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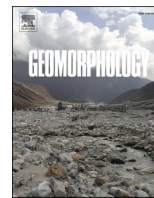
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Quantifying spit growth and its hydrodynamic drivers in wind-dominated lake environments

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ABSTRACT

Many sand spits are morphodynamically complex landforms, that are either analysed with complex and expensive computational models or at a conceptual level. Therefore, most case studies on spits in different environments are descriptive. A novel method based on the use of polar coordinates was devised to quantitatively analyse spit morphodynamics in a non-tidal, wind-dominated lake environment, using the Marker Wadden islands in Lake Markermeer, the Netherlands, as a case study. A high-resolution morphological data set allowed for the quantification of sedimentation processes around two spits, in two distinctive depth zones. Spit-platform growth is governed by alongshore currents that transport sediment over the spit-platform into deeper waters; the size of the spit-platform in turn affects the growth of the spit around the mean water level. Insight in this complex interplay of processes is crucial to understand spit behaviour in low-energy lake environments. At the Marker Wadden the submerged spit-platform grows during high energy wind events while the emerged spit part grows under mild to moderate energy conditions. With this new method we can quantitatively explore the role of different wave and flow conditions and predict spit growth direction in non-tidal, wind-dominated environments, beyond the level of conceptual descriptions.

1. Introduction

Along our coasts, different types of coastal systems and landforms can be defined. A special type of landform is a sand spit, which often has complex morphodynamics (Allard et al., 2008). Spits can be defined as a partly subaerial ridge or embankment of sediment attached to the land at one end and terminating in open water at the other, which needs to be fed by longshore processes (Allen, 1982; Evans, 1942). Spits often occur at places where the coastline changes its longshore uniform direction, as this gives the longshore current more room to disperse and lose transport capacity, resulting in sedimentation (Uda, 2018). Therefore, spit growth is for a large part dependent on sediment supply (Simeoni et al., 2007).

Besides the societal functions spits may have, like recreation and flood protection, they are also valuable and unique coastal habitats for a wide range of flora and fauna (Allard et al., 2008; Rossel and Westh,

2020). Spits are highly dynamic, and their shape and size can change in very short timespans depending on various complex drivers (Randazzo et al., 2015). Different drivers at different locations result in an abundance of spits with different types and shapes all around the world, of which several different categories can be distinguished (Robin et al., 2020; Uda, 2018). Several categories of spits are:

1.1. Recurved spit

These are the most common. They occur mostly on places where wave-driven longshore transport occurs on one side of the spit. This creates a single, or possibly multiple hooks (Allen, 1982). The changing angle of incidence of the waves, which surpasses the optimum 45-degree angle at the fulcrum point, and the corresponding changing longshore transport stands as the primary driver for the formation of this shape (for

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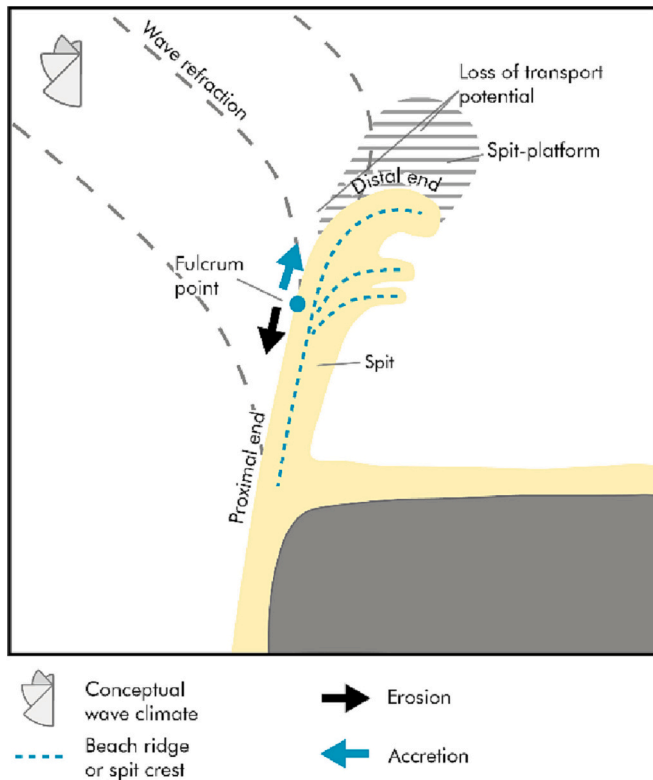


Fig. 1. A schematic representation of a recurved spit. Illustration based on Rossel and Westh (2020).

definitions, see Fig. 1) (Ashton et al., 2016). Typical recurved spits, with hooks formed by originally low angle or even perpendicular waves are the Arçay spit (Allard et al., 2008), the Buctouche Spit (Davidson-Arnott et al., 1995) and the spit on Hagemeister Island (Ashton et al., 2016) (Fig. 2a).

1.2. Simple spit

Simple spits have a relatively linear shape, caused by two longshore currents coming from both sides of the spit. Each current effectively erases the hook caused by the current on the other side (Rossel and Westh, 2020). Examples of simple spits are Skagens Odde in Denmark (Bruun, 1993; Rossel and Westh, 2020) and the spit in Cape Helopen in the USA (Kraft et al., 1978) (Fig. 2b).

1.3. Flying spit

According to Ashton and Murray (2006), spits in regions with predominantly high angle waves tend to protrude from the beach. These, so called, flying spits originate from the principle that high angle waves result in higher wave-driven transport at the sides of a protrusion than at the top. Examples can be found in lake Mega-Chad in Central Africa, the Azov Sea in Ukraine (Bouchette et al., 2010) and Lake Erie in Canada (Davidson-Arnott and van Heyningen, 2003) (Fig. 2c).

1.4. Non-wave dominated spit

Tidal and lake circulations can also create significant longshore currents (Nutz et al., 2018). These spits tend to be more linear as the waves that are essential in shaping the hook (Ashton et al., 2016) are not present. Examples include the Lubec Spit in the USA (Randazzo et al., 2015) and the ‘El Puntal’ Spit in Spain (Losada et al., 1991) (Fig. 2d).

However, in practice it is not always clear in which class a spit

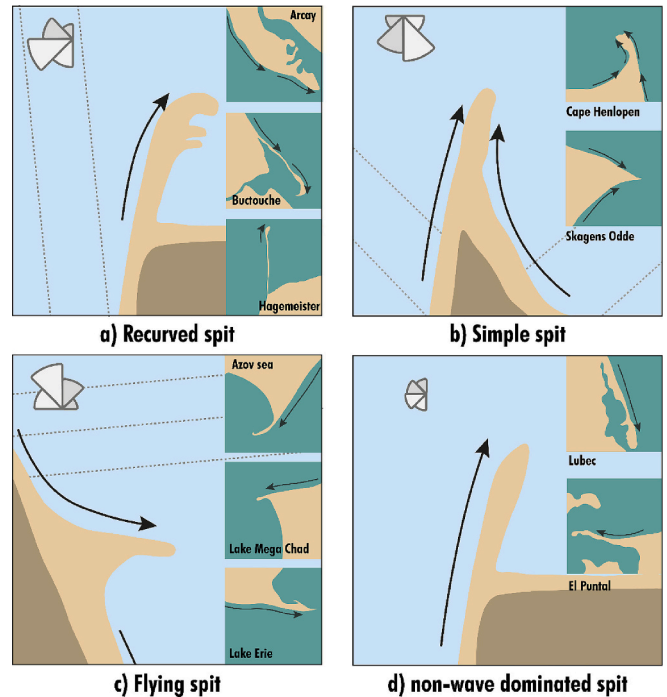


Fig. 2. The different classes of spits, recurved spits, simple spits, flying spits and non-wave dominated spits respectively. For every spit the main figure is a schematic representation of the spit type, with on the right the examples referred to in the introduction. The wave rose on the upper left indicates the schematic wave climate, the dashed lines indicate the incoming wave crests, and the black arrows the sediment transport along the spit.

belongs as there can often be multiple hydrodynamic drivers attributed to their formation. For each of these drivers the effect on the morphodynamics can be completely different. In practice, the role of each of these hydrodynamic drivers in morphological development needs to be distinguished to be able to describe and predict the eventual spit development. Therefore, methods for quantifying hydrodynamic drivers and spit growth are needed.

The general effect that the hydrodynamics have on spit growth behaviour is well understood for the different types of spits. However, few case studies have managed to quantify, or even link, spit morphology and its process drivers (Allard et al., 2008; Héquette and Ruz, 1991). As a result, most research on spits is descriptive.

There is much that is already known about spit growth, especially from a schematic perspective. Meistrell (1966) showed that the growth of the subaerial ridge of the spit is preceded by a submerged spit-platform. The interaction between the emerged part and the platform is often important for the spit shape and its growth. Kraus (1999) continued the research of Meistrell by stating that with unrestricted spit growth all the material that is transported towards the distal end accretes partially in the subaerial spit and partially on the spit-platform (Fig. 1). They assume that the ratio with which the spit and its platform grow is always the same, although Meistrell’s experiments showed that spit and platform growth are inversely related.

Spit growth has been quantified with computational models with success, using flexible grids in studies such as Ashton and Murray (2006) and Ashton et al. (2016). However, in these studies typical, theoretic, cases instead of existing sites were modelled. The modelling of dynamic spits has specific requirements, such as a flexible grid, and as a result computational models are expensive and require great expertise (Roel-vink et al., 2020). On the other side analytical models can be used (Kraus, 1999; Palalane et al., 2014). Analytical models simplify the complex spit shape to a simple block, of which the growth can be calculated by dividing the cross-section with the incoming sediment

transport. These models are convenient to use but discard the three-dimensional variability of spits. A new model, Shoreline-S, seems to be a bridge between these two extremes and is applicable to existing sites (Roelvink et al., 2020). However, here the ratio between submerged and emerged growth of the spit is not taken into consideration.

Studies on individual spits often aim to quantify their growth. Nonetheless, there exist considerable variations among studies in the manner and criteria utilized for quantifying spit growth. A lot of studies quantify growth by an extension rate in meters a year. This growth rate can be determined as the distance between the furthest point on the spit at different moments through time (Rodríguez et al., 2003; Simeoni et al., 2007). Other studies use the increase in length in time along a manually determined longitudinal cross-section (Allard et al., 2008; Robin et al., 2020; Bruun, 1993; Davidson-Arnott et al., 1995). Both methods discard the change in spit shape that may occur. Also, because the exact manner of quantification differs between case studies, comparisons are difficult. Another method that is often used is to determine the area with which a spit increases over time (Allard et al., 2008; Rodríguez et al., 2003; Simeoni et al., 2007). This approach encompasses alterations in the morphological configuration of the spit. However, it lacks the capability to differentiate between various types of growth resulting from distinct underlying drivers. A novel method, to quantify and show spit growth is necessary to fully describe three-dimensional spit growth, both above and below the waterline.

Spits can be present in low-energy, non-tidal environments, such as Lake Markermeer, the Netherlands. Since little is known about these environments in general (Vila-Concejo et al., 2020), the development of spits is also overlooked. These environments have limited wave energy and are therefore dependent on high-energy events for large scale morphodynamic developments, without receiving sediment replenishments during low-energy periods. Additionally, lakes have circulation currents due to water level set-up differences across the lake at high winds (Ton et al., 2021; Wellen, 2021). Both hydrodynamic processes can have a pronounced effect on spit development. Also, beach profiles in low-energy lake environments typically have a long platform in front of the coast (Brideau et al., 2022; Jackson et al., 2002; Ton et al., 2021; Vila-Concejo et al., 2020). This can be of large influence on spits as platforms have proven to be of essence for spit development.

The two spits of the constructed Marker Wadden islands in Lake Markermeer, the Netherlands, provide a unique opportunity to study their development quantitatively. Bathymetry and topography of these sites is monitored extensively, and hydrodynamic measurements and model results are available. As these spits are part of a beach and dune system protecting these islands, knowledge on the development of the spits will help with maintaining the islands and perhaps the design of similar islands. The goal of this research is to identify key drivers of spit development in wind-dominated, low-energy, non-tidal environments, through quantification of hydrodynamic drivers and morphological development.

