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Application of Persistent Scatterer Interferometry (PSI) Indicates a Significant Sediment Sink for the Ems Estuary

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Abstract: The Ems Estuary enters the North Sea between the Netherlands and Germany. The Estuary has vast tidal flats consisting of fine-grained sediment. It is highly modified e.g. for land reclamation, coastal protection and navigability. Thus, the tidal behavior changed and natural sediment sinks vanished. The latter is identified as the most important reason for the substantial increase in suspended sediment concentration (SSC) from the 1990's onwards. Extensive research is being done to better understand the hydraulic and morphodynamic systems in order to keep the area in a stable state while balancing different concerns and interests, including future sea-level rise. Therefore, sediment budget calculations and morphodynamic modellings are carried out, taking into account all known sediment sinks and sources, such as dredging, land reclamation and fairway deepening. An additional sediment sink, which is hardly considered today, can be caused by the offshore subsidence due to hydrocarbon extraction. So the onshore subsidence above the huge Groningen natural gas field west of the Ems estuary is well known. In this study, we estimate the offshore extension of the subsiding area to the seafloor of the Ems Estuary.To do so, we apply Persistent Scatterer Interferometry (PSI) to generate around the Ems estuary a Wide Area Product (WAP) of interferometric ground motion information. We combined information about the extension of Dutch and German natural gas fields, the WAP-PSI-derived subsidence onshore east and west of the estuary and verified with Global Navigation Satellite Systems (GNSS) Stations including those mounted on tide gauges offshore in the estuary.Interpretation with further thematic data led to the identification and volume estimation of a new significant sediment sink in the Outer Ems. Starting in 1992, the offshore subsidence of the seafloor is estimated. Between 1992 and 2001 a maximum subsidence of 42 mm is detected. An area of approximately 200 km² is affected by a subsidence rate > 2 mm a^{-1}. The subsidence volume in the 9-year period from 1992 to 2001 adds up to approximately 5.5 Mil. m³. The resulting average annual volume change of ca. 0.6 Mil. m^3a^{-1} is in the same order of magnitude as the estimated annual sediment sink of the total Ems Estuary between 1994 and 2015. With the data of the PSI-based BBD, up-to-date sedimentation volumes can be evaluated. We suggest to take this sediment sink and in general, the subsidence of the seafloor and tidal flats due to natural gas and oil extraction into account in future sediment budget calculations and morphodynamic modelling approaches. The politically decided end of natural gas extraction from the Groningen gas field will also put an end to a huge sediment sink in the Ems estuary probably increasing SSC further.

Keywords: Persistent Scatterer Interferometry (PSI), ERS-1/2, Copernicus, Sentinel-1, sediment sink, suspended sediment concentration (SSC), Ems Estuary, Ground Motion Service Germany (BBD)

1 Introduction

Frisia, the coastal region of the southern North Sea is densely populated and an important economic, recreational and natural area. West Frisia is the eastern most part of the Netherlands and East Frisia the westernmost part of the German coast. In between, the Ems Estuary is situated. There, vivid economic centers, traffic routes and precious natural reserves line up, surrounded by dike-protected, mostly low-lying coastal marshes. Humans had according to its possibilities a big influence on the development of the estuary similar to many other estuaries. Land reclamation, harbor development and coastal protection went on for many centuries. Today, around one million people live and work in the districts of Aurich, Leer, Emden and the Dutch province of Groningen.

The Ems estuary consists of two parts: The Outer Ems from the mouth into the North Sea to the downstream of the flood barrier Gandersum 3 km upstream of Pogum and the Lower Ems from the upstream of the flood barrier to the tidal limit at the weir Herbrum south of Papenburg. Along the Outer Ems lies the border between Germany and the Netherlands. More details can be found e.g. in Krebs and Weilbeer (2008), Masterplan Ems (2014), and van Maren et al. (2015).

The largest ports of the region - Eemshaven, Delfzjil and Emden - handle significant trade flows. A number of the world's largest cruise ships are built at a Papenburg shipyard. In addition, the region is intensively used for agriculture and recreational purposes. The dike-protected lowlands are drained via sluices and pumping stations.

On the Dutch side besides smaller natural gas fields at the northern shore of West Frisia, the huge Groningen gas field was discovered in 1959. With production starting in 1963, a since then growing geodetic levelling monitoring network was established (e.g. Fokker et al. 2018, NAM 2015b). Significant subsidence around Groningen is observed and connected to the natural gas extraction (e.g. van Thienen-Visser and Fokker 2017). Subsidence is also occurring in the tidelands of the Wadden Sea (e.g. NAM 2015b, van der Spek 2018, Fokker et al. 2018). Due to seismic activity caused by natural gas extraction, the Dutch government decided in 2018 to cease production from the Groningen field until 2030 (Vlek 2019). On the German side, natural gas was extracted from the today decommissioned smaller fields of Borkum-Juist, Emshörn, Manslagt, Groothusen, and Wybelsum (LBEG 2018).

