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Morphological and lithological features of the erosion-denudation valley (Zielony Parów catchment) on the cliff coast of Wolin Island

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Abstract: Erosion-denudation valleys are an important element of the relief of the cliff coast of Wolin Island. Detailed research covered the Zielony Parów catchment area with an area of approximately 9.57 ha. The length of the studied form is 491 m. Lithological studies have shown that the bottom of the valley is composed of sandy sediments with a poor and moderate sorting. The data obtained from the airborne laser scanning (ALS) made it possible to conduct a study of the morphometric conditions of the catchment area. In the first stage, a digital elevation model (DEM) with a resolution of 1 m was created, which was then used to create a series of morphometric models. The analyses carried out made it possible to present a quantitative assessment of the valley morphology and to indicate the areas most susceptible to water erosion processes. The differences between the maximum height measured at the top of the valley slope (Hmax) and the minimum height at the bottom of the valley (Hmin) are 66.4 m. The data indicate a high potential energy of the relief. The maximum valley depth is 34 m. The catchment area is dominated by strongly inclined and steep slopes. Using erosion potential indices (LS-factor, SPI) allowed the selection of areas most susceptible to water erosion. In the analysed area, slopes in the south-eastern and western parts of the catchment show a high erosion potential.

Key words: coast morphology, morphometric features, physiographic parameters, erosion processes, denudation processes, Southern Baltic

Introduction

The individuality of the relief of the South Baltic Sea cliff coast includes erosion-denudation valleys, an important element of the modern morphogenetic system. The genetic classification of valleys was adopted after Maruszczak (1968) and was also used by Gołębiewski (1981), Mazurek (2010) and Paluszkiewicz (2016). Dry valleys are divided by Maruszczak (1968) into denudational troughs – shaped mainly by denudation processes (abrasion, solifluction, corrosion, nivation), erosional cuts – shaped mainly by erosion, erosion-denudation valleys, shaped with the participation of both groups of processes mentioned above.

A characteristic morphological feature of these forms is the significant depth of the indentation and the valley mouth hanging on the cliff top.

Studies of dry valleys in cliff areas have not been the subject of detailed studies. These forms were only described in general regions and geological structure analysis, e.g. Pawłowski (1922), Rudowski (1965), or descriptions for a detailed geological map of Poland (Matkowska et al. 1977, Piotrowski, Schiewe 2021, Schiewe 2021). However morphological features of dry or periodically dry valley forms are well recognised, e.g. in the young glacial area of the Polish Lowlands. Complexes of valley forms, such as denudation valleys and basins, as well as erosion incisions, were the subject of research by, among others, Kostrzewski (1963) in the Leszno Upland, Churska (1965) on the edge of the Drwęca proglacial valley, Szupryczyński (1967) on the outwash plain of the Wda, Gołębiewski (1981) in the catchment of the upper Radunia, Marsz (1964, 1995) on the northern slope of the Kashubian Lake District and the Kashubian Coastland, Florek et al. (1999) and Majewski (2008) on the slopes of the Jasień ribbon lake basin (Polanów Upland), Kostrzewski et al. (1997) on the slopes of the basin on the ribbon Lake Rymierowo, Smolska (2005) in the Suwałki Lake District, Paluszkiewicz (2016) on the edges of the moraine plateau in the Drawa Lake District and Karasiewicz et al. (2019) on the slopes of the Drwęca valley. Complex research on the young glacial area were also carried out by Jonczak, Kuczyńska (2008), Jaworski, Juśkiewicz (2014), Jaworski (2018). Most of these forms are characterised by a multi-stage development (e.g. Marsz 1964, 1995, Gołębiewski 1981, Majewski 2008, Paluszkiewicz 2016), and among the processes responsible for their formation, the authors indicate the processes of washing and solifluction operating in the Late Vistulian, when permafrost occurred in the substrate. The water erosion resulting from the melting of dead ice blocks located at the back initiated the process of shaping the valley forms (e.g. Stach 2003, Smolska 2005). The fundamental development of valley forms, related to the transformation of the early glacial relief of Poland, took place at the turn of the Late Glacial and Holocene (Gołębiewski 1981, Marsz 1995). The changes in the Holocene constituted only a touch-up of the relief formed in glacial and periglacial conditions. Some valley forms have resulted from deforestation in the last 100–200 years. At present, the forestation of zones with high relief energy limits the intensity of denudation processes (Smolska 2007), and changes in valley morphology may occur under the influence of extreme weather phenomena.

The types of valleys with Late Glacial structures and fresh erosional cuts were identified within the study area. At the turn of the Pleistocene and Holocene, the washing and erosion processes transformed forms of Late Glacial origin. Progressive abrasion (cliff retreat rate of 0.22 m/year) (Kostrzewski et al. 2015, Winowski et al. 2019, 2022) has an impact on the further development of valleys whose bottoms are currently hanging to the base of the cliff. Over a length of about 4 km, several forms have been delimited, which are visible in the terrain. These forms show an NW–SE orientation and have diverse morphometric features. Particularly noteworthy is one of them, Zielony Parów, of a deep indentation with a hanging outlet on the top of the cliff. Within this form, pilot studies were conducted to formulate a measurement system for erosion and denudation processes shaping the cliff coast. Within the scope of detailed research, morphometric and lithological features were analysed. The aim of the study is to determine the physiographic parameters of the catchment area of the studied valley and to indicate potential areas of the valley most susceptible to erosion, taking into account the lithology of the valley bottom sediments and the calculated indicators.

