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DECADAL EVOLUTION OF TIDAL CHANNEL HYPSOMETRY IN THE OUTER WESER ESTUARY, GERMANY

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Abstract

This study focuses on the morphodynamics of the Fedderwarder Priel tidal channel, located in the Outer Weser estuary (German Bight). Tidal channels and adjacent flats are highly dynamic systems whose morphologic evolution is mainly driven by tidal and wind forcings. These coastal systems react to changing hydrodynamic conditions in various time and length scales. Annual digital elevation models are available covering the time period from 1998 to 2016. We used hypsometries and vertical dynamic trends to analyze and visualize the morphologic evolution of the Fedderwarder Priel and adjacent tidal channels. Besides evaluating the applied methods sediment accumulation on intertidal flats was assessed. The findings indicate that tidal flats accrete with a rate exceeding sea level rise. Results are discussed with respect to further studies in the German Bight.

Key words: tidal flat, hypsometry, morphology, time-series, vertical dynamic trend

1. Introduction

The Weser Estuary is part of the world heritage Wadden Sea, a unique ecosystem of tidal flats and barrier islands extending from the Netherlands to Denmark (Elias et al., 2012). The cone-shaped Outer Weser Estuary mainly consists of large areas of intertidal flats, several tidal channels, and an artificially maintained navigational channel. The mean tidal range in the estuary is around 2.8 to 3.8m. The estuary is of highly economic importance for the ports located along the Weser River (e.g. Bremerhaven, Nordenham, Brake, Bremen). The coastline and riverbanks are diked, protecting the hinterland against storm floods. In order to maintain economic efficiency, and to keep the Wadden Sea ecosystem in a stable state, a deep understanding of the sediment transport characteristics and budget, as well as their impact on the morphology is crucial.

The main shipping channel in the Outer Weser is the Fedderwarder Fahrwasser, which is kept in its current position by dredging and river training structures. One of the main tidal channels is the Fedderwarder Priel (FWP), which branches off from the shipping channel to the south (Weser-KM 90) (Figure 1). The Fedderwarder Priel has an extent of more than 10km in length and around 2km in width. The depth of the FWP main channel ranges from 5 to 10 meters with a maximum depth of 14m, and is surrounded by extensive tidal flats. The Langlütjendamm training wall was built in 1934 at the outlet of the FWP to the Weser. The latest deepening of the nearby navigational channel was performed from 1998 to 1999.

Tidal channels constitute a pathway for the tidal wave to propagate towards the tidal flat areas surrounding the channel. The system of flats and channels is undergoing a constant morphologic evolution through sediment redistribution. The bed morphology is adapting to changes in hydrodynamics, such as an increased tidal range (Hofstede et al., 2016), or asymmetry in the tidal wave (Dronkers, 1986). Investigations on the drivers of tidal channel and estuarine morphodynamics have been performed in different study areas before (Friedrichs, 2012; Herrling and Winter, 2016, 2014; Hibma et al., 2004; Le Hir et al., 2000). Le Hir et al. (2000) reviewed tidal flat hydrodynamics and named the tide, meteorological events, and waves as the main physical forcings. Hibma et al. (2004) combined observations and process-based models to describe macro- and mesoscale estuarine morphodynamics, such as channel shoal patterns.

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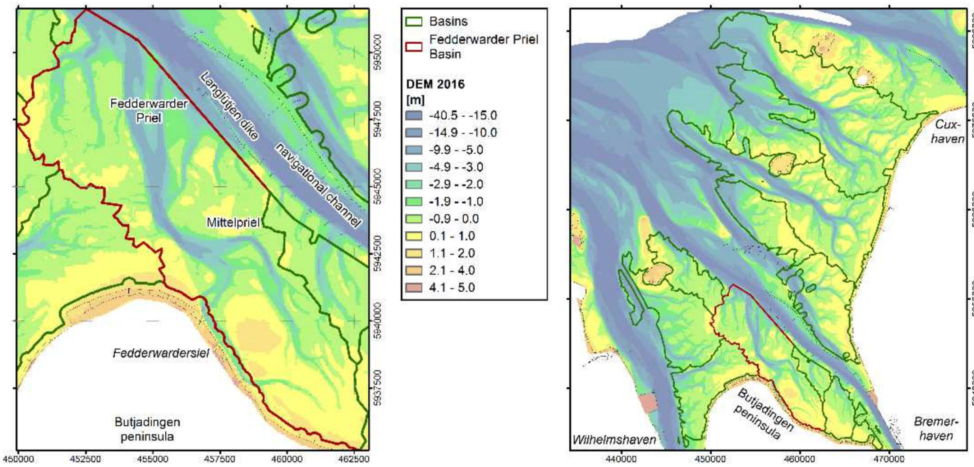