The study sites and methods are further discussed in Section 2. This section discusses a novel approach to quantifying spit growth in two vertical sections: the emerged part and the submerged spit-platform part. Moreover, we show a new method for quantifying spit growth in the horizontal plane, through using polar coordinates. Results are covered in Section 3 where the results of a morphological analysis are linked to the results of a hydrodynamic analysis. In this section also the ratio between submerged and emerged spit growth are discussed. Section 4 discusses the benefits, possibilities, but also the limitations and inaccuracies of the findings and novel method. Section 5 presents the conclusions.

2. Study sites and methods

2.1. Study sites

To research spit behaviour in a typical low-energy lake environment,

the Marker Wadden islands in the Netherlands are used as a case. The Marker Wadden are an artificial island group of 1300 ha in Lake Markermeer. Lake Markermeer is a closed-off lake that can be classified as a low-energy, non-tidal environment. The Marker Wadden, an artificial archipelago, was constructed in 2016 to improve the ecological value of Lake Markermeer as a whole (Jin et al., 2022). This makes the Marker Wadden one of the biggest nature restoration projects of Europe. The islands themselves are protected by two sandy beaches with dune rows (Fig. 3, Fig. 4). Each beach begins at a groyne and has an open ending or head. It is from these two heads that new, young spits start to develop.

Lake Markermeer is a non-tidal, shallow lake (~4 m) that can be subject to significant lake circulation currents due to water level set-up differences in the lake during storms. Because of the limited fetch in this lake, the waves generally have too little energy to transport sediment back to the shores during normal conditions but do erode during storms. This gives the beaches a profile, with an elongated platform below the waterline, typical for these low-energy lake environments (Ton et al., 2021; Vila-Concejo et al., 2020; Wellen, 2021). Thus, this is a system with multiple drivers, and large differences between moderate and storm conditions.

By previous field and hydrodynamic modelling studies, it was determined that the northern beach and spit are affected by waves with a high angle of incidence as well as currents caused by the circulations in the lake, affecting the spit from both sides (Boskalis Nederland, 2015; van Santen, 2016; Wellen, 2021) (Fig. 4). Considering the different classes from the introduction it can be expected that this spit would be a combination of a simple spit and a flying spit. Meanwhile the southern beach and spit is mainly subjected to perpendicular and very low angle waves from one side (Fig. 4) (Boskalis Nederland, 2015; van Santen, 2016; Wellen, 2021). According to the classes from the introduction, this spit would resemble a recurved spit.

By comparing the shape and size of the spits at the Marker Wadden to the classification of spits, as presented in the introduction, a general idea about the drivers behind the development of the northern and southern spit can be formed. To get the desired amount of insight into the developments of both spits and nuance the extent to which both spits can be attributed to a spit class, a novel method of quantifying spit morphodynamics and hydrodynamics has been developed and used.

2.2. Method

Spit growth was analysed using topographic and bathymetric data of both spits at successive times. This data is analysed with a novel method that uses a polar coordinate system on the horizontal plane. This methodology is divided in the following subsections: data collection and processing, the model for data analysis, flow around the spit, sedimentation around the spit and sedimentation on elevation classes.

2.2.1. Data collection and processing

Sedimentation and erosion of both spits is quantified by using topographical data of the Marker Wadden, measured by Boskalis Nederland. These measurements were done four times per year and the interval between measurements varies between 2,5 to 4,5 months (Fig. 5). The measurements consist of drone photogrammetry and underwater multibeam measurements (Fig. 6e). Using Structure-from-Motion technology, pointclouds containing height data have been created, that have a general vertical accuracy of around 5 cm (Fig. 6a, b, d) (Westoby et al., 2012). Elevation changes are calculated from the pointclouds (Lague et al., 2013) and are linearly interpolated over a grid, with grid cells that span several points, to get a mesh with elevation changes. Changes in elevation averaged over a single grid cell were multiplied with the area of that square grid cell to compute erosion and sedimentation volumes at their locations, in a period between two topographic measurements.

Hydrodynamic data was obtained from already existing output of a Delft3D model of Lake Markermeer, made and validated with field data



Fig. 3. Marker Wadden islands, seen from the tip of the southern spit. Picture made by Van Kouwen and Ton (2022).

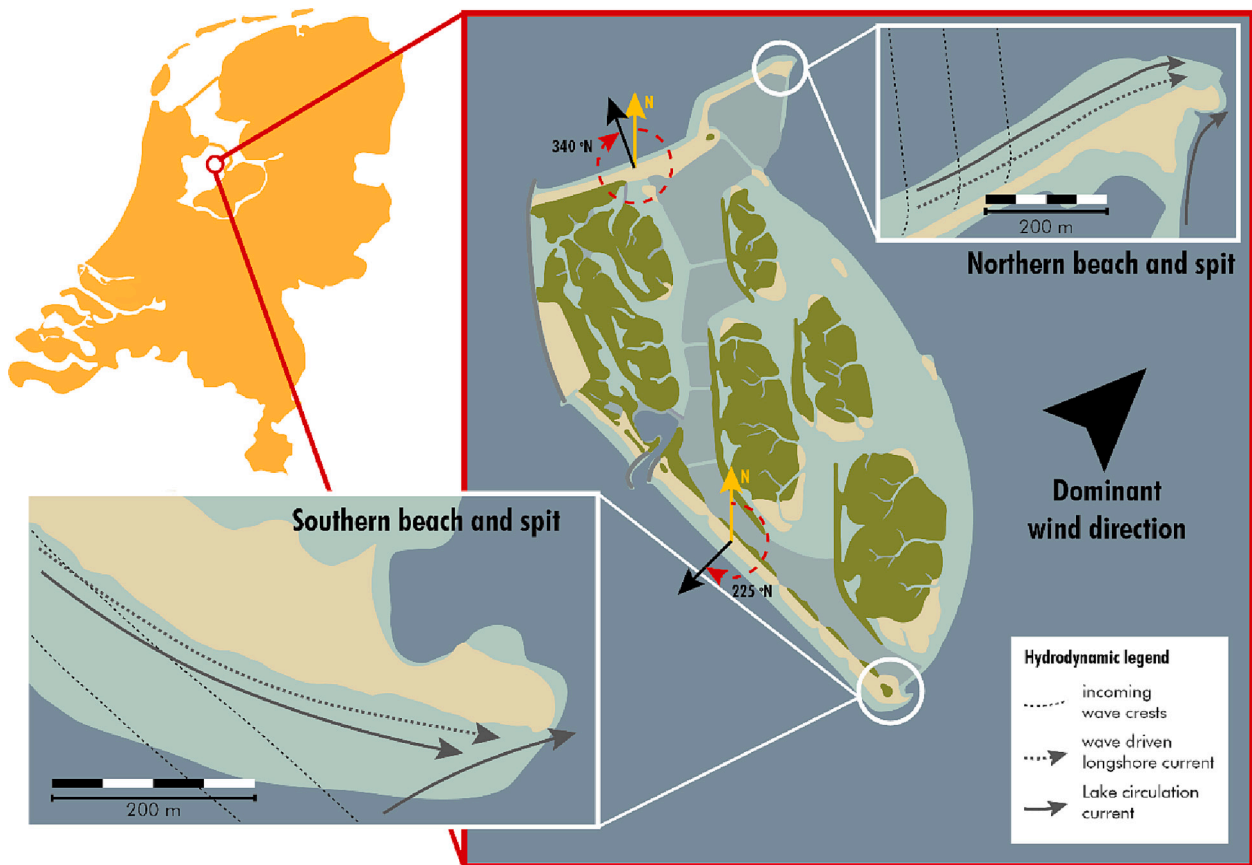


Fig. 4. Location and situation of the Marker Wadden islands, in Lake Markermeer in the Netherlands. The black and red arrow combination indicates the orientation of the beaches relative to the north. Drawing based on Boskalis Nederland (2015).

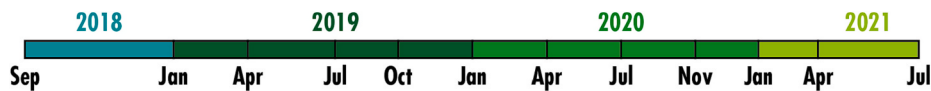


Fig. 5. Timeline of the topographic measurements (both above and below the waterline) done by Boskalis. With the month of measurement indicated in black.

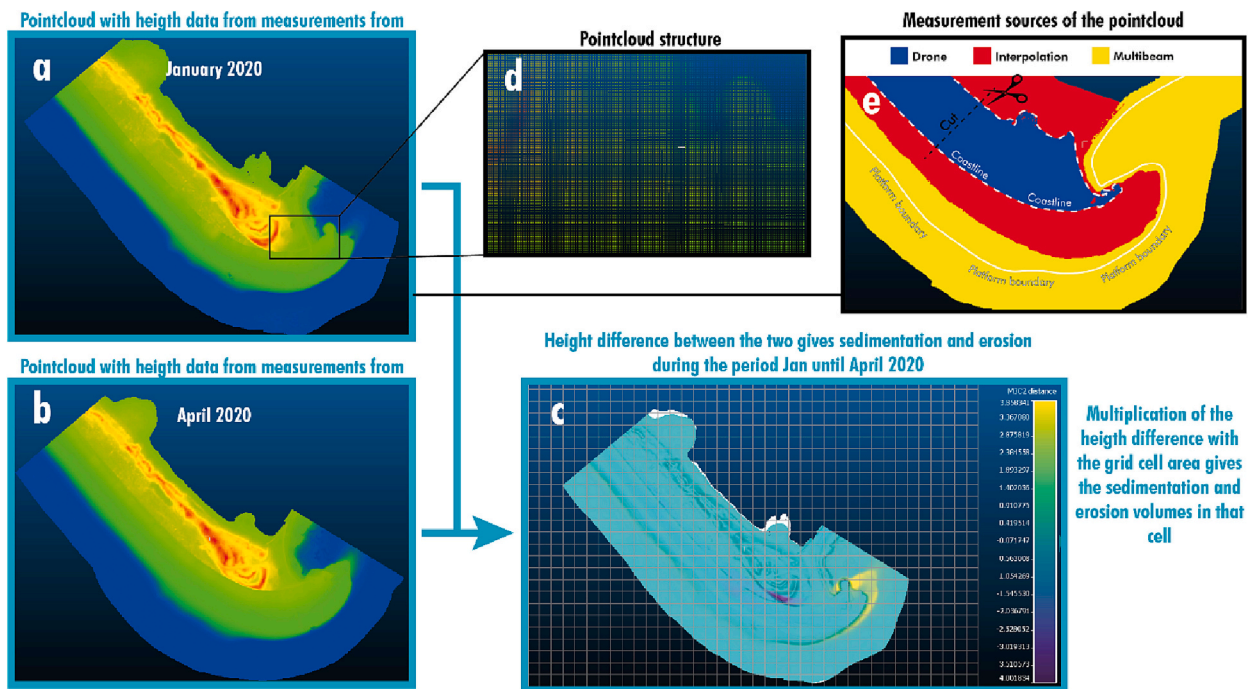


Fig. 6. Height measurements from bathymetry and photogrammetry surveys (e) are processed to pointclouds (a,b,d) and then subtracted to get the sedimentation and erosion in the period between measurements (c) (grid cells in this figure are indicative).

by Ton et al. (2022). In this non-tidal environment, the hydrodynamics are completely dependent on the local wind conditions and therefore 32 wind scenarios have been modelled in Delft 3D based on 8 varying wind directions and 4 wind velocities (Table 1).

By using the same method of data analysis for calculating and analysing the sedimentation volumes as well as the hydrodynamic conditions, a link between spit morphodynamics and its drivers can be made.

