Dune Monitoring During Storm Surge Events

Nils KOLDRACK, Ralf BILL, Constantin SCHWEIGER, Christian KAEHLER, Sebastian FÜRST, Fokke SAATHOFF, Matthias JONAS, Konrad MIEGEL, Germany

Key words: dune, breakthroughs, deformation, numerical modelling, hydrological processes

SUMMARY

The research project PADO (Processes and Implications of Dune Breaching at the German Baltic Sea Coast) aims to generate essential knowledge about dune dynamics and the behaviour of dunes in breakthrough situations. This should improve the design concept for dunes and combined coastal protection systems.

For this purpose, a large-scale dune structure designed for an annual storm surge event was constructed on the beach of Rostock-Warnemünde. The construction was loaded by an occurring flood up to failure (dune breakthrough) and was monitored by an extensive instrumentation. With a 3D measuring concept, the dune surface could be continuously measured and the processes that took place, such as the formation of breaches, could be recorded. The data obtained serves, among other things, as a basis for the calibration of numerical models and for further investigations of the long-term consequences of dune breakthrough on the hinterland. The main focus is on the associated salinisation and the possible sweetening process. In addition, socio-economic evaluations are carried out on the basis of the flooded areas, in which technical, hydrological and economic assessments of coastal regions protected by dunes are carried out.

SUMMARY

Ein für ein jährliches Sturmflutereignis bemessenes großmaßstäbliches Dünenbauwerk wurde am Strand von Rostock-Warnemünde errichtet und beobachtet. Das Bauwerk wurde durch ein auftretendes Hochwasser bis zum Versagen (Dünendurchbruch) belastet und dabei durch eine umfangreiche Instrumentierung überwacht. Mit einem 3D-Messkonzept konnte die Dünenoberfläche kontinuierlich vermessen und die stattgefundenen Prozesse, wie die Breschenbildung, erfasst werden. Die gewonnenen Daten dienen unter anderem als Grundlage für die Kalibrierung numerischer Modelle sowie für weiterführende Untersuchungen langfristiger Folgen eines Dünendurchbruchs auf das Hinterland. Hierbei wird das Hauptaugenmerk auf die damit verbundene Versalzung und den möglichen Aussüßungsprozess gelegt. Darüber hinaus finden auf Basis der überschwemmten Gebiete sozioökonomische Auswertungen statt, bei denen technische, hydrologische und ökonomische Bewertungen der durch Dünen geschützten Küstenregionen durchgeführt werden.

Dune Monitoring During Storm Surge Events

Nils KOLDRACK, Ralf, BILL, Constantin SCHWEIGER, Christian KAEHLER, Sebastian FÜRST, Fokke SAATHOFF, Matthias JONAS, Konrad MIEGEL, Germany

1. INTRODUCTION

In view of the fact that the ever more intensive use of coastal regions means that the risks to people and economic assets in the event of extreme natural events are constantly increasing, the further development of future-oriented concepts and infrastructures in coastal protection must be promoted.

The integration of coastal ecosystems into coastal protection and the development of adaptive, near-natural, cost-efficient and sustainable coastal protection structures is becoming increasingly important. On the German Baltic Sea coast, near-natural flood protection dunes form an essential element of the protection system against flooding. In order to be able to forecast and plan the protective effect of dunes, especially against the background of the expected increase in extreme events due to climate change, it is necessary to understand both the processes of dune erosion and dune breakthrough and the flooding processes following dune breakthrough.

The aim of the BMBF-funded project PADO (Processes and Effects of Dune Breakthroughs on the German Baltic Sea Coast) is to generate essential knowledge about dune dynamics with a large-scale research dune and then to use this knowledge to calibrate numerical models and apply them to model regions in Mecklenburg-Vorpommern. Finally, they shall serve as a basis for an improved measurement concept for full protection and system protection dunes. The project investigates three sites (Warnemünde, Graal-Müritz and Ahrenshoop) along the coast of Mecklenburg-Western Pomerania.

2. LOCATION AND DIMENSIONING OF THE RESEARCH DUNE

Several factors and boundary conditions had to be considered when choosing the location for the research dunes. The research dunes were built in the winter months 2017/2018 and 2018/2019 on the beach of Rostock-Warnemünde. An important factor for the choice of the location is the proximity of the research dune to the Internal Coastal Monitoring Network (IMK) (StALU MM, 2019). This ensures that the data collected in the case of loading can be directly related to the hydrodynamic data (water level and sea state).

The successful implementation of the field experiment requires a storm surge, which occurs regularly on the German Baltic Sea coast during the winter months. It was planned to dimension the research dune in such a way that it is loaded by water during an annual storm surge until a formation of a breach. First, it was investigated which annual maximum water levels of the Rostock-Warnemünde gauge (WSA, 2019) have been measured so far. The mean 50 % of the annual maxima lie between 0.84 m and 1.19 m above NHN. The empirical probabilities of occurrence are shown in Figure 1. On average, a water level of about 1 m per year can be expected.