Study area

The research was conducted on the cliff coast of Wolin Island (Kostrzewski et al. 2015, 2017, Kostrzewski, Zwoliński 1994, Zwoliński et al. 2024), which is located in north-western Poland. The analysed area is part of the western section of the Southern Baltic coast (Pomeranian Bay). The studied erosion-denudation valley is located within the northern part of the frontal-moraine ridge called the Wolin Range (Solon et al. 2018). From the west, it is adjacent to Biała Góra settlement (AMU Natural Environment Monitoring Station). It is entirely located within the Wolin National Park (Fig. 1).

The Wolin Range, a series of moraine hills, is the most important and characteristic element of the relief of Wolin Island (Kostrzewski 1994, Zwoliński et al. 2024). It stretches from the Szczecin Lagoon through Międzyzdroje to Świętouście, located at the base of the Dziwnów Peninsula. The main morphological axis of the moraine is NE–SW. The Wolin Range is morphologically diverse; vast moraine surfaces form it, often as isolated hills (Grzywacz 116 m a.s.l., Gosań 93 m a.s.l.) and basins. The secondary differentiation of the relief results from the impact of erosion and denudation processes, which occurred with great activity in the areas of extensive moraine surfaces with significant height differences and slopes. A crucial feature of the relief of the Wolin

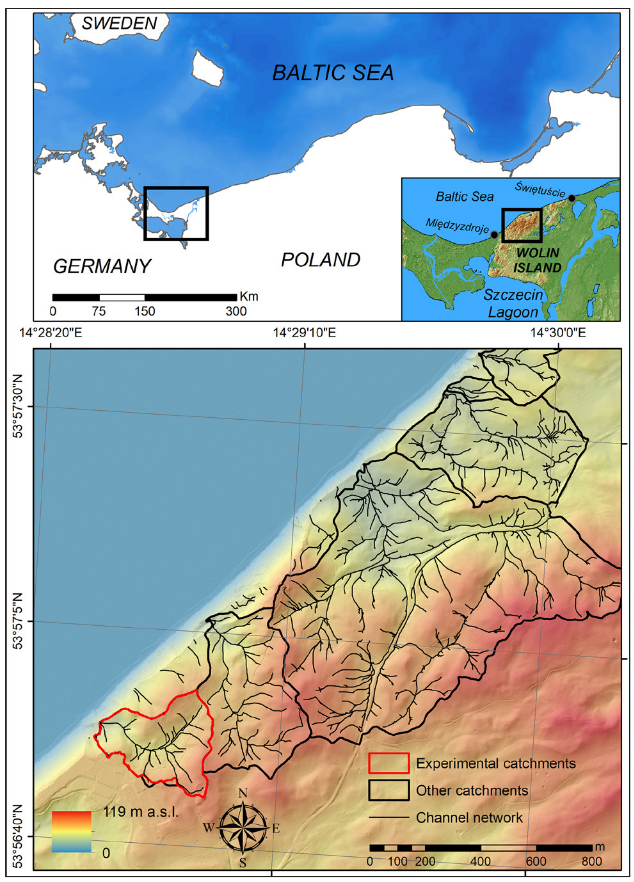

Fig. 1. Map showing the location of the analysed catchment of the experimental erosion-denudation valley against the background of the coastal catchment

Range is the presence of numerous endorheic depressions and deeply incised erosion-denudation valleys. They sometimes reach considerable sizes – a maximum of 1000 m in length, 300 m in width and 30 m in depth.

The Wolin Range was formed during the oldest Dryas, in the Gardno-Wolin phase (Borówka et al. 1982, 1986), to undergo partial remodelling in the Late Vistulian (MIS 2). In the geological structure of this unit, two series of moraine tills should be distinguished, of which the bottom layer is made of grey tills (Kostrzewski, Krygowski 1967). These tills were deposited during the Odranian (Wartanian stadial, MIS 6) and, in many places, are up to 40 m thick. They are usually sandy with high shear strength and can swell under water's influence (Kostrzewski 1985). The overlying layer is sometimes made up of brown tills of the Vistulian Glaciation (MIS 2). Compared to grey tills, the thickness of the brown ones is small, reaching a maximum of 4 m. These sediments are lightly sandy, silty loams. The degree of processing of brown till's quartz grains is slightly higher than that of the grey tills' (Kostrzewski 1985). In places, the bottom part of the brown till consists of loamy sands (Borówka et al. 1982). A series of fluvioglacial sands with a thickness of up to 40 m was deposited on moraine till beds. The fluvioglacial sands are separated in places by thin interbeddings of silty and clayey sands (Borówka et al. 1982, 1999). In the top layer of sediments of the Wolin Range, there are beds of aeolian cover sands of varying thicknesses from 2 m to 15 m (Borówka et al. 1986). Two layers of fossil soils are common within these series (Borówka et al. 1982, 1986, 1999).

Material and methods

The erosion-denudation valley Zielony Parów is a form which is located on the edge zone of the Wolin cliff. Therefore, it was decided that it would become an experimental catchment, enabling field experiments in the development and transformation of valleys and their impact on the morphodynamics of the cliff coast of Wolin Island.