Extensive hydraulic engineering measures influence the hydro- and morphodynamics of the Ems estuary. These include the damming of bays such as the Ijsselmeer in 1932 and the Lauwersmeer in 1969, which have since then been obsolete as sediment sinks for the eastward directed coast parallel sediment transport and thus increase the material input into the Ems estuary. Furthermore, land reclamation and numerous coastal protection measures reduced possible sedimentation areas. On the other hand, West Frisian offshore sedimentation space is enlarged by salt mining activities and gas extraction in the Wadden Sea (Wang et al. 2018). In addition engineering measures to improve navigability like fairway deepening, the construction of the Ems flood barrier at Gandersum, and ongoing sediment management are taken. Since 1990, a strong increase in suspended sediment concentration (SSC) is observed (Krebs and Weilbeer 2008, van Maren et al. 2015, van Maren et al. 2016).

2 Bathymetric development and natural gas extraction

2.1 Sediment dynamics and bathymetric development in the Ems Estuary

The Ems is the westernmost of the three German Bight estuaries Ems, Weser, and Elbe. There, an eastward-directed longitudinal transport of sediment along the coast is present. This results in a continuous sediment entry into the Ems estuary area and into the whole German Bight. The sediment entry through the Ems river itself and its tributaries, however, is negligible. Recently, Milbradt et al. (2015a) determined an average annual sedimentation rate in the German Wadden Sea of 0.74 cm/a, which compensates for the mean sea level rise.

The sediment balance in the German Bight and in particular, the Ems estuary has been determined for example in Milbradt et al. (2015a), in van Maren et al. (2015) and in van Maren et al. (2016). They use among others the findings of Herrling and Niemeyer (2007) that the total littoral surface area of the Outer Ems between their seaward limit close to Eemshaven and Pogum where the Lower Ems discharges into the Dollard bay, has decreased from 435 km² to 268 km² from 1650 until 2005.

Van Maren et al. (2016) conclude the masses of fine-grained sediments deposited in the estuarine area between 1550 and 2015 are attributable to land reclamation measures in the former, much larger Dollard region. In addition, the authors denote sedimentation in the remaining Dollard bay, sediment extraction (e.g. sand for industrial use), and filling of side arms of the Ems in the Wadden Sea as further processes. For the period between 1994 and 2015, the authors deduce a sedimentation rate of 1.3 ± 0.1 t/a (1994 – 2015). That is only half as much as calculated for the three decades before 1994.

To maintain the navigability of the Ems, extensive sediment management is in operation. Fairways are dredged and the material is dumped elsewhere in the estuary or deposited on land. In the 15 years from 2000 to 2014, on average 2 Mio m^3/a were dredged from the Lower Ems and 6.5 Mio m^3/a from Outer Ems (WSA Emden, 2019). Since 1994, no building sand has been extracted anymore from the system. All dredged material was re-dumped. Only recently, the extraction and deposition of dredged material on land is under discussion again.

2.2 Fluid mud in the Ems Estuary

Estuarine turbidity and suspended sediment concentration (SSC) of the Ems Estuary are on the rise. Large parts of the Ems estuary silt up increasingly and show SSC up to 300 g/l. The state of the sedimentary system shifted into a hyperturbid estuary and thick layers of fluid mud occur especially in large parts of the Lower Ems (e.g. de Jonge et al. 2014). Fluid mud increases the maintenance expenses and worsens the ecological status. Therefore, many scientific and technical studies focus on the investigation and understanding of the long-term development of the sedimentation behavior and SSC in the Ems estuary (e.g. Krebs and Weilbeer 2008, Becker 2011, Heyer and Schrottke 2013, van Maren et al. 2015, van Maren et al. 2016, Stanev et al. 2019).