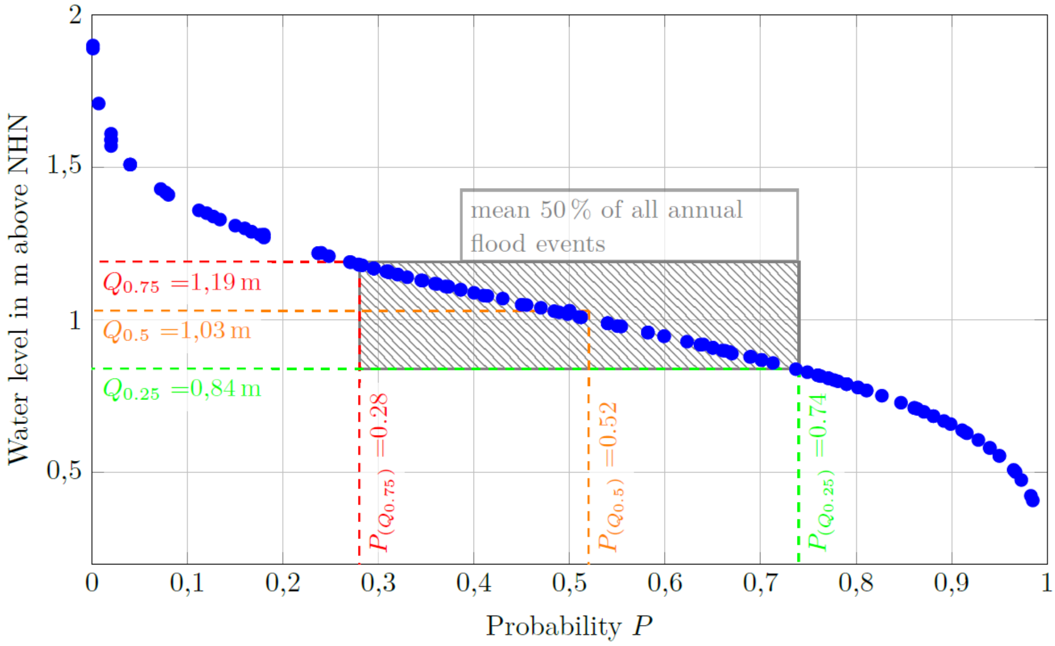

Figure 1: *Empirical probabilities of occurrence for the middle 50% of all annual events.*

These statements refer only to the highest water levels in the year and do not contain any information on the abundance and duration of storm surges. In a further investigation, a synthetic designed sequence for an average high water event with a peak value of 1.0 m above NHN and a duration of 18 h (water levels above 0.65 m above NHN) in Warnemünde was derived on the basis of the measured data and used to dimension the research dune.

The geometry of the research dune in the winter 2018/2019 was based on the standard cross section of a full protection dune. The embankments were constructed with an inclination of 1:2. In order to ensure the metrological recording of the fracture propagation in the longitudinal direction of the dune, the crown width was significantly reduced in relation to the height of the research dune. The research dune was 150 m long, had a crown height of 1 m and a crown width of 2 m. The beach area around the dune was straightened and a formation level was created. In total, the dune had a fill volume of ~700 m³. On the basis of the determined probabilities of the water levels a height of 0.5 m above NHN was chosen for the dune foot.

The construction of the dune took two weeks. During the first week, the sand from the accumulation area of the pier in Warnemünde was transported to the site of the research dune. In the second week the dune was profiled. The research dune was irrigated in layers (every ~30 cm) and compacted with a vibratory plate in order to obtain a storage density comparable to that of the state coastal protection dunes. Finally, a predetermined breaking point was created in the middle of the dune by removing about 0.25 m of the upper layer over a length of 5 m. Figure 2 shows the research dune on the beach of Warnemünde in November 2018.

Figure 2: Orthophoto of the research dune from 16.11.2018.

For the metrological monitoring, a measuring pile with a height of 4 m was installed on a row of groynes at a distance of 15 m from the dune. The measuring pile construction had to meet various requirements:

- easy installation of the technology in adverse conditions,
- a sufficient distance to the research dune,
- minimal vibrations caused by wind and swell,
- energy supply for measurement technology,
- resistance to salt water.

The requirements were met by a stainless steel measuring pile, which was braced with two concrete weights. The structure of this construction is shown schematically in Figure 3.

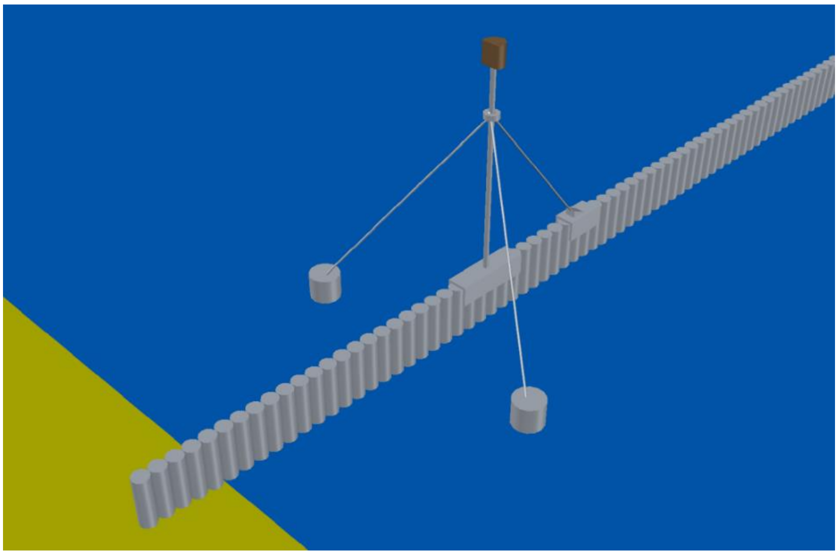

Figure 3: Schematic representation of the measuring pile construction.

3. DEFORMATION MEASUREMENT

Two days after completion of the dune, a storm surge occurred on 18.11.2018 and eroded most of the dune. By means of extensive surveying, the deformation of the structure could be fully documented over the period of the storm surge (18.11, 15:30 pm - 19.11, 5:30 am).

A terrestrial laser scanner (TLS - *FARO Focus3D X 130*) mounted on the measurement pile was used for the event-related surface survey (Figure 4). Thus, during the storm surge, the entire dune surface could be scanned again and again by millions of points and a break event could be recorded spatially and temporally. In order to georeference the recorded 3D point clouds of the research dune afterwards, measurement piles with a height of 1.55 m were set up behind the dune. For image documentation and redundant evaluation using photogrammetry of the events, a camera system (*GoPro Hero4 Black*) was additionally installed on the measuring pile. In addition, the area under investigation was recorded before and after as 3D point clouds and orthophotos using UAV technology.

The entire measuring system was controlled via WLAN. For this purpose, an access point was set up on top of the full protection dune, which is connected to the local network with a network cable.

