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Large-scale bedforms in the vicinity of Serwy Lake (NE Poland): their morphometry and links to the high-energy glaciofluvial environment

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Abstract. The Suwałki Glacial Megaflood Landsystem documented in NE Poland led to further morphological analysis of bedforms that originated from glacial lake-outburst floods (GLOFs) in the central and eastern parts of the Augustów Plain. This article focuses on (1) the recognition of large-scale subaqueous dunes in the vicinity of Serwy Lake, (2) the creation of a database consisting of relevant morphometric parameters (lengths, heights and gradients of stoss and lee slopes) and indexes (steepness and asymmetry ratios) and (3) comparison with other landforms that undoubtably indicate glacial floods (e.g., Missoula, Altai, British Columbia, Wigry Lake). The remote identification and measurement of the megadunes' morphometry based on LiDAR data and digital elevation model with resolution 1×1 m (using hillshade and geomorphons) yielded data characterising 254 bedforms. These represent two-dimensional large-scale subaqueous dunes, which have lengths varying between 23.6 and 241.8 m and average heights of 0.6–5.4 m. Moreover, their morphometric variation creates a continuum typical of subaqueous dunes and has similarities to prominent examples linked to GLOFs. The study is especially crucial due to the lack of a wide range of information about megadune development under unconfined settings during the Weichselian glaciation.

Key words:
glacier lake-outburst floods,
outwash,
geomorphometry,
subaqueous megadunes,
Weichselian glaciation

Introduction

As with modern glaciers, the dynamics of the Scandinavian Ice Sheet (SIS) in the Pleistocene was, both while it was advancing and in retreat, dependent on the capacity and type of meltwater drainage, which in turn directly affected the erosion and accumulation action of these waters in the forefields of the SIS. The release of meltwaters from the SIS, which resulted from global climate changes, caused a transformation in the morphology and geological structure of the proglacial area through the development of extensive outwash plains. Such transformation occurred due to "normal" meltwater outflow or as an effect of individual releases of very large quantities of meltwater into the proglacial area (glacial lake-outburst floods), which generally happened shortly after the ice sheet reached its maximum extent (Marren 2005), and may have been one of the main causes of the formation of the European Lowland's system of ice-marginal valleys (e.g., Marks 2012; Toucanne et al. 2015; Weckwerth et al. 2019).

The recognition in Poland of outwash morphology, which is typical for "normal" meltwater discharges, has been carried out for many years and has distinguished valley-confined outwash and unconfined outwash plains, both of which are characterised by many hypsometric levels with surfaces intersected by subglacial channels or deformed by kettle holes (e.g., Galon 1961; Niewiarowski 1968; Roszko 1968; Wiśniewski 1971; Zieliński 1993). The origin of selected fragments of outwash plains in NW Poland was linked to glacial lake-outburst floods (GLOFs), based on morphometry investigations (Szafraniec 2008, 2010a, b, 2013). In the case of NE Poland, large-scale subaqueous bedforms were identified, which developed in a proglacial setting and unambiguously indicate the occurrence of extreme high meltwater discharges as catastrophic glacial lake-outburst floods (GLOFs) and prove that the proglacial area was significantly and rapidly transformed during NE Poland's deglaciation (Weckwerth et al. 2019, 2020; Weckwerth and Wysota 2024).

Indicator landforms of GLOFs recognised near Suwałki (NE Poland; Fig. 1) form the comprehensive Suwałki Glacial Megaflood Landsystem (Weckwerth et al., 2019, 2020, 2024). The most spectacular of its components are the scabland landscape, linear clusters of kettle holes and large-scale dunes. Aside from the Suwałki Glacial Megaflood Landsystem, the literature also describes landforms caused by glacial floods from the Weichselian glaciation associated with the meltwater outflow from ice-dammed lakes (terminoglacial lakes) in North America, Asia and Northern Europe (e.g., Carling 1996a, b; Rudoy 2002; Teller 2004; Herget 2005, 2012; Høgaas and Longva 2016) and in Iceland as a result of jökulhlaups (e.g., Maizels 1989a, b); Russel et al. 2001, 2010; Carrivic et al. 2004), where modern-day catastrophic glacial floods develop their own indicative landforms and deposits (e.g., Russell 1994, 2007; Russel et al. 2001, 2010; Marren 2002). GLOF-related landforms and sediments from the Saalian glaciation are also known from European Lowlands (e.g., Lang and Winsemann 2013; Lang et al. 2017, 2019, 2021; Winsemann et al. 2016; Frydrych and Rdzany 2022); however, the recognition of such features from the Weichselian glaciation in this area is still insufficient (Weckwerth et al. 2019, 2020, 2022a, b). Thus, the geomorphological records of Pleistocene GLOFs in NE Poland should be identified because they are not commonly recognised in the European Lowlands, and they should be verified by proofs from areas in which similar landforms (e.g., large-scale dunes) were created by well-documented outburst floods.

