Bed form dynamics in relation to headwater discharge and human influences in the tidal Elbe river, Germany

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Abstract
The major part of the navigation channel in the tidal Elbe river in Germany is covered with bed form structures. When increasing in height, these structures impair the safety of navigation and therefore have to be eliminated by dredging or water injection procedures. Hence it is important for river managers that the understanding of bed form dynamics is improved. Therefore we analyzed eleven echo-sounding datasets from March to August 2010 during different headwater discharge with the Rheno Bedform Tracking software. In our study area near St. Margarethen we detected over 10.000 individual bed form structures with an average height of 2m and an average length of 82m. Results of the bed form height and length do not show correlation with headwater discharge. But we identified a correlation between migration rate and headwater discharge. Using the example of one individual bed form structure we were able to monitor the re-development of this structure after it has been eliminated by water injection procedure. It could not be established whether sediment supply on relocation sites close to the navigation channel in the study area has an influence on growth rate of bed form structures in the navigation channel.

1. INTRODUCTION

The tidal Elbe river is the largest estuary at the German North Sea coast and it is an important waterway connecting the Port of Hamburg with the North Sea. To maintain the safety of navigational purpose and a certain navigational depth the system is frequently dredged since the last Elbe channel adjustment in 1999. The major part of the navigation channel in the tidal Elbe river is covered with bed form structures. When increasing in height these structures impair the safety of navigation, therefore the bed form crests have to be eliminated by dredging or water injection procedures. In 2010 about 36% of all water injection procedures in the tidal Elbe river were carried out between Elbe-km 680 and 690, where our study area is located. There are only a few studies on bed form dynamics having conducted a regional focus on the tidal Elbe river (Vollmers and Wolf, 1969; Nasner,1974; Dammschneider, 1983; Möhl, 1996 and Zorndt et al., 2011). Nasner (1974) for example analyzed echo-sounding data between Elbe-km 624.4 and 624.7 in an area of the Port of Hamburg with an average bed form height of 1.15m and bed form length of 21.5m. But to a large extend all these relevant reports except that from Zorndt et al. (2011) where done with former echo-sounding techniques. Study area of Zorndt et al. (2011) was a 3km long river section directly downstream of the Port of Hamburg. For the entire study period between 1995 and 2010 they determined an average bed form height and length of 1.8m and 49m. However, in the tidal Elbe is still a lack of studies with regional focus especially in more downstream regions. To improve sediment management strategies and to maintenance the navigational depth river managers need better answers to questions such as: (I) What is the geometry and the dynamic of the bed form structures, (II) What is the exact impact of headwater discharge on the rate of increase in bed form height. (III) Is there an impact of relocation sites on bed form dynamics?. To answer these questions river managers at least require an semi-automatic method to analyse geometry and migration of bed forms in an operational way. This case study is investigating the bed form dynamics in a river section of the tidal Elbe near St. Margarethen.

Flemming (2000) mentioned, that in deep rivers bed form growth is not limited by water depth and that bed forms will continue to grow in response to increase in mean flow velocity until a critical suspension threshold for a given grain size is reached. For the study presented here no velocity measurements are available. Zorndt et al. (2011) determined that headwater discharge is strong enough to alter tidal asymmetry and outweighed influence of the tides. Therefore a particular focus of our analysis is the impact of headwater discharge and the impact of water injection procedures (as a human influence factor) on bed form structures in the study area near St. Margarethen.

2. STUDY AREA

The Elbe river with its length of 1.094km is one of the major rivers of central Europe and originates in the Krkonose Mountains in the northern Czech Republic before transverses Germany and enters the North Sea at Cuxhaven (IKSE, 2005). The tidal Elbe river extends from the weir in Geesthacht (Elbe-km 585.9), which is the border between the tidal and the non-tidal part of the river Elbe, to the mouth at Cuxhaven and has a total length of about 140km. The study area is located in the navigation channel in the river bend near St. Margarethen between Elbe-km 685.4 and 689.9 about 60km downstream of the Port of Hamburg (figure 1). The study area has a length of 4300m and a width of 450m. The area is characterized by semi-diurnal tides with a distinct diurnal asymmetry and classified as upper meso- to lower macro-tidal with a maximum tidal range up to 4m at spring tidal conditions (Kappenberg and Fanger, 2007). The river width between the mean high tide level is 2.6 to 2km at the location site. The navigation channel of the tidal Elbe is frequently dredged and the dredged sediments are given back to the river in so-called relocation sites. Major relocation sites are located on both sides next to the navigation channel in the study area (figure 1).

