Coastal Dynamics 2017
Paper No. 216

HYDRO- AND SEDIMENT DYNAMICS IN A NON-TIDAL LAGOON BASED ON IN SITU OBSERVATIONS AND NUMERICAL MODELLING: RØDSAND LAGOON, SOUTHEAST DENMARK

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Abstract

Rødsand lagoon is an enclosed coastal embayment inhabited by benthic flora and fauna. The lagoon is vulnerable to increasing turbidity levels and is designated as a Natura 2000 protected site. The lagoon is under pressure from both climate change and human impact, both of which could potentially cause an increase in the turbidity levels and thus harm the ecosystem health. Numerical modelling studies and field observations during 2015 and 2016 of the lagoonal hydro- and sediment dynamics revealed the importance of flora and fauna for the sediment resuspension and thus the turbidity levels. Benthic flora and fauna affect the sediment dynamics both spatially, in terms of the spatial distribution, and temporarily, in terms of the seasonal variance. Rødsand lagoon is different from typical coastal lagoons due to a strait connecting the environment with the inner Danish waters. Flushing through the strait has the potential to impact the internal lagoonal water exchange and the sediment dynamics due to an amplified sediment transport to and from the lagoon.

Key words: Coastal lagoon, turbidity, flora and fauna, external flushing, numerical modelling

1. Introduction

Coastal lagoons are shallow coastal water bodies separated from the ocean by shore-parallel barriers that fully or partially enclose the lagoon; the barriers impede the water exchange to the sea and dampen wave, wind and current action (Kjerfve, 1994; Kennish & Paerl, 2010). Coastal lagoons are due to the sheltered characteristics typically inhabited by marine flora and fauna, which contribute to the individual lagoon characteristics and functioning (e.g. De Wit, 2011). The ecosystem health of coastal lagoons is vulnerable to increasing turbidity levels due to hindered light penetration (Middelboe et al., 2003). Hence, coastal lagoon systems are potentially vulnerable to changing environmental conditions, whether driven by climate change or human impact. A proposed future increase in storminess due to climate change (IPCC, 2014) could exacerbate local turbidity levels due to increased sediment resuspension (e.g. Madsen et al., 1993), and likewise a sediment spill related to offshore construction work may pose a threat to the coastal lagoon health. The lagoon of the present study, namely Rødsand lagoon, is potentially under pressure from both climate change and human impact. The construction of a fixed-link between Denmark and Germany, the Fehmarnbelt connection, which is planned 10 km west of Rødsand lagoon is anticipated to spill 0.75 million m^3 fine-grained sediment into Fehmarnbelt during the first 18 months of construction (Femern A/S, 2013). This sediment spill could lead to an import of sediment to the lagoon, which is protected by the European Commission as a Natura 2000 area; a designation that prohibits a permanent disruption of the natural habitat.

In order to understand how a temporary sediment spill and increased storminess may affect Rødsand lagoon it is of key importance to investigate the natural variation of the present sediment dynamics. Understanding the local sediment dynamics of a coastal ecosystem and the potential future stressors is an important step towards appropriate environmental management; a topic which has been stressed in several recent studies, e.g. by Gaertner-Mazouni & De Wit (2012), Spalding et al. (2014) and Ferrarin et al., (2016). Coastal lagoons can according to Kjerfve (1986, 1994) be sub-divided into three types depending on the wave energy, tidal range and water exchange with the adjacent sea. Rødsand lagoon shares characteristics with the three proposed lagoon types encompassing “Choked”, “Restricted” and “Leaky” with regards to wave energy and tidal range; however, Rødsand lagoon holds morphological and hydrodynamic differences in terms of a connecting strait that generates additional flushing, which complicates assigning the lagoon to one of the classical lagoon types.

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The present study aims at investigating the large-scale hydro- and sediment dynamics of Rødsand lagoon through numerical modelling and in-situ observations in order to assess the natural system variations *and* the system response to future disturbances i.e. an increase in storminess (a ramped system disturbance) and a sediment spill from the planned construction of the Fehmarnbelt fixed-link (a pulsed system disturbance). The objectives are to:

1) Simulate the effect of increased storminess and an exterior sediment spill on the lagoonal turbidity;
2) Evaluate the impact of flora and fauna on the sediment dynamics;
3) Conceptualize Rødsand lagoon as a separate addition to the classical lagoon types.

