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Sediment tracer tests to explore patterns of sediment transport in coastal reed beds – a case study from the Darss-ZingstBodden Chain

Abstract

Common reed (*Phragmites australis*) is an engineer of its own environment. Seawards, reed beds act as a buffer by dissipating wave energy, reducing turbulence and thus sediment suspension. They enhance particle trapping and organic matter accumulation. On the other hand, these wetlands serve as a buffer by trapping wind-eroded particles from the landward side. The objective of this study was to elucidate the interplay of sediment transport with vegetation patterns and topographical characteristics in a coastal reed bed at the *Darss-ZingstBodden Chain*, a lagoon system of four inner coastal water bodies connected to the southern Baltic Sea. Fluorescent sand particles were used to examine the sediment transport pathways in two different parts of the reed bed. Dense reed beds reduced wind speed and severely inhibited sediment transport in the terrestrial part of the reed bed during the first tracer study. The second tracer experiment was carried out in the littoral part of the reed bed and the tracer particles followed the flow channels of the small-scale basins, which in turn are influenced by the reed stands in the water. The fluorescent tracer tests showed that both plant morphology and local-scale topography have an impact on sediment transport processes and deposition patterns.

Keywords: sediment tracer test, sediment transport, *Phragmites australis*, coastal wetland

1 Introduction

Coastal wetlands and vegetated marine habitats provide various ecosystem services including sediment retention and protection against coastal erosion (ADAME et al. 2010). Partially submerged vegetation dissipates wave energy whereas high sedimentation rates and litter supply raise the seafloor, enabling a buffer mechanism against sea level rise and increased storm and wave action associated with climate change (DUARTE et al. 2013). Higher intensity and frequency of flooding and erosion of vulnerable coastal areas is predicted due to climate change with accelerated sea-level rise, increases in the strength of storm surges and storm-related precipitation as well as increases in the frequency of extreme waves (MEEHL et al. 2007; DUARTE et al.

2013). Apprehending how sediments react to climatic or hydrodynamic forces and how their motions are distributed over space and time is of paramount importance. To understand the long-term shoreline evolution enables society to adapt to future challenges related to coastal erosion and sea-level rise (STIVE et al. 2002; MINISTERIUMFÜRLANDWIRTSCHAFT, UMWELT UND VERBRAUCHERSCHUTZ 2009).

Marshes are among the ecosystems most threatened by sea-level rise and significant marsh loss is projected in sediment-starved coastal areas (STEVENSON & KEARNEY 1996). Increased sediment accretion is needed in the near future in order to allow marshes to keep up with the current rate of sea level rise (ROOTH et al. 2003). Yet, it is not well understood how different plant species affect sediment accretion processes in marshes. Only after a profound look on the behavior of different species, researchers and resource managers will be able to evaluate the differential impacts of sea-level rise on coastal wetlands (REED 1995). ROOTH& STEVENSON (2000) adopted this hypothesis and compared sediment accretion patterns in *Phragmites australis* stands and mixed *Spartina* stands. In the *Phragmites* stands the rates of mineral and organic particle trapping was higher and the authors emphasized that wetlands covered by *Phragmites* may provide an opportunity to counteract sea-level rise and coastal erosion.

The intention of this study is to elaborate the differences of sediment transport within one coastal wetland covered by *Phragmites australis*. Fluorescent sand particles (luminophores) were employed to examine the sediment transport pathways in the terrestrial and the littoral part of a wide coastal reed bed at the *Darss-ZingstBodden Chain*, a lagoon system of four inner coastal water bodies connected to the southern Baltic Sea. Sediment tracer tests are used to track particles and visualize their pathways using uniquely labelled tracers (WHITE 1998). The mapping of the distribution of those luminophores over a specific space and time offers insights into sediment transport patterns (BLACK et al. 2007). In general, three techniques are applied to monitor sediment transport in coastal zones: repeated topographic surveys, sediment traps or sediment tracers (e.g. SHTEINMANN et al. 1998;SEAR et al.2000;KLEIN et al. 2007; BLACK et al. 2007). With the emergence of radioactive and fluorescent marking techniques in the mid 1950's, sediment tracking started to become more popular and successful. Prior to the adoption of those techniques, the examination of particle motion was done by mathematical modeling or in laboratory flume and wave basin experiments (INGLE 1966). WHITE (1998) referred to tracer experiments as 'point' experiments, since tracers are dispersed at one point and their distribution over space and time is followed. The objective of this study is to elucidate the interplay of sediment transport with vegetation patterns and topographical characteristics in the different parts of the coastal reed bed.

2 Study site and methodology

Fluorescent sand particles were used to examine sediment transport pathways in a coastal reed bed at the *Darss-ZingstBodden Chain* (Figure 1). The Darss-ZingstBodden Chain is a lagoon system that was formed after the Weichselian glaciation during the Litorina transgression in an area with glaciogenic basins and meltwater channels (LAMPE 1990; NIEDERMEYER et al. 2011). The entire lagoon system with its four sub-basins covers an area of almost 200 km² and salinities decrease from 0-3 PSU in the innermost lagoon to 7-10 PSU in the outermost (SCHUBERT et al. 2003;

SELIG et al. 2007). Wide, monospecies stands of *Phragmitesaustralis (Cav)* Trin. Ex Streudel (common reed) are characteristic for the Bodden coasts and the plant tolerates the salinities at the outermost bodden without problems (LAMPE 2002; KARSTEN et al. 2003). The topography of the coastal reed bed at our study site Dabitz is heterogeneous with small-scale basins and fluctuating water levels. Such small-scale basin morphology is common within reed beds along the Darss-ZingstBodden Chain. The adjacent land is agriculturally used and soils were classified as luvisols (VOIGTLAND 1983).