3. DATASETS

5.1. Echo-sounding data

Within the navigational channel the German Federal Waterways and Shipping Administration carries out hydrographical measurements to achieve changes in bathymetry. The survey vessels are equipped with Kongsberg company multi-beam sonar (EM 3002). To determine bed form structures in the study area, we analyzed eleven bed level measurements between 01.03.2010 and 16.08.2010 (table 1). The measurements were conducted during different headwater discharge and tides. The use of a precise differential global positioning system leads to accurate surveying. The point density of the echo-sounding measurements is approximately one point per m^2.

table 1. Overview over evaluated echo-sounding measurements, belonging headwater discharge and determined mean bed from heights and length.

date	headwater discharge [m3.s-1]	bed form height [m]	bed form length [m]
01.03.2010	1004	1,99	70,82
09.03.2010	1874	2,30	91,45
31.03.2010	1614	2,16	87,82
28.04.2010	741	1,81	75,75
10.05.2010	646	1,86	71,10
31.05.2010	920	2,29	89,02
15.06.2010	1370	2,01	76,88
30.06.2010	572	2,44	86,93
12.07.2010	371	2,55	86,14
04.08.2010	519	2,66	84,82
16.08.2010	1296	2,48	83,00

5.2. Headwater discharge

The headwater discharge from the inland river catchment into the tidal Elbe river is measured at the last gauge upstream of the weir Geesthacht at Neu Darchau (Elbe-km 536.4). The headwater discharge is given by means of daily values. The mean headwater discharge amounts 916.8$m^3.s^{-1}$ in 2010. During study period a peak of 1870$m^3.s^{-1}$ occurred on 09.03.2010 and a minimum of 269 $m^3.s^{-1}$ on 22.07.2010. The headwater discharge belonging to each echo-sounding measurement is listed in table 1.

5.3. Bed sediments

The bed sediments in the navigation channel consists mainly of fine and middle sand fractions (BfG, 2012). Based on dataset from 2005, provided by the German Federal Waterways Engineering and Research Institute, in the study area an average grain size distribution was determined with 4% coarse sand, 27% middle sand, 43% fine sand and 26% silt and clay fractions.

5.4. Dredging and supply

In 2010 the German Federal Water and Shipping Administration has supplied about 2.5 Mio m^3 to the relocation sites near St. Margarethen, a substantial part of 47% of this was relocated within the whole April 2010. Depending on the origin of the dredged material the supplied sediments were covering a wide range of fractions: silt, fine sand and middle sand. When being released from the hopper dredger most of the silty sediments are expected to remain in suspension and drift with the current. For coarser fractions, mainly middle sand, are assumed that they accumulate on the river bed, afterwards they attend in bed-load transport and get in the navigation channel in some places (BfG, 2010). In the study period between March and August 2010 about two to three times a month water injection procedures were carried out in the navigation channel to eliminate individual bed form crests. Due to ice drift no water injection procedures take place during February (Qrefa-Sander, WSA Hamburg, pers. comm.).

4. METHODS

5.1. History

A first version of the dunetracking software DT2D (Dune Tracking in 2 Dimensions) was launched in 1997. A final version of the program, called DT2D 3, was released in 2000 (Wesseling & Wilbers, 2000) and was successfully applied in a large number of studies for the quantification of transport rates in Dutch rivers (e.g. Wilbers, 2004; Frings, 2005a, 2005b; Wilbers and Ten Brinke, 2003; Frings and Kleinhans, 2008). In 2007 the German Federal Institute of Hydrology expressed the wish to convert DT2D into a tool for operational management, which led to a completely new development of the software now being called Rheno Bedfrom Tracking (Rheno BT). Refer to Frings (2011) for further readings about the software.