2. Study area

Rødsand lagoon is located in southeast Denmark between the islands of Lolland and Falster. The lagoon faces Fehmarnbelt to the south, an energetic strait connecting the Baltic Sea with the inner Danish waters, sheltered by two barrier islands and a spit. The lagoon is directly connected with the inner Danish waters through the north-eastern strait Guldborgsund (Fig. 1). Rødsand lagoon is predominantly inhabited by *Zostera Marina* (eelgrass), which grows in the shallow and sheltered regions of the lagoon (FEMA, 2013). An extensive monitoring program has been in place in Rødsand lagoon from 2013 until 2015. The program included permanent stations along the coast of Lolland and within the lagoon, which provided continuous measurements of the hydro- and sediment dynamics. In 2015 and 2016 periodic stations were deployed, which supplied detailed information about the sediment composition of the water column and the bed. The in-situ observations were used as calibration parameters for the numerical model of the lagoon.

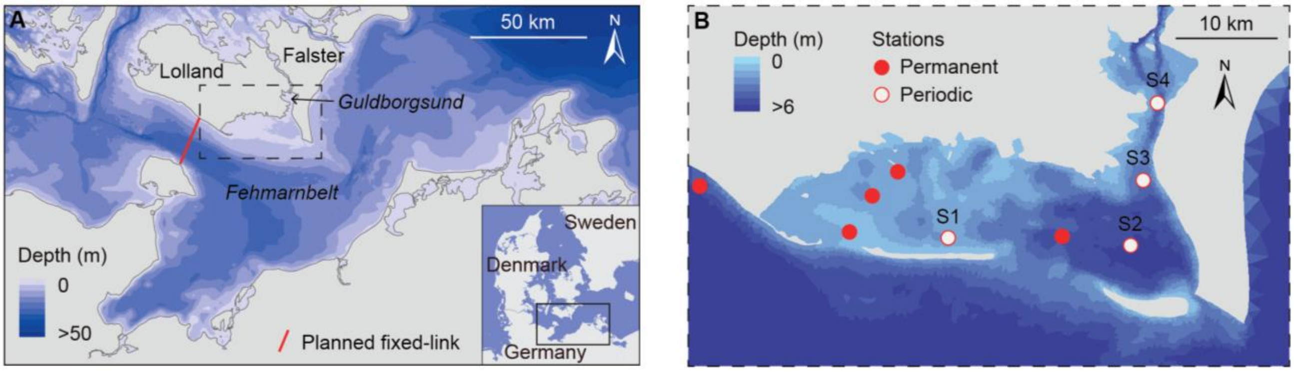

Figure 1. A) Location of Rødsand lagoon. B) Lagoonal bathymetry used for the numerical model including field stations (S1-4).

3. Preliminary results

The wave height in Rødsand lagoon was dependent on the wind speed, wind direction and available fetch. During two-months of field measurements north of the western barrier in 2015 (S1) the greatest wave heights relative to the wind speed were observed when the wind was directed from west, east and north, compared to southerly directions due to the western barrier island. North of the western barrier it required wave heights of 0.05 m to resuspend material from the bed (S1); in the deep region of Rødsand lagoon it required wave heights of 0.2 m to resuspend material from the bed (S2). The sediment dynamics in Rødsand lagoon were closely coupled to the hydrodynamics. On an annual basis, simulated through model studies for the year 2009, the main flow from Fehmarnbelt to Rødsand lagoon occurred through the western and middle inlet. The mean discharge flow was 25 m^3 s^{-1} through the western inlet and 63 m^3 s^{-1} through the middle inlet; the sediment import and export patterns resembled the in- and outflow dynamics. As a test case to investigate the impact of benthic fauna on the sediment dynamics a mussel reef was implemented in a numerical model of Rødsand lagoon. The mussel reef, which was implemented outside of Rødsand lagoon (oriented seaward from the western barrier spit), reduced the sediment import to the lagoon with 13-22 % depending on the reef length and mussel filtration rate. Within Rødsand lagoon approximately 6 km north of the western inlet, the mussel reef generated a SPMC reduction of 5-9 %. The total area of reduction stretched approximately 6-7 km into the lagoon. Field measurements north of the western barrier showed that high-energy events during the winter season reduced the vegetation cover (S1). The reduction caused a decrease in the critical bed shear stress for sediment resuspension, i.e.

material was more easily resuspended after the eelgrass cover was reduced. Field measurements in Guldborgsund showed current speeds up to 9 cm s^{-1} (S3) and 36 cm s^{-1} (S4) at a height of 0.6 m above the bed. Based on observations from previous studies at the same height above the bed within Rødsand lagoon, both current speed levels were expected to resuspend material from the bed. Flushing through Guldborgsund was thus expected to generate a sediment transport to and from Rødsand lagoon.