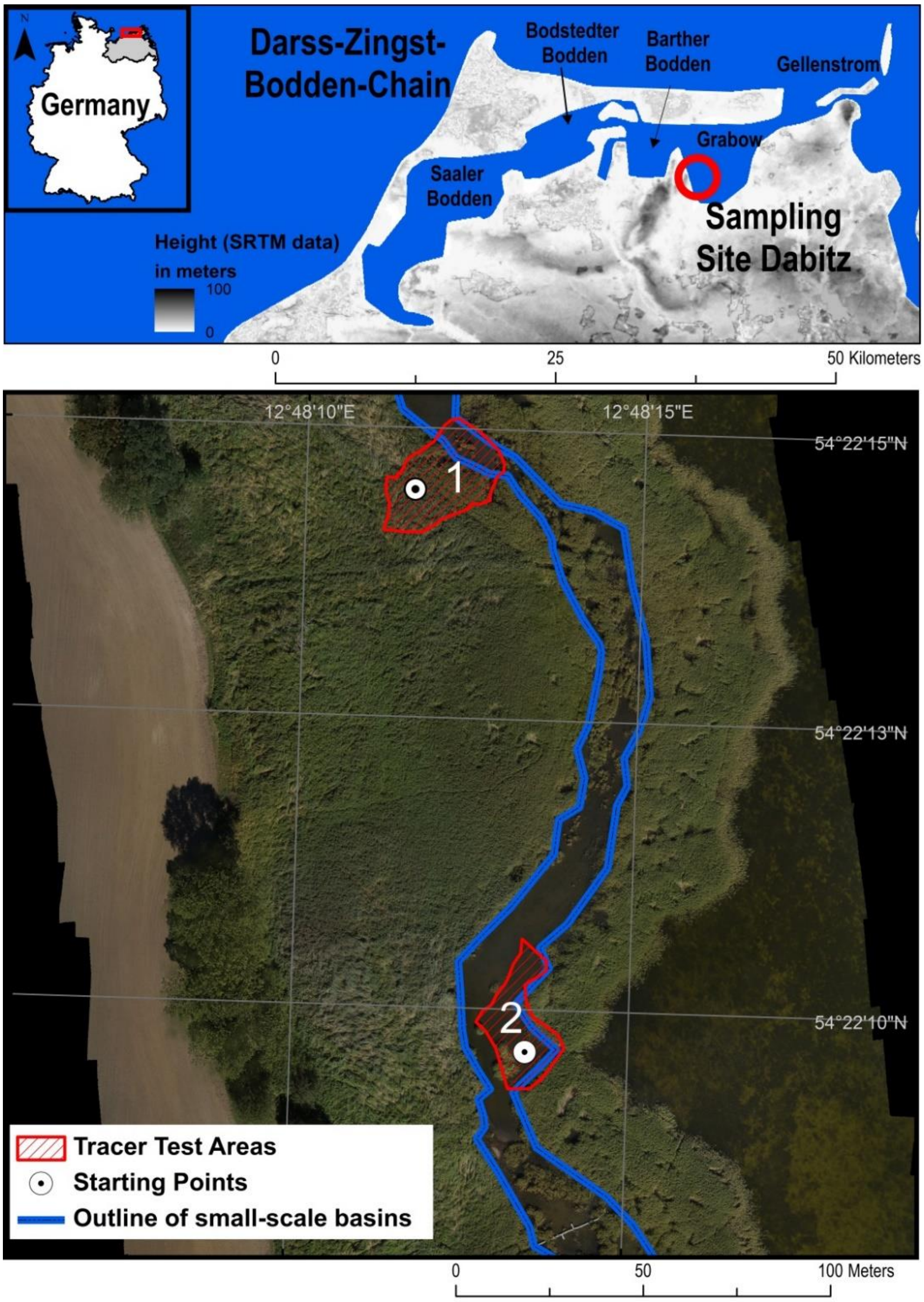

Fig.1: Location and sketch of the study site at the Darss-ZingstBodden Chain in Mecklenburg-Western Pomerania, northeast Germany. The reed bed is very wide with a variety of small-scale basins inside.

The first tracer study was carried out during the winter storm *Xaver*in December 2013 inside the terrestrial part of the reed bed with high vegetation density. The second tracer test was conducted in August 2014 in a small-scale basin within the littoral reed (Figure 1). Tracer experiments allow the exploration of sediment mobility on a timescale of a few hours to several months and can elucidate sediment transport pathways (SCHWARZER 1989). The pink fluorescent tracer particles with diameters between 0.063 and 0.2 mm used in this study were produced by the company *Partrac (*Newcastle upon Tyne, *UK)*. The pink color which luminesces under UV light allows the tracers to be identified unequivocally in the sediment samples (BLACK et al. 2007). Prior to the experiments, sediments from the coastal reed bed were analyzed and the median particle diameter was found to be 0.2 mm in the upper 0-2 cm sediment surface layer.

The first tracer study was carried out on the 27th of November 2013: 2 kg of luminophores were dispersed inside the terrestrial part of the dense reed bed and approximately 10 m away from the basin structures (Figure 1). The fluorescent tracer particles were scattered homogeneously within a 2 m² area, rather than at a single point, in order to avoid superimposition and interaction among tracer particles. Detailed sediment sampling to elucidate the spatial transport patterns of luminophore particles took place three weeks thereafter on the 17th of December. Samples were taken approximately every 1-2 m² with a soil sample ring (250 cm³, internal diameter 72 mm) within a 600 m² area and the spatial locations were recorded for each sampling position using GPS. Since westerly winds dominated during the tracer study, the sampling raster was adapted and enlarged eastwards. Topographic features (e.g., elevation, depressions, rills, animal pathways) as well as vegetation and litter status were noted for each sampling point. Vegetation and litter status was categorized for each sampling location into 10 classes with values between 0 (no vegetation, no litter) and 10 (very dense vegetation, thick litter layer). Comprehensive vegetation mapping was done before and after the tracer experiment. Leaf area (cm²) per culm was calculated as length×width×0.51+5.7 (ONDOK 1968, SCHIEFERSTEIN 1997). Since the local weather station was temporarily damaged during the storm *Xaver* in December, weather data from the nearby Station in Barth of the German Meteorological Service were used for further analyses.

The soil samples were dried at 105 °C overnight and homogenized. Thereafter, three sub-samples of 0.25 g were taken from each sample for further analysis. Prior to the experiment 0.0011 g of tracer material was analyzed under a microscope and the particles were counted. Accordingly, we could extrapolate that 2 kg of tracer material contains approximately 1.8×10^9 luminophore particles. Assuming a homogenous distribution of luminophore particles within the area of 600 m², a sampled area of 0.0082 m² per sampling point and mean dry soil bulk density of 0.386 g cm^{-3}, 64 tracer particles would be found in one 0.25 g sub-sample. Therefore we expected a sufficient number of luminophore particles within one sub-sample, although the results showed that the assumption of total homogeneity was not met. All sub-samples were photographed three times in a black box under UV-light (UV-C 254 nm and UV-A 366 nm) and the number of luminophores was counted using the software *VisionBuilder*(RENZ & FORSTER 2013) (Figure 2).