5.2. Bed form analyses with Rheno BT

Rheno BT software detects bed form structures in echo-sounding data. Data input (I) are three-dimensional echo-sounding data, which represent the height characteristics of the river bed. Using Rheno BT software we could (II) indicate bed forms, (III) calculate bed form properties and finally (IV) determine the bed form migration between two consecutive measurements. First of all, we import the three-dimensional bed-elevation data, after that Rheno BT calculates two-dimensional bed-elevation profiles, called BEPs to the left and to the right of the used tracking axis, in our case in a distance of every 20m. This is executed in two steps and continues as long as the number of points contributing to the BEP did not drop below a certain threshold. Points which contribute in a circuit of 5m to one BEPs are selected. Afterwards the points are projected to BEP separated in sections. In the second part bed forms are identified downstream in two-dimensional longitudinal direction. In order to achieve information about spatial variability Rheno identifies bed forms for several BEPs located next to each other in lateral direction. A periodogram is used to provide us the possibility to determine a window length for the moving average line therefore a power is plotted against distance. The larger the power, the more suitable is the distance as window length. For our analyses we used a window length of 120m and a zero down crossing factor of 0.3m prevents noise to be recognized as bed forms and skip the smaller bed forms. In the third part Rheno BT provides the determination of the bed form properties of the identified bed forms like bed form height, bed form length, bed form area and the shape factor. The shape factor determines the similarity between an identified bed form and a related idealized triangle. In the fourth part we determined the bed form migration based on our three-dimensional bed-elevation data between two consecutive BEPs using a cross correlation procedure with a maximum migration distance of 60 m.

5.3. Post-processing

The post-processing is carried out in the same way for each dataset. Average point density in Rheno BT was determined at one point per m^2. Reflecting the work of Wilbers and Ten Brinke (2003) we supposed that bed form length could determined accurate when the bed form consists at least of ten points. Therefore we deleted bed forms with a length shorter than 10m from our dataset. Also 2% of the largest bed forms were selected and deleted as outliers. For each dataset and BEP a mean bed form height and length is calculated and all BEPs in the same distance to tracking axis were averaged. Migration rate was calculated using the migration distance which was computed in Rheno BT between seven echo-sounding datasets and dividing it through time interval between the two datasets. Migration rate is plotted against the headwater discharge which is averaged over the corresponding time period. Afterwards we compared our migration rate depending on headwater discharge with results from Nasner (1974) and Zorndt et al. (2011). To describe development of an individual bed forms after water injection, we monitored height of bed form crest in each dataset after the cut back of the crest. We determined a rate of increase by dividing increase of height of the bed form through time interval.

5. RESULTS

5.1. Geometry

The averaged bed form geometry over time and space is about 2.2m in height and 82.2m in length. Figure 2 shows mean bed form heights and lengths averaged for BEPs in the same distance to tracking axis. Bed form length varies between 71m and 95m with the longest bed forms in the middle of the navigation channel close to the tracking axis (0). Minimum bed form lengths were observed in the north eastern part of the navigation channel. Bed form heights vary between 1.7m in the south western part and 2.6m close to the tracking axis. In south western part of the tracking axis the bed forms are not as high as on the north eastern part.

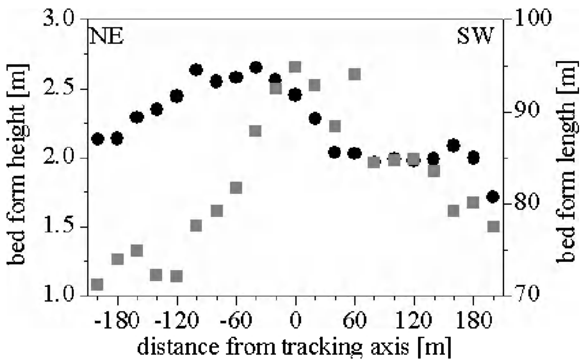

Figure 2. Average bed form height and length in cross section of the navigation channel .

5.2. Geometry and discharge

The mean bed form height and length for each dataset is plotted against headwater discharge in figures 3. There is neither a clear correlation between headwater discharge and bed form height nor between headwater discharge and bed form length.