2.3 Gas extraction from below the Estuary

After the discovery of the Groningen gas field in 1959 in West Frisia, natural gas production started in 1963. This Dutch gas field is one of the ten largest in the world and extends below the Ems estuary. Land subsidence above the Groningen gas field west of the Outer Ems is well known and monitored onshore since production started. Among other geodetic methods, satellite-based Persistent Scatterer Interferometry (PSI) is applied (Ketelaar 2009, Rijksoverheid 2014, NAM 2015a, Commissie-Bodemdaling 2019). In East Frisia and offshore on the German side, natural gas has been also extracted from other, smaller fields. The latter fields are abandoned today (LBEG 2018). As subsidence can be observed onshore on both sides of the Outer Ems, offshore subsidence is plausible. If the subsidence is continually filled with sediment from the water column, it remains hidden. Therefore, it cannot be detected by bathymetric measurements (e.g. NAM 2019).

2.4 Masterplan Ems 2050

To restore the aquatic environment and to achieve a sustainable long-term development of the Ems Estuary, the Masterplan Ems 2050 was signed in June 2014 (cf. Masterplan Ems 2050, 2014).

In order to achieve the goals, a deep understanding of the hydrodynamics of the waterbody and the sediment transport is required to be able to estimate and predict the effect of measures. Among other things, sediment balances are set up and maintained for this purpose. They serve as input variables for morphodynamic model calculations. With such developed methods, the morphodynamic behavior of the estuary can be predicted. Measures can be tested for their effects before implementation.

3 PSI-WAP around the Ems estuary

3.1 The Wide Area Product (WAP)

PSI is a popular remote sensing monitoring technique invented by Ferretti et al. (2000) based on the space borne Interferometric Synthetic Aperture Radar (InSAR) method. It measures the Earth's ground motion with millimetre precision from space. Nowadays, PSI measurements are operationally available and complement ground motion measurements from levelling and from GNSS. Of course, it can similarly be applied for the monitoring of onshore coastal and low land subsidences. For example, Rijksoverheid (2014), Ketelaar (2009), and Commissie-Bodemdaling (2019) report the monitoring of the Groningen gas field via InSAR. In this study, DLR's operational PSI processing system (Adam et al. 2009) has been used for the processing of radar satellite data. In recent years, the processor has been extended coping with non-urban areas. The developed principle is named Wide Area Processing (WAP) (Adam et al. 2011, Adam et al. 2013).

Originally, PSI has been developed for urban areas and has been demonstrated on respective test sites only. The reason is the availability of suitable radar scatterers, which provide the measurement points. In order to generate e.g. a ten years' time series with relative motion, the radar scatterers need to persist unchanged in their radar scattering characteristic. These are mostly man-made features, which are typically made of metal e.g. metal roofs, metal gratings, street-lamps and metal poles. In PSI, Persistent Scatterer (PS) is the established name for such a point. In practise, PSs are available by chance and are typically concentrated in urban areas. In such areas, the atmosphere effect can be mitigated in a straight-forward way. However, the onshore region around the Outer Ems is characterized by wide-open spaces mainly used for agriculture. Consequently, the number of usable measurement points is very low and a spatially sparse PS density results which also varies spatially. I.e. in agricultural areas, no PS and in cities, plenty of PSs can be detected. In order to spatially sample the subsidence effect sufficiently and compensate the atmosphere effect, a high and homogeneous PS density is needed. The compensation of atmosphere effects relies on relative measurements in a reference network in which the PSs are no more than one kilometre away from each other. In the Ems test site, the generation of a reference network is a challenge and requires up-to-date algorithms implemented in DLR's WAP development.

Finally, a GNSS calibration transforms the relative ground motion estimates into absolute measurements. Consequently, PSI-WAP complements the sparse GNSS-network with dense deformation measurements. The high measurement density of PSI allows assessing the shape and spatial extension of ground motion areas and the interpolation of the data.