Figure 1. Basins created from a watershed analysis. Anthropogenic structures (groins, dikes, waterways, dredging/dumping sites) are cropped including a buffer of 200 meter.

Based on numerical modelling results it has been shown that the resilience of tidal basins against sea level rise can be related to the mean tidal range. The resilience is pronounced by accumulation of sediment on the intertidal flats, keeping the relative height to the mean tidal range on a constant level (Hofstede et al., 2016).

A higher mean sea level leads to a longer time of tidal inundation, which is one of the parameters that determine the sediment accumulation on the intertidal flats (Hofstede, 2002). The height of the tidal flats adapts to reach an equilibrium relative to the mean sea level (FitzGerald et al., 2008). The induced sediment accumulation, along with an increase in the intertidal height, composes a negative feedback loop (Hofstede, 2002; Hunt et al., 2015).

The hypsometry of tidal basins and their respective channel shoal patterns reveal the maturity of the system. The channel hypsometry describes the relation between surface area and depth, and has been frequently used to characterize tidal basins and predominant forcings. Tidal basins can be classified by the concavity of their hypsometric area-depth curve. Convex-up hypsometries indicate a higher degree of infilling (higher maturity), and a larger tidal influence (Hunt et al., 2015).

Morpho- and hydrodynamics are essential parts of the estuarine environment. However, the morphodynamics of tidal channels in the Outer Weser estuary are still insufficiently understood. For a detailed morphodynamic analysis, the Fedderwarder Priel, located in the Outer Weser estuary, is the main focus area of this study. The variation of tidal basin hypsometry is analyzed over an 18 year time period based on sedimentation-erosion profiles and the vertical dynamic trend (VDT).

2. Methodology

2.1. Data basis

The study is based on a time series of raster-based digital elevation models (DEM). The dataset was provided by the Bundesamt für Seeschifffahrt und Hydrographie, covering the German Bight in a 50x50m grid for the time period 1998 to 2016 (Valerius et al., 2013) in an annual resolution. DEMs were produced by combining data from multiple campaigns and different types of measuring devices, such as airborne laserscanning, single- and multibeam echo sounder. Tidal flats were measured less frequently than channels and official waterways. Additionally, the dataset was created by applying a spatio-temporal interpolation method (Milbradt et al., 2015). For calculating vertical dynamic trends, temporally interpolated data was filtered by applying a threshold of 0.5 decimal years.

2.2. Vertical Dynamic Trend

The evolution of channel shoal systems is analyzed in the geographic information system ArcGIS. For each of the overlapping grid cells in the annual DEMs a vertical dynamic trend (VDT) is calculated, which is based on a linear regression analysis (Figure 2) (Van Dijk et al., 2012). Instead of considering only two points in time the vertical dynamic trend represents constant linear evolution, with a control on its statistical significance.

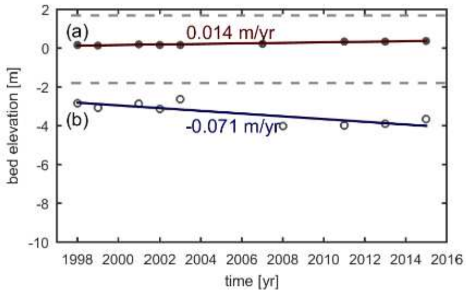

Figure 2.Vertical dynamic trend (VDT), showing erosion (a) and deposition (b) of two exemplary grid cells in the DEMs.