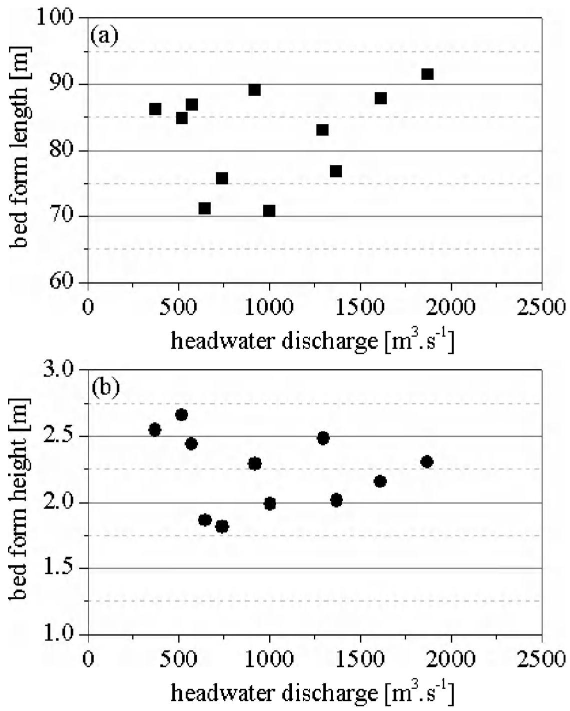

Figure 3. Averaged bed form length (a) and height (b) over time and space against headwater discharge.

5.3. Migration

The migration rate is plotted against headwater discharge in figure 4. A good correlation can be found between these two factors. In the study area near St. Margarethen migration rate was about 0.6 $m.day^{-1}$ in the direction of the North Sea when headwater discharge was higher than $1200m^3.s^{-1}$. During periods of headwater discharge less than 500 $m^3.s^{-1}$ the migration rate is close to zero with 0.1 $m.day^{-1}$ in the direction of the North Sea with 0.1 $m.day^{-1}$. Figure 4 also shows our results together with the migration rates determined by Naser (1974) and Zorndt et al.(2011). All studies show a good correlation between migration rate and migration direction with headwater discharge.

To highlight the correlation we used a linear regression. For each location and headwater discharge there might be a point of reversal where bed forms change their migration direction.

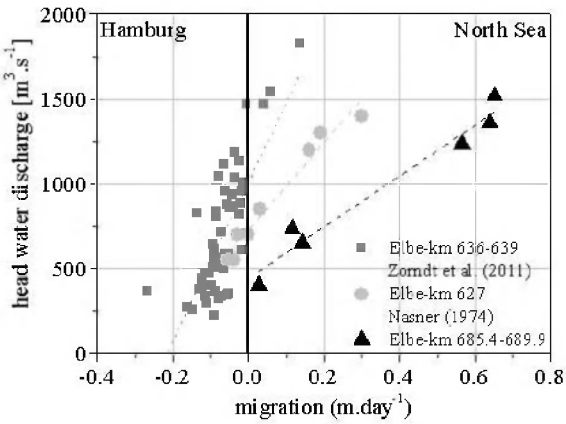

Figure 4. Averaged bed form length (a) and height (b) over time and space against headwater discharge

5.4. Bed form height after water injection

Figure 5 and figure 6 refers to the same individual bed form structure, located 180m northward of the tracking axis within the navigation channel. To maintain the required navigational water depth of -13.9m SKN the crests of these structures were eliminated by water injection procedure on 23.04.2010. The following echo-sounding measurement on 28.04.2010 shows that the crest were cut back from -13.25m SKN to -14.65m SKN. On 12.07.2010 within a few months this individual bed form was observed to reshape and to regain almost its previous height with -13.68m SKN (figure 5).

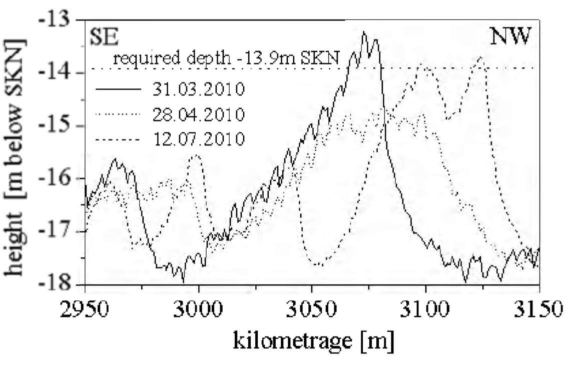

Figure 5. Development of a individual bed form, 180m northward of tracking axis after a water injection.

Figure 6 focuses only the bed form crest. During low headwater discharge the crest increase and during high headwater discharge the crest decrease in height.