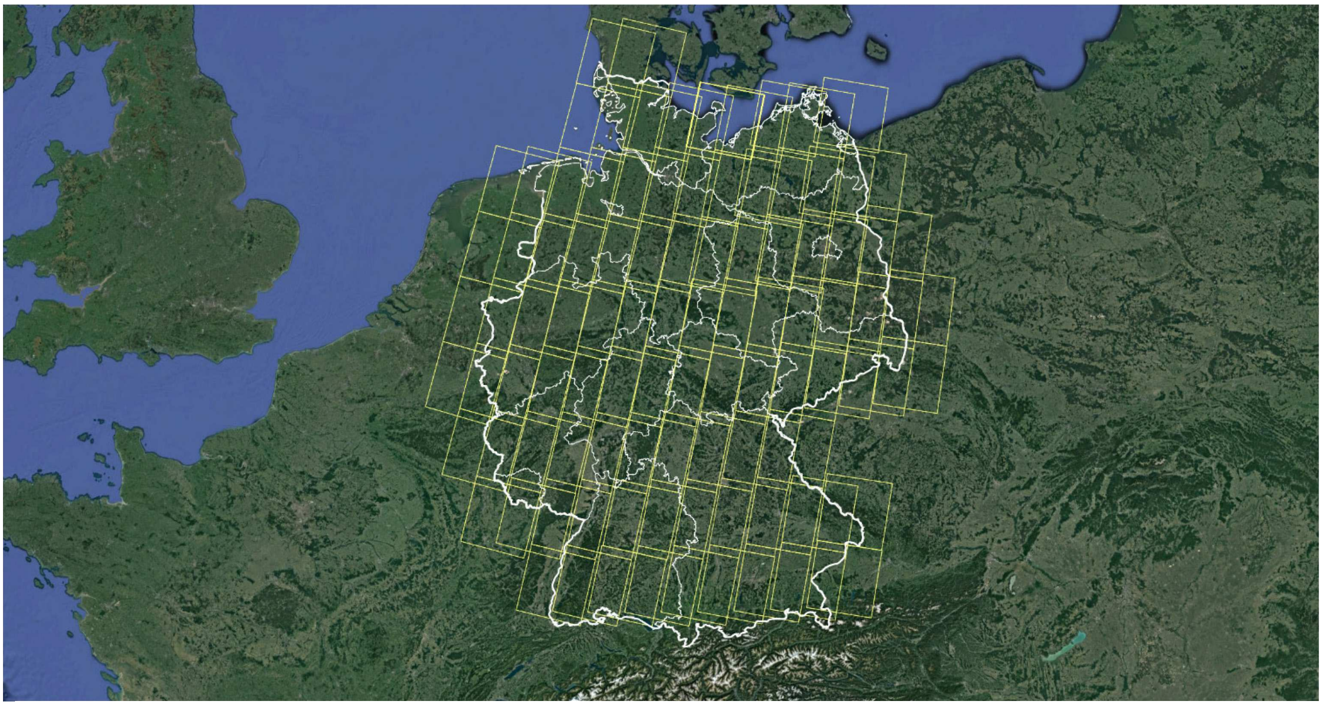

Fig. 1: Coverage of the ERS scenes (descending) for the Germany-wide Wide Area Processing (WAP). Optical imagery from Google Earth (2019) serves as background.

3.2 PSI-WAP of the European Remote Sensing Satellites (ERS)

The two European Remote Sensing (ERS) satellites, ERS-1 and -2, of the European Space Agency (ESA) were launched into the same orbit in 1991 and 1995, respectively. Their payloads included a C-band synthetic aperture imaging radar. ERS-1 operated until 2000. The compatible ERS-2 sensor operated until 2001. Therefore, the ERS data cover a time span of approximately ten years of the 1990s. In practice, the acquisition mode with a repeat cycle of 35 days forms PSI stacks with up to 100 SAR scenes. The SAR acquisitions cover an area of about 100 km x 100 km. In the course of pilot studies in the framework of Terrafirma, the BBD (Lege et al. 2016, Kalia et al. 2017) and of DLR developments, ERS data over the whole German territory and, where technically necessary, adjacent areas like parts of West Frisia have been processed by DLR (fig. 1).

3.3 PSI-WAP of the Copernicus Sentinel-1 satellites

Sentinel-1 is the first of the Copernicus Programme satellite constellation conducted by ESA. The mission is composed of a constellation of two compatible satellites, Sentinel-1A and Sentinel-1B, which share the same orbital plane. They carry a C-band synthetic-aperture radar instrument. Sentinel-1A was launched in April 2014 and Sentinel-1B in April 2016. The SAR acquisitions are composed of bursts and each composed scene covers an area of about 240 km x 240 km every six days. In the course of the BBD project (Kalia et al. 2017, Lege et al. 2019), DLR was contracted to compute PSI-WAP ground motion maps for the periods 2014-2017 (descending), 2014-2018 (ascending) and 2014-2019 (descending and ascending). To ensure the quality of the nationwide ground motion data, GNSS data based on homogenized GNSS time series of 230 German SA*POS*® reference stations are used (Brockmeyer et al. 2018).

3.4 PSI-WAP of Frisia

The result of the WAP processing in Frisia shows subsidence on both banks of the Outer Ems. Inspired by this and by the subsidence rates established by IKÜS (2008), assumptions were made as to how the values observed on the eastern and western shores could be interlinked by interpolation over the water-covered areas of the Outer Ems (fig. 3). The results, which are assumed to be linear subsiding rates, should reflect the subsiding rates of the Outer Ems gauging stations “Dukegat”, “Knock” and “Emden Neue Seeschleuse”, as well as current GNSS-velocities of “Knock” and “Emden Knock” (IKÜS 2008, Sudau 2017, Brockmeyer et al. 2018).