The vertical dynamic trends were calculated in ArcGIS. A toolbox was designed to allow for a fast calculation of trends for different time intervals and locations. The slope of the VDT is calculated by

$$b_{zt} = r_{tz} \frac{S_z}{S_t} \tag{1}$$

with

$$r_{tz} = \frac{S_{tz}}{S_t S_z} \tag{2}$$

being the respective correlation coefficient and S_t and S_z the empirical standard deviation for the depth (z) and time (t) values, as well as the empiric covariance S_{tz} (Papula, 2008, p. 621). The reliability of the vertical dynamic trends is determined by means of the correlation coefficient (r_{tz}). The significance of the absolute value of the correlation coefficient is resolved with the help of a Student's t test:

$$\mathrm{t} = |r_{tz}| * \sqrt{\frac{n-2}{1-{r_{tz}}^2}} \tag{3}$$

The correlation is significant when t is smaller than the Student's t distribution ($t_{(0.975,n-2)}$) (Faes, 2017; Papula, 2008, p. 742).

The resulting grid of VDTs shows constant bed level accretion (positive values) or erosion (negative). Spatial distribution patterns may reveal horizontal movement of morphologic elements (e.g. tidal channel migration). The trends systematically vary regarding depth and location. An average value of all vertical dynamic trends was calculated for the intertidal and subtidal area, representing the mean vertical bed accretion rate.

2.3. Watershed analysis

Based on the DEM covering the year 2012, a mask was created, which covers subtidal (>-10m) and intertidal areas. Areas of and surrounding artificial structures, such as dikes, groins, cables, pipelines, navigational channel, as well as dredge- and dumping sites, were identified by means of a web map service provided by the BSH (Bundesamt für Seeschifffahrt und Hydrographie, 2017) and cropped with a buffer of 200 meter in all processing steps to lessen anthropogenic interferences.

In order to distinguish several tidal basins in the Outer Weser estuary (Figure 1) a watershed/basin analysis on the 2012 DEM was performed. The size of the 12 basins range from 6.4 to 176km², with an average of 60.0km². The determined basin polygons were combined with the crop-out mask defined before.

2.4. Mean tidal range and intertidal area

A hydrodynamic model of the Wadden Sea was applied to calculate the mean low/high water levels (MLW/MHW) of the German Bight for the first half year of 2012 (Chu et al., 2013). Intertidal mean low water levels were assigned by using a Euclidean allocation to the nearest deep water (<-5m) grid cell. The MLW/MHW values for each basin were averaged and used to determine the intertidal and subtidal surface areas, as well as intertidal sediment volumes.

2.5. Hypsometries and histograms

For the Fedderwarder Priel basins two hypsometric curves were calculated, which describe the distribution of surface area over depth, for the years 1998 and 2016. The hypsometric curves were calculated by using the cumulative sum of the DEM's histogram, which depicts the count of grid cells for the corresponding depth (bin size: 1cm, cell size: 50m). The difference between the two histograms reveals the net loss and gain over depth, referred to as sedimentation-erosion profile.

By using the equation given by Boon & Byrne (1981) it is possible to characterize the hypsometry as the relationship between the normalized surface area and depth:

$$\frac{a}{A} = \frac{G}{r+G(1-r)} \text{, and } G = (1-\frac{h}{H})^{\gamma} \tag{4}$$

A,H are the maximum surface area and the height interval. a is the surface area at a certain height h. Parameter r controls the basin curvature, and was set to $r = 0.01$. The volume below the hypsometric curve is expressed by the parameter γ, which can be used to characterize the curve. In addition, γ describes the concavity or convexity of the curve, giving insights on a possible tide or wave domination.

3. Results

3.1. Hypsometries, histograms and intertidal area

The hypsometry of tidal basins describes the surface area distribution over depth. For the Fedderwarder Priel basin the hypsometry has changed from 1998 to 2016 (Figure 3a). Both curves show a convex-up hypsometry from the deeper depth to the intertidal, while in the higher intertidal the curves are concave-up. The concavity parameter γ has changed from 3.23 to 3.00, which reveals that a shift towards more infilling has happened over the 18 years considered.