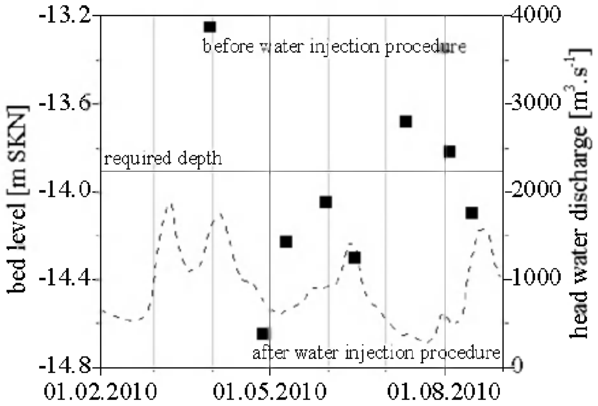

Figure 6. Reshape of bed form crest in relation to headwater discharge after the water injection.

6. DISCUSSION

The applied Rheno BT software and therefore the dune tracking method which are used to analyse bed form structures in the presented study area near St. Margarethen is a reliable tool to determine bed form geometry, migration distance and direction between two consecutive echo-sounding datasets. Rheno BT is a functional and stable software and provides proper and reproducible datasets.

The presented dataset from March to August 2010 covered a period with a range from high headwater discharge in March to low headwater discharge in July. Although the spatial resolution of the dataset is not very high, we were able to determine bed form geometry, migration rate and distance for the period between March and August 2010. We also got an impression of the development of individual bed form structures after water injection procedures.

We found out that geometry of bed form structures varies across the width of the navigation channel in our study area. This seems reliable because our study area is located in a river bend with the inner bend in south western part and outer bend in north eastern part. It is likely that there are different velocities in cross sectional area and therefore bed form height might be higher in north eastern part than in south western part of the navigation channel. Unfortunately we have no in-situ velocity measurements in the study area to check the assumption.

A correlation between bed form geometry and headwater discharge could not found. Probably bed form structures not yet achieved a equilibrium because of the constantly changing hydrological influences such as current direction and current velocity, headwater discharge or even because of human interventions.

Almost all bed forms in the study area show a asymmetry in shape, which indicates a migration in direction towards the North Sea. In the study area we found out that even during low headwater discharge the residual bed form migration is directed downstream. In river sections located more upstream close to the Port of Hamburg, where the study of Nasner (1974) was conducted, bed form structures migrate upstream during headwater discharge smaller than $700m^3.s^{-1}$ and downstream during higher discharge (Nasner, 1974). Zorndt et al. (2011) presented a dataset in a flood dominant area downstream of the Port of Hamburg where the bed form migration direction is upstream except during high discharge over 1468 $m^3.s^{-1}$. However, all three studies show the same trends: (I) Bed form migration rate decrease downstream to the North Sea with a decrease in headwater discharge, (II) each study determined a point where bed form migration direction is being turned or becomes almost zero. We suggest that this reversal point is depended on the location in the tidal Elbe river, flood dominance in the river section and headwater discharge.

If we want to correlate bed form geometry to human influences like sediment supply in relocation sites and water injection activities, there is no dataset which is not affected by human influence except that from 01.03.2010, because in February there was ice in the water and therefore no water injection and no artificial supply took place in this area. We know from our experience that individual bed forms especially close to the border of the navigation channel increase in height and impair the safety for navigational purpose. We suggest that the reason for this is the artificial supply on the relocation sites close to the navigation channel during the entire year. The sediments which are coarser than a particular grain size are transported into the channel and participate in the sediment transport and contribute by building bed form structures. We cannot document this with data at the moment, but we know that water injection procedures in the study area were carried out more and more and the frequency increase.

But we were able to document the development of an individual bed form structure after a water injection procedure in April 2010 in the navigation channel which was showed in chapter 5.4. Bed form structures generate to their original height in only a few month. We suggest that this development is a kind of circulation process, because sediments were re-arranged and not removed during water injection procedures and it will not end until water injection procedure stops. But we also mentioned that the observed bed form crest decrease for a while during high headwater discharge, although there was no clear correlation between bed form geometry and headwater discharge in our dataset.

7. CONCLUSION

In this study we applied Rheno BT software as an operational tool for river managers to determine bed form geometry, migration direction and migration rate. The computed results were further investigated to appoint the influence of headwater discharge and water injection procedures on bed form geometry, migration rate and direction in the tidal Elbe river in the study area near St. Margarethen. In total eleven measurements between March and August 2010 were analysed. Moreover daily values of discharge from the gauge Neu Darchau, sediment samples from relocation sites and the navigation channel and information on dredging, artificial supply and water injection procedures were available.