The Suwałki Glacial Megaflood Landsystem recognised in NE Poland indicates the outflow of large quantities of meltwaters which inundated the western part Augustów Plain and fed the the Biebrza Basin (Figs 1 and 2). Considering this fact, the origin of the central and eastern parts of the Augustów Plain as a result of GLOFs cannot be excluded, taking into account also (1) the existence of the Skidel ice-dammed lake in the eastern vicinity of the Biebrza Basin and its drainage during the Weichselian glaciation (Vozniachuk and Valchik 1978; Pavlovskaya 2004; Marks and Pavlovskaya 2007; Marks 2012) and (2) meltwaters input from the area of southern Lithuania to the Augustów Plain (Blažauskas et al. 2007; Kazbaris et al. 2013). Thus, the main objectives of the article may be summarised as (1) identification of landforms that most likely originated from GLOFs in the area of the central part of the Augustów Plain, (2) recognition of their morphometry and (3) comparison of the results against prominent examples of landforms that unambiguously indicate catastrophic glacial floods. These research aims are all the more important for the fact that such landforms that developed during the Weichselian glaciation in the European lowlands are still poorly recognised.

Background

Outwash morphology

Outwash plains (sandurs) cover large areas of northern Poland and are features representing meltwater activity along the southern periphery of the SIS during the Weichselian glaciation. These waters contribute to the deposition of gravels and sands under confined settings (valley-confined outwash tracks) and unconfined settings (extensive outwash plains), which both constitute outwashes commonly occurring in proglacial landscapes (Benn and Evans 2010). As these features represent accumulative proglacial landforms, their morphology is dominated by flat surfaces, the height of which decreases downstream according to the direction of meltwater outflow. In addition, the slope and length of outwashes can change as a response to variations in the position of the ice-sheet front where the ice portals developed at the mouth of englacial channels, forming the meltwater outflows from the beneath the ice sheet. Moreover, the slope of outwashes can change as an effect of variation in energy of meltwater outflow, resulting in switching between the sand- and gravel-dominated braided rivers which formed outwashes in proglacial settings. In addition, the

Fig. 1. Location of the study area, regional units and morphology of north-eastern Poland (after Solon et al. 2018) (Pm – presumable extent of the Scandinavian ice sheet during or shortly after the Pomeranian Phase of the Weichselian glaciation, modified from Ber (1967), Lisicki (1993) and Dzierżek and Zreda (2007), when the glacial lake-outburst floods occurred Key: WS – Western Spillway and ES – Eastern Spillway of Suwałki Megaflood after Weckwerth et al. (2019) black rectangle indicates the study area, shown in detail in Figure 2

variable meltwater discharges were related to seasonal ablation rate, both of which influenced the changes in sedimentary environment and bedforms morphology. Considering these circumstances, the large proglacial areas were transformed by proglacial rivers characterised by changeable length and discharges, which caused the formation of different topographic levels in outwash plains and confined outwash tracks in NE Poland (Galon 1953, 1961; Niewiarowski 1968; Wiśniewski 1971; Zieliński 1993). In Poland, it was until recently believed that these levels were surfaces that change in width and slope and that their hypsometry was often modified by postglacial landscape transformation triggered by (1) the degradation of dead ice, which occupied older depressions than outwash sediments (e.g., subglacial channels) and ice blocks transported by meltwaters and finally grounded during outwash