For the second tracer study, 1.5 kg of luminophores were released in suspension inside a basin in the littoral part of the reed bed (Figure 1). The focus was on the basin structure and the total sampling area of 439 m² was selected accordingly. During the second tracer study, south-westerly winds predominated and consequently the sampling raster was adjusted to this wind direction. Sampling was carried out already on the next day. A “stamp-technique” with grease-coated cards was used to collect samples (see INGLE 1966). For this purpose waterproof cards otherwise used as photographic paper were cut into 8x8 cm squares and coated with Vaseline. The cards were attached to a wooden pole and pressed onto the sediment surface (Figure 2). Sediment stuck to the grease-coated cards and was pinned along with the corresponding sample number to a sample board for later analysis. This technique is described in detail by INGLE (1966) who modified the sampling procedure from INMAN & CHAMBERLAIN (1959). Applying this method it must be taken into account that vertical movements and incorporation of luminophores tracers into deeper sediment layers are left out of consideration (SCHWARZER 1989). As sampling took place within the next 24 hours this was accepted. The grease-coated cards were dried and subsequently, as in the first tracer study, photographed under UV-light in a black box and the number of luminophores counted with the software *VisionBuilder*(RENZ & FORSTER 2013).

For the second tracer test a digital elevation model from a UAS (unmanned aerial system) flight could be used to study topographic differences and vegetation patterns. Therefore, no individual locational data had to be collected for the sampling points. The first UAS flight took place on the 12^{th} of March 2014. Water level at that time was very low and almost no water covered the basin areas in the reed bed. This allowed the recording of the bathymetry of the basin structures. The second flight took place on the 29^{th} of August during vegetation maximum shortly after the second tracer study. The UAS images were georeferenced with 20 ground control points. The digital elevation model with a resolution of 0.07596 m per Pixel, a point density of 533006 points per m^2, and a vertical resolution of 0.02 m was analyzed using the software ArcGIS (ESRI, USA). The raster calculator and the conversion tools were used to extract areas with specific depths.

Weather data from the local weather station were used for evaluation of wind speeds. Mean flow velocity and flow direction were measured with a 3D acoustic Doppler velocimeter (Vector, Nortek, Figure 2). The velocimeter measurements consist of three velocity components (X,Y,Z) based on an acoustic echo from particles moving through the cylindrical measuring volume which is located approximately 10 cm from the base of the three sensors. A data output rate of 16 Hz was chosen, separated into bursts with 4800 samples within 300 seconds (DEVARD et al. 2003; NEUMEIER& AMOS 2006; NEUMEIER et al. 2013; WANG et al. 2014). Matlab’s 3-D quiver function was used to simulate flow paths during the second tracer experiment. The three-dimensional quiver plot pictures vectors with velocity components.

Wind attenuation profiles were created by comparing wind speeds inside the dense reed stands at several heights with wind speeds measured at 2 m height. Wind speed at 2 m height was recorded by a permanently installed weather station located at the border of the reed bed (*DALOS 353-W, Germany*). A smaller wireless weather station (*PCE Instruments, Germany*) was placed inside the reed at five different heights ranging between 10 and 135 cm. In total, 29 hours of wind speed data during 11 different days were collected and compared with wind speeds at 2 m height. Water level loggers (*Solinst, Canada*) were deployed in January 2015 to check if water level fluctuations at the study site Dabitz match the water level fluctuation at Barth, the nearest official gauge operated by the waterways and shipping office Stralsund.

Fig.2: (A) Fluorescent tracer particles under UV light (only tracer particles without "normal" sediment particles (B) Wireless weather station inside reed stands to measure wind attenuation. (C) Usage of the stamp sampling device with grease-coated cards in a muddy area of the basin. (D) The 3D acoustic Doppler velocimeter (*Vector* – *Nortek*) measures three velocity components (X, Y, Z) based on an acoustic echo from particles.

3 Results

3.1 First tracer test (terrestrial part)

In early December 2013, the winter storm *Xaver*with maximum wind speeds of 16 m/s was the most important event during the first tracer study. Wind direction throughout the tracer test varied between south and southwest (Figure 3). The vegetation mapping before and after the first tracer study showed that the vegetation density did not change significantly during this period. The *Phragmites* stems resisted the storm *Xaver* and did not crack, but more leaves fell and the thickness of the litter layer increased compared with the conditions prior to the storm.

Tab.1: Summary of weather parameters during the first tracer study (27th of November – 17th of December 2013). All parameters were recorded by the DWD weather station in Barth, except soil temperature. Soil temperature was recorded using a weather station (*DALOS 535-W*) located directly at the sampling site, but recording of soil temperature started on 10-12-2013 in 5 cm depth.

Mean wind speed	Mean wind direction	Mean air temperature	Mean soil temperature	Total precipitation
5.6 m/s	240.5°	4.3°C	4.7°C	44.1 mm

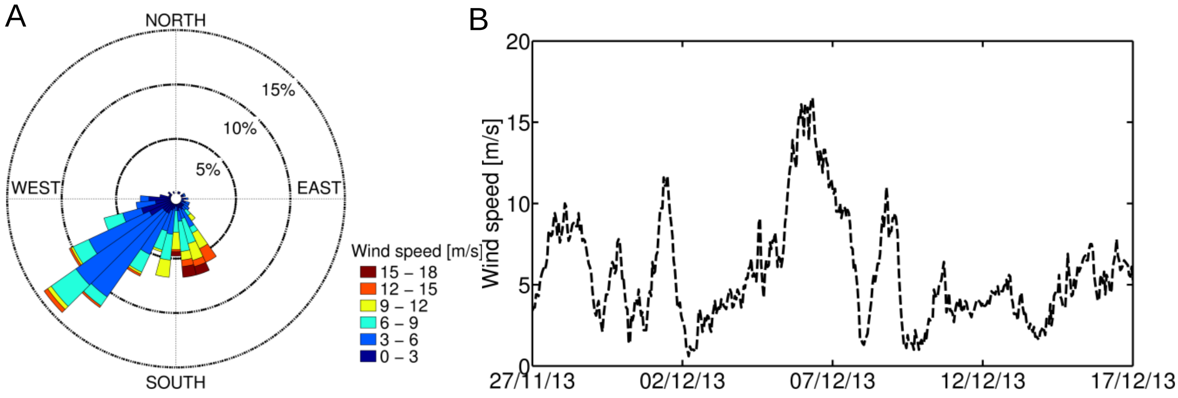

Fig.3: (A) Wind rose for the first tracer study. (B) Timeline of wind speed. Hourly values recorded between the 27th of November and 17th of December 2013 (Data from DWD weather station Barth).