4 Volume of sediment sink due to subsidence

Based on the assumption that the subsidence is linear over time and spatially correlated, inverse distance weighting (IDW) interpolation has been performed (Philip and Watson 1982).

The result of the IDW interpolation is a velocity field based on PSI velocity in line-of-sight. In order to compare the interpolated velocity field with independent data (levelling, GNSS) and finally to approximate the volume of the lowering trough, a line-of-sight conversion in the vertical direction was carried out. This procedure uses the cosine of the angle of incidence of the PSI data and assumes that there are no horizontal motion components. In order to approximate the volume of the depression in the area of the Outer Ems, the outer edge of the depression determined by the -2 mm/a isocatabase and the shoreline is calculated in a grid of 100 m x 100 m. The sum of the cell values of this grid approximates the volume of the depression. It amounts to 595,000 m^3/a based on the descending ERS PSI dataset 1992 - 2001 (fig. 2). The sediment density of 1.59 t/m^3 after Milbradt et al. (2015b) results in a mass ΔM of just under 1 million t/a.

In fig. 3 the interpolated ERS PSI velocities are compared with independent levelling datasets of the “Emshörn”, “Dukegat”, “Knock” and “Emden Neue Seeschleuse” gauge stations located in the Ems estuary (IKÜS 2008), as well as with the current GNSS velocities of the two gauging stations “Delfzijl” (Pijpers and van der Laan 2016) and “Knock” (Sudau 2017). The mean deviation between the interpolated ERS PSI velocities and the levelling, respective GNSS data, of all the stations is 0.92 mm/a, the maximum deviation is 1.4 mm/a. This is considered a good consistency and a confirmation of subsidence in the estuary.

Further verification can be made with results of subsidence measurements and modeling of the Groningen natural gas field. According to this, the shape and the depth of the sinking trough in Rijksoverheid (2014), NAM (2016), and Ketelaar (2009) reflects well the size of the interpolated area based on ERS PSI data. The movement rates are of the same order of magnitude as those of the ERS PSI results, but the cumulated value of the subsidence is bigger because of the longer time span of the observation period.

The same workflow was applied to the Sentinel-1 PSI dataset 2014-2017 (descending). Although the longer dataset 2014-2018 (ascending) is already available as part of the BBD project, the shorter dataset 2014-2017 was used in this study for better comparability with the descending ERS data. There, the interpolation result shows a subsidence volume of only 86,000 m³/a (fig. 4). This adds to a mass ΔM of approximately 137,000 t/a. This result does not seem to meet the calculated reductions of NAM (2015) and van Thienen-Visser and Fokker (2017). One possible reason may be the end of gas production from German fields near the coast around the year 2000 (LBEG 2018). As a result, subsidence on the German side may be lower today than in the 1990s, with the result that the interpolation from the Dutch to the German coast via the Outer Ems yields lower subsidence rates. Also on the Dutch side, extensive engineering measures have been implemented to counteract subsidence. An important example is the uplifting of the Delfzijl port (Commissie-Bodemdaling 2019).