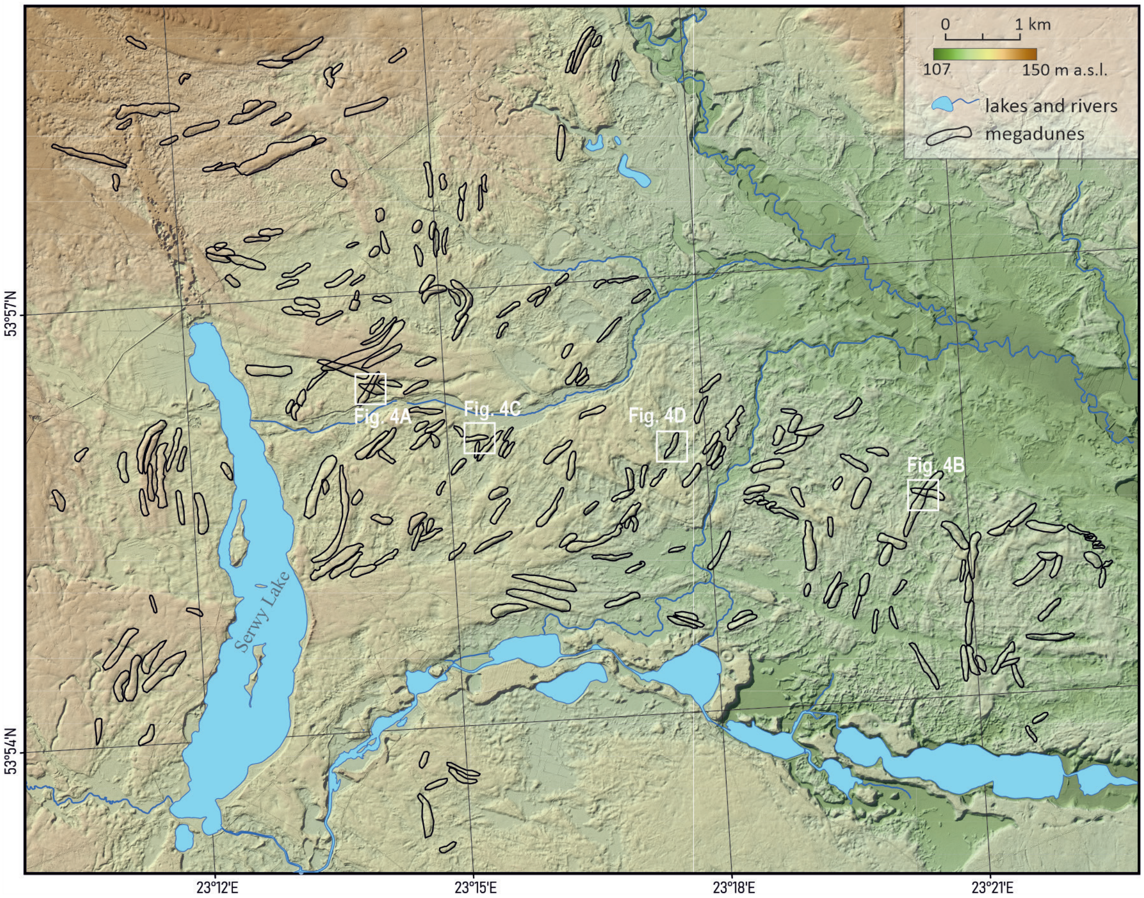

Fig. 2. Megadunes located near Serwy Lake study area with marked extracted megadunes (for details see Fig. 4)

formation (preventing them from being filled by outwash deposits), (2) aeolian activity and (3) river valley development in postglacial period. According to these, the recognition of indicator bedforms typical for extreme high or "normal" meltwater outflows is difficult and would have been almost impossible until LiDAR data became available for Europe (e.g., Høgaas and Longva 2016; Weckwerth et al. 2019, 2022a, b).