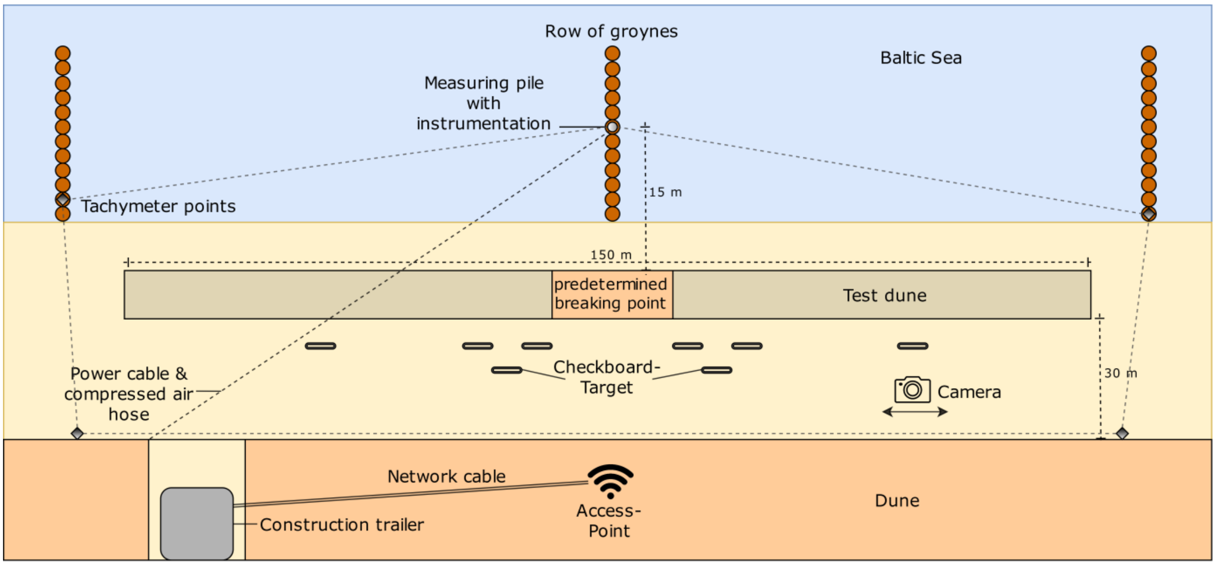

Figure 4: Schematic structure of the measuring system.

With this method, the dune could be completely scanned once every eight minutes on average during the measurement campaign. In addition, a total of 19:45 hours of video material, taken with a GoPro camera also mounted at the measurement pile, was recorded.

During the first laser scan, the research dune had a volume of 681.57 m³ (Figure 5). Less than four hours after the start of the measurement, the total volume had already been halved. The reason for this large volume loss was the hydrodynamic boundary conditions (Figure 6). Because already at 2:30 pm the dune foot was loaded at a water level of 0.28 m above NHN. In addition to the water level, which rose to 0.55 m above NHN by 6 p.m., the wave run-up also played a major role as a loading factor. In the following hours until the last measurement at 5:30 a.m. the volume decreased by a total of 68.82 % (469.05 m³) during the storm surge.

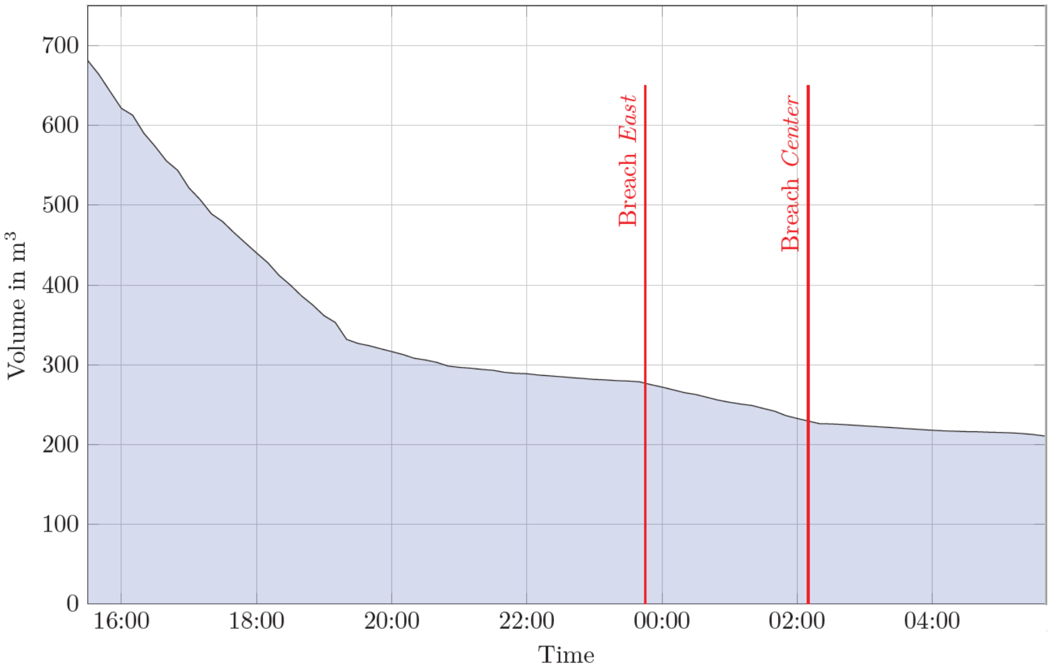

Figure 5: Volume change of the research dune during the measurement campaign.