Determining the relief of the catchment area of the experimental erosion-denudation valley Zielony Parów, developed on the cliff coast, required numerous geomorphological analyses. The research included fieldwork, laboratory analyses and data processing, and their main goal was to determine the lithological and morphometric conditions of the formation and development of the studied form.

Field and laboratory work

During the field and laboratory work, the lithology of the shallow subsoil of the studied valley was recognised. During lithological mapping, 6 manual drillings were made along the longitudinal profile to a maximum depth of 3 m below ground level. Samples were collected in the profiles using the point method at intervals of 0.3 m. The collected samples were then subjected to laboratory analyses to identify the features of the sediments that build the studied form (Derucki 2019). As part of laboratory work, the mechanical composition of sediments was analysed using the sieve method and Casagrande's areometric method modified by Prószyński (Racinowski 1973, Racinowski, Szczypek 1985). The results determined the dominant types of sediments occurring in the bottom of the erosion-denudation valley. However, the lithological analysis of the valley slopes was the subject of research by Tylkowski et al. (2021).

Data analysis

The morphometric parameters of the catchment area of the erosion-denudation valley were developed based on a point cloud from airborne laser scanning (ALS) in 2011. Based on the obtained data (GUGiK 2024), a digital elevation model (DEM) with a resolution of 1 m was created. In the first stage of data development, the research area was designated, where further analyses were carried out. For this study, it was decided to limit the detailed morphometric analyses to the catchment area of the experimental erosion-denudation valley. The relief features of the study area were presented using several morphological, morphometric and hydrological models: digital elevation model, hillshade model, slope model, aspect model (Carter 1992), valley depth (Conrad et al. 2015), convergence index (Koethe, Lehmeier 1996), slope length and steepness factor (LS-factor) (Boehner, Selige 2006), topographic wetness index (Boehner, Selige 2006), flow accumulation (Seibert, McGlynn 2007), flow direction (Zhang et al. 2017) and the stream power index (Moore et al. 1991). The calculated morphometric parameters are the most frequently used in soil erosion studies. In addition, they highlight, among others: the diversity of relief within the analysed catchment area and allow the identification of areas most susceptible to erosion processes. In addition, a longitudinal profile of the bottom of the valley and transverse profiles were made to determine the degree of inclination of the bottom and slopes of the valley.

Results

Morphometric characteristics of the erosion-denudation valley

Basic morphometric parameters were calculated, describing the geometry and morphology of the experimental catchment (Derucki 2019). The area of the experimental catchment (A) is about 9.57 ha. The length of the form (L), determined as the length of the line along the main watercourse from the mouth to the point on the watershed in the extension of the source section, is 491.0 m. The average width of the catchment area (B), calculated as the quotient of area and length, is 194.9 m. Using basic dimensions of the catchment geometry, the form index (Cf) was calculated. Comparing the shape of the catchment to a square with an area equal to the area of the catchment, the value of the index Cf = 0.4 was obtained. The lower the indicator's value, the more elongated the shape of the catchment. Comparing the catchment shape to a circle, it is possible to calculate the following indices: elongation (Cw), circularity (Ck) and compactness (Cz). The elongation index calculated based on Schumm's formula (1956) for the studied catchment takes the value of 0.7. Index values close to 1 mean that the shape of the catchment is close to a circle. The value of the circularity index (Ck) is 0.3. The compactness index (Cz) informs about the degree of development of the catchment boundary. It is assumed that if the length of the catchment border is equal to the circumference of a circle with the same area, then Cz = 1. The compactness index is generally higher. For the examined catchment, the value of the Cz index is 1.7, indicating a well-developed relief and elongated shape of the catchment.

Within the catchment area of the erosion-denudation valley, parameters describing the area's mor-