The accuracy of investigations of outwash morphology and the possibilities for interpreting the origins of bedforms is much higher for contemporary glaciated areas. Modern outwashes are narrow because they are formed in belts between mountain massifs and shoreline, which forces the formation of relatively short (up to 10–30 km) meltwater outflow tracks (Zieliński and van Loon 2002). Nevertheless, these tracks reveal the wide spectrum of bedforms typical for "normal" meltwater discharges controlled by seasonal fluctuations in ablation rate (e.g., Boothroyd and Ashley 1975; Maizels 1995, 2002; Marren et al. 2002) and/or indicative for contemporary GLOFs (e.g. Russell 1994, 2007, 2009; Russel et al. 2001, 2005, 2006, 2010; Russell and Knudsen 2002; Fay 2002; Carling 2013). Such GLOF-related bedforms that have evolved in contemporary glaciated areas have been investigated in terms of glacial flood hydrology and geomorphology, and thus are controls and markers for the interpretation of GLOFs during the Pleistocene. The fresh and undisturbed morphology of outwashes formed by present-day GLOFs is highly variable and comprises macro-, meso- and small-scale bedforms (e.g., Maizels 1992, 1993, 1995; Russell 2009). Macro-scale bedforms are represented by different types of bars (e.g., expansion, longitudinal and eddy bars), while meso-scale features are giant dunes, which have been identified only for GLOFs from the Pleistocene. Smaller-scale megadunes that originated from contemporary GLOFs were recognised in the forefield of Solheimajökull in

Iceland (Maizels 1989a, b) and in the forefield of the Russell Glacier in Greenland (Maizels 1995; Russell 2009). Moreover, a set of small-scale bedforms developed due to present-day GLOFs comprises multi-crested esker ridges, fracture-fill ridges and jökulhlaup fans in the marginal zone, as well kettle-holes, kettle-scours, chute channels, gravel dunes and gravel sheets – almost all located on lateral or central bars (e.g., Maizels 1995; Russell 2009; Russel et al. 2006, 2010).

Large-scale dunes in glaciofluvial environment

The occurrence of depositional large-scale two- and/or three-dimensional dunes, with crests generally perpendicular to the flow direction, is indicative for high-energy glaciofluvial environments, including GLOFs (e.g., Allen 1984; Baker 1973; Carling 1996a, b; Carling et al. 2002; Clague and Rampton 1982; Waitt 2002; Høggas and Longva 2016). The majority of these bedforms is made from coarse sands and gravels (Ashley 1990; Carling 1999; Carling and Breakspear 2007). According to Carling et al. (2009), the megadunes indicate the existence of subcritical flow conditions scaled with dune heights and wavelengths (Allen 1984). Another important factor is that gravel flood-dunes usually display the morphology of lee slope steeper than stoss-slope (Carling 1996a, b), and the size of these bedforms increases downstream (e.g., Johnsen and Brennand 2004; Høggas and Longva 2016). In channelised (confined) sedimentary environments, the characteristics of large-scale dunes, which are composed of coarse sand, are mostly well-known (e.g., Baker 1973, Maizels 1995, 1997; Baker et al. 2016). However, Hansen et al. (2020) found an example of large-scale bedforms composed of fine, well-sorted sand in south-eastern Norway. This example proves megadune formation under conditions of ponding and the creation of a major flood basin at the time when glacial flood levels rose. Smaller-scale megadunes (up to 0.5 m high and 10.5 m length), originated from contemporary GLOFs, were recognised in the forefield of the Solheimajökull in Iceland (Maizels 1989a, b) and as gravelly dunes superimposed on larger bars in the forefield of the Russell Glacier in Greenland (Maizels 1995; Russell 2009). Similar bedforms developed in valley-slope confined settings in Channel Scabland (Baker 1973) and were identified also on the terraces in the Katun and Chuya River valleys, where they are interpreted as antidunes (Altai Mountains; Rudoy 2002).

There is much evidence of large-scale GLOF-related bedforms developing in unconfined settings. Such bedforms were recognised in Kuray Basin (Altai Mountains) and their origin has been interpreted in many papers (e.g., Rudoy 1998, 2002; Carling 1996a, b, 2013). Furthermore, subaqueous gravel dunes, including antidunes and reverse dunes, developed under similar conditions during the draining of the largest Glacial Lake Missoula at Camas Prairie (e.g., Pardee 1942; Baker 1973; Alho et al. 2010; Bohorquez et al. 2019). In the vicinity of Wigry Lake in north-eastern Poland, an instance of megadunes in an unconfined area right at the mouth of two proglacial spillways was described by Weckwerth et al. (2019).