2.2.2. Model for data analysis

Spit growth is often evaluated by calculating changes in length (Kraus, 1999). But this method can be very subjective as it depends on

Table 1

32 scenarios consisting of different combinations of wind directions and wind velocities.

Wind dir	Wind vel	Wind dir	Wind vel
N (North)	5 m/s	N	15 m/s
NE (Northeast)	5 m/s	NE	15 m/s
E (East)	5 m/s	E	15 m/s
SE (Southeast)	5 m/s	SE	15 m/s
S (South)	5 m/s	S	15 m/s
SW (Southwest)	5 m/s	SW	15 m/s
W (West)	5 m/s	W	15 m/s
NW (Northwest)	5 m/s	NW	15 m/s
N	10 m/s	N	20 m/s
NE	10 m/s	NE	20 m/s
E	10 m/s	E	20 m/s
SE	10 m/s	SE	20 m/s
S	10 m/s	S	20 m/s
SW	10 m/s	SW	20 m/s
W	10 m/s	W	20 m/s
NW	10 m/s	NW	20 m/s

definitions, such as exact location of the spit tip for example. Also, growth in length is not suitable to quantify growth in all three dimensions, which is important considering the curvature of spits. For an analysis model that aims for a more detailed analysis, it is necessary to indicate locations of sedimentation independent of the change in length and curvature of the spit. This will make it possible to find trends in spit growth while the spit is changing shape and size.

The traditional Cartesian or GPS-based coordinate system does not have this independence and therefore another coordinate system is more desirable. Since most processes of spit growth take place around the distal end and the spit grows from a semi-circular head, a polar coordinate system is more suitable. Polar coordinates allow for continuity in the analysis as the length of the spit changes because besides distances, the orientation in degrees can be considered as well.

For this polar coordinate system, a centre point is chosen. Both the sedimentation volumes and hydrodynamic model output will be analysed in degrees around this centre point. For the centre point it is important that it is subaerial during the entire period over which data is analysed. Also, between the centre point and a considered sedimentation location there has to be only one transition from land to water (Fig. 7b). As long as the centre point meets these two requirements with the exception of some possible deviations, a location for the centre point can be manually picked based on the expected growth patterns beforehand.

Hydrodynamic data and morphological changes will be quantified and analysed at degrees around the centre point. This way currents and sedimentation can be described around the spit. The boundaries of the 180° that are analysed (chosen for convenience), are set around the distal end of the spit. So, the complex locations of sedimentation in the horizontal plane can be simplified by indicating the degree around the spit where the sedimentation has occurred.

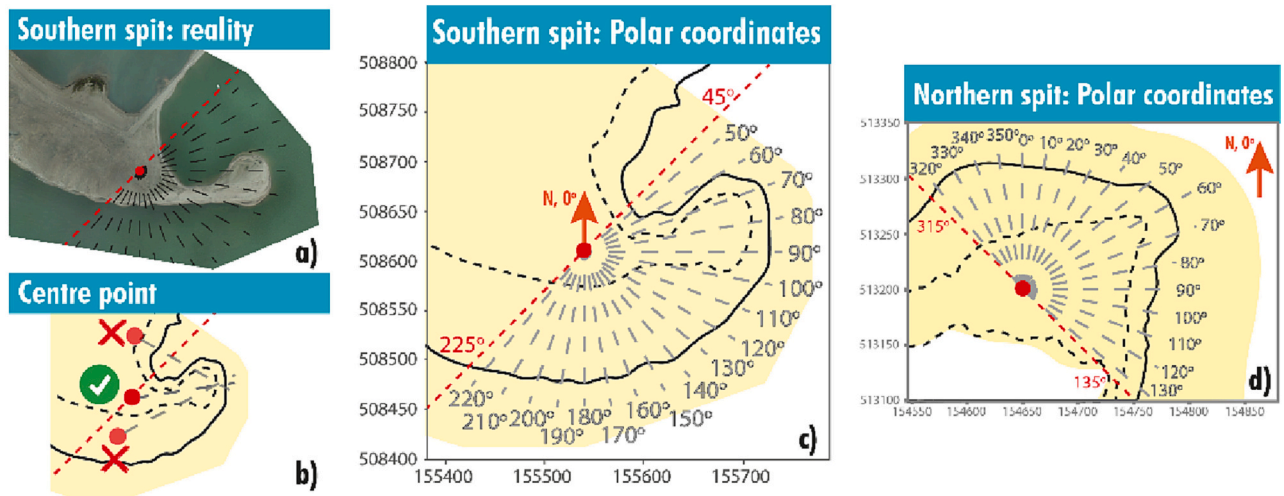


Fig. 7. The polar coordinate system used for spit quantification. a) Represents how the schematic drawing of c) is situated in reality. b) Here it is indicated how the centre point should be chosen. c) Gives the set-up of the polar coordinate system; here different directions in degrees are indicated around the centre point (red dot). All 180° are relative to the north and the boundaries of the considered area are indicated by the red dashed lines. d) Gives the same information as figure c) but for the northern spit.

To quantify changes in elevation, the bathymetry and the sedimentation on this bathymetry will be simplified to three elevation classes. These classes are chosen based on the scale experiments of Meistrell (1966) where the submerged spit-platform grew under different hydrodynamic conditions than the subaerial ridge of the spit. The three elevation classes that are distinguished in this paper are:

- The subaerial level (above the waterline: -0.3 m NAP (Dutch standardized elevation level equal to the average of the sea level at the North Sea)), sedimentation on this level is limited on the Marker Wadden islands and thus analysed in less detail in this paper. This level is emerged most of the time but is partly submerged during storms. Once this level is submerged sedimentation on the subaerial level can occur.
- The platform level (below -0.3 m NAP and above -1.2 m NAP, generally -1 m NAP).

- The sub-platform level (below -1.2 m NAP), this is the level below/in front of the spit-platform.

The subaerial level and platform level are separated by the coastline and the platform level and sub-platform level are separated by the platform boundary. After a level boundary there is a steep drop towards the next elevation class (Rijkswaterstaat, 2018; Ton et al., 2021) (Fig. 8).

These two boundaries divide the spit into two cross-sectional parts, the emerged part, and the submerged spit-platform part. The emerged part grows in length when sedimentation on the platform level has occurred, and the submerged part grows in length when sedimentation on the sub-platform level has occurred (Fig. 8c).

Thus, the model for data analysis has been set up as follows: The location and magnitude of sedimentation and hydrodynamic properties (current directions and velocities) will be quantified based on the orientation (in degrees) around to the centre point, relative to the north,

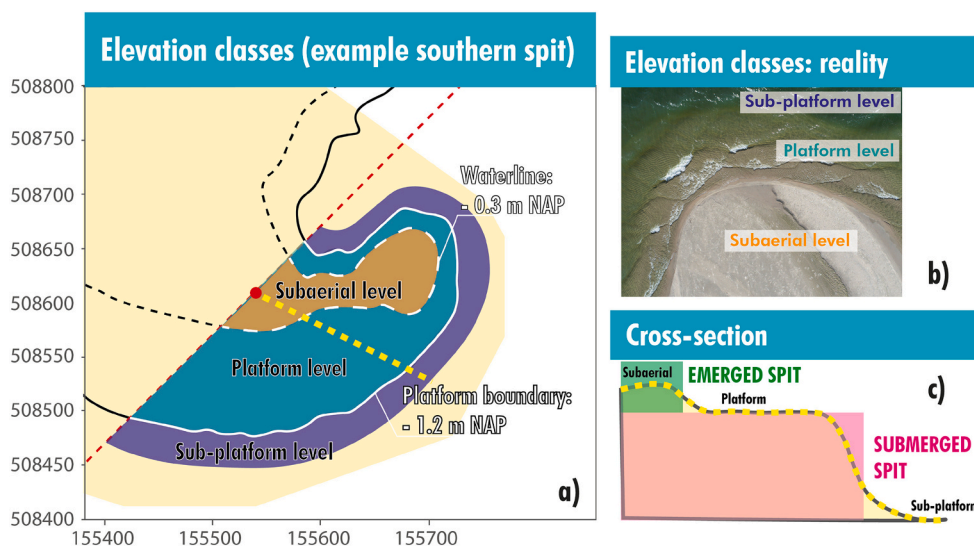


Fig. 8. Three used elevation classes: subaerial level, above the waterline; the platform level, below the waterline and above the platform boundary; the sub-platform level, below the platform boundary. In the cross-section these boundaries split the spit into the emerged spit and the submerged spit-platform.

and the elevation class on which it occurs, which allows us to see trends without getting lost in small scale dynamics.

2.2.3. Flow around the spit

Data of the hydrodynamic model output was available for 32 wind scenarios. For each scenario the flow directions and velocities were computed in the polar coordinate system around the spit for the combined current, driven by both waves and lake circulations. Although wave-driven flow has a different effect on sediment transport than flow driven by lake circulations, a combined current is analysed to be able to link hydrodynamics better to observed spit growth. The flow directions and velocities are computed for every degree around the spit by averaging over that one direction/degree, ranging from the coastline to slightly past the platform boundary (indicated by the grey lines in Fig. 7c). Flow directions are weighted with the flow velocity in this averaging, as currents with larger flow velocities have a larger influence on sediment transport. Hereafter, these averaged flow directions can be fitted for the whole observed 180° degrees to be able to link these currents to the sedimentation that has occurred during the same wind conditions. With these fits, the frequency of each wind scenario was determined, during a period between measurements.

Flow velocity is especially important to represent the transportation capacity of incoming flow. The flow velocity immediately upstream of the spit tip, from now on indicated with v_{in} , is computed as it is most important for spit growth behaviour and is expected to occur around this location. In a low-energy environment not all windspeeds have an effect on the morphodynamics and therefore not all wind climates have been taken into account equally (Ton et al., 2021; Vila-Concejo et al., 2020). For the analysis of historical wind conditions during a period, not very low energetic conditions but windspeeds above a threshold of 7,5 m/s were considered.

Also, to get a representative incoming flow velocity for the energy conditions during the period (v_{in}) not the mean flow velocities during a measurement period are considered but the 97 % quantile of the flow velocity during a period. This 97 % quantile is the highest possible quantile for which the ratio between low-energy events and storm events still can be observed but also shows flow velocities that are more representative regarding their morphological effect.

2.2.4. Sedimentation around the spit

Sedimentation around the spit is quantified by computing the orientation in degrees of an accretion around the centre point, relative to the north. For the analysis between sedimentation around the spit and hydrodynamics, these sedimentation volumes around the spit are grouped. Those groups are from now on defined as deposits. During a period between measurements, groups of adjacent degrees around the spit with above average sedimentation will be considered a deposit and its centre of mass the location of the deposit. This means that a deposit can be identified as a deposit if at a certain degree $s_{N=1st\ deg} \geq s_{mean}$, where $s_{N=1st\ deg}$ is the total accreted volume that is calculated at that particular degree and s_{mean} the mean accreted volume taken over the whole considered 180°. The end boundary of a deposit can be identified if $s_{N=last\ deg} \leq s_{mean}$, where $s_{N=last\ deg}$ is the total accreted volume that is calculated at that degree. Then the centre of mass, and thus the location of the deposit is:

$$deg_{dep} = \frac{\sum_{deg_{N=last}}^{deg_{N=1st}} deg * s_{deg}}{\sum_{deg_{N=last}}^{deg_{N=1st}} s_{deg}} \quad (1)$$

with deg_{dep} the degree at which the deposit is located, $deg_{N=1st}$ the degree at which the deposit starts (lowest degree), $deg_{N=last}$ the degree

at which the deposit ends (highest degree), and s_{deg} the total accreted volume at a certain location.

2.2.5. Sedimentation on elevation classes

Additionally, for spit growth it is important to consider sedimentation on the different elevation classes. The amount of sedimentation on an elevation class is dependent the potential of the energy of the flow to transport sediment. Thus, the sedimentation on a specific location is dependent on the incoming transport capacity of the flow, and the loss of transport capacity on the considered location/elevation class. The loss of transport capacity of the flow is from now on defined as flow dissipation. Flow dissipation occurs when flow enters an area with more space for the flow to disperse and lose its energy, which was used to transport sediment. Additionally, the change in the angle of incidence of the waves along the spit also results in wave-driven flow dissipation.

