Estuarine, Coastal and Shelf Science 184 (2017) 67–82

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

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

A modeling approach to assess coastal management effects on benthic habitat quality: A case study on coastal defense and navigability

Francesco Cozzoli [a, *], Sven Smolders [b, c], Menno Eelkema [d], Tom Ysebaert [a, e], Vincent Escaravage [a], Stijn Temmerman [b], Patrick Meire [b], Peter M.J. Herman [a], Tjeerd J. Bouma [a]

[a] Netherlands Institute of Sea Research (NIOZ), P.B. 140, 4401 AC Yerseke, The Netherlands
[b] Ecosystem Management Research Group, University of Antwerp, Universiteitsplein 1, 2610 Wilrijk, Belgium
[c] Flanders Hydraulics Research, Berchemlei 115, 2140 Antwerp, Belgium
[d] Delft University of Technology (TU Delft), Stevinweg 1, 2628 CN Delft, The Netherlands
[e] Wageningen University, Institute for Marine Resources and Ecosystem Studies (IMARES), P.B. 77, 4401 NT Yerseke, The Netherlands

ARTICLE INFO

Article history:
Received 24 June 2016
Received in revised form
11 October 2016
Accepted 31 October 2016
Available online 2 November 2016

Keywords:
Estuary
Macrozoobenthos
Hydrodynamic modeling
Species distribution modeling
Coastal management

ABSTRACT

The natural coastal hydrodynamics and morphology worldwide is altered by human interventions such as embankments, shipping and dredging, which may have consequences for ecosystem functionality. To ensure long-term ecological sustainability, requires capability to predict long-term large-scale ecological effects of altered hydromorphology. As empirical data sets at relevant scales are missing, there is need for integrating ecological modeling with physical modeling. This paper presents a case study showing the long-term, large-scale macrozoobenthic community response to two contrasting human alterations of the hydromorphological habitat: deepening of estuarine channels to enhance navigability (Westerschelde) vs. realization of a storm surge barrier to enhance coastal safety (Oosterschelde). A multidisciplinary integration of empirical data and modeling of estuarine morphology, hydrodynamics and benthic ecology was used to reconstruct the hydrological evolution and resulting long-term (50 years) large-scale ecological trends for both estuaries over the last. Our model indicated that hydrodynamic alterations following the deepening of the Westerschelde had negative implications for benthic life, while the realization of the Oosterschelde storm surge barriers had mixed and habitat-dependent responses, that also include unexpected improvement of environmental quality. Our analysis illustrates long-term trends in the natural community caused by opposing management strategies. The divergent human pressures on the Oosterschelde and Westerschelde are examples of what could happen in a near future for many global coastal ecosystems. The comparative analysis of the two basins is a valuable source of information to understand (and communicate) the future ecological consequences of human coastal development.

1. Introduction

Estuaries and coastal embayments are a preferential habitat for humans (Small and Nicholls, 2003), thereby causing major alterations to the sea-scape. Firstly, the increase in coastal populations, in combination with sea level rise and increasing intensity of extreme storms, is bringing a large part of the world's human population under the threat of coastal storm surges (McMichael et al., 2006). This has led to the still ongoing realization of a high number of dams, embankments and storm surge barriers in the richest countries (Fig. 1). With the growing prosperity of developing countries (where most of the endangered population lives) these measures will likely be more commonly adopted worldwide (Temmerman et al., 2013; Perkins et al., 2015).

Secondly, waterways have for centuries played an important role in trade, causing civilizations to develop in delta areas with good direct access to both the sea and the land behind. Nowadays, the handling capacity of estuarine ports is a crucial factor for the economic development (Halpern et al., 2008). The continuously growing global trade network and the ongoing increase of the commercial ships are pushing toward a more intensive dredging of

---

* Corresponding author. Present address: DiSTeBA, Centro Ecotekne, S.P. Lecce-Monteroni, 73100 Lecce, Italy.
E-mail address: francesco.cozzoli@unisalento.it (F. Cozzoli).

http://dx.doi.org/10.1016/j.ecss.2016.10.043
0272-7714/

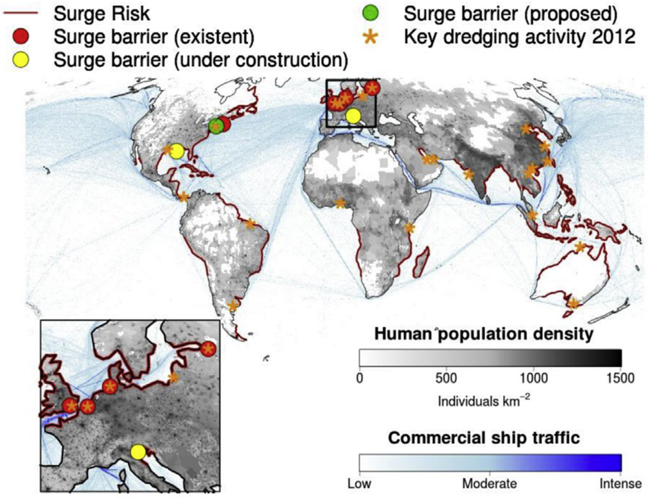

Fig. 1. Coastal Anthropocene. A large part of the human populations is nowadays endangered by storm surge risks (coastlines enlighten in red). In the northern hemisphere (particularly in Europe) this led to the construction of coastal defense infrastructures like open surge barriers. In the map we show the largest existent (red circles), under construction (yellow circles) or proposed (green circle) storm surge barriers. Other smaller storm surge barriers exist, mostly on tributaries rivers (e.g. along the Elbe, the Hull leading into the Humber). Contextually, the increasing exchange of goods through sea routes is pushing to a more extensive dredging of the waterways to harbors (main dredging operations in estuaries, embayments or straits are reported on the map with orange asterisks). Sources for flood risk: World Bank; ship transit: NCEAS, population density: FAO; key dredging projects 2012 in estuaries, lagoons, embayments or straits: International Dredger Association and China Dredger Association (representative of ca. 70% of the global dredging market). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the waterways to the harbors (Fig. 1). The global dredging market increased by nearly threefold over the past decade from $ 5.3 bn in 2000 to $ 14.7 bn in 2011, according to the International Association of Dredging Companies.