Regional setting

The study area is located in north-eastern Poland and in the central part of the Augustów Plain, which represents an extensive outwash plain formed as a result of meltwater activity during the last glaciation (Ber 1972, 1974; Bogacki 1976, 1980; Zieliński 1989, 1993; Weckwerth et al. 2019) (Fig. 1). This region lies at the front of the former SIS margin from the Pomeranian Phase of the Weichselian glaciation (Weckwerth and Wysota 2024). Thus, the border between this basin and the Western and Eastern Suwałki Lakelands is well-defined in morphology and in terms of the extent of glaciofluvial sediments, because these lakelands comprise flat or undulating till plains (Ber 1972, 1974; Bogacki 1976, 1980; Weckwerth et al. 2019; Weckwerth and Wysota 2024).

To the south, the flat surface of the Augustów Plain extends to the border of the Biebrza Basin (Fig. 1). Although the southern limit of the Augustów Plain is only slightly curved, its northern limit exhibits few intersections, which host the Rospuda and Czarna Hańcza River valleys located between Ełk Lakeland and the Western and Eastern Suwałki Lakelands (Fig. 1). Thus, the northern part of the Augustów Plain represents a set of narrow and confined spillways of meltwaters, which finally inundated the central part of the Augustów Plain during the Pomeranian Phase of the Weichselian glaciation (e.g., Ber 2000; Pochocka-Szwarc and Krzyszkowski 2015), including GLOFs of different sources (Weckwerth et al. 2019, 2022b; Weckwerth and Wysota 2024).

The surface of the northern part of the Augustów Plain, where few spillways intersected the till plains, declines to the south-east along the Rospuda River outwash (from 165 to 120–130 m a.s.l. near Augustów) and along the Western and Eastern Spillways (from 230 and 192 m a.s.l., respectively, to 160–170 m a.s.l. near Suwałki) (Fig. 1). In the area of the Serwy Lake, the surface of the Augustów Plain has a height of 133–137 m a.s.l., and then lowers gently to the south and east to ~120 and 115 m a.s.l., respectively (Fig. 1). The outwash surface nearby the Serwy Lake is intersected by large tunnel valleys associated with the maximum ice sheet limit of the Late Weichselian (Ber 1972, 1974, 1982, 2000; Krzywicki 2002; Weckwerth and Wysota 2024) or comprises the remnants of older glacial and glaciofluvial landforms (Ber 2000; Sobiech 2019).

Research methods and data

Large-scale bedforms were mapped on the base of hillshade (with solar azimuth 315° and solar angle 45°), hypsometry and geomorphon maps prepared on the base of DEMs with pixel size 1×1 m (generated from LiDAR data) (Jasiewicz and Stepinski 2013; Sărășan et al. 2019; Gawrysiak and Kociuba 2020) (Fig. 3A). Such a procedure allowed the detection error to be minimised (Schillaci et al. 2015). The bedform mapping resulted in the creation of a database of morphometric parameters and indexes corresponding to 254 mapped features. These parameters include the bedform total length (L) defined as a sum of the lengths of its stoss and lee slopes (L_1 and L_2, respectively), the heights of stoss and lee slopes (H_1 and H_2, respectively), average height (H_{avg} – arithmetic mean calculated for H_1 and H_2) and lee and stoss slope angles (α and β, respectively) (Fig. 3B). Calculated morphometric indexes are the ratio between megadune total length and lee slope height (L/H_2 – steepness index) and the ratio between stoss and lee slope lengths (L_1/L_2 – asymmetry index) (after Carling 1996a) (Table 1).

The obtained morphometric data were analysed on the basis of statistical parameters (mean, minimum, maximum, first and third quartile, median, standard deviation, skewness and kurtosis), which describe the data distributions (Figs 5 and 6; Table 1).