The increase in space for flow dissipation occurs in multiple occasions around the spit, in all three dimensions. However, this increase in space occurs especially when the bathymetry becomes deeper, for example, during flow over the platform boundary. The increase in space is limited on the platform level because of the small depth. Thus, the potential of the energy of the flow to transport sediment needs to be low enough on the platform level for sedimentation to occur there. Otherwise, most material will accrete on the sub-platform level where space (in depth) for flow dissipation is significantly larger (Fig. 8).

So, the ratio between the accreted volumes on the platform level and accreted volumes the sub-platform level can be deduced from the incoming transport capacity of the flow, represented by the incoming flow velocity: v_{in} , and the dissipation of flow on the platform level. This ratio is in this paper defined as the sedimentation ratio,

$$r_{sed} = \frac{sed_{plat}}{sed_{sub-plat}} \quad (2)$$

here r_{sed} is the sedimentation ratio, sed_{plat} the accreted volume on the platform level and $sed_{sub-plat}$ the volume on sub-platform level. For each grid cell (Fig. 6c) at each degree around the spit (Fig. 7) it was determined if the points in the cell were originally on the platform level or the sub-platform level. Thus, volumes accreted on the platform level, and the volumes accreted on the sub-platform level, can be calculated for each degree around the spit. The space for flow dissipation on the platform level can be expressed with the area of the platform where sedimentation occurs. This is calculated by the sum of the area of every grid cell on the platform, where generally more sedimentation occurs than erosion.

3. Results

Although the two Marker Wadden spits are located in the same region, the morphodynamic developments and hydrodynamic drivers differ substantially. Firstly, the hydrodynamic behaviour around the spit will be presented, followed by the morphologic behaviour. These will then be linked for the spit growth on the horizontal plane (Section 3.3) and the vertical plane (3.4). Finally, the potential of this method for making predictions will be explored.

3.1. Flow around the spit

With the numerical model, the flow field around the spit was computed for all wind scenarios (Fig. 9). When looking at the lines with equal colours, it can be seen that for scenarios with increasing wind velocity but constant direction, flow directions around both spits stay

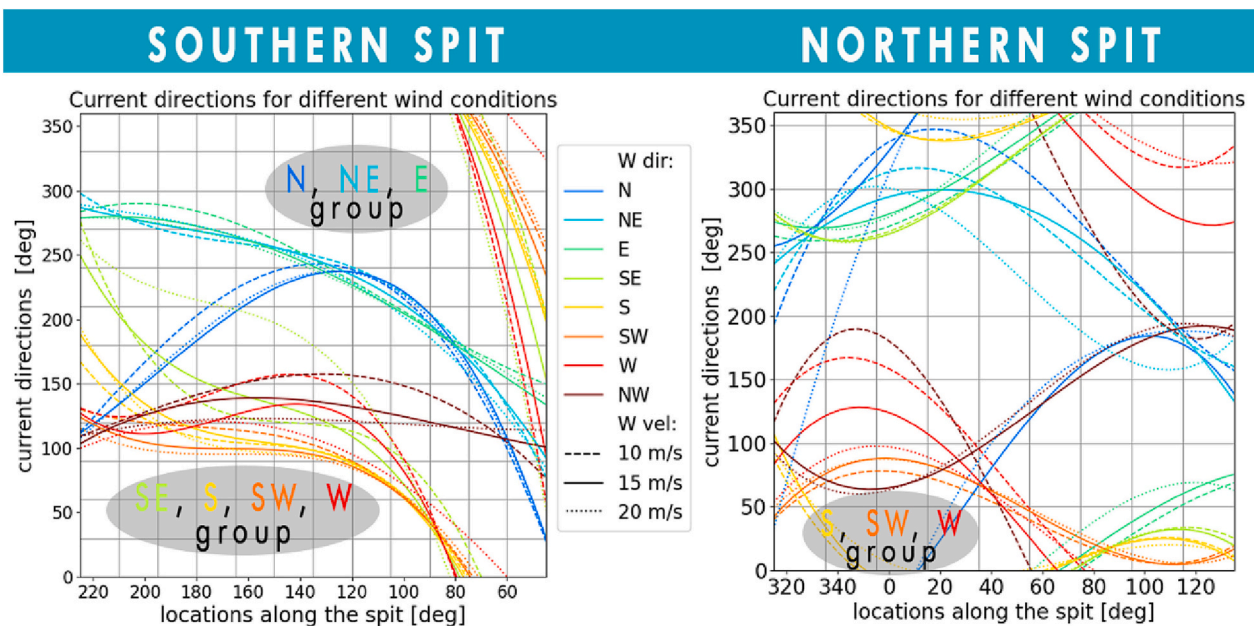


Fig. 9. Current directions around both spits for different wind conditions. Currents that occur during different wind conditions can be grouped on similarity of the wind induced current directions. (This is further used in section: Growth orientation linked to flow).

relatively constant. Therefore, the direction of the current is mostly dependent on the wind direction and changes gradually when moving around the spit. Different groups can be distinguished based on similarity in flow pattern. In the case of the southern spit, winds from the SE, S, SW, and W all have similar current directions, especially near the spit tip (90° southern spit and 50° northern spit). The same holds for the northern spit for winds from the S, SW, and W.

For a better understanding of the flow patterns, a high energy case per location is highlighted (Fig. 10). Currents along the southern spit are caused by a combination of lake circulations and waves (Fig. 10Ib). The northern currents at the northern spit are both caused by lake circulations and waves, while the current coming from the south and flowing to the north can only be caused by lake circulations as that area is sheltered from waves (Fig. 10Ib).

3.2. Spit growth quantification

For every direction (one degree) around the spit, sedimentation volumes are divided over the different elevation levels (Figs. 11a and 12a). This shows the locations where sedimentation is concentrated, thus significant spit growth occurs, and the locations where growth is limited. Erosion (red) occurs on a scarp, at the proximal end of the spit and sedimentation (blue) occurs on the distal end (Figs. 11b and 12b). If deposits are found at directions with gradually higher or lower degrees in succeeding periods, this can indicate that the spit grows towards a certain curvature. Deposits that occur constantly at a certain orientation relative to the centre point indicate a growth direction trend of the spit.

For both the northern spit and the southern spit there is a clear range of directions around the centre ($120\text{--}70^\circ$ for southern spit, $45\text{--}70^\circ$ for northern spit) in which the sedimentation is multiple times higher than on other parts around the spit, especially on the sub-platform level (Figs. 11a, 12a). This range of directions with significantly higher accreted volumes indicates the propagation direction of the spit and is

fairly constant over all different morphological periods, which can experience different wind conditions (Figs. 11 and 12).

The morphological behaviour is different for periods with high-energy conditions than for periods with lower energy conditions (Figs. 10 and 11). In periods with higher wind velocities, thus higher flow velocities, more erosion occurs at the proximal end, creating a scarp (Fig. 11Ib, IIb). In these periods also more sedimentation occurs in general, and more sedimentation occurs on the sub-platform level, relative to the platform level (Fig. 11Ia and IIa). This last observation indicates that when flow velocities are high, the transport capacity is too high on the platform level, and decreases insufficiently, for sedimentation on top of the spit-platform to occur.

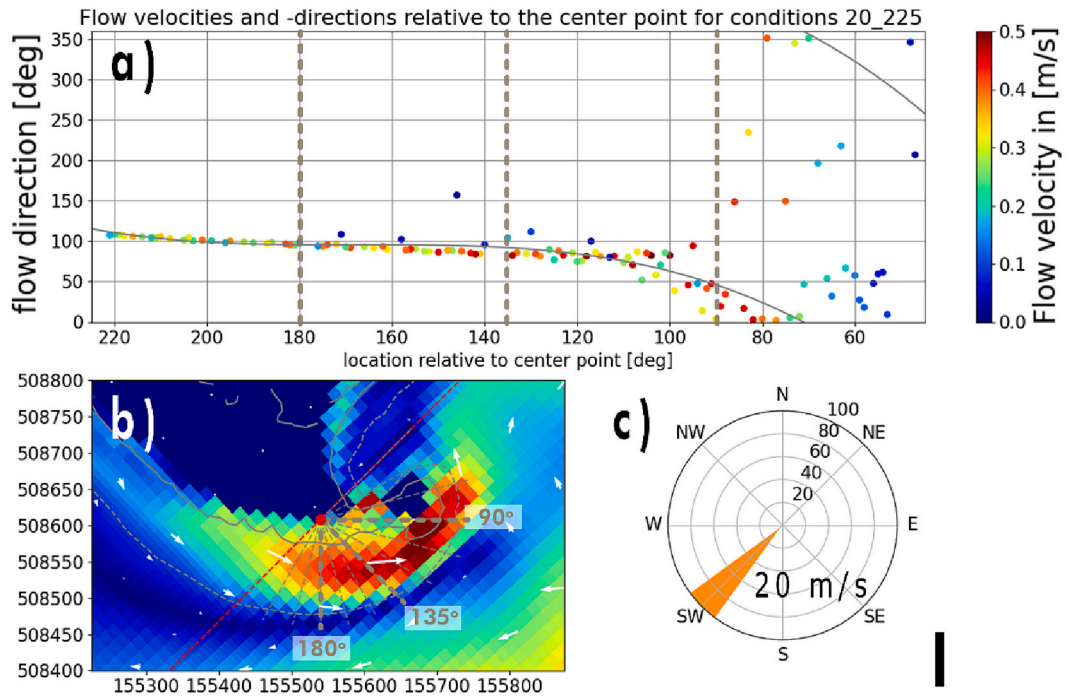
To examine the overall distribution of material around the spit, a general distribution of material was made based on all data (Fig. 13). The distribution of accreted material in volumes for the whole measured timeseries, indicates the likely percentage of the total sedimentation that accretes on a location/degree around to the centre point. For example, for the southern spit at 100° degrees relative to the north, around 1,25 % of the total sedimentation volume accretes. For the southern spit the main sedimentation direction, and thus propagation direction, is between 70° and 120° degrees orientated from the centre point, while for the northern spit this is between 45° and 70° degrees. Fig. 11a, Fig. 12a and Fig. 13 denote that the daily sedimentation of the entire domain of the northern spit is less than half of the sedimentation at the southern spit. This explains the smaller developments that are seen at the northern spit.