During the study interval, ground frost did not occur (soil T > 3.9 °C) and the particles did not freeze on the ground (Tab. 1). Total precipitation during the three week study interval of the first tracer test was 44.1 mm. Daily maximum precipitation with 19.1 mm occurred on Dec 8 during the winter storm *Xaver*. However, rainfall within 6 hours was 13.5 mm and hence below the threshold for a heavy rain event (i.e., >20 mm within 6 hours according to DWD). According to KOPPE&STOZEK (1999), this is categorized as a "moderate rainfall". Therefore, precipitation is probably of minor significance as a driver for erosion.

After three weeks, 63 % of the deployed tracers were still found at the starting point. Only in 29 samples out of 225, luminophores were found (Figure 4). At 15 sampling points more than one tracer particle was found in the sub-samples, whereof only three sampling points were located beyond a 5 m radius from the starting point. For those three sampling points in the north the vegetation density was comparatively low (2-3 on a scale of 0-10). No luminophores were found at sampling points with high vegetation densities (8-10 on a scale of 0-10). Furthermore, thirteen of the sampling points at which several tracer particles were retrieved, featured "pathways", "rills" or "traces of trampling" according to the field protocol. While on the majority of rills and animal pathways no tracers were found, it cannot be excluded that those topographic structures function as pathways for sediment transport.

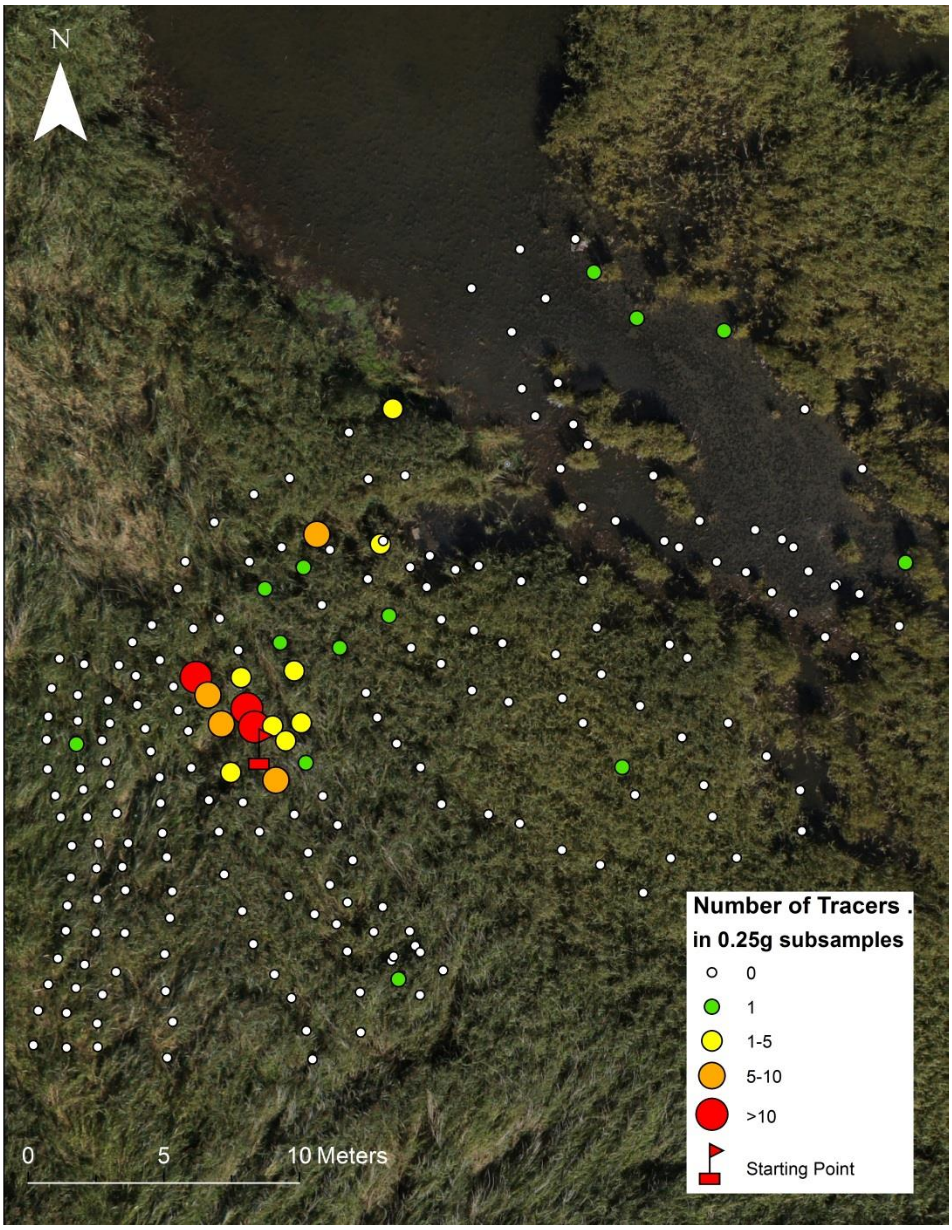

Fig.4: Result of the first tracer test. The symbols denote the location of sampling points and the number of tracer particles retrieved in 0.25 g subsamples (3 replicates per sampling point; total n= 225). The aerial image was taken in August 2014.

The results suggest that wind-energy was effectively buffered by the dense reed stand such that even under such an extreme event as storm *Xaver,* almost no sediment transport occurred. The wind attenuation profiles for the dense reed bed support this finding. Below 50 cm, less than 10 % of the wind speed compared to those at 2 m height was measured (Figure 5). Up to 1.5 m height, the wind in the reed bed is attenuated by more than 50 %. This is due to the high amount of biomass in the terrestrial part with a maximum of 8.37 kg m^{-2} in August, a decrease during fall and winter to 3.6 kg m^{-2} and a minimum of 1.72 kg m^{-2} in March (after ice drift). Stem density goes down from 550 stems per m^2 in August to 350 stems in November and 250 stems in March. During the growing season in May when most shoots appeared, leaf area per stem was 90 cm^2. The leaf area reached its maximum in September with 670 cm^2 per culm and went down to 390 cm^2 in November. In January, no leaves were left on the Phragmites stand, since presumably they had been completely incorporated into the litter layer on the ground. Litter mass in the terrestrial reed stands is 517±151 g per m² in November and 825±25 g per m² in January. Water content of the sediment in 0-2 cm depth in the terrestrial part of the reed bed is 59.5±15 mass-% and increases toward the transitional part of the reed bed where water content reaches values up to 89 %.