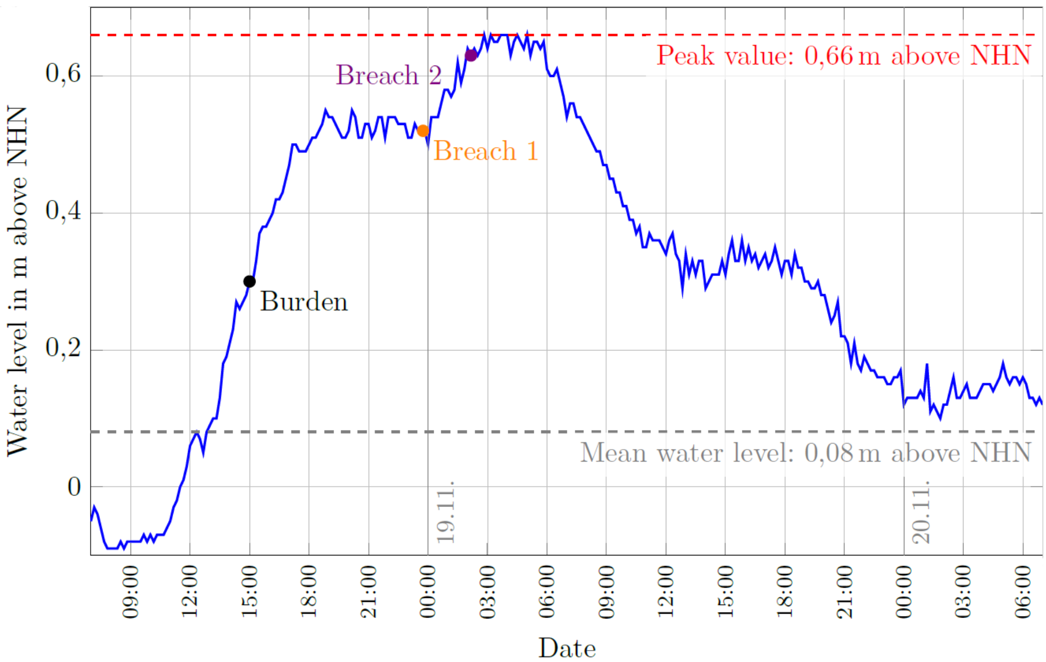

Figure 6: Water level hydrographs during the storm surge.

Figure 7 shows cross sections of the research dune at different times of the measurement campaign. At 3:45 pm, the time of the first laser scan measurement, the foot of the dune was exposed to stress for more than an hour. One hour later, about 0.1 m of sand was washed away at the foot of the dune and only little material from the dune top had slipped. After two hours the dune foot was eroded by 0.42 m, sand had deposited in front of the dune and the foot had risen by 0.09 m. After three hours, the dune body at this location had decreased in depth by 1.37 m, and significantly more material had accumulated in front of the dune foot, so that the waves had to cope with a greater terrain height to load the dune. Four hours after the first measurement, the dune top had shrunk by 0.15 m due to the high wave impact and the dune body had receded by 2 m. During the next two hours, considerably less material was washed off the dune, only in the last hour did the dune crest decrease to a terrain height of 1.07 m. This corresponds to a reduction of 0.4 m. The average height of the dune crest at this time was 1.02 m above NHN. The waves overflowed the dune and the first breach was created.

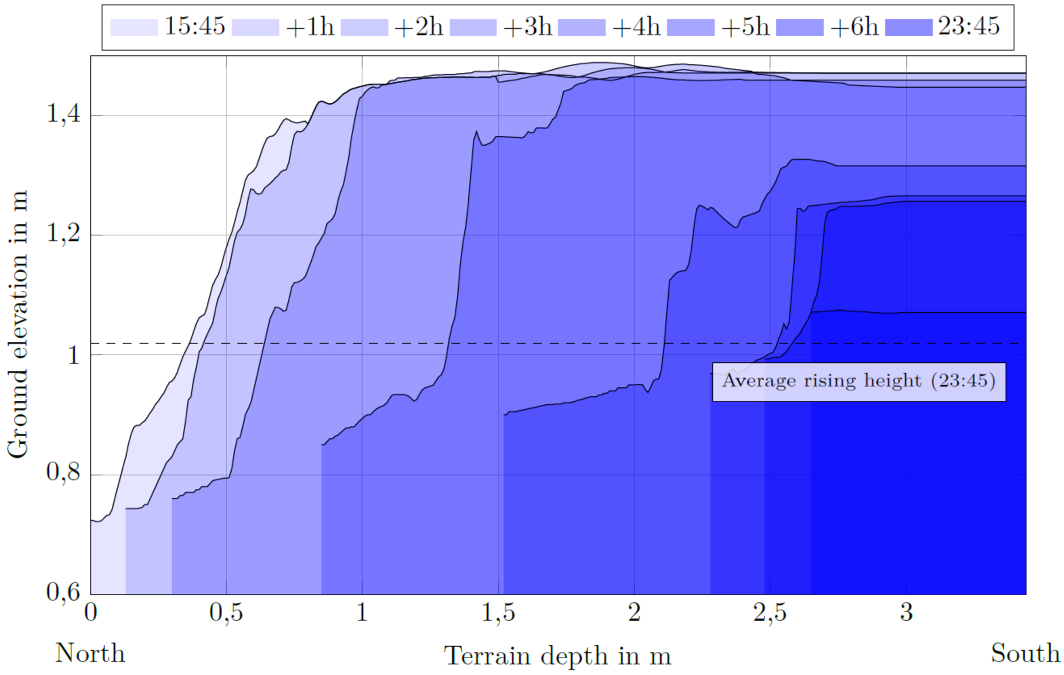

Figure 7: Cross sections of the research dune at a breach.

On 19 November, the day on which the storm surge abated, the partial investigation was flown by a drone to the site. From the derived differential model for the drone flight on 16 November, the day the research dune was completed, it becomes clear in which regions the dune was completely eroded (Figure 8). In the eastern area, up to the predetermined breaking point, the dune body was completely eroded. In the western area, however, the storm surge could not completely erode the dune and a small part (212.52 m³) remained standing. Especially in the eastern area sand accumulated in front of the dune. Over an area width of 40 m the terrain height increased by more than 0.4 m. East of the dune as well as on areas in the eastern polder area the relief also rose by up to 0.2 m.