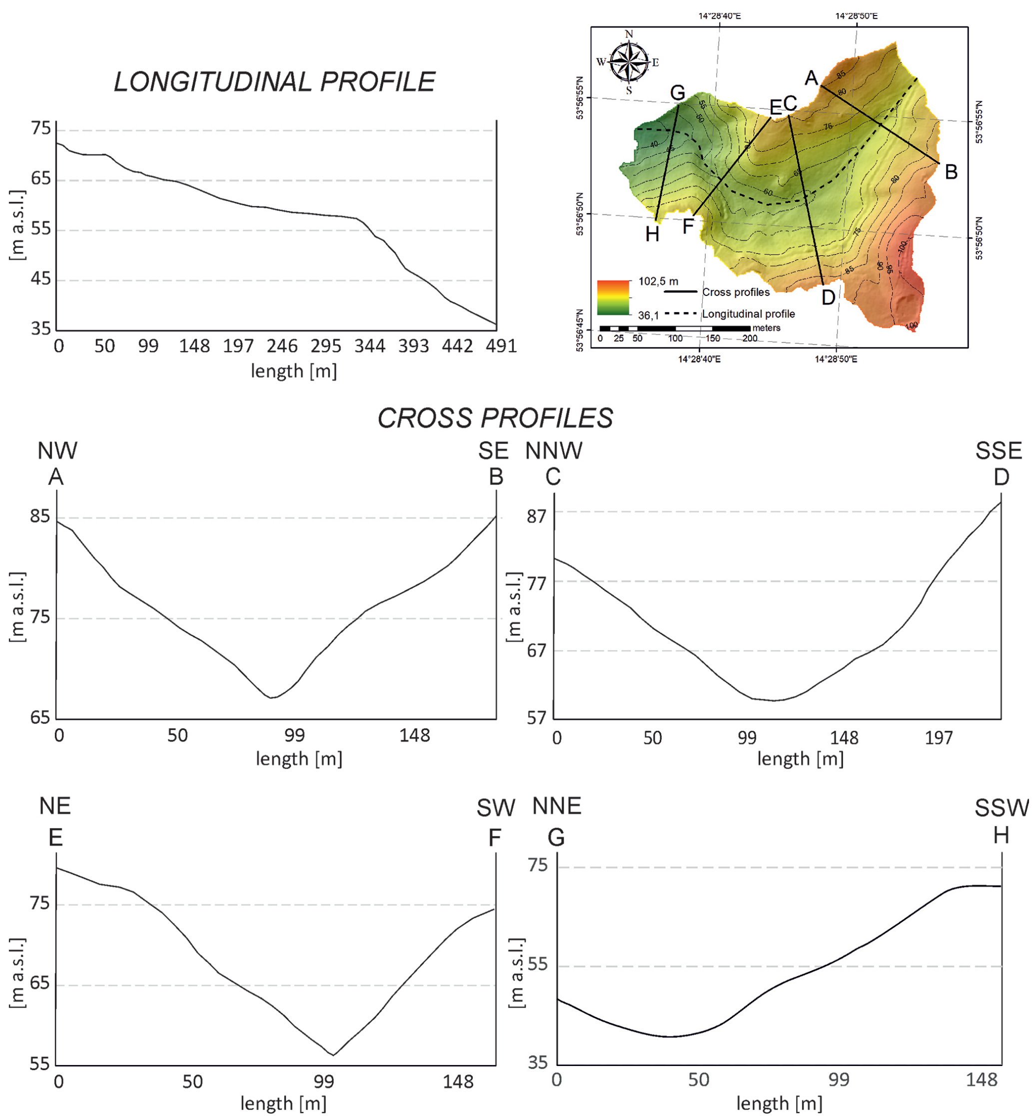

Fig. 2. Morphological profiles of the erosion-denudation valley with its location

phology were also calculated. The differences between the maximum height measured at the top of the valley slope (Hmax) and the minimum height at the bottom of the valley (Hmin) are 66.4 m. The data indicate a high potential energy of the relief (Fig. 3A). The slope of the watershed (Rp) is 0.03.

In the longitudinal profile of the valley, three sections, upper, middle and lower, can be distinguished based on slope values and morphology. The studied valley shows a complex course. Initially, it is NE–SW, turning to SE–NW. The upper part is located at the back of the cliff, and the lower one is on its top. The highest elevations occur in the SE part of the catchment. Three sections are visible in the longitudinal profile of the bottom of the valley. The upper one, 80 m long, has a slight slope of 6.3%. In the place where the direction of the valley floor changes, the middle section begins with a length of 200 m and a slope of 6.5%. It ends with a clear morphological threshold, below which the lower section begins, 150 m long and with a slope of approx. 10%. The average slope measured along the entire length of the longitudinal profile of the valley is 7.9% (Fig. 2). At the mouth of the incision, within the cliff top, a system of fractures was recorded as a result of the increased dynamics of landslide processes (Buchwał, Winowski 2009, Winowski 2011). The longitudinal profile is concave-convex-concave. The shape of the transverse profiles is mostly symmetrical. Only at the end of the valley, an asymmetric course of the transverse profile is observed.

The maximum depth of the incision is over 30 m (Fig. 2, profile G–H). The width of the bottom of the valley is varied: narrow in the upper section, and wider in the middle and lower sections. The maximum width of the bottom is about 30 m (Fig. 2, profile C–D). It should be noted that in the transition zone between the middle and lower sections, the bottom