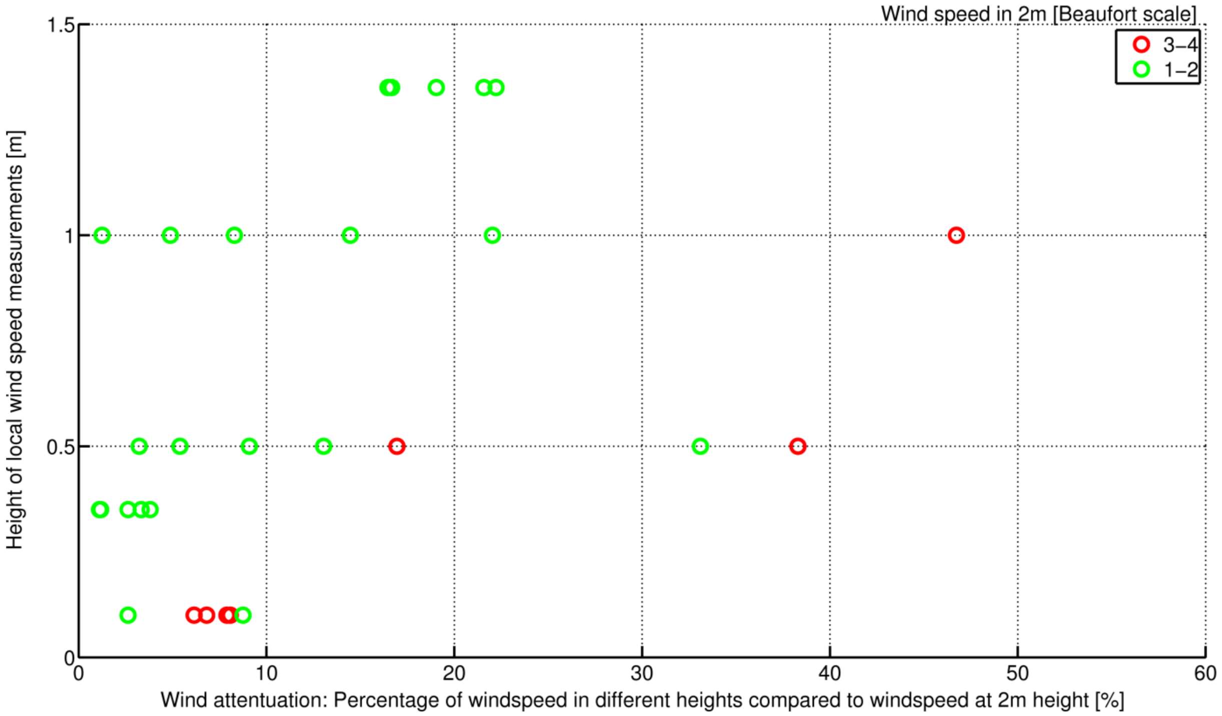

Fig. 5: Wind attenuation profiles recorded within the reed bed. Wind speeds (averages over 1 hour) in 2m height were compared to wind speeds at different heights between 10 and 135cm inside the reed bed (n = 29 hours of wind data during 11 days).

During storm *Xaver* the water level at the official gauge station at Barth dropped initially on the 5th and 6th of December by half a meter, but flushed back on the next day (Figure 6 B). Data from the applied water level logger at our study site showed that the water level fluctuations at Dabitz and Barth correlate significantly (Figure 6 A; R^2= 0.9054) and thus the water level fluctuations at the study site Dabitz could be calculated. The tracer material was deployed in the terrestrial part of the reed bed at 0.29 m [NHN] and the water level fluctuations show that the tracer material was not exposed to waves or currents during storm *Xaver* (Figure 6 C). Thus, transport due to flushback effects in the Bodden during storm *Xaver* can be excluded.