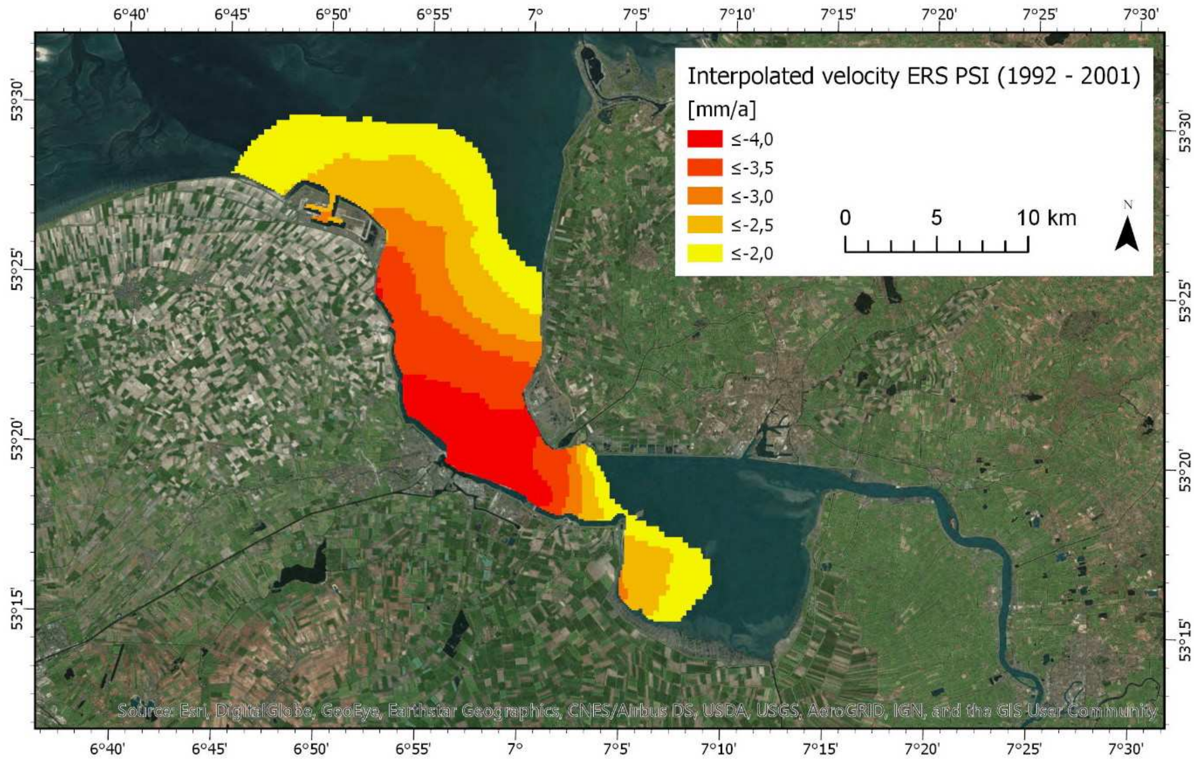

Fig. 2: Interpolated velocity in vertical direction based on ERS PSI 1992-2001. Optical imagery from ESRI (2019) serves as background.

Furthermore, a comparison of the Sentinel-1 PSI results with independent GNSS data from the SA*POS*® reference station "Emden Knock" (cf. fig. 3, Brockmeyer et al. 2018) yields a deviation of 1.5 mm/a in vertical direction. It is worth mentioning that the GNSS data of "Emden Knock" also show a significant horizontal velocity vector of v_{East} = -2.0 mm/a (while v_{Up} = -2.8 mm/a) which is lost by the projection of the PSI LOS velocity in vertical direction. Thus, in order to improve the PSI-method for the approximation of the subsidence volume, the horizontal velocity has to be considered. This can be done by e.g. using ascending and descending PSI datasets to estimate the vertical and East-West velocity (Fuhrmann and Garthwaite 2019). The upcoming datasets of the BBD include ascending and descending PSI datasets and can be used for this purpose.

However, there is a big difference between the results in fig. 2 and fig. 4 and between fig. 4 and the recently calculated ongoing compaction due to pressure depletion of the Groningen field from van Thienen-Visser and Fokker (2017) and Fokker et al. (2018). The modelled subsidence from (NAM 2016) seems like the latter also more like the ERS results of the 1990ties. In addition, the visual impression of the statistically aggregated subsidence values of freely accessible Ground motion maps of the Netherlands (GVL 2019, NGC 2019) is that there is substantial subsidence between Delfzijl and Eemshaven in the period between 2014 and 2018. The differences of the SAR interferometric results and the differences of the estimated subsidence volume indicate well the sensitivity of the PSI-WAP-processing and the interpolation of the data across the Outer Ems. In this case, a transnational WAP-

PSI-dataset using additionally the Dutch geodetic database for calibration could also improve the results. In addition, some GNSS benchmarks on the tidal flats between the Dutch and the German coast would be of great help in improving the subsidence estimation. Examples are the Benchmarks located in the West Frisian Wadden Sea (Fokker et al. 2018). We also suggest to separate different deformation processes (cf. Fokker et al. 2018) prior to the interpolation.