3.3. Growth orientation linked to flow

The exact location of an accreted deposit is dependent on the sediment transport by a current or multiple different currents from different wind conditions. A current is considered essential for large-scale sedimentation if it delivers sediment to the location that experiences most

Hydrodynamics during high energy conditions

SOUTHERN SPIT



NORTHERN SPIT

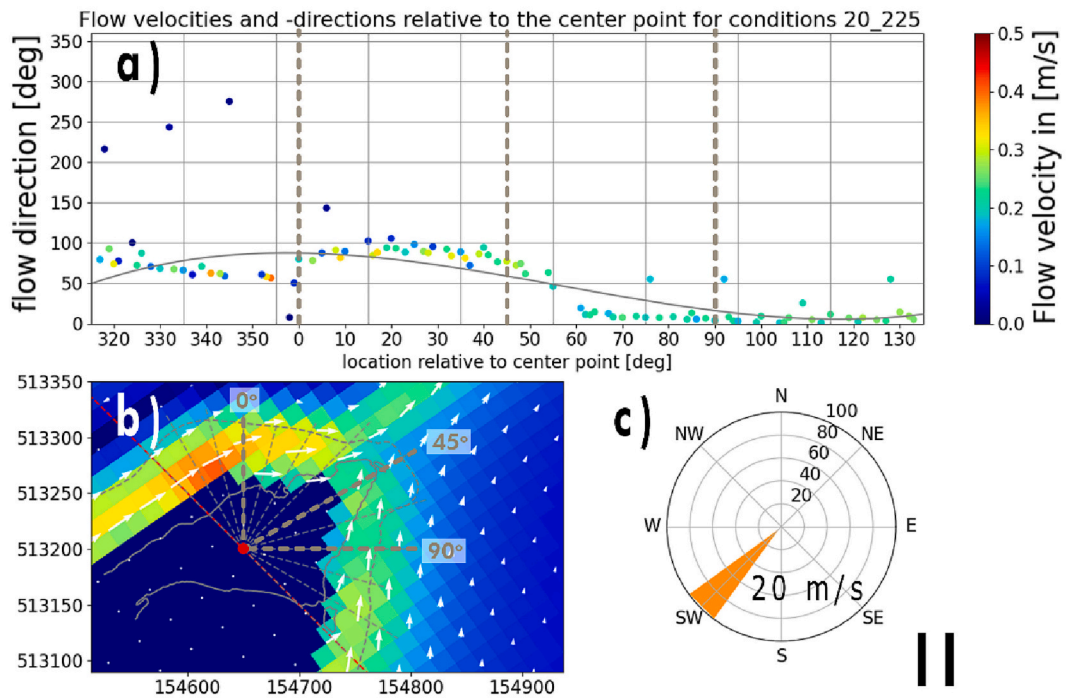
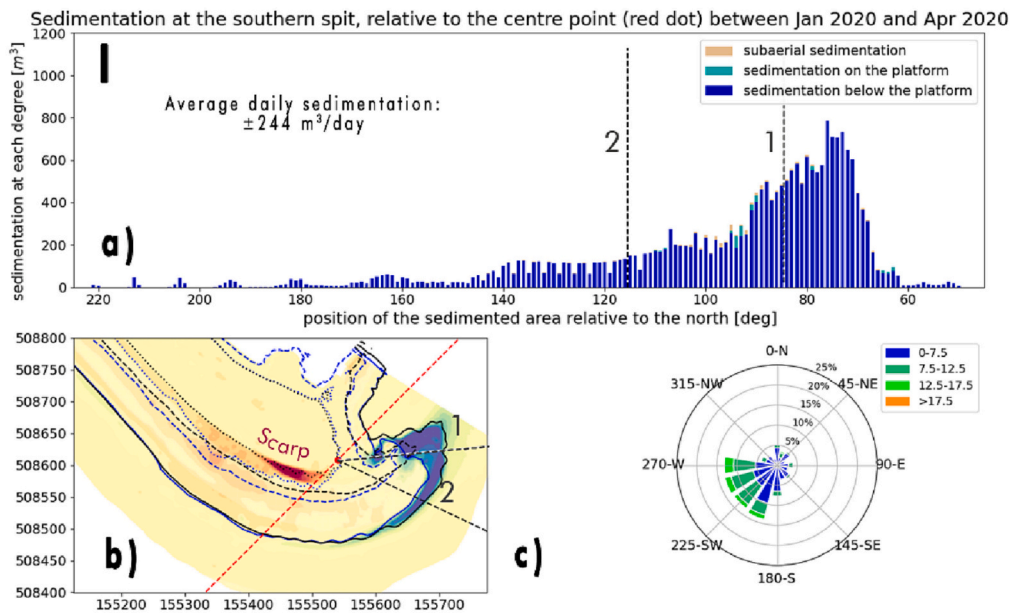


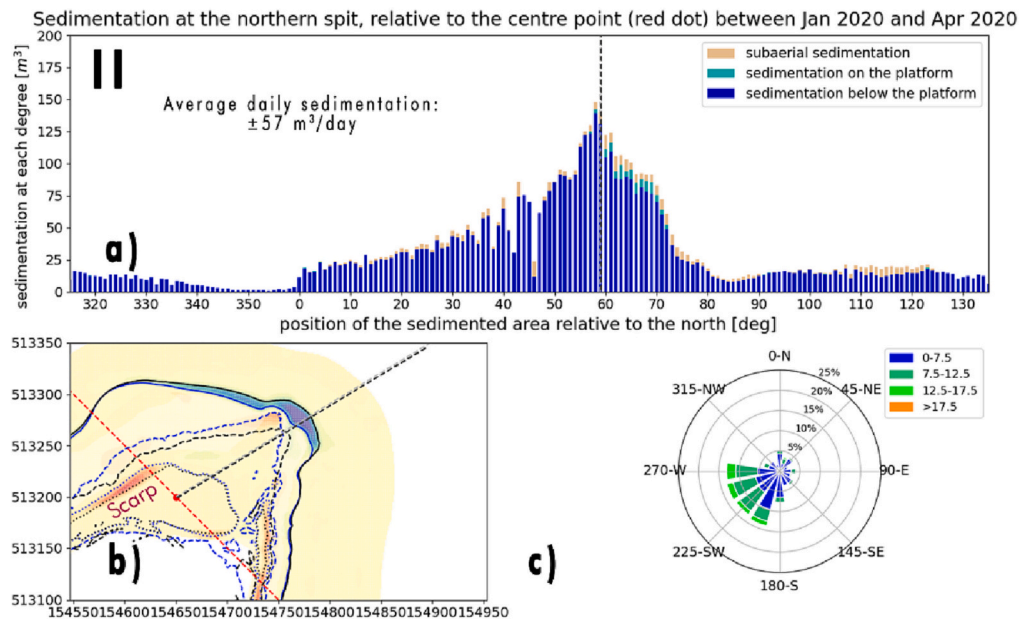
Fig. 10. Examples of current patterns and velocities during high energy/storm conditions. a) Fitted in grey to obtain a distribution of current directions and velocities along the spit for each of the 32 scenarios. Flow velocities are indicated by the colour scale. b) Visual current directions (arrows) and velocities (colours) around both spits. The grey polar lines indicate how far from the centre point the currents are concerned. c) The windrose gives the wind conditions that are modelled.

Sedimentation around the spits: HIGH ENERGY conditions

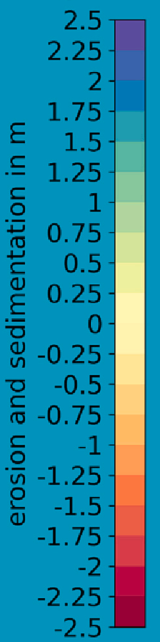
SOUTHERN SPIT



NORTHERN SPIT



Legend

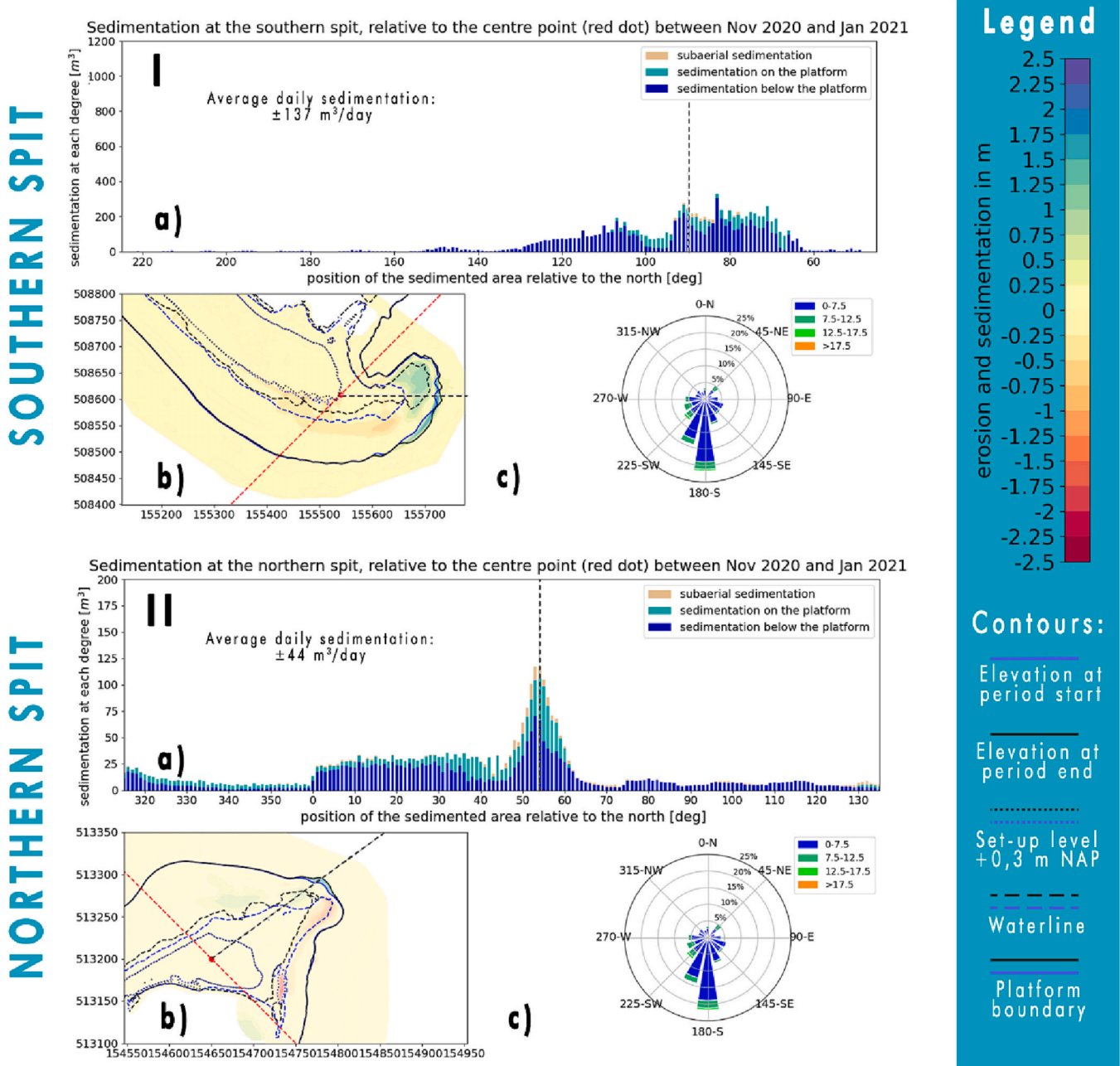


Contours:

- Elevation at period start
- Elevation at period end
- Set-up level +0,3 m NAP
- - - Waterline
- Platform boundary

Fig. 11. Examples of sedimentation patterns on both spits during high-energy periods. a) Each bar gives the sedimentation that occurred in the period on that particular direction. In the bar graphs the grey lines indicate the centre of mass of a distinguishable deposition. The difference in the elevation of sedimentation locations can be seen by the size difference between the sub-platform level (blue) and the platform level (turquoise). b) A visual representation of the location of sedimentation (blue) and erosion (red). c) The windrose gives the wind conditions during the period.

Sedimentation around the spits: LOW ENERGY conditions



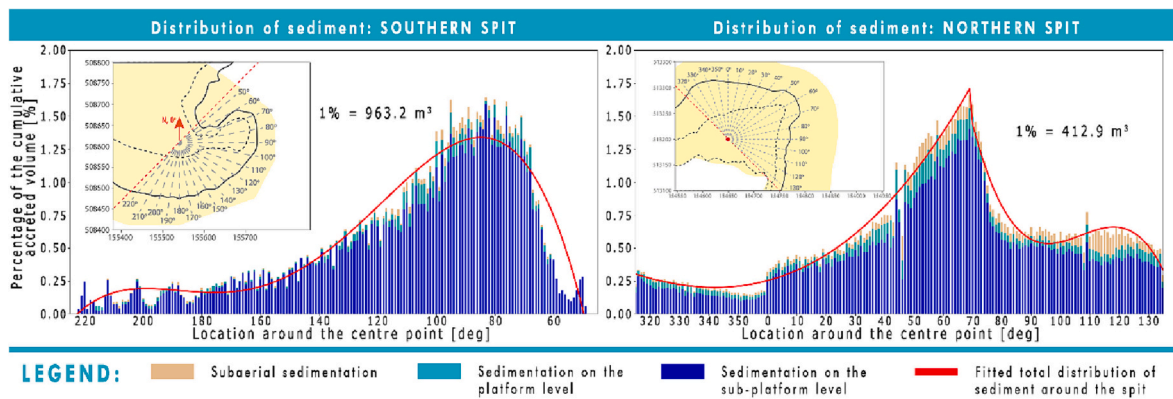


Fig. 13. Distribution of sediment around both spits for the total measurement period (Sep 2018 - Jul 2021). Each bar gives the percentage of the total sedimentation that occurred on that particular degree. With a fitted non-linear relation for the distribution of total sediment in red. The distribution in the elevation of sedimentation locations can be seen by the size difference between the sub-platform level (blue) and the platform level (turquoise).

spit growth, thus flows from or by a sediment source to the sediment sink. In the case of the Marker Wadden this means that the current must flow from the areas with significant erosion (the scarp for example, Fig. 11) to the location with the highest volumes of sedimentation, the propagation direction.