Another approach was used to identify the relationship between megadune morphometric parameters. Two-dimensional graphs were created whose axes represented the spread of selected morphometric parameters. According to Ashley (1990), the megadunes should occur as a continuum when the L/H_2 relation is disputed, so the estimated boundary of the continuum was added (Fig. 4). Additionally, the relation equation and trend lines were used to compare megadunes recognised in study area with the similar data presented by Baker (1973), Ashley (1990) and Weckwerth et al. (2019) (Fig. 7).

Results

The widespread availability of LiDAR data allowed the detection of 254 bedforms in the central part of the Augustów Plain and their morphometric analysis (Figs 1 and 2). We interpret these bedforms as dunes (giant dunes, large-scale subaqueous dunes or megadunes) because of their morphology, which is typical for such bedforms (e.g., Allen 1984; Ashley 1990; Baker 1973; Carling 1996 a, b; Carling et al. 2002; Clague and Rampton 1982; Waitt 2002; Høggas and Longva 2016; Maizels 1997), and sedimentary successions dominated by sandy-gravelly cross-bedded and horizontally stratified sands and gravels, which exclude their aeolian origin. Sedimentary successions of megadunes will constitute the main subject of the next article.

Megadunes identified near the Serwy Lake are closely spaced and superimposed in many cases, forming a cluster located between the western shore of Serwy Lake and the right bank of the Czarna Hańcza River (Figs 2 and 4). This cluster has a length of 14 km in an east–west direction and 8 km in a north–south direction (Fig. 2). The substratum of megadune cluster is characterised by the surface inclining eastward from 107 to 140 m a.s.l. in the eastern vicinity of Serwy Lake (Fig. 2).