The differences in the hypsometry can be divided into several sections. In the deeper areas from -10m to -7m barely any difference is noticeable. In between -7 to -3.4m the hypsometric curve is characterized by increased values, indicating that relatively more surface area is situated below a depth of -3.4m in 2016. Above this depth the hypsometric curve has decreased values, which is indicative for an accumulation of sediment, as well as a relative extension of the shallower parts in the intertidal.

Similar to the hypsometric curves for 1998 and 2016 (Figure 3a) histograms can be derived as well, the difference of which is shown in Figure 3c. Less grid cells are present in the depth between -5.35 and -0.35m. The intervals are shifted as the hypsometry shows a cumulative curve only. It is safe to assume that sediment redistribution has occurred from this depth onto the tidal flats, where a net growth is visible (-0.35 – 1.75m). Moreover, the difference plot shows, that the intertidal is not exhibiting overall growth. The interval between mean low water (MLW) and -0.35m in 2016 makes up less surface area than in 1998, whereas the higher intertidal areas show clear growth. This development may indicate a steepening of tidal channels.

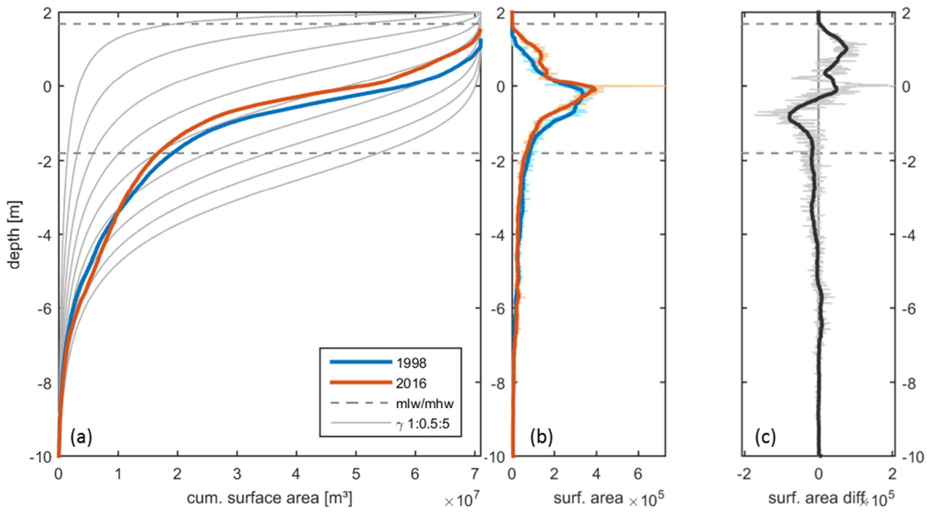

Figure 3. (a) Hypsometry of the Fedderwarder Priel (FWP) basin. (b) Histogram (surface area per bin size (0.01m)). (c) Sedimentation-erosion profile (difference between histograms).

Overall, the total intertidal surface area of the FWP experienced an extension of 4.1%, whereas the intertidal sediment volume gained 19.6%, which is comparable to a mean vertical bed accretion rate of 1.63cm/year (Table 1). This increase exceeds the current mean sea level rise values for the nearby gauge Cuxhaven (1993 to 2011: 3.7 ± 2.3mm/yr)(Wahl et al., 2013).

Table 1. Intertidal area and volume for the years 1998 and 2016.

Fedderwarder Priel	**interidal area**	**intertidal volume**	**area extension**	**volume gain**	**vertical bed accretion**
	[m²]	[m³]	[m²]	[m³]	[m/yr]
BSH 1998	5.01E+07	6.92E+07	2.10E+06	1.50E+07	0.0163
BSH 2016	5.22E+07	8.42E+07			

3.2. Vertical dynamic trend

The vertical dynamic trend (VDT) shows linear bed-level accretion or erosion for successive overlapping grid-cells in digital elevation models, which also can be interpreted in terms of channel migration. The vertical erosion and accretion rates for the analyzed period of 18 years (1998 – 2016) are up to 1.7 meters per year. The map is showing significant VDTs only, white areas indicate unreliable correlation coefficients. The reliability was determined based on the number of measurements and the Student's t-distribution. Patterns suggest a westward channel migration indicated by the blue and red stripes at the northern part of the Fedderwarder Priel, and an eastward channel migration in the Mittelpriel (Figure 4). The small white path between the opposing areas indicates a channel passing through, where sediment erosion is directly followed by deposition, hence removing a clear trend to either direction for the whole time span.

