand mixtures (Boon and Byrne, 1981), and mud (Kirby, 2000).

Two kinds of hypsometric curves are used in practice to characterize the morphology of tidal basins (Oertel, 2001). The first kind, called volume hypsometry, is the water volume below a reference elevation as a function of this elevation (Wang et al., 2002). The second kind, called area hypsometry, is the horizontal basin surface area below a reference elevation with respect to this elevation (Friedrichs and Aubrey, 1996). In order to compare the shape of hypsometric curves, these parameters, which include water volume, surface area, and elevation, are usually normalised to some characteristic values. Normalisation is particularly essential when the relevant parameters vary significantly between different basins. If the tidal system is simplified to a one-dimensional cross-shore figure, the area hypsometric curve degenerates

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0278-4343/$ - see front matter
doi:10.1016/j.csr.2011.05.011

into the cross-shore tidal flat profile (Friedrichs and Aubrey, 1996).

There are still some unknown aspects about tidal basin and tidal flat hypsometry. A first problem concerns scale effects. Germorphological and sedimentological systems are generally suggested to respond on specific spatial scales (Dodds and Rothman, 2000), such scale-dependent hypsometric characteristics having been observed and successfully modelled in the case of fluvial basins (Willgoose and Hancock, 1998; Hurtrez et al., 1999). In the case of tidal basins, however, such hypsometric scale effects are still in dispute. Thus, for the volume hypsometry of German Wadden Sea tidal basins (southern North Sea), Renger and Partenscky (1974) found a logarithmic relationship between the water volume below a certain elevation and this elevation with an empirical coefficient for any individual tidal basin, and suggested that this coefficient reflected a power–law relationship with the basin area. This means that the hypsometry is scale-dependent. On the other hand, comparing two American tidal basins, Boon (1975) and Boon and Byrne (1981) suggested that area hypsometry was scale-independent. Then, following the early work of Strahler (1952), they used the area hypsometry as an indicator of the evolutionary stage of tidal basins regardless of scale differences, relating a certain shape of the hypsometric curve to an immature, mature, or more mature state of tidal basins. This concept has been applied by Moore et al. (2009) to evaluate the development of estuary morphology. In this context, and besides the unclear definition of 'mature', a systematic investigation of scale effects on tidal basin hypsometry is still lacking.

The second problem concerns the influence of tidal range on tidal basin hypsometry. For the area hypsometry of tidal flats in German Wadden Sea tidal basins, Dieckmann et al. (1987) suggested that the hypsometric curves tended to be more concave-up for tidal flats having a lower tidal range and less concave-up for tidal flats having a higher tidal range. Friedrichs and Aubrey (1996) attribute the concave-up hypsometry of tidal flats in low tidal range basins to the dominant forcing of wind waves rather than tidal currents, but the question remains whether tidal processes alone could generate the observed responses of the hypsometric shapes to the tidal ranges.

Numerical modelling was suggested to be useful tool to study the morphodynamics of tidal basin systems (Wang et al., 1995; de Swart and Zimmerman, 2009). With the development of new numerical modelling techniques (Latteux, 1995; Lesser et al., 2004; Roelvink, 2006), long-term morphodynamics of tidal basins in the Wadden Sea have been successfully studied by means of two-dimensional (2D), process-based models (Wang et al., 1995; Dastgheib et al., 2008; Dissanayake et al., 2009).

In the present study, two series of numerical modelling exercises have been carried out to investigate the two problems of back-barrier tidal basin hypsometry outlined above: (1) is hypsometry scale-dependent or scale-independent? and (2) how is basin hypsometry influenced by tidal range (mean tidal current strength)? The study focuses on the hypsometry of tidal flat area between the mean low-water level (MLW) and the mean high-water level (MHW) of tidal basins because (a) it is of particular importace for ecological systems and (b) it can be directly compared with the results of previous studies (Boon, 1975; Eiser and Kjerfve, 1986; Dieckmann et al., 1987; Friedrichs and Aubrey, 1996; Kirby, 2000).

2. Study area

The study area is the East Friesian sector of the German Wadden Sea, which borders the coast of the southern North Sea between the river Ems in the west and the Jade Bay in the east (Fig. 1). The East Friesian Wadden Sea is 4–12 km wide and stretches over 90 km along the coast, comprising a chain of seven barrier islands and six large tidal basins characterised by a network of tidal channels (Ehlers, 1988). The back-barrier tidal basins are predominantly controlled by tidal forcing, although the locally generated wind waves are strongly dependent on the fetch distances and water depth and play an important secondary role (Krögel and Flemming, 1998). The tide is semidiurnal with an averaged tidal range of 2.2 in the west and 2.8 m in the east, respectively. Tidal current speeds during fair weather reach up to 1.3 m/s in the inlets and 0.3 m/s on the tidal flats (Davis and Flemming, 1991). Current velocities are stronger near the inlet mouths and decrease toward the landward boundary and tidal basin drainage divides. Within the back-barrier tidal basins, surface sediments mainly consist of sand, slightly muddy sand and mud, the grain-size distribution patterns revealing a well-defined landward fining trend (Flemming and Ziegler, 1995). Due to land reclamation, the position of the mainland dike appears

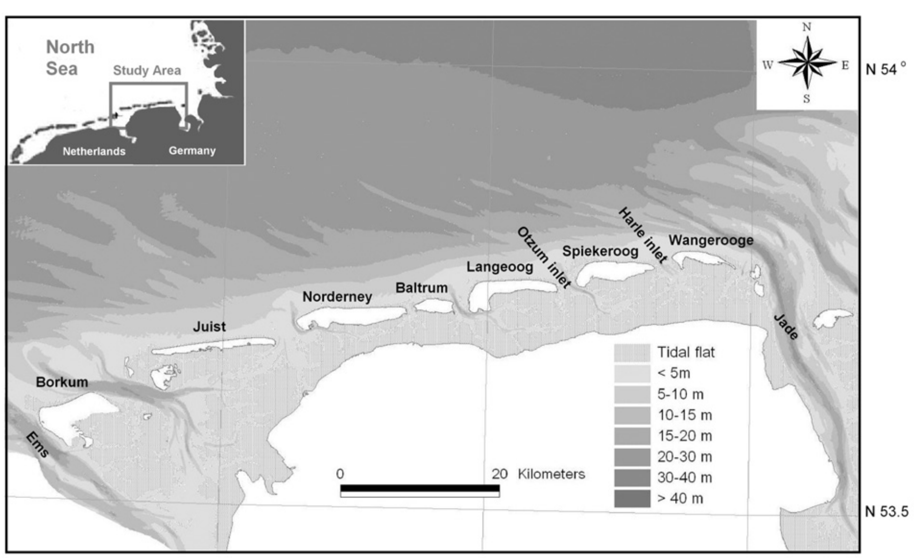

Fig. 1. Location map of the study area along the East Friesian barrier–island coast of the German Wadden Sea (southern North Sea). The colour bar denotes the water depth relative to mean sea level (m).