SOLVING A 40-YEAR OLD COASTAL SEDIMENT TRANSPORT PROBLEM USING INTEGRATED FIELD AND MODELLING APPROACH

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INTRODUCTION

Case studies provide valuable lessons for successfully solving coastal engineering and management challenges. This paper gives an overview of a typical man-made coastal sediment trap case and presents a multi-method research carried out at different time scales into solving the problem. In the context of previous geological, oceanographic and historic research in the eastern Baltic Sea, the paper presents new results based on discreet water flow measurements, beach profiling as well as analysis of orthophotos and bathymetric data. These data were coupled with SWAN modelled waves and currents with resulting sediment transport in Delft3D. With relatively small budget we were able to get novel results which are used in the future management of the study area in the changing climate.

Lehtma harbor is situated on Hiiumaa island in the eastern Baltic Sea, Estonia (Figure 1). The quays of the harbor form a jetty on a peninsula characterized by very active coastal sediment transport processes. The 400 m long jetty was extended in 1984-1985 (built in 1950-s) and effectively blocked most of the natural coastal sediment transport, causing significant erosion downstream. This has been confirmed by previous studies over 30 years.

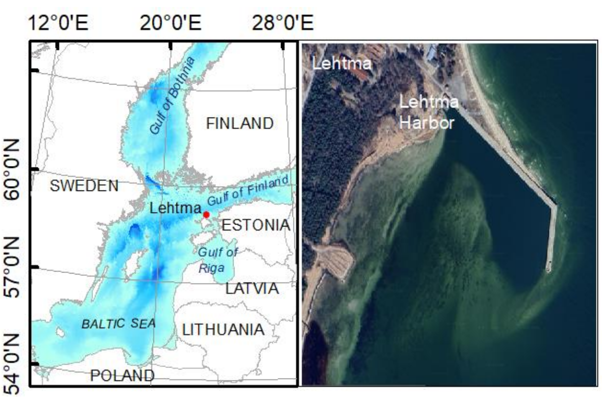

Figure 1 – Location of Lehtma harbor in the Baltic Sea.

DATA

Aerial- and ortophotos from 1955-2021 were analyzed. Shoreline and sand-bar locations change south from harbor were mapped and cross-shore profiles were measured to calculate the sediment volumes and characterize shore processes. Sand on the shore was coarser (median grain size mostly over 0.3 mm) while sand bar and sea bottom samples consisted of fine sand (median grain size just below 0.2 mm).

Near-bottom hydrodynamic parameters (flow speed and direction) were measured at 1 Hz sampling rate from October 2017 to May 2018 using Marotte HS current meters (http://www.marinegeophysics.com.au/current-meter/). Six instruments were placed on the seafloor (Figure 2). Time series lengths recorded by individual instruments varied somewhat depending on the seabed conditions and battery life.

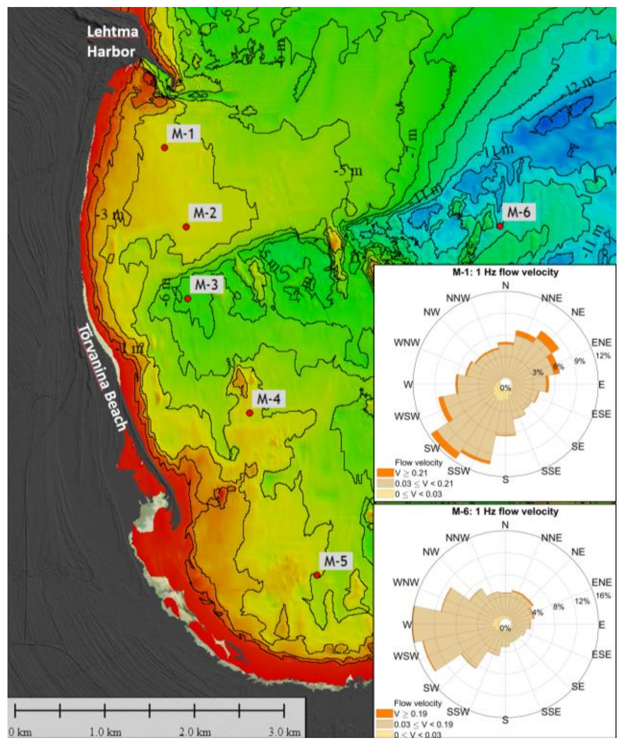

Figure 2 – Coastline configuration and near-shore bathymetry of the study area. Red dots (M-1 to M-6) mark the locations of seafloor current meters. Inset panels present rose diagrams of measured current parameters during 2017-2018 season. Flow velocities are given in m/s.

We used wave data modelled with SWAN and forced with modelled ERA-5 winds for 1991-2021 (Giudici et al., 2023). The first level of three level nested grid had a resolution of 3 nmi and its cell node was located approximately 2 km NE from Lehtma harbor. The Bathymetry (resolution 7…45 m) was provided by Estonian Transport Administration. Water levels and winds were measured at Heltermaa (30 km away in SE).