Within the study area 10.000 individual bed form structures with an average bed form height and bed form length of 2.2m and 82.2m were detected. But bed form geometry varies over the navigation channel and over time due to natural fluctuations, to river morphology and to water injection procedures. Therefore neither bed form height nor bed form length in our study area correlate with headwater discharge.

The determined migration rate depends on headwater discharge, we found a migration rate of

0.6m.day^{-1} during discharge >1200m^{3}s^{-1} and a migration rate smaller than 0.2m.day^{-1} during low discharge <700m^3.s^{-1}. Studies by Nasner (1974) and Zorndt et al. (2011) show for migration rate results in the same order of magnitude.

We found out that individual bed form structures only need a few month to regain its previous height before their elimination by water injection procedures.

In future research, the development of bed forms after water injection and the development of the crest and troughs will studied in more detail. In addition the results of this study will be used for further calculations of the sediment transport. Modeller are able to use the results to reconstruct the thickness of the active layer and to calculate spatial variations in bed form-related to hydraulic roughness

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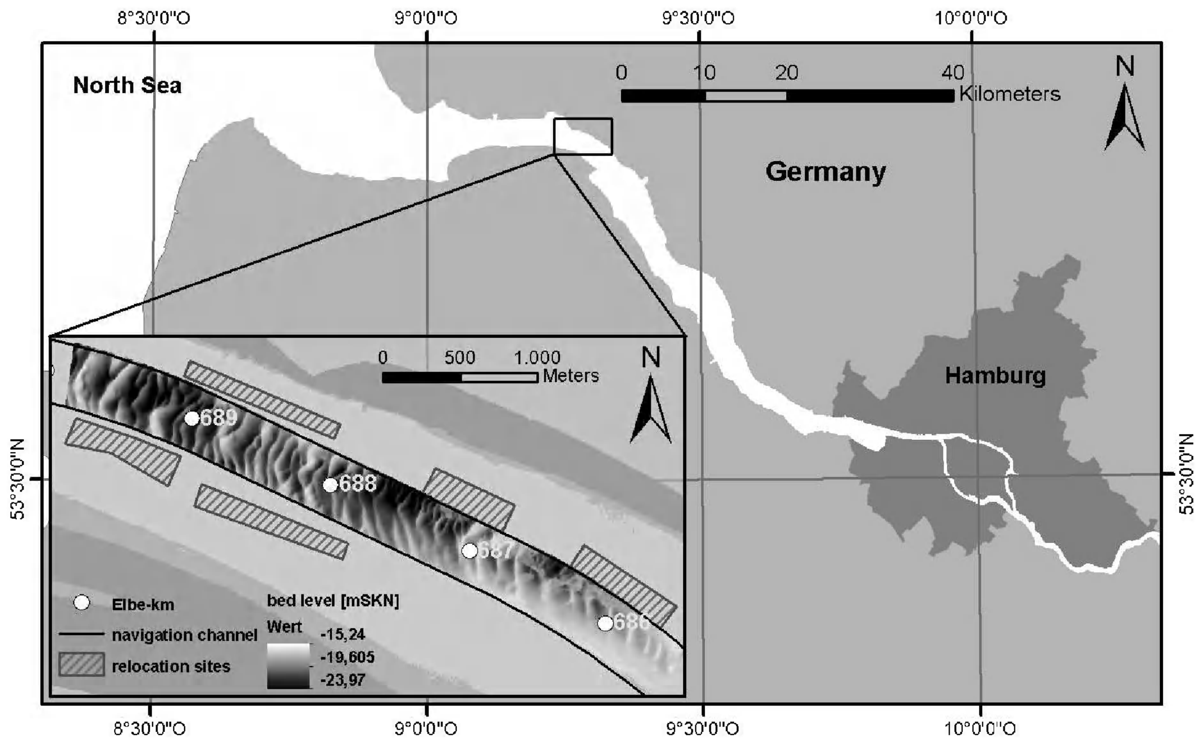

Figure 1. The tidal Elbe river and the study area near St. Margarethen between Elbe-km 685.4 and 689.9.