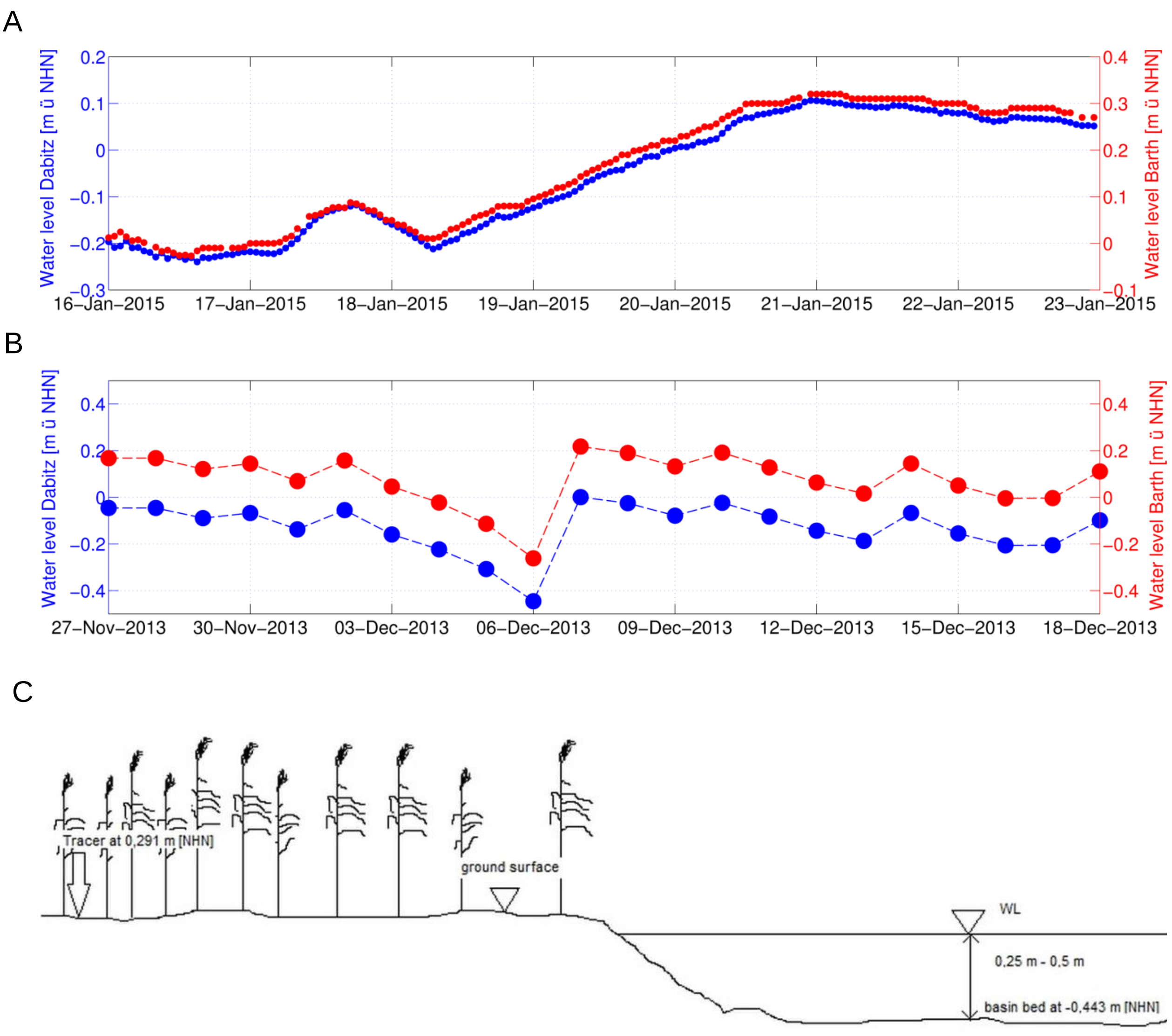

Fig. 6: (A) Water level fluctuations at the study site Dabitz, measured with *SolinstLevelloggers*, and water lavel fluctuations at Barth measured by the waterways and shipping office Stralsund. (B) Measured and calculated water level fluctuations during the first tracer test. (C) Schematic sketch of the tracer test stating point and the adjacent basin structures.

3.2 Second tracer test (littoral part)

During the second tracer experiment in the basin the mean wind speed did not exceed 5 m/s and wind direction was mainly from southwest. The mean flow velocity was 0.0172 m/s and flow direction reflected the wind path with water movement from south-southwest to north-northeast (Figure 7). This pattern is reflected in the results of the tracer distribution. Most luminophores were counted along the deeper channels in the north and north-east (Figure 8).

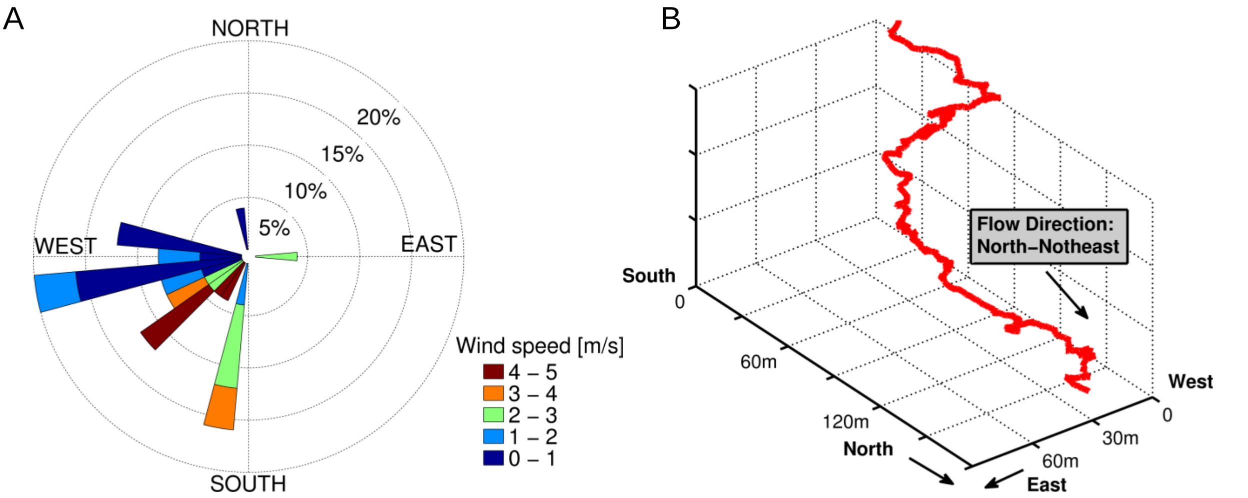

Fig. 7: (A) Wind rose for the second tracer study. (B) Simulated flow path of a particle using the XYZ velocity components of the acoustic Doppler velocimeter at the starting point of the tracer study (path over 24 hours: 2014-08-12 noon until 2014-08-13 noon).

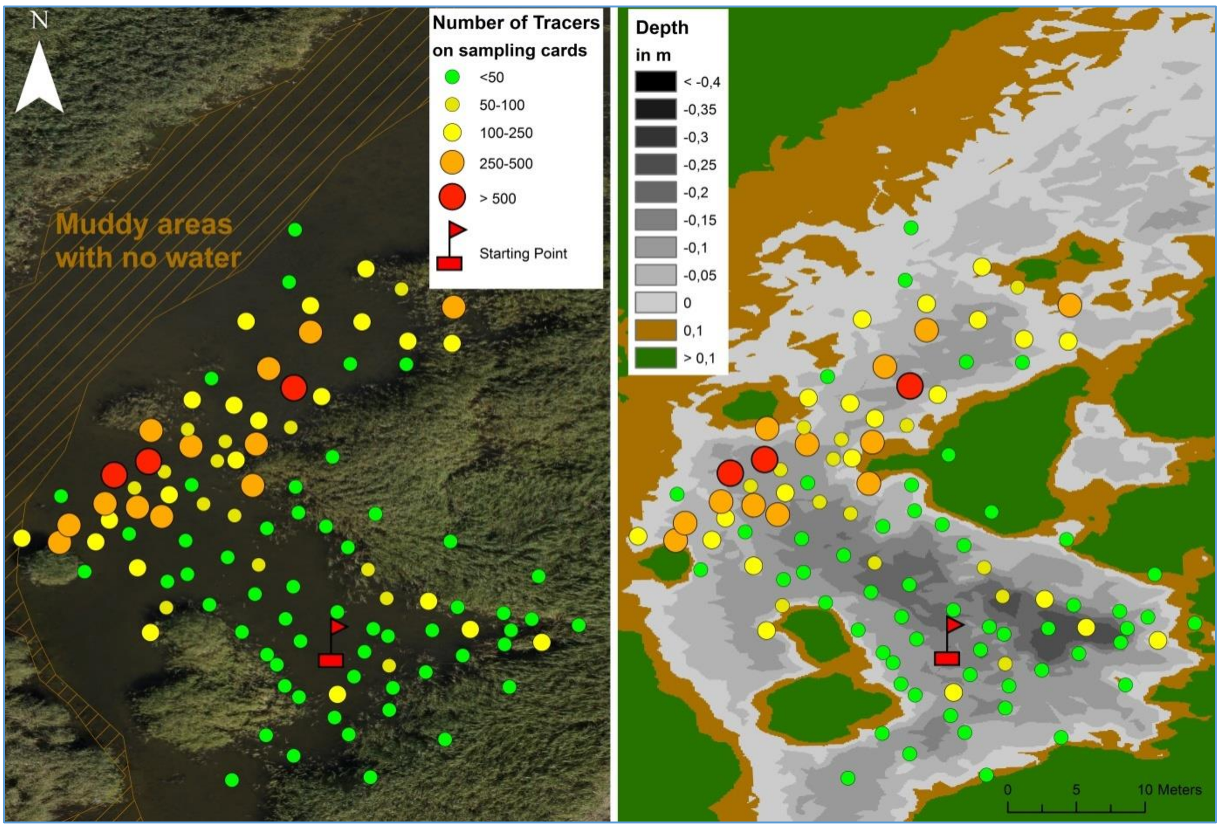

Fig. 8: Result of the second tracer test (n=108). The left figure shows the aerial image taken on the 29th of August. On the right side the bathymetry of the basin structures is displayed.