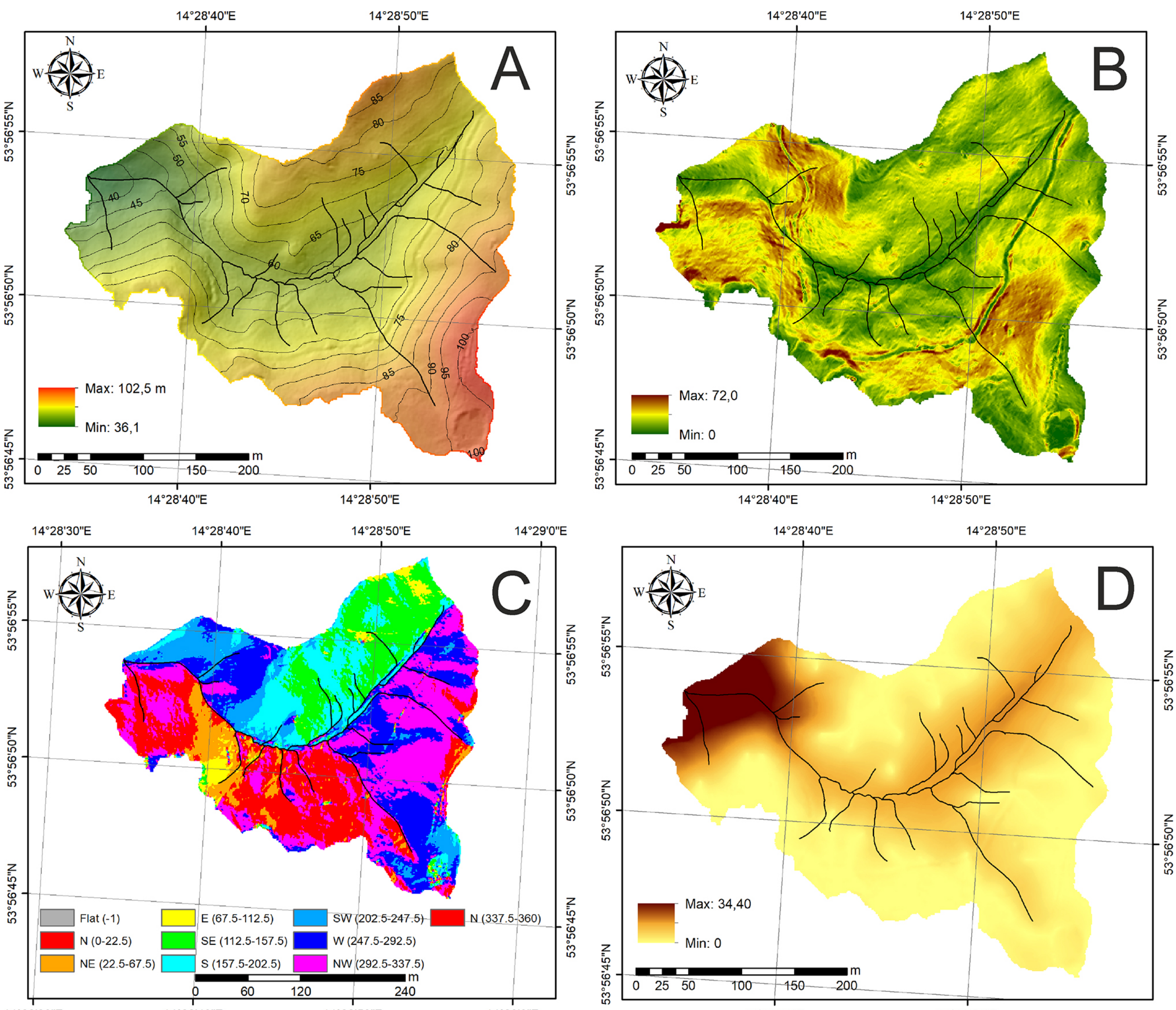

Fig. 3. Physiographic parameters of the erosion-denudation valley catchment. A. Digital Elevation Model, B. Slope (classified according to Klimaszewski 1963), C. Aspect, D. Valley Depth

of the valley quite clearly cuts into the ground, creating a V-shaped system (Fig. 2, E–F profile).

The slope and aspect (Fig. 3B, C) are among the basic parameters of the terrain surface. Slope (slope gradient) describes the change in height per length unit in the direction of greatest descent (Carter 1992). The highest inclination of the slopes is observed in the western and southern parts of the catchment, where their values reach even 50°. According to the classification of slopes (Klimaszewski 1963), the catchment is dominated by strongly inclined slopes (9–19°) and steep slopes (19–45°) with an area of 49 423 m² (51.6%) and 23 977 m² (25%), respectively. Moderately sloped slopes (17 299 m² – 18.1%) also have a significant share (Fig. 3B). The intensity of surface runoff within the studied catchment, conditioned by the slope gradient, is, therefore, the highest in the NE and S parts. The aspect of the slopes (Fig. 3C) shows great diversity (9 classes have been distinguished within the studied catchment) with the predominance of slopes with the following aspects: N, NW, S, and SE.

An important morphometric parameter of the relief of concave forms is their depth. In the case of erosion-denudation forms, the valley depth is considered. In the presented model (Fig. 3D), the calculated indicator values for the entire catchment range from 0 m to 34 m, with this parameter measured in the valley axis ranging from 10 m to 34 m. The smallest depth (10 m) is observed in the north-eastern part of the valley, and the largest (34 m) is at its outlet (north-western part).

The lithology of sediments forming the erosion-denudation valley

Detailed identification of sediment features within the experimental catchment area Zielony Parów was made along the longitudinal profile of the valley, at a length of about 0.5 km (Fig. 4). The geological structure is dominated by a series of Quaternary sediments, mainly represented by massive fine- and medium-grained sands, sometimes interbedded with coarse-grained sands. The thickness of the sediments was recognised up to 3 m deep. In the upper section of the valley bottom (drillings I and II, Fig. 4), medium-grained sands were recorded at the bottom of the drilling. This series shows a moderate degree of sorting.