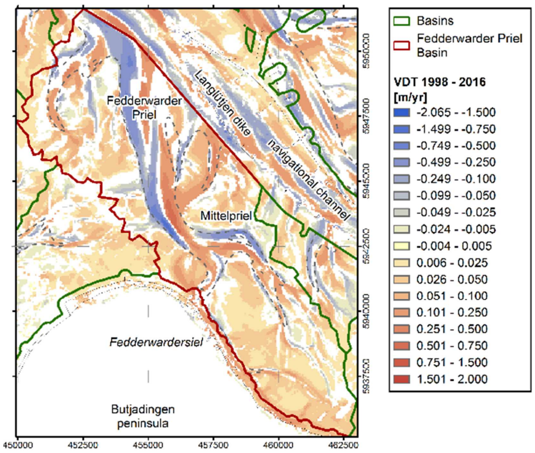

Figure 4. (a)Vertical dynamic trend (VDT) in the Fedderwarder Priel (FWP) from 1998 to 2016.

Besides the horizontal migration, a positive trend is noticeable in most of the tidal flats surrounding the channel-shoal system. Most tidal flats experience a constant accretion of sediments. The vertical dynamic trend ranges from 0.01 to 0.10m/year. The mean value of all VDTs in the Fedderwarder Priel intertidal area is 0.022m/year, whereas the subtidal area (>-10m) indicates a negative value of -0.008m/year, in accordance with the hypsometric analysis.

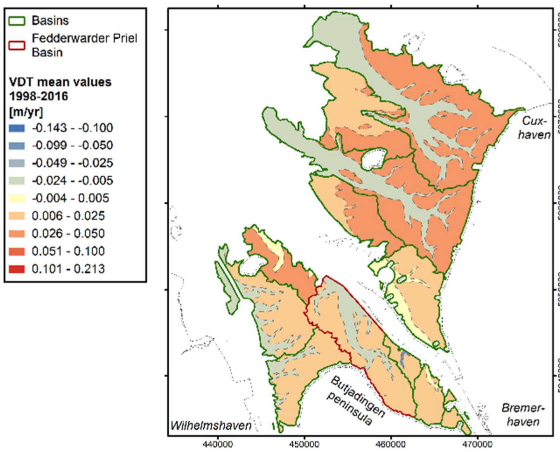

Figure 5. Mean values for vertical dynamic trends in the intertidal and subtidal areas of their respective basins. The dashed line depicts the (smoothed) border between intertidal and subtidal.

Although the absolute values from the VDT analysis differ from the calculated intertidal sediment volume gain they can be used to depict intertidal bed accretion in the adjacent basins (Figure 5). Positive mean vertical dynamic trends, as seen in the Fedderwarder Priel, express sediment accumulation. A negative value represents the opposite case (erosion). The basin shapes have been adjusted to ignore human constructions and interference with a buffer of 200 meter. By contemplating the Outer Weser estuary it is noticeable that all intertidal flats feature a positive mean vertical dynamic trend in the range from 0.9 to 4.3cm/yr, whereas a majority of the subtidal areas show a clear deepening (-5.0 to 1.9cm/yr).

4. Discussion

In this study we analyzed Outer Weser estuary morphodynamics by means of geoprocessing for the time-period 1998 to 2016. We used two methods to delineate the morphologic changes: a) hypsometries and b) the vertical dynamic trend.