We applied two level grid system built with Delft3D modules which employed boundary data of modelled waves and measured sea levels at Heltermaa. The first grid (WAVE) covered Lehtma and adjacent bay (area 13 × 12 km, resolution 100 m). The second grid (FLOW) covered a smaller area (2.3 × 4.5 km, resolution 14…23 m. FLOW was forced with the results of waves at its boundaries (water level and Neumann type of boundaries).

ANALYSIS OF COASTAL PROCESSES

Previous and current investigations suggest that the average sand transport rate along the shoreline is 1300-1600 m^3/year. Additionally, similar amount (1200 m^3) of sand is moving on the sand bars in the southern nearshore sea. There is no major sand movement from extensive sandy shoal in the southern shallow water and beach.

Construction and extension of the jetty has caused major sediment deficit downstream, extending over 4.5 km to the south from the harbor. Largest erosion was registered 3.5 km south from jetty where the shoreline has receded up to 68 m during 1955-2021. The seaward border of nearshore sandbars (at approx. 2 m isobaths) has moved up to 130 m towards the shoreline making the coastal slope steeper and allowing larger waves to reach closer to the shore. Today the shore is very narrow (some places less than 10 m), foot of the coastal scarp is often located 0.5-1 m above mean sea level and storm waves reach the coastal scarp number of times every year.

The measured flow speed and direction were compared with wind records at Heltermaa approx. 30 km SE of Lehtma harbor and modelled waves. Although the agreement between different datasets was generally good, significant discrepancies occasionally occurred. In particular, the differences in directions were somewhat challenging to explain.

NUMERICAL MODELLING

For modelling the currents at specific time frames, we employed instantaneous wave and sea level data. For the sake of brevity, we modelled short discreet periods where higher velocities at different measurement points were noted. The results were delivered with 5 min time step.

The comparison between modelled and measured velocities showed moderate correlation and minor differences. The measured values were volatile, while modelled results were more stable. The results with directions were more volatile. As explanations of these discrepancies were somewhat ambiguous, we decided to test the model by trying to reproduce the sediment movement patterns.

For modelling the sediment transport, the modelled wave spectrum was grouped into different classes based on the significant wave heights and directions. The dominant classes in terms of the wave energy distribution were then modelled separately. The resulting sediment transport patterns were summed up considering the frequency of wave heights of classes. This simplified approach does not consider the sequence of processes, but is qualitatively replicating the sediment transport surprisingly well. In order to validate this approach, we used two bathymetry maps in 2021 and 2022 where accumulation process at the spit of sand in the end of the jetty was clearly seen. The modelled wave climate only during this period was considered. The observed and modelled data agreed reasonably well and we continued to investigate sediment transport in different dumping cases which were used in environmental impact assessment study.

The wave climate of 30-years was used in the above described method to select dominant classes. Three different dumping locations were qualitatively analyzed. The analysis showed that dumping sediments into relatively shallow water (3-5 m) south of the harbor had small effect on shoreline as most of the dumped sand moved directly southwards. Placing the dredged sand onto shore or nearby shallow water seafloor (less than 1 m water depth) has clear positive effect in terms of protecting the shoreline as sand is not moving away so fast (Figure 3).

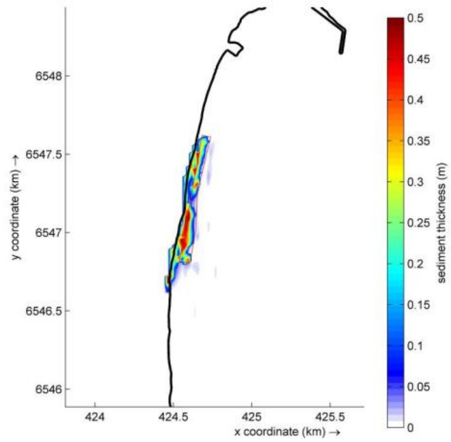

Figure 3 – Thickness of the dumped sand after 6 months has changed very little. The initial area was below the colored area on the map and the initial sand thickness was 0.5 m. The waves approached from NE.

CONCLUSION

Jetty construction and dredging at Lehtma harbor have caused sediment deficit downstream in the order of 2500 m^3/year. Compared to the open ocean coasts with abundant sediment availability, it appears that even small construction at the shoreline may disrupt coastal processes in very large areas in the Baltic Sea e.g. in our study area the erosion extended 4.5 km down-drift while the largest erosion was reported 3.5 km from the jetty. The general shortage of loose (sandy) sediments in the coastal system is due to the fact that new sediment is derived only by coastal erosion of old beach ridges and sand dunes. This creates a delicate dynamic balance of coastal sediment budget which makes our coasts very vulnerable to disruptions in alongshore sediment supply upstream. Hence, even relatively minor coastal structures, let alone large jetties such as at Lehtma harbor, may trigger erosion many kilometers away.

Reconciliation of measured flow speed and direction with winds, waves and modelled currents is challenging. Specific care must be placed on carefully examining different conditions and specifics of individual locations. Modelling sediment transport based on dominant classes of wave climate yields good results that are validated with bathymetric measurements and analysis of coastline.

REFERENCES

Giudici, Jankowski, Männikus, Najafzadeh, Suursaar, Soomere (2023): A comparison of Baltic Sea wave properties simulated using two modelled wind data sets. Estuarine, Coastal and Shelf Science, ELSEVIER, VOL 209.