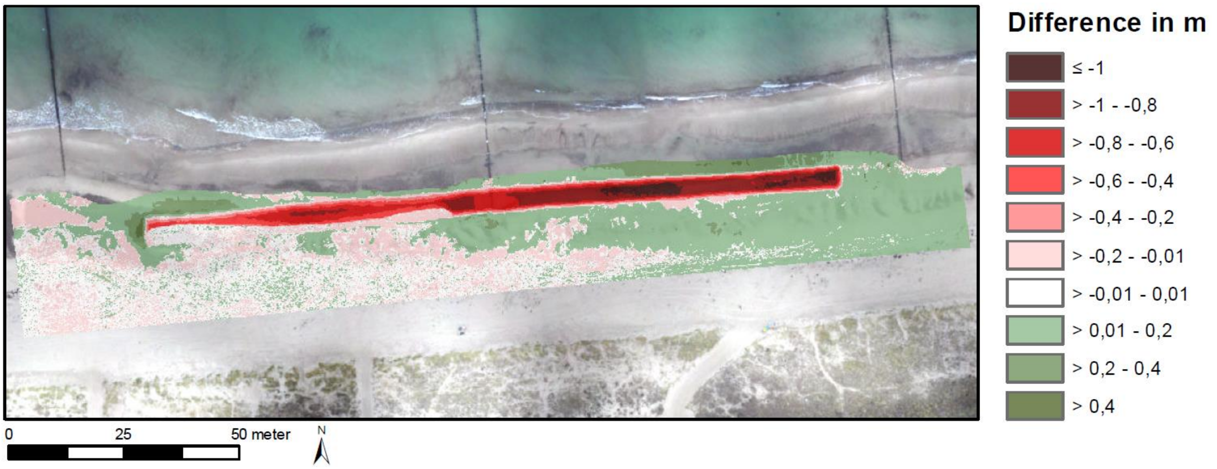

Figure 8: *Difference in altitude between 16.11 and 19.11.2019.*

Based on the video data from the camera in the polder area, the optical flow was used to analyse how the polder area behind the dune in the eastern area was flooded by the breach and how the inflowing water partially receded after the storm surge had subsided. The optical flow represents a vector field, which gives movement information for each pixel in the form of movement direction and movement length.

Figure 9 shows the wave movement in a breach. The uniform vector field is used to evaluate the break development and the movement information in the form of movement direction and movement length gives information about the wave movement. The green arrows describe the incoming water and the red arrows describe the water flowing out of the polder surface. The points in the vector field have a horizontal distance of 50 cm and a vertical distance of 10 cm.

At 11:55:00 pm the breach was 1.875 m and there is hardly any movement to be seen. 10 seconds later, a wave of water flowed through the breach into the polder area. At 11:55:20 pm the storm surge was so high that it swept over the western part of the area next to the breach in the dune, in the area where a second breach occurred eight minutes later. Until the last image at 11:55:40 pm, the breach grew by 25 cm compared to the first image. Water flowed through the opening and was pushed westwards due to the wind direction in the polder area.

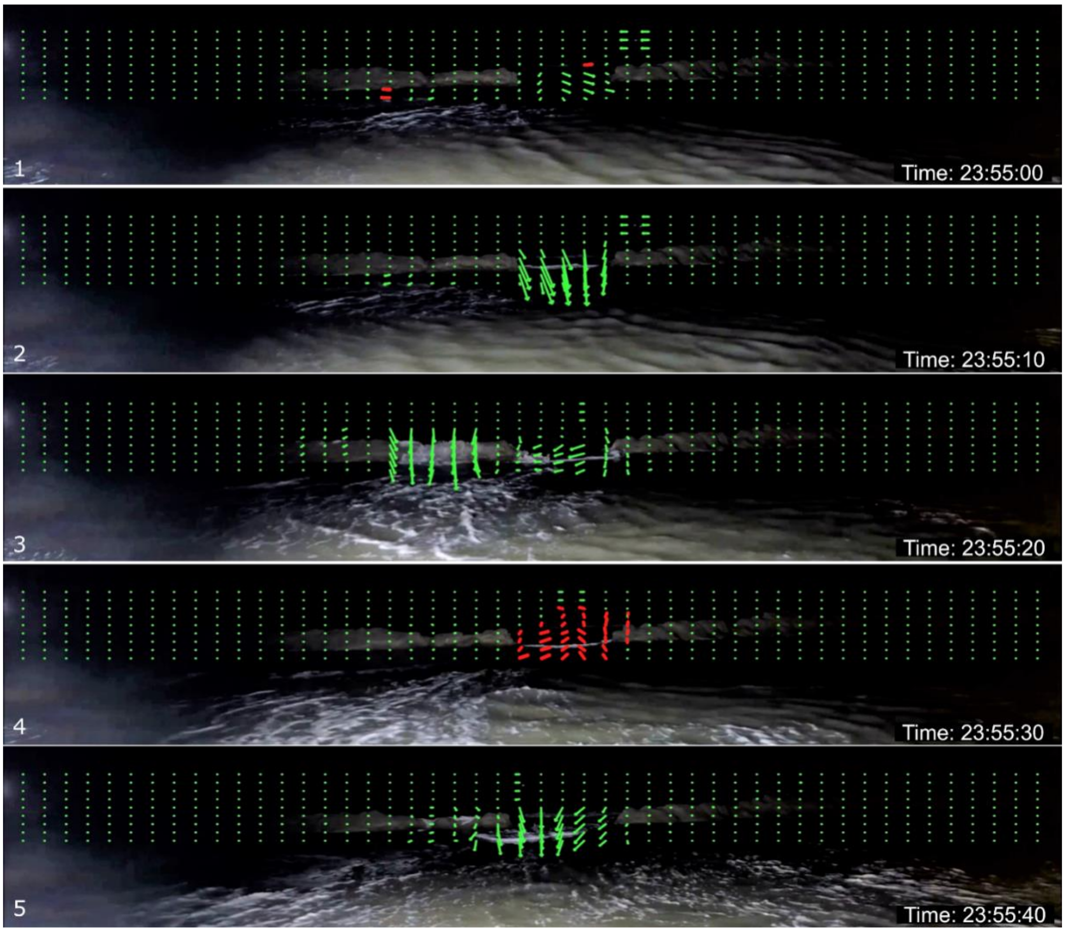

Figure 9: Representation of the wave motion, using the optical flow.