In drilling II, at a depth of about 1.5 m below ground level, coarse sands are interbedded. This sediment shows poor sorting. Fine-grained sands with a

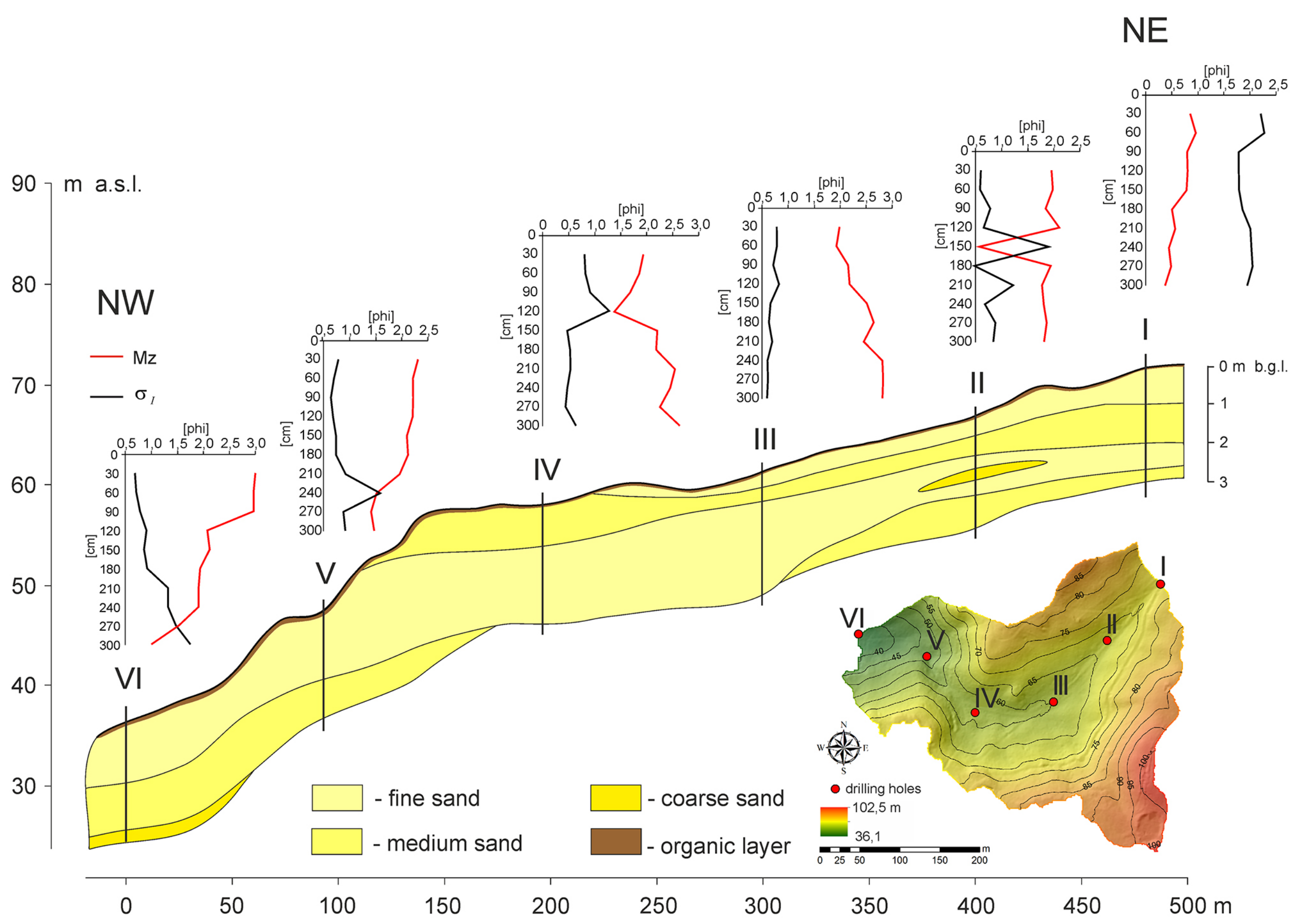

Fig. 4. Lithological cross-section along the bottom of erosion-denudation valley with grain size statistics charts

moderate degree of sorting lie at the top of the profiles of the upper section of the valley. The lithology of the middle section of the valley bottom (drillings III and IV, Fig. 4) includes two series of sediments: fine- and medium-grained sands, with fine-grained sands being the dominant fraction in drilling III. Only at a depth of 0.5 m below ground level, there is an interbedding of medium-grained sand with a thickness of about 0.3 m. This series is much thicker – 1.3 m – at the top of drilling IV. The geological structure of the lower section of the valley bottom, identified based on drillings V and VI, indicates the dominance of fine-grained sands in the top section of the profile. This series reaches significant thicknesses of over 1.8 m in drilling V (Fig. 4). As in other drillings, this sediment shows moderate sorting. In the bottom of drilling VI, coarse-grained sands with poor sorting are recorded. The identified sediments in the bottom of the erosion-denudation valley mostly have an average degree of sorting, which indicates moderate dynamics of the depositional environment. The share of the coarser fraction, i.e. coarse sand, is the evidence of changes in the dynamics of the depositional environment (greater energy of the environment, Mycielska-Dowgiałło 2007).

The sediments of the bottom of the erosion-denudation valley Zielony Parów are mainly represented by fine- and medium-grained formations in the range of sandy fraction, with a small content of coarse-grained fraction. The greatest diversity of sediments in grain size is observed in the upper part of the valley, while in the middle part, the greatest thickness of fine-grained sands is recorded.

Previous studies of the valley carried out by Tylkowski et al. (2021) showed that the slopes of the valley, like its bottom, are composed of fine-grained, poorly and moderately sorted sands.