In the same manner of reasoning, the current must flow to a location where flow dissipation can occur. For example, over the platform boundary offshore towards the sub-platform level. Also, currents that occur more frequently can build up larger deposits. Likewise, similar currents that lose energy at the same location also can build up larger deposits.

If we know the location of the deposit relative to the spit, and we know the average wind conditions during the period of the deposit, we can deduce the flow patterns that occurred during the deposit. When a wind condition, and thus a flow pattern, occurs more than 5 % of the time during such a period, it is marked as a possible cause for that deposit. We know the flow direction at the deposit site for that wind condition (Fig. 9) and can indicate this with a marker (Fig. 14). When doing this for all deposits, a pattern occurs which indicates the possible wind scenarios and thus which current patterns cause the most deposits. This is from now on defined as the ‘sedimentation current pattern’, and it is the averaged combination of the currents responsible for sedimentation. For the southern spit this sedimentation current pattern is the combination of currents caused by SE, S, SW and W winds, while for the northern spit the S, SW and W winds are used.

This sedimentation current pattern can be combined with the distribution percentage of the total sedimentation, around the centre point, from Fig. 13 (Fig. 15I and II). We assume that the flows closest to the ‘upstream’ beach, transport the most sediment, from the beach and scarp at the proximal end (Fig. 15III (b) and IV (b)). These flows eventually pass over the spit-platform boundary at the locations where most sedimentation takes place. Thus, the flow dissipation that arises as the flows pass over the spit-platform boundary, is a very important mechanism for the growth direction of the spits.

The northern spit has a straight shape, which can be attributed to the lake circulation currents that result in longshore currents approaching from two sides (Fig. 15 IV). These currents each transport sediment and erase the hook that is created by the opposite current, resulting in a simple spit (Rosset and Westh, 2020). The curved shape of the southern spit can partly be attributed to the change in wave angles, but also to the

lake circulations that are found to move along the spit. The primary finding derived from Fig. 15 is that the location where the currents move over the platform boundary (IIIa, IIIb, IVb) is also the location of most sedimentation and thus the main growth direction.

3.4. Sedimentation on elevation levels

During high-energy periods almost all sedimentation occurs on the sub-platform level while there is a more even distribution of material between the platform level and sub-platform level during lower energy periods (Fig. 11a and Fig. 12a). This indicates that the submerged and emerged growth of the spit is dependent on the energetic conditions during a period. The sedimentation ratio (r_{sed} , Eq. (2)) depends on the transport capacity of the flow on the platform level that should be low enough for sedimentation on this level.

The incoming transport capacity is represented by the incoming flow velocity (v_{in}) while the flow dissipation on the platform level is represented by the platform area on which sedimentation occurs. Also, the platform area takes into account that it is more likely that descending sand grains are ‘caught’ by the spit-platform if the platform is larger.

The elevation on which sedimentation occurs is dependent on wind energy. This indicates that the emerged spit and spit-platform do not grow simultaneously. When flow velocities are high, most sedimentation occurs on the sub-platform level. When the spit-platform is large, more sedimentation occurs on the platform level. This also works the other way around. It means that the shape of the spit-platform is essential for the growth of the emerged spit. Both the spit-platform and emerged spit influence each other's growth.

The platform area and flow velocity (v_{in}) do not have an equal contribution when it comes to the sedimentation ratio (r_{sed}). Nor are they the only parameters of effect. By multiplying the platform area with the flow velocity on the x-axis (Fig. 16), and by giving the flow velocity a negative weight (a large area and a small flow velocity have the same effect on the ratio), the best fit for the contribution of the platform area and flow velocity can be found. Thus, there is an empirical fitted relation, specific for every spit, that approaches the ratio of sedimentation (r_{sed}) on the platform level and the sub-platform level with the platform area and flow velocity (v_{in}) (Fig. 16). These relations can indicate what main drivers were responsible for the observed emerged and submerged spit growth.

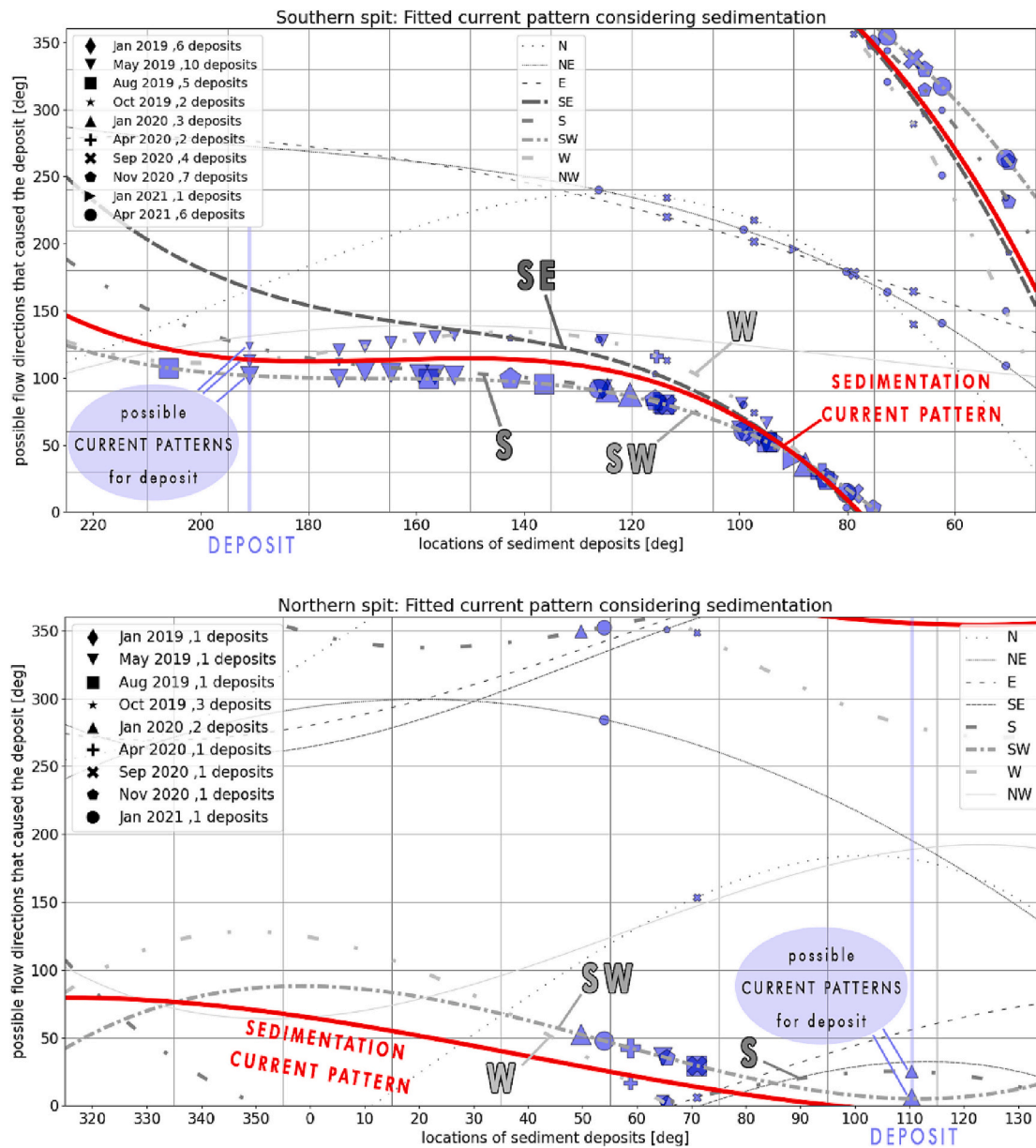


Fig. 14. The sedimentation current pattern that is mainly responsible for sedimentation (red). The blue markers indicate a deposit during a morphological period. This deposit can be caused by a number of current patterns. When a current pattern occurs more than 5 % of the time it becomes a possible current for this deposit and gets indicated by a marker. The size of the marker indicates the occurrence of the current and the more likely it is that it has caused the deposit (in this case only flows where considered, created by winds higher than 7,5 m/s). The currents that are the most likely driver of most deposits are indicated by thick lines.

Both fits can approximate the sedimentation ratio (r_{sed}) relatively well with two parameters (Fig. 16). The fits have roughly the same accuracy, which is relatively high but cannot be improved any further as the platform area and incoming flow velocity (v_{in}) are not the only parameters that can affect r_{sed} (Eq. (2)). The exponent on v_{in} is the exponent for which the accuracy of the fit is highest and is purely a representation for the importance of v_{in} relative to the platform area for the sedimentation ratio. For both spits this exponent shows that the higher the incoming flow velocities are, the more important this parameter becomes for the sedimentation ratio. This effect is more severe for the southern spit than for the northern spit. The first number of the best fit represents the slope of the fit which is not the same for the southern and northern spit. All in all, the effect of the incoming transport capacity and the loss of this capacity at the platform level on the

sedimentation ratio (r_{sed}) can be approximated well with the incoming flow velocity and platform area.

In Fig. 16 outliers are present for both spits because they are periods that had relatively calm conditions with a very short moment of high flow velocities near the end of the period. It is likely that these events eroded away material on the platform level and therefore resulted in a relatively low r_{sed} . Other phenomena were also not incorporated in the approximation, such as the different behaviour of the southern spit when it started to form (Jan 2019). But keeping in mind that v_{in} and the platform area are not the only important parameters for r_{sed} it was chosen to keep this data in the approximation. However, the erosion processes are not considered in this method of analysis and therefore excluded.