4. NUMERICAL MODELLING

The surface models of the dune are the basis for the numerical modeling of storm surge-induced dune erosion with the open source software *XBeach*. This is a two-dimensional, depth-averaged (2DH) coastal erosion model which can be used to simulate various hydrodynamic and morphological processes as well as various impacts on sandy coasts during a storm surge (Roelvink, 2009).

The model structure (model grid and boundary conditions) is based on the data collected during the physical model test. For the model grid, in addition to the DEM of the research dune, the bathymetry of the foreshore, which was surveyed with GNSS and tachymetry, a DGM5 of the surrounding coast and bathymetry data with a resolution of 50 m of the freely accessible *GeoSeaPortal* of the Federal Maritime and Hydrographic Agency (BSH) were used. In order to achieve a fine resolution of the relevant area under investigation on the one hand and to reduce the required computing time on the other hand, a model grid with a variable cell size was created. In the area of the research dune a resolution of $dx_{min} = dy_{min} = 1$ m was chosen, which increases in the direction of the model entrance and the lateral boundaries to $dx_{max} = 14$ m and $dy_{max} = 10$ m, respectively. Additionally, the grid was artificially extended from a water depth of 10 m with a constant gradient of 0.05 to a maximum water depth of 20 m at the model inlet. The final model grid is shown in Figure 10 (left). Additionally, the locations of the IMK monitoring network are marked. Figure 10 (right) shows the used hydrodynamic boundary conditions (wave height, period, direction) from the measuring buoy in 10 m (P1) and the water level at the Warnemünde gauge (tide). The sediment properties were given on the basis of a grain analysis with D_{50} = 0.03 mm and D_{90} = 0.05 mm. Furthermore, a constant bed roughness of n = 0,02 s/m$^{1/3}$ was chosen.

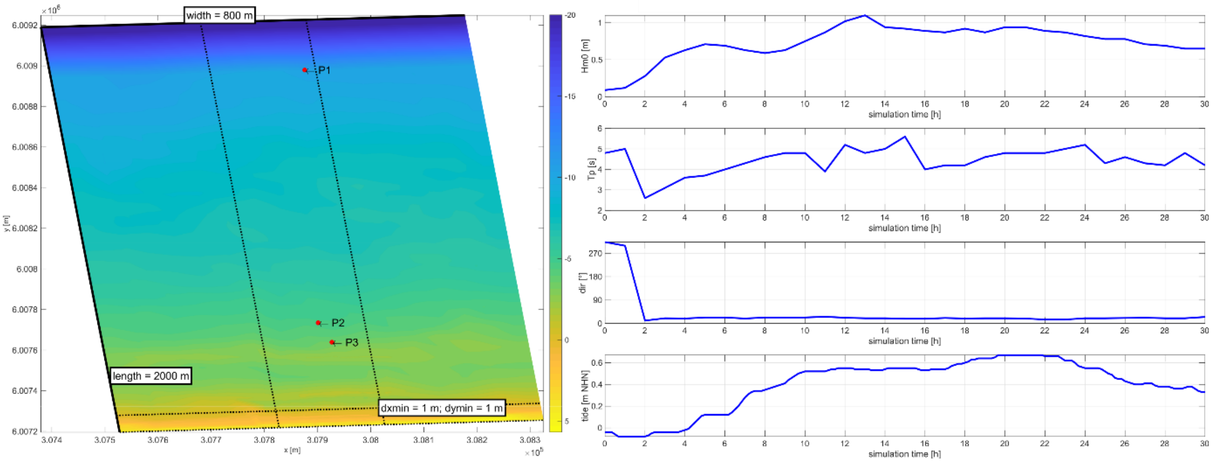

Figure 10: Resulting model grid with locations (P1 - P3) of the IMK measurement chain (left); hydrodynamic boundary conditions (wave height, period, direction) at the location of the measuring buoy and water level hydrograph of the Warnemünde gauge (right).

Figure 11 shows the comparison of the measured (left) and simulated (right) final elevation (top), the height difference ($zb_{post} - zb_{ini}$) in the entire survey area and as a detailed view (center), and the final height difference between simulation and measurement (bottom). For $zb < 0\ m\ above\ NHN$ there are large differences between measurement and simulation in the erosion zone ($1920\ m < y < 1940\ m$) as well as in the deposition area ($1900\ m < y < 1920\ m$) as the height differences show (middle figures). In the area of the research dune, however, a good spatial agreement follows both in the western area ($320\ m < x < 390\ m$) and in the eastern part, where the entire dune body is removed. As the height difference ($zb_{post} - zb_{ini}$) of the measured data shows, the rear part of the dune remains almost unchanged at $320\ m < y < 350\ m$ and $380\ m < y < 390\ m$. During the simulation, however, the dune is eroded in both sections and remains intact between $355\ m < y < 365\ m$ instead. The comparison of the final elevations (lower figure) between simulation and measurement confirms the deviations in the remaining part of the research dune. On the other hand, in the area of the second breach ($y \sim 400\ m$) there is a very good agreement of the final altitudes. In the area of the first breach ($y \sim 465\ m$) the erosion is underestimated in the simulation by a few centimeters.