The study is based on annual raster digital elevation models (DEMs) from the Bundesamt für Seeschifffahrt und Hydrographie. To achieve a comprehensive dataset, the DEMs were processed by merging multiple measurements, surveyed at different times, throughout the specified and adjacent years (Valerius et al., 2013). This involves uncertainties, since the precise calculation of trends and sediment transport rates relies on correct time differences. Seasonal differences in the morphology, e.g. induced by an increased number of storms in the winter months, are not considered in the DEMs and neither in this study. A spatio-temporal interpolation was used to create equal time intervals. The calculation of basin hypsometry is dependent on a spatially comprehensive dataset. Here, the impact of temporal interpolation is insignificant. However, the temporal interpolation leads to a severe distortion in the VDT. Hence, the temporally interpolated grid cells were removed for the application of this method. The datasets surely contain errors in terms of vertical measurement inaccuracies, which had to be neglected in this study because of a lack of information. With a resolution of 50m the raster-based DEMs cannot represent small scale morphologic features, such as small gullies and creeks. Still, by considering the extensive dataset with thousands of grid cells per basin, and by using statistical methodological approaches it was possible to depict the morphological evolution to a satisfactorily extent.

To differentiate between single morphologic elements (basins), a watershed analysis was performed on the 2012 DEM. Channel shoal systems are highly dynamic, as are the watersheds (Wang et al., 2013). The effect of shifting watersheds was not considered in this study. A mask was used to avoid direct signals of anthropogenic impact as far as possible. Thereby, groins, dykes, waterways, and dredged areas were cropped with a 200m buffer. The buffersize was chosen as a compromise between averting anthropogenic impact and loss of valuable and significant data. The study neither focuses on the impact of the most-recent Weser deepening that occurred in 1998, nor takes into account the maintenance dredging that is conducted in the Fedderwarder Fahrwasser near the Fedderwarder Priel.

The hypsometric curve describes the cumulative sum of all surface levels in the respective tidal basin. Results show clear shifts in the hypsometries of the observed basins. The shifts can be explained by sediment transport from the subtidal onto the intertidal areas. It indicates that tidal flats undergo bed level accretion. Furthermore, by observing the respective sedimentation-erosion profiles an extension of tidal flats is noticeable.

The hypsometry provides a possibility to classify the morphology by identifying the parameters fitting the model established by Boon & Byrne (1981). The shape of the hypsometry reveals whether tide (convex-up) or wave influence (concave-up) predominate. Long-term accretion in conjunction with a necessary sediment supply is also represented by a convex-up hypsometry (Friedrichs and Aubrey, 1996). As expected, the meso- to macro- tidal basins of the Outer Weser estuary show a convex-up hypsometry (Figure 3).

Ideally, the hypsometric curve describe a stable state, or dynamic equilibrium. Seasonal variances in hydrodynamics and individual storms may alter the hypsometry temporally, but basins return to their previous configuration afterwards (Hunt et al., 2015). However, by comparing two basin hypsometries and histograms, and combining the findings with the vertical dynamic trend, a clear trend of sediment accumulation in the intertidal is noticeable. An accumulation of sediment in the intertidal is linked to the prevailing flood dominance (Friedrichs, 2012; Hunt et al., 2015) and the positive net sediment supply in the German Bight and Outer Weser estuary (Eisma, 1998, p. 144). The findings correlate partly with Dissanayake's (2011) long term observations of the Ameland tidal inlet evolution in the Dutch Wadden Sea. A deepening of the deep areas and accretion in the shallow areas from 1930 to 2005 was observed. The trend in sediment accumulation on the tidal flats can be confirmed, but there is no significant deepening of the deep areas noticeable in the hypsometries. Moreover, our findings are able to confirm longer-term observation in the German Bight. Dieckmann (1987) presented hypsometries from 1936 to 1982 in the Meldorf Bight, 50 kilometers north-east of the Weser estuary. Sedimentation-erosion profiles of the Flakstrom basin showed a similar accumulation of sediment in the higher tidal flats that we found in the Fedderwarder Priel (Figure 3).