While almost no sediment transport occured in the dense terrestrial reed stand during the first tracer test, the fluoroscent particles which were released in suspension in the littoral basin during the second tracer experiment moved far and fast. Tracer particles were recovered as far as 30 m away from the starting point (Figure 8). The highest numbers of tracer particles were found in the north-northeast along the deeper flow channels. These flow channels were clearly visible during the field sampling. Comparatively few particle tracers were found within reed stands bordering the basin structures. Wind direction gave the impulse for the direction of water movement, but the bathymetry of the basin modified the water flow and consequently the sediment transport patterns.

An important aspect of the second tracer study is that the grain size distribution of the tracer material does not reflect the grain size distribution of the basin sediments (Figure 9). This was known prior to the study and the aim of the second tracer study was to investigate how particles from the terrestrial or the littoral part would be transported in the basin areas. The tracer material with a median grain size of 207 µm reflects well the sediments sourrounding the basin structures. Median grain size in the adjacent littoral ranges between 177-190 µm (BITSCHOFSKY et al. 2015) and around 209 µm in the terrestrial part of the reed bed. The basin structures are therefore enclosed by sediments with larger grain sizes and our second tracer study demonstrates that particles entering from the littoral or the terrestrial side are effectively transported within the basin structures along the deep flow channels.

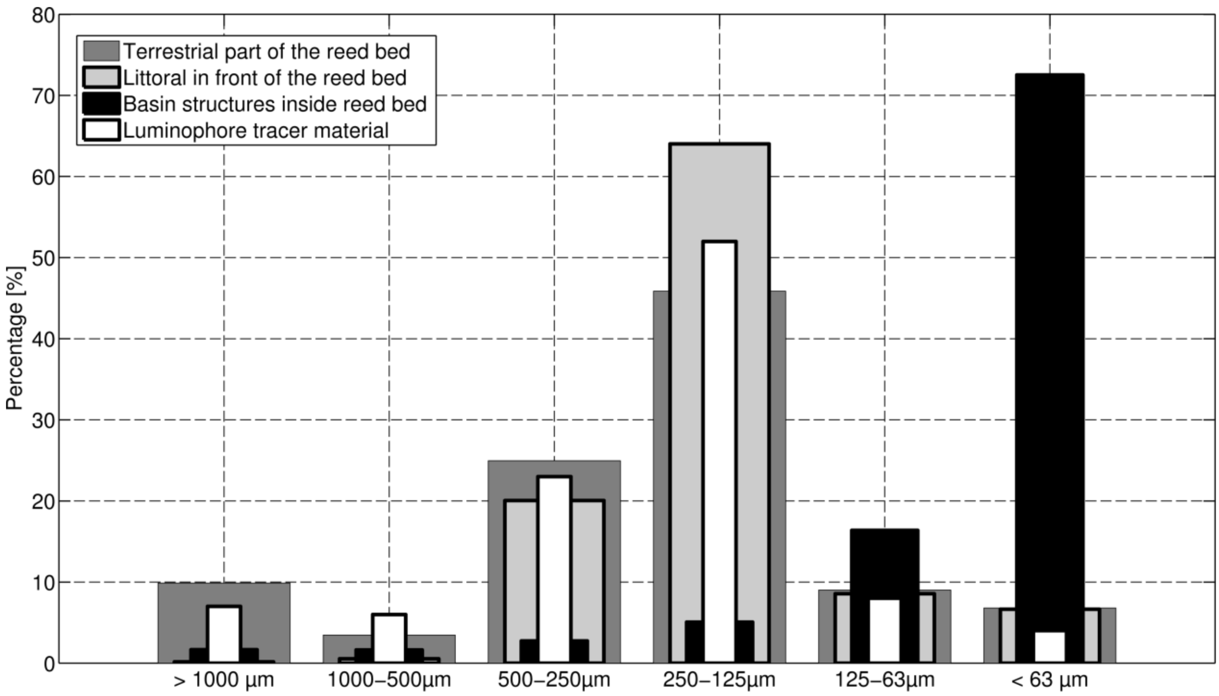

Fig. 9: Grain size distribution of sediments in the terrestrial part of the reed bed, in front of the reed, in the basin structures and of the fluorescent tracer particles.

4 Discussion

The fluorescent tracer tests show that both vegetation characteristics and local-scale topography have an impact on sediment transport processes and deposition patterns. In the first tracer study in the terrestrial part, the dense reed stands reduced wind speed and thereby effectively inhibited sediment transport by wind. After three weeks, 63 % of the deployed tracers were still at the starting point and the few tracers found further away than 5 m were located in spots with low vegetation density, with rills or animal traces. In contrast, in the second tracer test, the fluorescent particles moved fast and far within the small-scale basin of the littoral reed and followed the deeper flow channels which in turn are influenced by the reed stands in the water. Water flow direction measured at the starting point of the second tracer test was north-northeast but comparatively few tracers were found directly north-northeast of the starting point. This suggests that water and particle movement are modified by the bathymetry of the flow channels. At the bend to the right of the deep flow channel (Figure 8), water movement is presumably reduced, particles can settle down and consequently most tracers are found at the curve of the flow channel. The reed stands around the small-scale basin and inside the basin impact water movement and the bathymetry on a longer time-scale. Vegetated coastal habitats in general have a direct impact on the attenuation of flow energy via friction and thus directly reduce the risk of coastal erosion. But their ability to trap and accumulate sediment and thereby to change the bathymetry is of higher importance for shoreline protection (DUARTE et al. 2013).