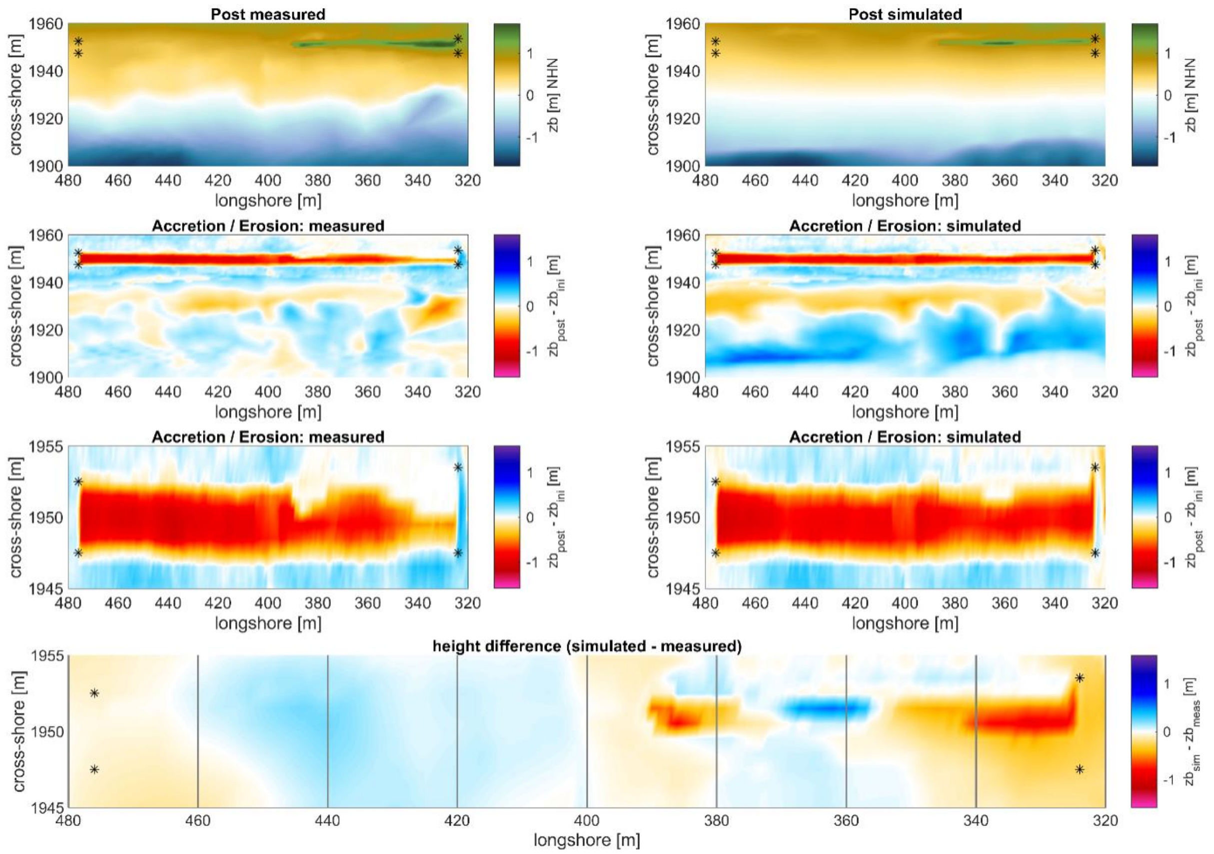

Figure 11: Comparison between measurement (left) and simulation (right) of the final elevation (top), elevation difference (final - initial) in the entire survey area and as a detailed view (center) and difference of the final elevations (simulation - measurement

The results of the numerical modelling show a very good agreement between the simulation and the measured data regarding the final height values in the area of the research dune. This applies especially to the left side area, where the storm surge leads to an erosion of the entire dune body. In the right-hand area, the observed seaward dune erosion is satisfactorily represented by the model, but the areas with higher/lower erosion deviate slightly from the measured data.

5. HYDROLOGY

The task of hydrology is to record the hydrological system status of the reference area near *Graal-Müritz*. The hydrological processes of a flood event caused by the breakthrough of dunes and the associated salt input into the hinterland are examined more closely.

The reference area near *Graal-Müritz* is located about 20 km northeast of Rostock on the German Baltic Sea coast. It is drained via the *Moorgraben* ditch system and the pumping station of the same name (WBV, 2019). The area consists of the sub-areas, the grassland *Müritzer Wiesen* and the western part of the wetland *Ribnitzer Großes Moor*. In the north the study area is limited by the flood protection dune running parallel to the Baltic Sea. The sub-areas are hydraulically connected to each other by an underground passage (DN 800) from a water level of about 1 m above NHN. The area is characterised by two superimposed sandy aquifers, which are separated from each other by a slightly conductive layer of boulder clay (LUNG-MV, 2019). In the area of the fen, a thin peat layer is also deposited on the upper sand layer. Two load cases were assumed for a flooding event caused by dune breakthrough:

- load case 1 with an inflow of Baltic Sea water in the area of the *Ribnitzer Großes Moor* and
- load case 2 with an inflow of Baltic Sea water in the area of the *Müritzer Wiesen* (Figure 12).