Surface runoff conditions within the erosion-denudation valley

In the study of erosion-denudation valleys, a very important aspect is determining the susceptibility of the morphology to the occurrence of erosive processes. The most commonly used parameter for this purpose is the slope length and steepness factor (LS-factor). This index is the product of the length of the slope and its inclination. As a result of the algorithm's calculation, dimensionless values greater than or equal to 0 are obtained. In the study area, the LS-factor ranges from 0 to 20.1 (Fig. 5A). The greatest susceptibility to soil erosion is observed in the southern part of the catchment, on relatively long, steep slopes. The maximum values are at the bottom of the valley, in the transition zone between its middle and lower reaches. High coefficient values are also observed in the north-western part in the close vicinity of the mouth of the valley. On the other hand, the lowest sediment transport capacity can be observed in the watershed zone and the upper reaches of the valley bottom (Fig. 5A).

Another indicator describing the erosive potential of water flowing down the slope is the stream power index (SPI). This indicator assumes that the amount of runoff water is directly proportional to the surface of the supply area, i.e., the area from which water flows into a given cell (local catchment area). The consequence of the increase in the volume of runoff water and slope inclination is an increase in the risk of erosion. The stream power index is often used to predict erosion in areas with convex slopes and accumulation on concave slopes in areas where the speed of flowing water decreases. This index corresponds to a very large extent with the sediment transport capacity coefficient (LS-factor). In the analysed area, the highest values of the index are characteristic for slopes in the southeastern part of the catchment and, to a small extent, in the northwestern part. Therefore, these areas are potentially exposed to the strongest erosion. On the other hand, the lowest values of the indicator can be observed at the bottom of the valley, especially in its middle and lower parts. These areas should therefore be considered as a zone with favourable conditions for the accumulation of sediments removed from eroded slopes (Fig. 5B)

To determine the morphological conditions of surface runoff, the convergence index was used. This parameter shows the topography as a structure of converging (canals) and diverging (ridges) elements. In the presented model (Fig. 5C), negative values characterise areas where water flowing down the slope is concentrated. In contrast, positive values indicate areas where the terrain configuration favours the dispersion of runoff. In the study area, the values of the index range from −83 to 90. The tendency to concentrate the runoff at the bottom of the valley is quite clearly visible, where the index reaches the lowest values. In turn, runoff dispersion is characteristic of areas on the watershed, within small hills on the valley's slopes and at its bottom.

Another important parameter describing the water conditions in the catchment area is the topographic wetness index (TWI) (Fig. 5D). It describes the distribution of soil moisture and the terrain's influence on hydrological processes. This index determines the relationship between the size of the area involved in surface runoff and its slope (Beven, Kirkby 1979; Wieczorek, Żyszkowska 2011). The index reaches the highest values with a large supply area and a small inclination angle, and vice versa. In the study area, the highest values of the index are observed at the bottom of the erosion-denudation valley (especially in its middle and lower parts) and within its theoretical tributaries. Therefore, the highest