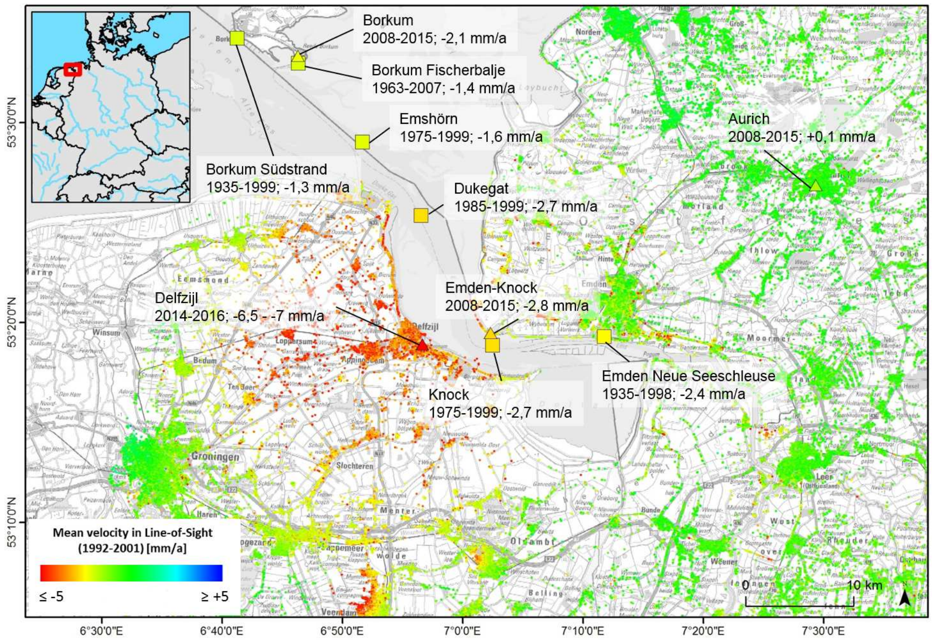

Fig. 3: Subsidence rates in the Outer Ems area (neg. values denote subsidence), GNSS: triangles (Δ); Nivellement: squares (□) (sources: GNSS Delfzijl: Pijpers and van der Laan (2016), GNSS Aurich/Emden/Borkum: Brockmeyer et al. (2018), Nivellement at gauging stations: IKÜS (2008)). A topographic map (BKG 2019) serves as background.

5 Impact of findings on models of the Ems Estuary

5.1 Models of the Ems Estuary

Numerous measures have to be developed to fulfill the Masterplan Ems 2050 (2014). A sufficiently predictive quantification of the long-term effects of hydraulic engineering measures on the sediment transport and SSC behavior in the Ems estuary can only be successful via the application of numerical hydro- and morphodynamic computer models.

In van Maren et al. (2016), the sedimentation rates and the sediment balance of the Ems estuary have been studied beginning in 1550 and average sedimentation masses per year (ΔM) in tonnes (t) per year are derived for different periods. For the two periods 1960-1985 and 1985-1994 a ΔM of 2.1 million t/a and for the period 1994-2015 a ΔM of 1.3 million t/a each with an error bar of ± 0.1 million t/a are denoted. These values are used in van Maren et al. (2016) as the basis for the investigation of the behavior of SSC in the Ems estuary on the one hand by an aggregated sediment balance modeling and on the other hand by means of numerical model investigations with the software package Delft3D.

Further numerical models and sediment balance calculations concerning especially the SSC situation of the Ems estuary are published by Becker (2011), de Jonge et al. (2014) and Oberrecht et al. (2016). Results for the Outer Ems can be found in van Maren et al. (2015). Milbradt et al. (2015a), Putzar and Malcherek (2015), Milbradt et al. (2015b), and Stanev et al. (2019) present results for the whole German Bight. Heyer and Schrottke (2013) and KFKI (2015) present the results of the research project AufMod on the morphodynamics of the German Bight. For future work we suggest to consider the influence of sediment sinks caused by subsidence of tidal flats or the seafloor.

For example, Wang et al. (2018) and Van der Spek (2018) considered the subsidence of tidal flats between the West Frisian barrier islands and the mainland caused by salt mining and gas abstraction. It is part of their work on estimating the influence of sea level rise on the sediment budget of the Dutch Wadden Sea.

These models calculate erosion and sediment accumulation and thus the development of the seafloor over time. Important bases for morphodynamic calculations are the sedimentation history and other parameters, such as those found in the so-called functional ground model of the sea floor and the tidal flats (Milbradt et al., 2015a).