The most relevant characteristics of vegetated coastal habitats that decide about their capability to protect the coast against erosion events is their specific location and geometry with respect to the considered event (waves, storm surges, tsunamis or currents) (DUARTE et al. 2013). Also MÖLLER& SPENCER (2002) state that the local-scale topography of wetlands determines to which extent the wave energy is reduced. Vegetation density, species composition, the type of sediment substrate and the quality and abundance of the aboveground biomass modify energy attenuation (BOUMA et al. 2005; DUARTE et al. 2013). But it is not only the geometry of the vegetated coastal wetlands as a whole, but also the geometry of each individual plant. The morphology of roots, stems and canopies affects the attenuation of waves and currents. MÖLLER et al (2011) measured in a reed bed at the southern Baltic Sea wave height attenuation of 2.6 % m^{-1} in a sheltered study site and 11.8 % m^{-1} at an exposed site at the transition from open water to reed vegetation. Biomass and stem density are high at the study site Dabitz. The stem density with 550 stems per m^2 in summer is comparable to other sites at the Southern Baltic Sea (e.g., 434 and 483 stems per m^2 at two study sites at the Pomeranian Bight, MÖLLER et al. 2011, and 179-425 stems per m^2 north of our study site Dabitz, VOIGTLAND 1983), but much higher compared to values of brackish *Phragmites* sites in North America (11-125 stems per m^2, six different sites, MEYERSON et al. 2000). Leaf area at our study site Dabitz was higher throughout the year than the leaf area measured by VOIGTLAND (1983) in 1981 and 1982 a few kilometers north, but comparable to other *Phragmites* sites in northern Germany (SCHIEFERSTEIN 1997). The high vegetation density at Dabitz explains the strong wind attenuation inside the reed. Wind speed at the sediment surface was less than 10 % of that measured at 2 m height. In addition, the high water content of the sediment ranging between 38-89 mass-% increases the threshold for wind erosion. It is well known that substantial moisture content in the surface sediments decreases the aeolian erosion potential due to capillary and adhesion forces significantly (CORNELIS et al. 2004; BAUER et al. 2009).

The possibility of aeolian sediment transport was hampered by the high vegetation density and soil moisture.

The litter layer inside the reed bed at the study site Dabitz was extremely thick during the first tracer test and proved to be another important parameter in preventing erosion. SCHIEFERSTEIN (1997) examined the litter layer in 12 different *Phragmites* stands in northern Germany. Depending on the location the litter layer varied between 132-711 g m^{-2}. In this context the mass of the litter layer in Dabitz with 517-825 g m^{-2} between November and January can be considered as high. While little quantitative data about the effect of litter on depositional processes in marsh areas is available, it is generally acknowledged that litter increases the roughness of the floor. The enlarged friction impacts water movement and supports particle settlement. Decomposed litter and trapped minerals and organic material will ultimately be incorporated into a newly formed sediment layer (FREY &BASAN 1978; REED 1995; ROOTH et al. 2003). According to ROOTH et al. (2003) the abundance of concentrated litter on marsh surfaces covered by *Phragmites* is responsible for the efficient trapping of organic and mineral matter in reed beds. At their study site Chesapeake Baythe yearly rate of accretion for a Phragmites-dominated system was 0.95 cm. This high rate compared to other marsh systems was explained among others by the high productivity of *Phragmites* and the absence of litter export in the mid-marsh regions. An earlier study revealed that 50 % of the accretion inside *Phragmites* dominated wetlands is organic, probably resulting from the litter, while the littoral part of the wetland is prone to wave action and dead material can be exported (ROOTH& STEVENSON 2000). In coastal wetlands dominated by *Phragmites* the sediment floor is continuously covered by dead plant material (ROOTH 2003). Monthly vegetation mapping at the study site Dabitz supports this statement. While the litter layer increases in autumn, it never vanishes and also during summer time the sediment surface is covered by dead plant material.

DUARTE et al. (2013) noted that vegetated habitats may not always be sufficient to protect the coastline due to seasonal and inter-annual variations in the vegetation cover. In contrast to other marsh systems, vegetation density in *Phragmites* dominated marshes does change over the year but is never low. Hence seasonality presumably does not have a big impact on the coastal protection function of reed beds. While during winter time the thick litter layer on the floor supports erosion control, the large amounts of leaves during summer support the attenuation of wind and precipitation energy and decrease erosion activities.

In contrast to artificial coastal protection structures, vegetation ecosystems can adapt to changes in sea level and wave energy by sediment accretion (DUARTE et al. 2013). The large mud layer in the basins of the reed bed at the study site Dabitz and the thick litter layer in the terrestrial part are signs that accretion rates might be high. In contrast to the terrestrial tracer study more fluorescent tracer particles moved in the littoral tracer study, but the movement of tracer particles was bound to the existing deep flow channels. These flow channels may be enclosed or vanish in the near future if the reed productivity remains high. This is an objective of an ongoing study with aerial images and digital elevation models at the study site Dabitz and definite statements cannot be made yet.

5 Conclusion

The fluorescent tracer tests show that besides the direct drivers for transport (e.g. wind speed, wave height etc.) both plant morphology and local-scale topography have an impact on sediment transport processes and deposition patterns. Dense reed beds reduce wind speed and inhibit sediment transport severely. In the small-scale basin particle transport follows the flow channels which in turn are influenced by the reed stands in the water. Both tracer experiments underline the importance of *Phragmites australis* regarding coastal protection with its ecosystem service of wave, current and wind attenuation.

Zusammenfassung

Schilf ist ein Ingenieur seiner eigenen Umgebung. Seewärts wirkt die Küstenvegetation als Puffer indem Wellenenergie abgeschwächt wird und Turbulenzen reduziert werden. Auch landwärts fungieren Schilfgebiete als Puffer indem sie Windenergie dämpfen. Ziel dieser Tracer-Studien war es, das Zusammenspiel von Sedimenttransport mit Vegetationsmuster und Topographie zu untersuchen. Fluoreszierende Partikel wurden verwendet, um die Sedimenttransportwege in zwei verschiedenen Bereichen eines Schilfgürtels an der Darß-Zingster-Boddenkette zu visualisieren. Im terrestrischen Teil des Schilfgürtels reduzierte der dichte Vegetationsbestand die Windgeschwindigkeiten und hemmte den Sedimenttransport während des ersten Tracer Tests. Das zweite Tracer Experiment wurde in den Beckenstrukturen des litoralen Bereichs durchgeführt. Die Wind- und Strömungsrichtung war von Süd-Ost nach Nord-West. Die Transportwege der Partikel wurden jedoch durch die Bathymetrie der Beckenstrukturen modifiziert und der Partikeltransport folgte den tieferliegenden Strömungskanälen, welche wiederum durch den Schilfbestand in den Beckenstrukturen beeinflusst werden. Die Tracer Tests zeigten, dass sowohl Pflanzenmorphologie als auch die lokale Topographie signifikante Auswirkungen auf Sedimenttransportprozesse und Ablagerungsmuster haben.

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