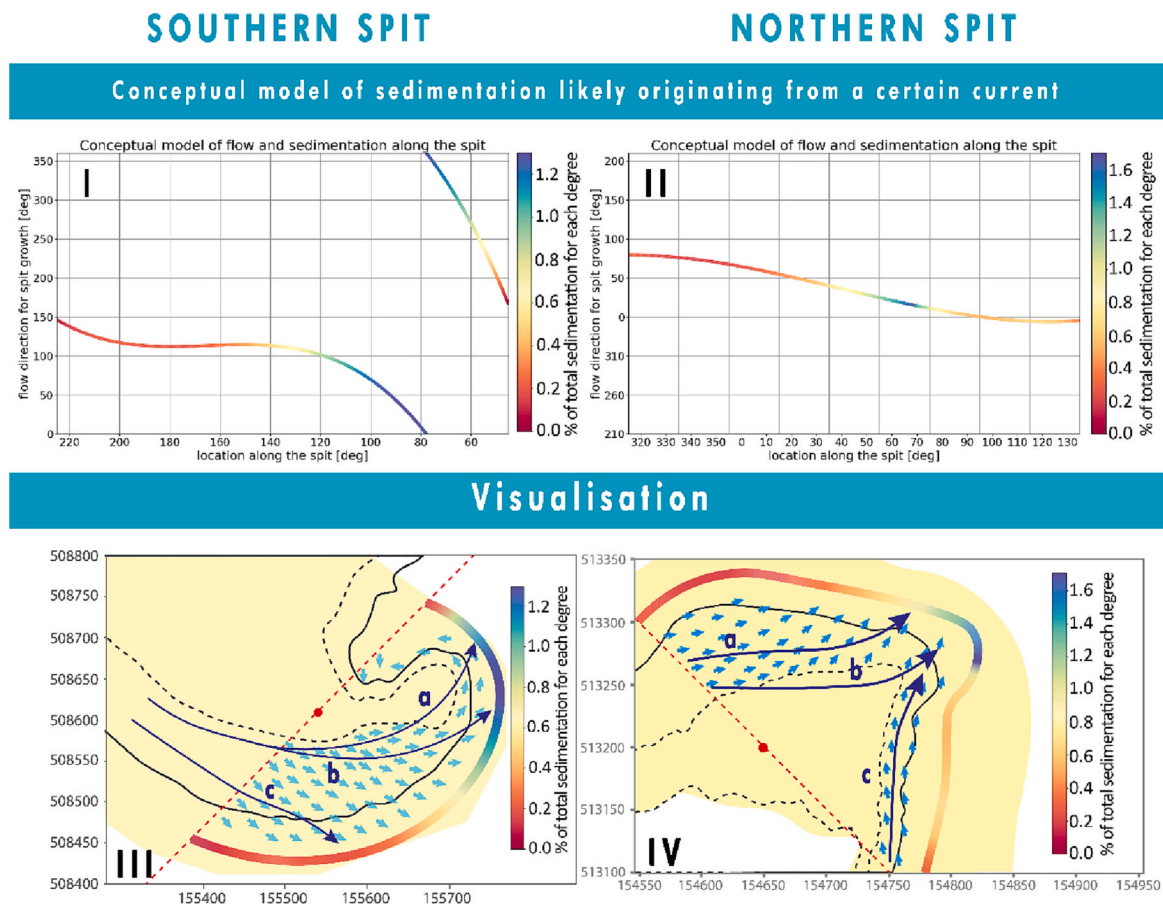


Fig. 15. Representative sedimentation current pattern that is responsible for the observed spit growth directions, with distribution of sediment around the spit indicated by the colours, the sedimentation current pattern indicated with the line itself (I and II) and light blue arrows (III and IV) and the paths of sediment indicated by the dark blue arrows (III and IV).

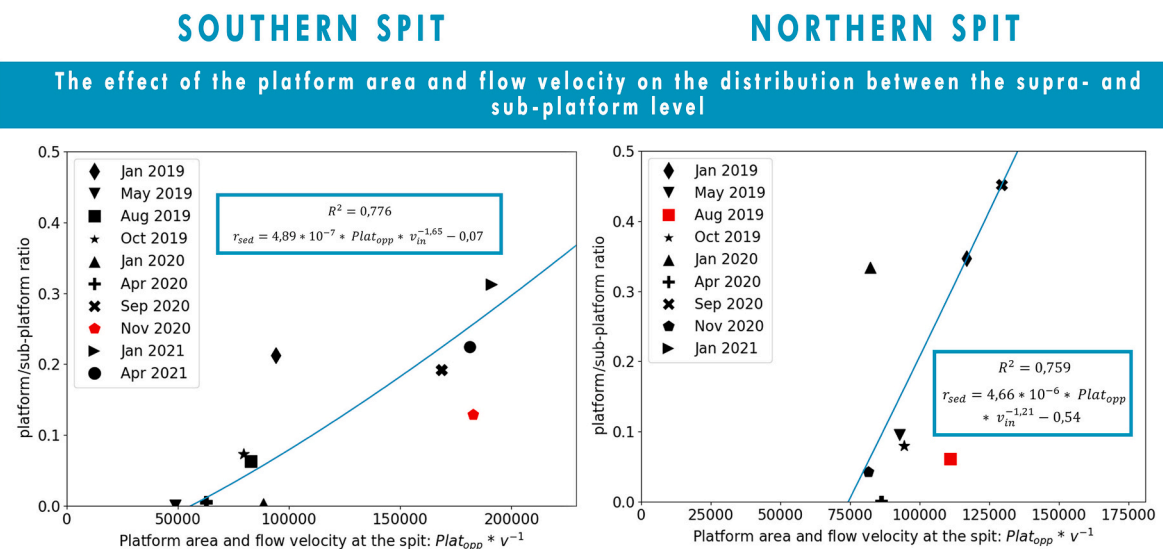


Fig. 16. The relation (best fit) between the platform area and flow velocity and the sedimentation ratio. On the x-axis we find the size of the platform at the start of a period divided by the flow velocity during this period. The indicated date is the date on which the measurement is taken, thus the date at the end of the considered period. In red the outlier periods are indicated. These points were likely affected by an erosion event that eroded the sedimentation on the platform, resulting in a relative low ratio. The height of R^2 indicates the quality of the approximation.

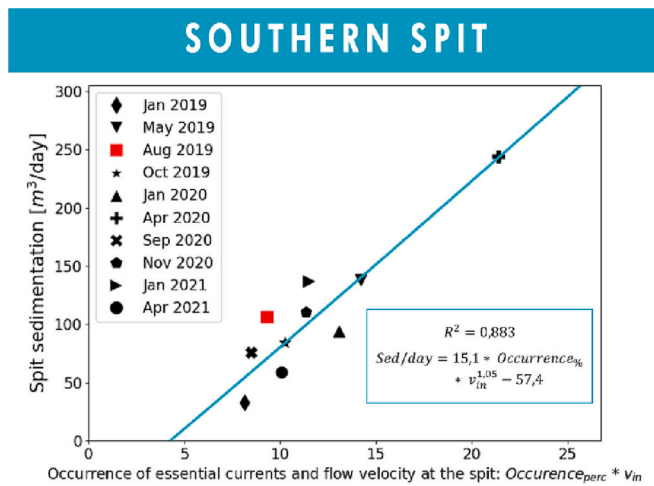


Fig. 17. Sedimentation per day, dependent on the occurrence of wind conditions that drive sediment supplying currents, and the incoming flow velocity. On the x-axis we find the occurrence of wind conditions that make up the sedimentation current pattern during this period multiplied by the flow velocity during this period. The indicated date is the date on which the measurement is taken, thus the date at the end of the considered period. The height of R^2 indicates the quality of the approximation. The red outlier is not considered as a nourishment took place during that period.

3.5. Predictive potential of empirical relations

The fitted empirical relations of the sediment distribution around the spit (Fig. 13) and the fitted sedimentation ratio (r_{sed}) allow for a detailed approximation of the three-dimensional distribution of material around the spit as a result of different energetic conditions for each specific case. Therefore, an empirical relation of the sediment supply or total sum of sedimentation volumes around the spit, would make it possible to give an estimate of where, what volumes will accrete because of certain wind conditions. This gives the novel method a predictive potential and makes it possible to predict future shapes of both spits at the Marker Wadden.

The total amount of sedimentation can be approximated by the incoming transport capacity and therefore incoming flow velocity (v_{in}), because the accreted volumes are higher during higher energetic conditions (Fig. 11a and Fig. 12a). Also, large-scale sedimentation is caused by the currents that make up the sedimentation current pattern (SE, S, SW and W winds for the southern spit). Therefore, the probability of occurrence of these currents determines the amount of sediment that is supplied to the areas of largest growth. So, the sedimentation per day in a period can be approximated in the same manner as in Fig. 16, but by using the flow velocity during a period and the percentage of occurrence of sediment supplying wind conditions, thus the occurrence of the sedimentation current pattern (Fig. 17).

This empirical relation does not pass through zero which bolsters the fact that morphodynamics in low-energy environments is dependent on higher energy events. So, indeed a minimum flow velocity is needed for large scale sedimentation. Also, the occurrence of the sedimentation current pattern and the incoming flow velocity (v_{in}) have almost the same relative importance (exponent of v_{in} is almost 1). This indicates that both flow directions and flow velocities are very important for the magnitude of sedimentation.

The accreted volumes on the platform level and the sub-platform level can be calculated for each direction around the spit, using the polar coordinate system, if the wind conditions of a period are known. By simplifying the topography to a schematic representation of an emerged part (which is filled by platform sedimentation) and a submerged spit-platform (which is filled by sub-platform sedimentation)

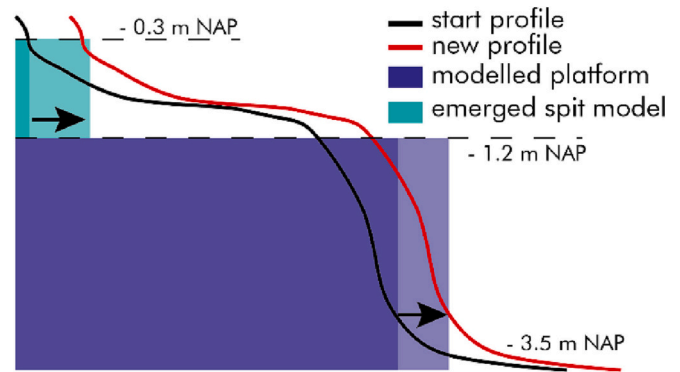


Fig. 18. Schematic representation of how the cross-sectional growth of the spit is modelled. If the emerged part of the spit should grow in reality (start profile to new profile) at a certain degree relative to the centre point, the turquoise bar at that degree increases. The same holds for the spit-platform and the blue bar.

predictions of the new locations of the coastline and platform boundary can be made for each degree around the spit, depending on the wind conditions of a period (Fig. 18).

To investigate the predictive potential of the found empirical relations, a year of developments of the southern spit (Apr 2021 – Mar 2022) have been approximated. This year is a well-balanced representation of the diversity of conditions that can occur at the Marker Wadden islands, with large storms like Eunice and Franklin but also calm summer conditions. By using the wind conditions as input, predictions have been made for the growth of the new coastline and platform boundary. Erosive areas are not included in this prediction as this was out of the scope of this research. These predictions are compared to the actual morphological changes (Fig. 19). The predictions of the submerged spit-platform have an average overestimation of 3 m more than was measured. This accuracy could be deemed promising considering the spit grew several dozens of meters all around the spit, and considering the prediction was based on the fits from previous data (Figs. 9, 13, 15, 16, 17). The predictions for the growth of the coastline were far less accurate with an average overestimation of 14.3 m all around the accreting parts of the spit. The spit tip was overestimated with 15.6 m on the coastline and 2.5 m on the spit platform boundary. Considering the general predictions for the growth directions all around the emerged spit resemble the pattern that has been measured, the emerged spit has much more processes that can affect the three-dimensional shape and is therefore harder to fully predict.

4. Discussion

4.1. Key drivers for spits in low-energy lakes

Previously, spit growth from measured data was mainly indicated in one or two dimensions and needed complex computational modelling to be explained (Roelvink et al., 2020). The loss of transport capacity of sediment rich currents at a location with immediate changes in shoreline orientation is designated as the key concept behind spit growth in literature. This loss of transport capacity can come in many forms, which can drive many forms of spit growth. Uda (2018) stated that spits grow because the flow enters a location where there is more space for the flow to disperse and lose energy, while others contributed the shape of a spit to the change in wave angle along a curving coastline, which results in a flying spit for high wave angles and a recurved spit for low wave angles (Ashton et al., 2016; Ashton and Murray, 2006). Quantification of spit processes and developments can be used to great effect to observe the role of these concepts around transport capacity loss, in spit sedimentation of cases like the Marker Wadden.