The hypsometries and sedimentation-erosion profiles were created for two single conditions (1998 and 2016). The vertical dynamic trend results from a linear regression analysis. It reveals that a significant, presumably linear trend exists. The trend is a good indicator for linear evolution in sediment erosion or deposition. Studies on the vertical dynamic trend were performed by van Dijk et al. (2012). Van Dijk et al. analyzed a large dataset of the Netherland Continental Shelf. The typical range of the dynamic trend was given by "absolute values of 0.1 to 0.35 m/yr with extremes up to 1.5m/yr" (Van Dijk et al., 2012) for the highly dynamic coastal zone. Even though the Weser estuary is not directly comparable to their study on the Netherland continental shelf, the findings are similar for areas in the Outer Weser estuary. In the Fedderwarder Priel (FWP) large areas easily exceed the 1.5m/yr range (Figure 4).

The VDT inhibits the application on non-linear morphodynamic elements. Channel shoal patterns like the FWP seldom follow a long-term linear vertical trend. Larger channel systems tend to oscillate, and smaller creeks and gullies may evolve and disappear in smaller time scales. The outcome of the VDT is highly dependent on the selected time scale and the temporal resolution. For the time period of 18 years (1998 to 2016), with a temporal resolution of up to one year, it was possible to detect vertical bed level accretion on the intertidal flats, as well as a significant migration of the FWP main channel in a westward direction (Figure 3).

A maximum of 12 overlapping DEMs were considered for the vertical dynamic trend analysis. The correlation coefficient specifies how well the bed level change over time can be expressed by the linear regression. A reliable correlation coefficient was chosen based on the Student's t-test for the VDT maps (Figure 4). However, for calculating mean intertidal sediment accumulation rates, all VDT were considered. This approach was chosen in order not to disregard areas that were measured less frequently.

Almost all basins show positive accretion rates in the intertidal area. Mean values range from 0.01 to 0.05m/yr in the Outer Weser estuary, which exceeds expected accretion rates resulting from the mean sea level rise (Cuxhaven: 3.7 ± 2.3mm/yr) (Wahl et al., 2013).

Hofstede (2002) conducted research in the German Bight on morphologic responses of tidal basins to a rise in mean sea level. According to his studies, changes in the tidal regime are the leading cause for long-term morphological changes in tidal basins. He argued that the higher water level and stronger tidal currents lead to sediment transport from the channels to the tidal flats. The longer tidal inundation allows sediment to accumulate on the tidal flats (Hofstede, 2002). This mechanism could also hold for the Outer Weser tidal flats. Hofstede elaborates that this leads to a negative feedback, as, in response to a rise in tidal flats, the time of tidal inundation decreases again (Hofstede, 2002). Since the vertical dynamic trend is based on a linear regression analysis we cannot make statements on a possible negative feedback loop and an associated reduction of the accretion rate on the intertidal flats. Moreover, the time period of DEMs in this study is 18 years and thereby not sufficient to make long-term statements (Dieckmann et al., 1987; Friedrichs, 2012).

The source of sediment are the tidal channels, which feature coarser material (Eisma, 1998, p. 137; Hofstede et al., 2016). In this study, no differentiation between intertidal salt marshes, mud flats and sand flats has been considered, all of which evolve differently under changing hydrodynamic conditions (Friedrichs, 2012). However, a classification of these environments can be crucial to a fundamental understanding of changes in the basin hypsometries in the Outer Weser estuary.

5. Conclusion

The presented results indicate that the intertidal flats in the Outer Weser estuary have experienced a linear accumulation of sediments in the past 18 years. The hypsometries and their respective sedimentation-erosion profiles reflect the extension of intertidal flats in the Fedderwarder Priel and a majority of adjacent basins. The vertical dynamic trend reveals that there is a significant and presumably linear trend. A negative feedback could not be observed due to the technical restriction.

We conclude that the Outer Weser estuary was not in an equilibrium state for the studied time period of 1998 to 2016. The leading cause of the shift in hypsometries may be sea level rise, to which the flats try to keep up. According to studies, vertical bed level accretion on tidal flats is accompanied by channel deepening. This may affect the stability of the channel shoal systems. Therefore, we suggest further investigations on the depth distribution of vertical dynamic trends**,** as well an extension of the study area to the whole German Bight.

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