4. Discussion and concluding remarks

Interpretation of the hydro- and sediment dynamics in Rødsand lagoon were performed through numerical modelling improved by in-situ observations from field campaigns performed in 2015 and 2016. Based on field observations north of the western barrier (S1) high-energy events increased the turbidity level within the lagoon. Based on numerical modelling an import of sediment caused by an exterior sediment spill from e.g. construction work was expected to be retained temporarily within Rødsand lagoon in the sheltered and deep regions. High-energy events could cause an activation of the deposits, which would cause resuspension and increase the turbidity levels. During flow discharge events this amplified resuspension would enable an increased sediment export, thus making the import a temporary disturbance only. The flushing of Guldborgsund could prove to be an important mechanism for both the internal water exchange and the import and export of sediment to the lagoon. Estimations of the residence time of spilled sediments within Rødsand lagoon and the impact of flushing through Guldborgsund are yet to be analyzed. Based on the preliminary results, flora and fauna appeared to have a significant impact on the sediment dynamics within Rødsand lagoon. The impacts were dependent on both the spatial and temporal variations within the lagoon.

4.1 Spatial impacts

Since mussels, through numerical modelling, showed to impact the sediment dynamics by increasing sediment deposition and thus reducing the turbidity level, the spatial distribution of mussels within Rødsand lagoon is an important factor to incorporate in numerical modelling. The turbidity reducing impact of mussels has been observed in several in-situ studies (e.g. Chamberlain et al., 2001; Schröder et al., 2014; Valeur, 2004). Likewise, the preliminary field results of the reducing impact that eelgrass has on sediment resuspension is an important factor to incorporate in numerical modelling, when the eelgrass distribution is known. It is typically the shallow regions of costal lagoons that are inhabited by benthic flora (and fauna) due to the light availability (Newell and Koch, 2004), which makes these areas especially sensitive to increasing turbidity levels. This adds to the importance of incorporating flora and fauna distributions in numerical models of sediment transport in coastal embayments and lagoonal environments.

4.2 Temporal impacts

Mussels have a natural seasonal variation in the filtration rate, and thus the ability to reduce turbidity levels, with the greatest rate during summer (Bayne and Widdows, 1978). This temporal variance is expected to impact the turbidity levels in shallow regions with an abundance of mussels, i.e. generating the greatest deposition of sediment during summer. The eelgrass cover in Rødsand lagoon was reduced during high-energy events in the winter, leading to increased sediment resuspension relative to the stress applied to the bed. It is thus assumed that the bed shear stress it requires for sediment resuspension will vary seasonally, i.e. generating the greatest sediment resuspension during winter. The turbidity reducing impact of aquatic vegetation compared to a bare bed has been mentioned in several studies (e.g. Lefebvre et al., 2010; Nepf, 2012; Vargas-Luna et al., 2015). The temporal variations of the impact that flora and fauna has on the sediment dynamics are also important aspects to consider when generating a numerical model of sediment transport in coastal embayments and lagoonal environments.

4.3 Coastal lagoon types

Rødsand lagoon differentiates from typical coastal lagoons due to Guldborgsund, the northern strait that *connects* the lagoon with the inner Danish waters. Flushing through Guldborgsund has the potential to impact both the internal water exchange and the sediment transport to and from Rødsand lagoon. Due to the expected impact of external flushing the morphological appearance of Rødsand lagoon is proposed as an addition to the classical *restricted* and *leaky* lagoon types (Fig. 2).

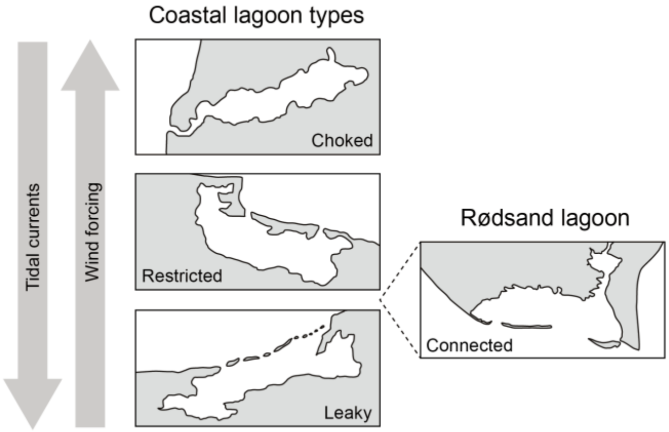

Figure 2. Subdivision of coastal lagoons into *choked*, *restricted* and *leaky* (after Kjerfve, 1986, 1994) extended with a *connected* lagoon, as suggested in the present study.

The degree to which climate change and human impacts could negatively impact the health of Rødsand lagoon through increased turbidity levels is a subject of discussion. The preliminary results of the present study suggested that both variables could impact the system temporarily, however not permanently disrupting the natural habitat. The spatial and temporal impacts of flora and fauna have been found to affect the resuspension of sediment in Rødsand lagoon, and are thus important aspects to consider in numerical modelling in order to improve the system understanding.

Acknowledgements

This study is part of the research project "SEDILINK" co-funded by Femern A/S, DHI and the Department of Geosciences and Natural Resource Management, University of Copenhagen.

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