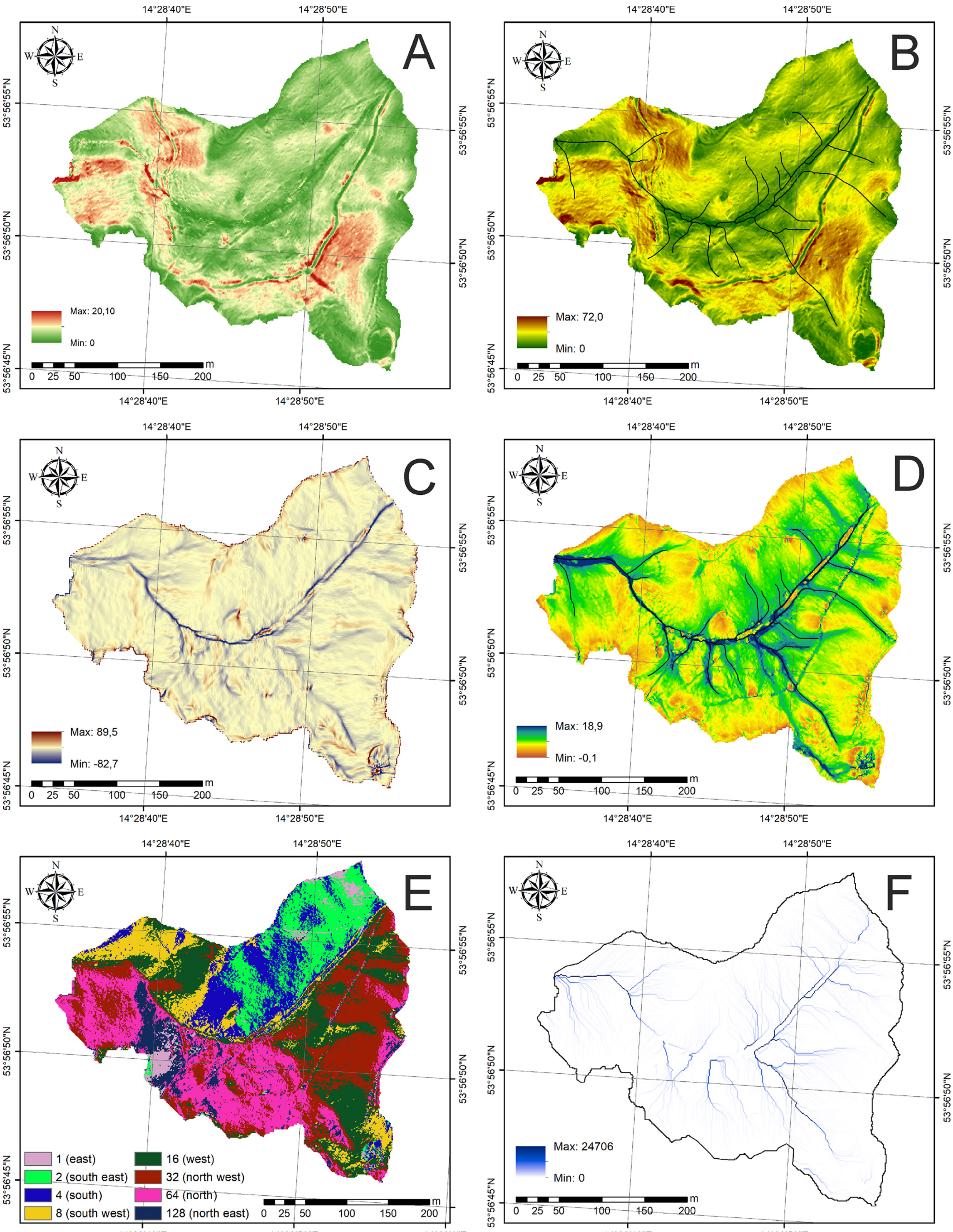

Fig. 5. Hydrological parameters of the erosion-denudation valley catchment: A. LS-factor (Slope Length and Steepness factor), B. Stream Power Index, C. Convergence index, D. Topographic Wetness Index, E. Flow direction F. Flow Accumulation

values of the index indicate potential places of water concentration, which, to some extent, corresponds to the runoff convergence model. On the other hand, the lowest values of the index occur in the highest areas, in the zone of the watershed line (Fig. 5D).

One commonly accepted parameter in the hydrological modelling of the catchment area is the unidirectional point flow direction model D8 (Wilson, Gallant 2000). This indicator is calculated based on a digital catchment elevation model, where for each raster cell, the direction of water flow to the adjacent cell is determined along the line of the greatest slope. As a result, a model is created in which cell values are encoded in the binary system, i.e. as successive powers of two. The numbering starts from the east and runs sequentially in the direction of the compass (1 – east, 2 – south-east, 4 – south, 8 – south-west, 16 – west, 32 – north-west, 64 – north, 128 – north-east) (Fig. 5E). The direction of the runoff corresponds very well with the exposure of the slopes and their inclination. In the northern part of the catchment, the flow of water is organised mainly in southern directions, with the south-eastern direction prevailing in the north-eastern part and the south-western and western directions in the north-western part. On the other hand, in the southern part of the catchment, the water usually flows north and northwest, i.e. towards the bottom of the valley.

Thanks to the created flow direction model, generating another important parameter characterising water circulation in the catchment area is possible: flow accumulation. This indicator informs about the amount of water flow in individual cells of the raster, i.e. it corresponds to the number of cells from which water flows to a given cell. In the analysed area, the values of the indicator range from 0 to 24 706. The minimum and maximum values mean the sum of cells from which water flew into the cell where this value was measured. The highest flow accumulation was recorded at the mouth of the valley bottom and in its central part, where the main tributaries concentrate. The lowest value of this indicator is recorded in the watershed zone (Fig. 5F).

Apart from morphological conditions, one of the factors influencing the nature of erosion processes within valleys is also land cover. Within the catchment area of the analysed valley, there is a deciduous tree represented by the acidic Pomeranian beech forest (*Luzulo pilosae-Fagetum*) (Piotrowska 2003, Tylkowski et al. 2021, 2023), which is characterized by a strongly dense canopy. Therefore, intense erosion processes are observed only during extreme precipitation events (Smolska 2007).

Conclusion

Detailed morphological and lithological analyses were carried out based on the planned research in the selected experimental catchment area Zielony Parów, located in the edge zone of the Wolin Island cliff coast. In the longitudinal profile at the mouth of the valley, the occurrence of slumps was found, which proves the increased dynamics of abrasive processes. On the other hand, the middle and upper part of the valley is erosive-denudative. The morphometric analyses carried out allowed for the quantitative determination of the parameters of the relief. The analysed erosion-denudation valley is well-cut; the depth in the upper section exceeds 10 m and increases in the lower section to over 34 m. The slopes surrounding it from the north and south are high, often exceeding 20–30°. The relatively high energy of the relief of the valley is conducive to the occurrence of erosion processes. Regarding lithology, the bottom of the valley is dominated by sandy formations of various sizes and a moderate degree of sorting.

Using erosion potential indices (LS-factor, SPI) allowed the selection of areas most susceptible to water erosion. In the analysed area, slopes in the south-eastern and western parts of the catchment show a high erosion potential. On the other hand, the configuration of the terrain is not conducive to erosion processes in the middle section of the valley floor. This area's considerable flattening is conducive to the accumulation of sediments. The exception is the lower part of the valley bottom, within which an increase in slope is visible. The highest values of the LS-factor describe this place.

The planned measurement system in the catchment area of Zielony Parów will enable stationary studies to quantify the course and intensity of erosion-denudation processes and abrasion and their role in the development of erosion-denudation valleys of the cliff coast of Wolin Island.

Author contributions

RP, MW, AK MD – Conceptualization, Methodology, Writing – original draft; RP, MW, MD – Data curation; RP, MW – Writing – review & editing; MW – Visualization.

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