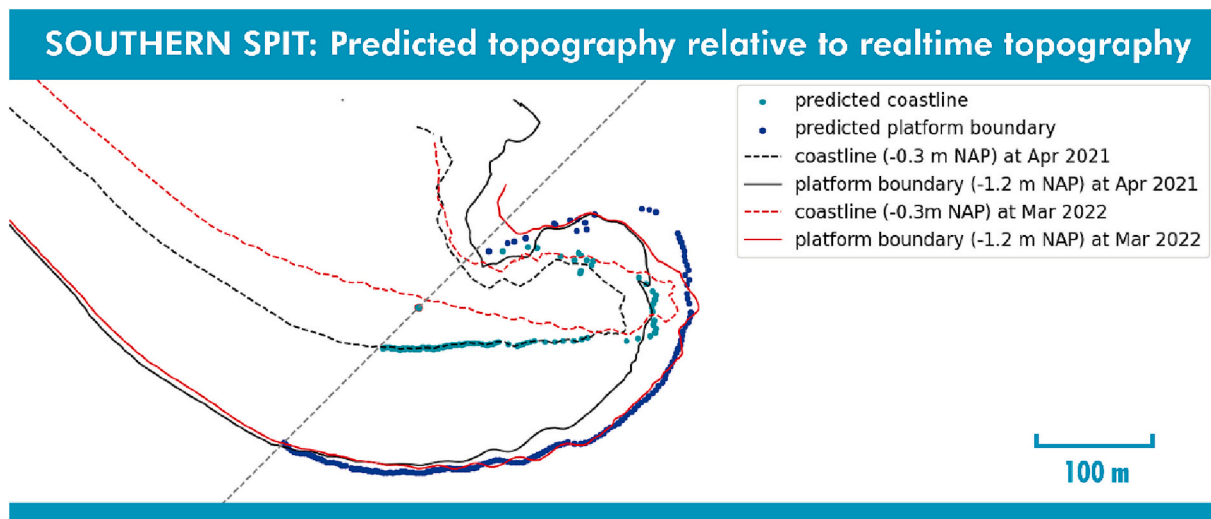


Fig. 19. Predicted coastline and spit-platform boundaries for the year Apr 2021-Mar 2022, compared to the real spit developments in that year. The prediction is based on the found empirical distribution of sediment around the spit, the empirical ratio between platform sedimentation and sub-platform sedimentation and the empirical relation for the total sedimentation as a result of currents caused by certain wind conditions.

The key process that dictates the spit growth of both spits in this low-energy lake environment are the sediment rich currents that transport material over the spit-platform boundary at a specific location (Fig. 15 IIIa/b and IVb). At these locations flow gets dispersed because of the drastically increasing depth, sedimentation occurs at the sub-platform level and therefore the spit-platform increases in length. Thus, this makes the spit-platform grow in a certain direction (Fig. 13). A larger platform means more flow dissipation, which results in sedimentation on top of the platform, and therefore the emerged spit grows (Fig. 16) in roughly the same direction as the spit-platform (Fig. 13).

Thus, for the absolute spit growth that is observed, the energy loss because of flow dispersion in expanding space and the resulting spit-platform growth is of more influence than decreasing wave-driven longshore flows because of changing wave angles, as described by Ashton et al. (2016). For the Marker Wadden, the effect of waves on absolute spit growth is limited, which can be expected in an area where wave energy is limited (Ton et al., 2021). This should be considered when using computational models, that use LST bulk formula like ShorelineS, to model spit developments in similar environments.

However, waves do have a significant effect on the shape of the emerged spit as that is above the depth-of-closure (Ton et al., 2021). The transport capacity does decrease on the platform level as the angle of incidence of incoming waves change. Waves are also important in the stirring-up of sediment around the coastline and emerged spit. This results in erosion near the proximal end, which is important for the complete shape of the emerged spit and is important for the sediment supply towards the distal end. Waves therefore have a large influence on the supply direction of currents responsible for sedimentation (Roelvink et al., 2020).

The submerged spit-platform and the emerged spit do not grow simultaneously at the same rate. Meistrell (1966) stated that growth of the submerged spit-platform is essential for the development of the emerged part of the spit. The calculations indeed show clearly that a small spit-platform has negative effects for the longitudinal growth of the emerged spit. In analytical modelling of spits for example, the submerged part and the emerged part are assumed to grow at an equal rate (Kraus, 1999; Palalane et al., 2014). From the results however, the submerged spit-platform and emerged spit almost work as two separate entities influencing each other and thriving under different wind conditions (Figs. 16 and 18).

4.2. Simplifications, assumptions, and inaccuracies

The main source for inaccuracies in understanding the development of a spit, especially in the approximation of the ratio between emerged and submerged spit growth (Fig. 16), is the fact that erosion has barely been considered in the analysis. Erosion was left out because the focus was finding the dominant drivers behind spit growth and this effect on the shape. Taking erosion into account would have been possible, in the same way as has been done for sedimentation. However, this would have made the analysis more complex and less efficient. More parameters would have to be included and therefore, would have made discovered relations and simplifications less clear. Nevertheless, including erosion can give more insights into the complete spit morphology and therefore including or excluding erosion from the analysis should depend on the aim of the study. For the predictive model, including spit erosion is essential to make accurate three-dimensional predictions (Fig. 19). Especially, to mitigate the inaccuracies of the predictions of the coastline and the emerged spit (Fig. 19a), erosion needs to be incorporated into the model as the emerged spit exists above the depth-of-closure (Ton et al., 2021).

A large part of the empirical relations that resulted from this method of quantifications were found by linking the growth orientation of the spit to the flow directions. This made it possible to express the distribution of sediment around the spit as the result of a single averaged current pattern. This sedimentation current pattern is an average of currents that occur during different wind regimes, that are of importance for large scale sedimentation (Fig. 14). This simplified representation of processes around the spit neglects hydrodynamic drivers that have a less pronounced role. For example, for the southern spit, currents caused by N to E wind regimes, do result in sedimentation around the spit, although this is eventually neglected in the sedimentation current pattern as sedimentation because of these wind regimes is relatively small due to their limited sediment supply and occurrence. However, the sedimentation current pattern (Fig. 15) does represent reality well considering the accuracy of the predictive model (Fig. 19). This is because only the currents that are important for large scale sedimentation have been considered. Only considering the hydrodynamics that are of essence for sedimentation can therefore be a fast method to examine the drivers behind spit growth, as long as currents in the system that are important for sedimentation, are relatively similar and can be grouped in a limited number of groups (Fig. 9).

The spit-platform area is a useful parameter to represent flow dissipation on the platform level. However, it does not represent loss of transport capacity one-on-one. For example, the parameter represents the increase in space, for the flow to disperse, well. But in this case the decrease in transport capacity, because of the changing angle of incidence, is underrepresented with this parameter. The fact that the incoming flow velocity and especially the platform area represent physical processes instead of being the physical process by themselves, explains the differences between the two best fits for the sedimentation ratio (Fig. 16). For example, the platform size is much smaller for the northern spit than for the southern spit, because the entire northern spit is smaller. Therefore, it is not surprising that the slope of both fits is different. This could be mitigated to some extent by using a parameter such as platform area divided by the area of the entire spit.

Also, platform area does not seem to be the best parameter to symbolize platform bathymetry. When energy dissipates, particles do not drop down immediately but slowly descend while going with the flow. The platform must be large enough to 'catch' this particle. So essentially, sediment particle path length, would be a better parameter but this is harder to quantify. However, this is possible by using a morphodynamically validated Delft 3D model for example. Flow velocities, the water depth and the fall velocity need to be combined in order to compute this path length.

Sediment supply is an important parameter that can be affected by all sorts of phenomena, like storage of material in sand banks and aeolian transport. For the Marker Wadden islands, the occasional collapse of scarps at the proximal ends were of significant influence. But also sheltering behind the spit tip, debris, different grain sizes, vegetation, local sand mining, dredging and nourishment operations and wind forcing over the shallow platform are of influence, to name a few.

4.3. Possibilities and limitations of the novel method for other spit cases

First of all, the implemented method of quantifying spit relations and developments using polar coordinates and a simplification of the elevations, works well for the applications used in this paper. However, to be able to conclude if this novel method can be applied well for spits in general, instead of only for spits in low-energy environments, more research needs to be done. Other cases of spits also have to be analysed to get more insight into the applicability of the method. Nevertheless, it seems like this method is efficient and flexible enough to be promising for other spit cases.

While most literature focuses on the large-scale spit, in space and time development (Evans, 1942; Allard et al., 2008; Randazzo et al., 2015), this method proves itself effective for analysing spit developments on a small scale. This makes it possible to quantify and analyse young spits and spit tips in a timeframe of a couple of years, in a detailed fashion. The larger the spatial scale the less accurate this method becomes. Increasing the temporal scale mitigates this problem to some extent as detailed sedimentation becomes less interesting and can be disregarded. Only, considering the main sedimentation locations and growth trends can filter out a lot of the errors that are made at a large spatial scale.

This method is also useful in locations with different kinds of hydrodynamic forcing. Complex currents, like in this low-energy lake environment, with eddies, lake circulations and an inconsistent wind climate, can be analysed well. The case of the northern spit is, hydrodynamically speaking, different from the case of the southern spit. However, still reliable results could be found, although these spits can be classified in completely different classes. This method is therefore likely also applicable in other environments and is very flexible to work with. It is relatively easy to tailor the method of analysis based on the parameters that are of interest for a specific spit case study. However, one must be wary of using too many hydrodynamic scenarios. In this case for example, 32 scenarios were analysed which were only dependent on the wind conditions. Once there is a case where tides also play a role,

this number of scenarios increases significantly, making the analysis much more time consuming. In these cases, it is therefore advisable to see if certain scenarios can be discarded in advance, as they are not likely to be of importance to the spit developments that are of interest.

The largest drawback of the method used for the Marker Wadden spits is that a considerable amount of data needs to be available. Most spit case studies are executed based on aerial photographs for example which can lead to a subjective and more qualitative analysis of spit growth. However, as can be seen from Fig. 19, merely knowing the location and depth of the coastline and platform boundary suffices to make use of this novel method of polar coordinates and elevation classes. In that case, these locations need to be known with high accuracy to avoid large mistakes in accreted volumes. Hydrodynamic data from measurements around the spit under different conditions can also be used, instead of hydrodynamic data from a model.

5. Conclusion

Spits form at places where the coastline drastically changes its orientation, which results in diverging flows and a decrease of sediment transport capacity. Spit growth in non-tidal, wind-dominated, low-energy environments, especially in lakes, have been unknown so far. The characteristic bathymetry, with extensive submerged platforms in front on the coast, makes it necessary to analyse spit growth for different depth zones. We have introduced a novel method to do so, based on the use of polar coordinates and the definition of two distinctive depth zones. This allows for the assessment of the dominant drivers behind different forms of spit growth.

The key mechanism behind spit growth in the system of the Marker Wadden islands, are the frequent, fast flowing and sediment rich currents that flow over the spit-platform boundary. Sedimentation occurs because of a sudden increase in water depth and the resulting increase in submerged spit-platform length at this location. The larger the spit-platform the more transport capacity gets lost by the flow on top of this platform. This results in sedimentation on the platform level and growth of the emerged spit. Waves play an important role in the eventual shape of the emerged spit. Firstly, by decelerating the flow at the location of growth on the distal end during low to moderate wave conditions. Secondly, by stirring-up the sediment around the proximal end and providing sediment supply of the spit. For a large part the growth direction of the emerged spit is thus dictated by the growth direction of the submerged spit-platform.

Considering the spit profile in two depth zones proved essential in understanding the morphodynamics of low-energy, non-tidal spits. Because of the characteristic presence of a submerged platform in the bathymetry and the limited wave energy in these environments (Ton et al., 2021; Vila-Concejo et al., 2020), it is likely that this novel method has broader applicability beyond the scope of our present case study. It is therefore recommended to model the emerged spit and submerged spit-platform as two separate components in similar environments.

Concluding, through the presented novel spit growth quantification methods, the loss of transport capacity of both wave driven and current driven flow, occurring differently during different energetic conditions at different depths around the spit, is identified as key driver for the characteristics of spit development in low-energy, non-tidal environments. This insight is an important step towards understanding spit morphodynamics in general and quantifying the contribution of spits to coastal defence systems.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at <https://doi.org/10.1016/j.geomorph.2023.108799>. These data include the Google maps of the most important areas described in this article.

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