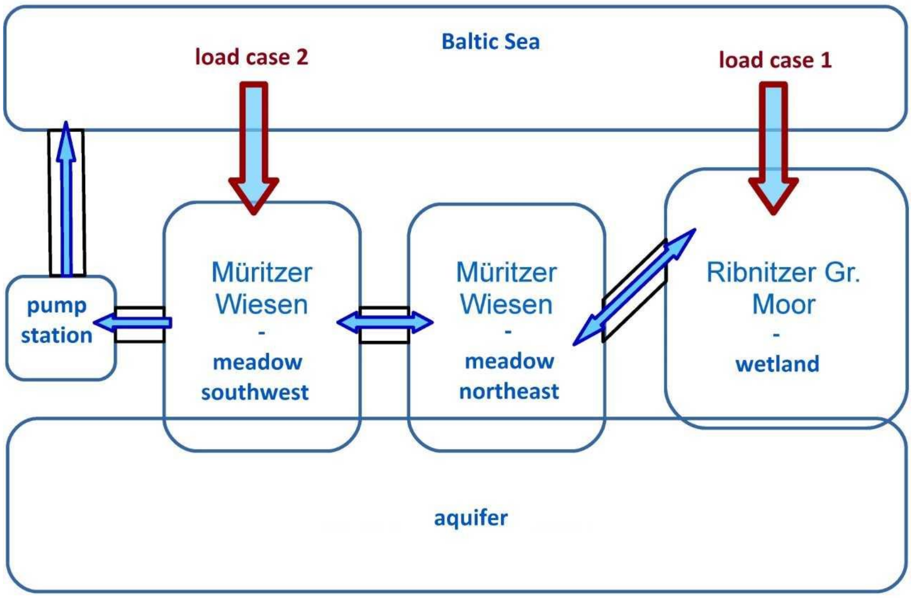

Figure 12: *Hydrological conditions of the Graal-Müritz reference area.*

Assuming an evenly reflected water surface in all sub-areas, a water level of at least 1.3 m above NHN is required so that water in the area of the *Ribnitzer Großes Moor* can leave the catchment area of the *Moorgraben* pumping station beyond the eastern area boundaries (Kirchner, 2018). For this reason, a flood level of 1.3 m above NHN was assumed for the potential inundation areas as an initial state for a transient modelling of the groundwater flow and groundwater pollution with saline water (Beimowski, 2019). The modelling was carried out with the modelling software *FEFLOW*. The aim was to investigate load case 2 and the resulting effects of saltwater intrusion into the aquifer in more detail. Furthermore, the question arises whether the wells of the water supplier *Nordwasser GmbH*, located about 500 m southwest of the *Müritzer Wiesen*, are endangered by salination.

The investigations show that in the case of a dune breakthrough, the triggering storm surge itself represents the critical system load and, moreover, the exchange processes of water between meadows and peatlands do not lead to a significant increase in the risk of damage. Inflowing Baltic Sea water would flood the *Müritzer Wiesen* and the adjacent moor and thus introduce salt into the system. In view of rising water levels, a threshold value results from which the ditches are filled up completely and overflow beyond the ditch system into the area of the *Müritzer Wiesen* begins. This value lies at 0.5 m above NHN. A lowering of the flood water level from 1.3 m above NHN to this threshold value can be achieved in about 31 days with maximum pumping capacity of the *Moorgraben* pumping station.

The groundwater model shows that five days after a potential flood event, the upper aquifer in the area of the flooded areas would be completely permeated with salt. After 31 days at the end of the lowering phase the salt would have reached the lower sand layer. Sweetening takes place following the large-scale groundwater flow direction towards the Baltic Sea. About five years after the flood event, the chloride concentrations in the aquifer would have fallen below the stipulated limit for drinking water of 250 mgl^{-1} (TrinkwV, 2001). Measured at the initial concentration, the leaching would be completed after 10 years. Due to the dominance of the large-scale groundwater flow towards the Baltic Sea, the drinking water wells of the water supplier *Nordwasser GmbH*, which are located southwest of the *Müritzer Wiesen*, are at no time endangered by salination within the 10 modeled years. Seasonal fluctuations such as those of groundwater recharge were not considered further in this study, which is why there is a need for further research in this area.

6. SUMMARY

With its investigations, the project has contributed to the improvement of the knowledge base and, building on this, to the further development of the existing design tools for dune planning and construction. A 3D measurement concept was developed to continuously measure a dune during a storm surge. On the basis of the collected surface models a deformation analysis of the research dune could be carried out. The terrain models also form the basis of the numerical modelling, which simulated the failure processes as well as the flooding/drawdown of polder areas and lowlands. Longer-term consequences of dune breakthrough on the hinterland of the protected coastal regions, especially with regard to the associated salinisation and the subsequent sweetening process, were shown by hydrological analyses. In the event of a flooding of the reference area, it can be assumed that leaching of the area will last for about a decade.

REFERENCES

Beimowski, F. (2019): Simulation der Auswirkungen eines Salzwasserüberstaus auf das Grundwasser im Bereich Graal-Müritz unter Anwendung der numerischen Modellierungssoftware FEFLOW, Master thesis in Environmental Engineering Sciences, Professorship for Hydrology and Applied Meteorology, University of Rostock.

Kirchner, T. (2018):Untersuchung der hydrologischen Verhältnisse in den Müritzer Wiesen unter Berücksichtigung des Zuflusses aus dem Großen Ribnitzer Moor: Grundlage für die Bewertung potenzieller Folgen von Überschwemmungen durch Sturmfluten, Master thesis in Environmental Engineering Sciences, Professorship for Hydrology and Applied Meteorology, University of Rostock.

LUNG-MV (2019): Landesamt für Umwelt, Naturschutz und Geologie Mecklenburg-Vorpommern: Landesbohrdatenspeicher, https://www.umweltkarten.mv-regierung.de/atlas/script/index.php.

Roelvink, D., Reniers, A., van Dongeren, A., van Thiel de Vries, J., McCall, R., Lescinski, J., (2009): Modelling storm impacts on beaches, dunes and barrier islands. Coastal Engineering 56 (11-12), 1133–1152. doi:10.1016/j.coastaleng.2009.08.006.

StALU MM. (2019): Internes Messnetz Küste Mecklenburg-Vorpommern. http://imk-mv.de/index.php.

TrinkwV (2001): Verordnung über die Qualität von Wasser für den menschlichen Gebrauch. Bundesministerium der Justiz und für Verbraucherschutz, Berlin.

WBV (2019): Wasser- und Bodenverband Untere Warnow-Küste: Steckbrief Schöpfwerk „Moorgraben", https://wbv-untere-warnow-kueste.de/schoepfwerke/moorgraben/.

WSA (2019): Bereitstellung der Pegeldaten durch die Wasserstraßen- und Schifffahrtsverwaltung des Bundes, WSA Stralsund.

BIOGRAPHICAL NOTES

CONTACTS

M.Sc. Nils Koldrack
Geodesy and Geoinformatic
Justus-von-Liebig-Weg 6
Rostock
GERMANY
Tel. +4903814983213
Email: nils.koldrack@uni-rostock.de
Web site: https://www.auf.uni-rostock.de/en/professorships/a-g/geodesy-and-geoinformatic/