Due to anthropogenic needs, wet infrastructures are so ubiquitously diffused that they have been proposed as a main driver of change in coastal environments (Bulleri and Chapman, 2010). Dams, embankments and storm surge barriers provide coastal protection by damping the tidal energy. In contrast, the deepening of estuarine beds often facilitate the inland penetration of seawater, leading to a landwards increase of the tidal energy (Stive and Wang, 2003). In both cases, the ecological implications can be large, and should be taken into account for development plans (Nienhuis and Smaal, 1994; Swanson et al., 2012; Nordstrom, 2014; Perkins et al., 2015). It is well known that hydrodynamic forces and their morphodynamic consequences structure estuarine life (Snelgrove and Butman, 1994; Ysebaert et al., 2003; Cefalì et al., 2016). Alterations of the eco-hydro-morphological environment can have negative, or even catastrophic, social consequences when they affect essential ecological services (Adger et al., 2005; Danielsen et al., 2005; Diaz et al., 2006; Perkins et al., 2015).

Distribution patterns and shifts can be assessed using Species Distribution Models (SDMs), which are statistical tools that combine observations of species occurrence or abundance with environmental variables (Elith and Leathwick, 2009). The application of SDMs in assessing the distribution of marine species has increased considerably in the last years as a tool for ecosystem management and marine spatial planning (reviewed in Robinson et al., 2011; Reiss et al., 2015).

Despite this, there are several challenges associated with the study and prediction of complex alterations of the eco-hydro-morphological environment. A first challenge is related to the large internal heterogeneity of coastal environments. Estuaries and embayments are indeed characterized by strong gradients in depth, salinity, current velocity, sediment composition and other factors (McLusky and Elliott, 2004; Morais et al., 2016; Trancart et al., 2016). A management strategy at the scale of the system may lead to strong spatial divergence in response, where different subhabitats are affected in very different ways (Cozzoli et al., 2013). Secondly, it is not an easy task to forecast long-term morphodynamics (Lesser et al., 2004), neither to translate morphodynamic conditions into habitat suitability (Cozzoli et al., 2014). Non-linear dynamics, unaccounted variables and unexpected features that can arise as the system develops, and the assumption behind physical and ecological expectations can be mismatched. Thirdly, extensive data series of field collected observations, inclusive of both hydromorphological (e.g. elevation, current velocity, granulometry, salinity) and biological (e.g. abundance and composition of ecological communities) measurements, are virtually never available with an extent that is relevant compared to the morphodynamic scales (decades, De Vriend et al., 2011). This reduce the possibility to fit and field-validate predictive models.

Despite the large uncertainty in predicting the environmental consequences, the realization of new coastal infrastructure is an unrestrainable need of human society (Temmerman et al., 2013; Nordstrom, 2014; Perkins et al., 2015), and the infrastructures design must attempt to account for ecological aspects. Presently, incomplete knowledge of ecological impacts undermines predictive management that would otherwise allow for appropriate spatial planning in coastal infrastructure design (Perkins et al., 2015). In this perspective, the study of existing anthropogenically modified ecosystems is a precious source of information to support adaptive management and future decisions (Folke et al., 2004; Matthews et al., 2011).

In this paper we hence focus on the ecological effects of contrasting hydrodynamic modifications of two adjacent estuarine habitats subject to large-scale infrastructural works. For this purpose, the neighboring Westerschelde and Oosterschelde estuaries (Dutch Delta, SW Netherlands, Fig. 2) are an ideal model system. The two basins share a common location, origin and regional pool

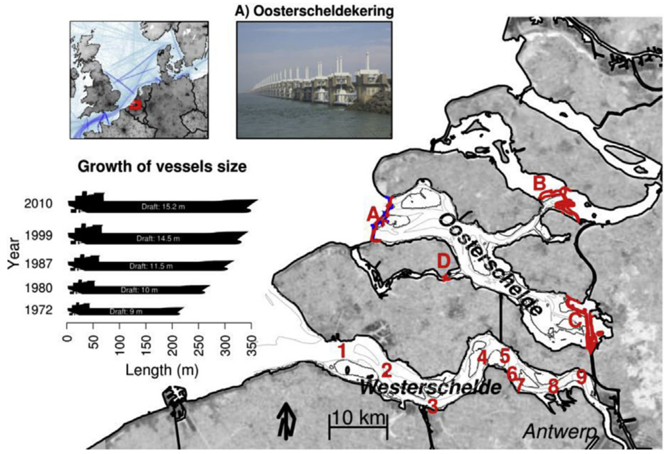

Fig. 2. The Oosterschelde and Westerschelde basins. A–D: main dams in the Oosterschelde; 1–9: main dredging sites in the Westerschelde. Intertidal areas are marked with a black line. Channels deeper than 10 m are enclosed by a grey line (bathymetry of 2010). Global trends in coastal development are well represented in the SW Delta of The Netherlands. On the one hand, the Oosterschelde was disconnected from the previous freshwater network (dams B & C) and embanked from the seaside by a storm surge barrier (Oostercheldekering, A). During recent decades, the maximal size of commercial vessels almost doubled. As consequence, channels in the Westerschelde were locally deepened (1-9) to enhance the shipping route capacity to the port of Antwerp (bottom right).