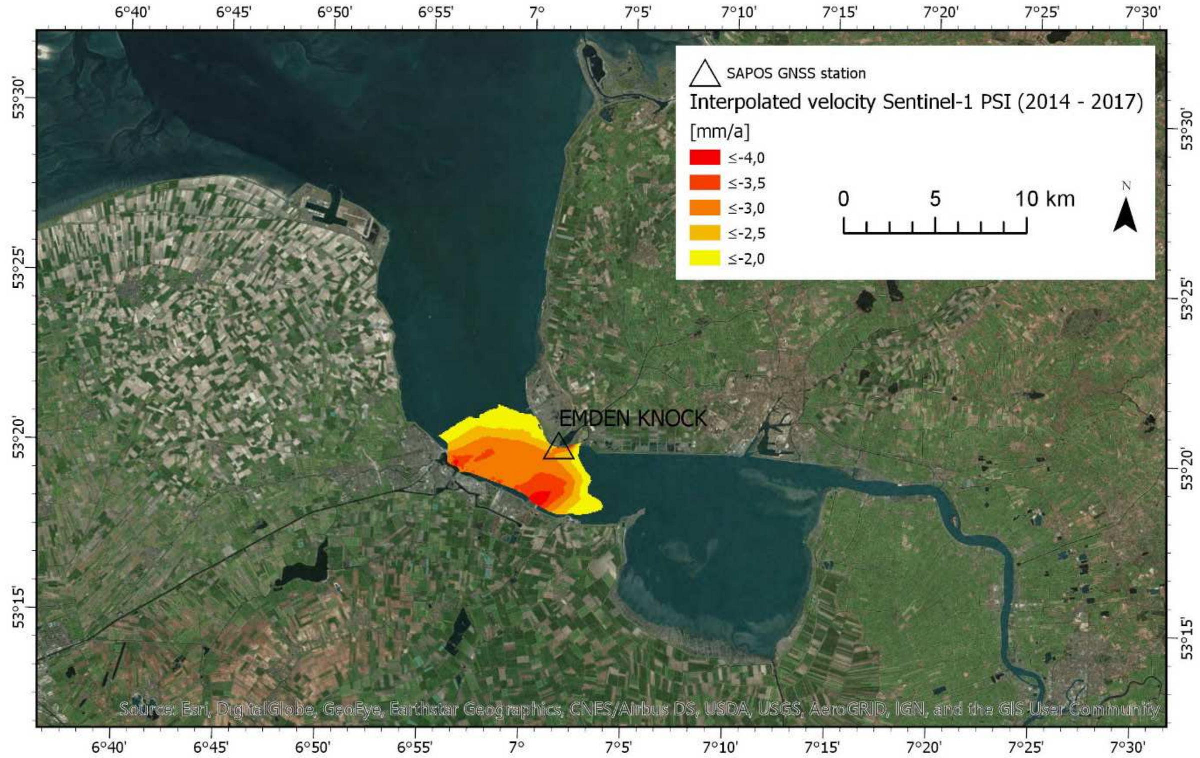

Fig. 4: Interpolated velocity in vertical direction based on Sentinel-1 PSI 2014-2017. Optical imagery from ESRI (2019) serves as background.

5.2 Suggested extensions of model input

According to KFKI (2015) and Heyer & Schrottke (2013), the functional ground model provides the morphological and sedimentological input data for numerical computational models. Therefore, the difference over the time span between sea floor topographies is the bathymetric rate of change. Another parameter, the morphological space, informs about the thickness of the sediment displacements.

Within the functional ground model, the consolidated horizon represents the Holocene base, a horizon that is assumed to be non-erodible in morphodynamic models. The difference between the consolidated horizon and the time-dependent sea floor represents the thickness of the so-called mobile or erodible layers, i. e. the volume mobilizable for sediment transport. Assuming that the whole subsidence has its cause in the gas extraction from rock formations deep below the consolidated horizon it also drops by the volumes calculated during the periods from 1992 until 2001 (0.6 Mio m³/a) and 2014 until 2017 (0.1 Mio m³/a).

Because of the subsidence due to gas extraction, the bathymetric rates of change and the morphological space derived from the functional model need corrections.

6 Conclusions

Significant subsidence rates are observed on the western and eastern shore and in the hinterland of the Ems estuary. The cause is mainly the extraction of natural gas. It is expected that there is subsidence also below the water level and the tidal flats, respectively. Offshore subsidence is also reflected in the GNSS-measured millimeter-wise downward movement of Ems tide gauges.

Assuming that the bathymetry of the tidal flats is unchanged due to continuous sedimentation, a sediment sink with a volume of 5.5 million m³ is deduced from space borne radar data for a nine year time span from 1992 until 2001. While this is the same order of magnitude as other sediment sinks of the outer ems, such as land reclamation or dredging, it is never mentioned in the studies known to us. We suggest to include this newly identified sediment sink in future sediment balance calculation and morphodynamic numerical model computations of the Ems estuary.

The result of the analysis of small-scale PSI-WAP datasets underlines the relevance of ESA's radar satellite missions and the importance of the European Copernicus program. The cross-border application shows the benefits of a consistent Ground Motion Service that can provide a better understanding of natural or anthropogenic ground motion processes. This is the base for suitable, sustainable and resource-conserving integration of coastal engineering measures into natural processes in densely populated economic regions of Europe.

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