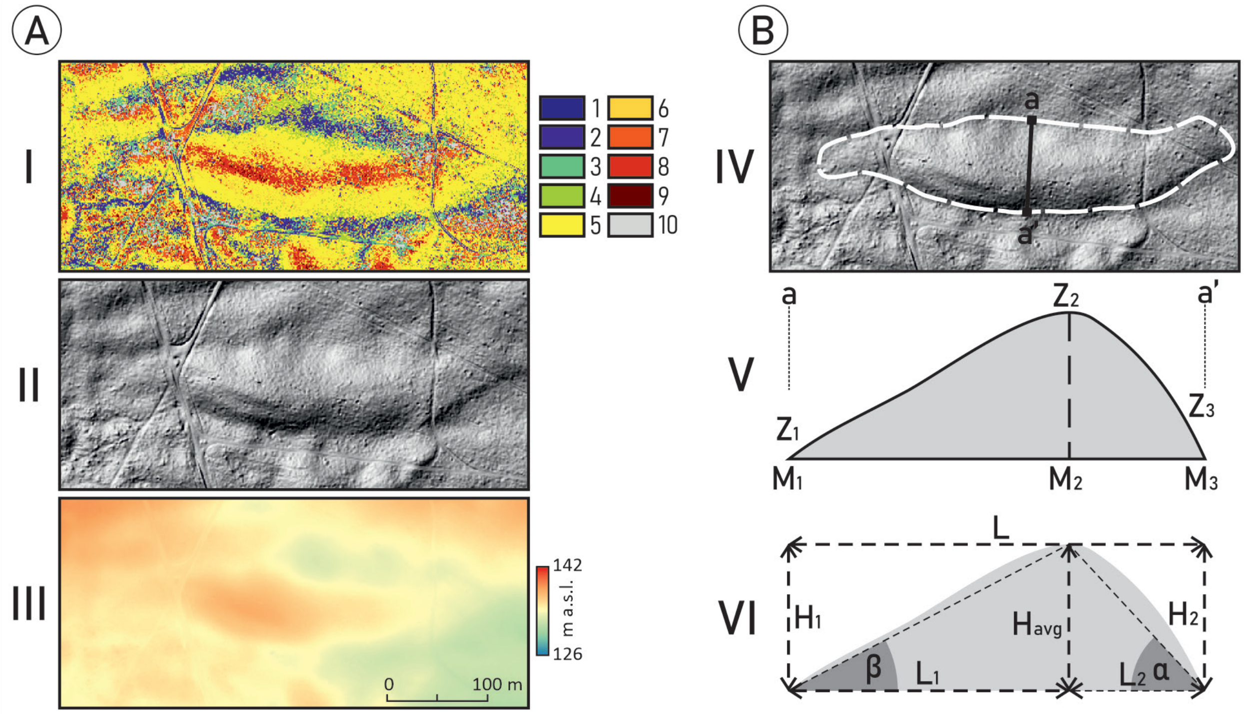

Fig. 3. A – megadune mapping using geomorphons (I), hillshade (II) and hypsometry (III) (1 – depression, 2 – valley, 3 – footslope, 4 – hollow, 5 – slope, 6 – spur, 7 – shoulder, 8 – ridge, 9 – summit, 10 – flat); B – morphometric data gathering based on cross-sectional profile (IV–VI) (M – distance from the beginning of the profile, Z – absolute height, 1 – the beginning of the stoss slope, 2 – the peak of the megadune, 3 – the end of the lee slope)

The morphology of the megadunes varies according to changes in their length, width and height. These bedforms have a length (L) in the range between 23.6 and 241.8 m, with mean and median values of 72.2 and 67.7 m, respectively (Figs 5A and 6C). Stoss slope length ranges from 9.6 to 188.3 m (mean value 40.1 m and median 37.3 m) and lee slope vary between 7.0 to 92.4 m with mean equalling 32.0 m and median 30.5 m (Fig. 6A, B). In addition, megadunes are characterised by average height (H_{avg}) 1.9 m (mean value 1.8 m), ranging from 0.6 m to 5.4 metres, with data distribution showing right-skewness (1.21) and leptokurtosis (1.7), the lowest of all analysed morphometric parameters and indexes (Figs 5B and 6F). The height of lee slope of megadunes (H_2) is between 0.3 and 7.3 m, while stoss slope height (H_1) varies within the range 0.4–5.9 m (both parameters have mean value 1.9 m and median 1.7 m) (Figs 5C and 6D, E). The distributions of both slope heights are skewed also rightwards and leptokurtic (Figs 5C and 6E). The inclination of stoss slope (β) varies from 0.8° to 7.7° with mean 3.0° and median 2.6°, whereas lee slope inclination (α) ranges between 0.8 and 12.7° with mean value 3.5° and median 3.3° (Fig. 6I, J).

The values of morphometric indexes and their distributions reveal significant variation in the megadune dataset. The ratio L_1/L_2 unveiled a mean value 1.34 (median 1.3), and changes between 0.5 and 3.7 (Fig. 6H). The data distribution is right-skewed and leptokurtic (Fig. 5D). Regarding the L/H_2 ratio, its mean and median values are 45.1 and 39.8, respectively, and data distribution ranges from 9.1 to 170.4, being characterised by a high standard deviation of 21.47, right-skewness and leptokurtosis (Figs 5E and 6G).

The analysis of the relationships between the morphometric parameters of megadunes in the area of Serwy Lake and between their morphometric indicators reveals the lack of clear correlations between L and H_2 and between the ratios L_1/L_2 and L/H_2 (Fig. 7D). This means that morphometric parameters do not show significant dependence on each other, but the concentration of analysed cases on scatter plots is undeniable (Fig. 7A, D). Relation between L and H_2 displays data continuum up to 5.5 m of lee slope height and 150 m of megadune length

Table 1. Statistical characteristics of the distribution of morphometric parameters and indexes calculated for megadunes near Serwy Lake

	L_1	H_1	L_2	H_2	L	H_{avg}	β	α	L/H_2	L_1/L_2
Mean	40.1	1.9	32.0	1.9	72.1	1.9	3.0	3.5	45.1	1.3
Min	9.6	0.4	7.0	0.3	23.6	0.6	0.8	0.8	9.1	0.4
Max	188.3	5.9	92.4	7.3	241.8	5.4	7.7	12.7	170.4	3.7
Quartile I	29.5	1.3	22.7	1.1	54.1	1.3	1.9	2.4	28.9	1.0
Median	37.3	1.7	30.5	1.7	67.6	1.7	2.6	3.3	39.8	1.3
Quartile III	47.4	2.4	39	2.5	85.6	2.4	3.6	4.4	57.5	1.6
Stand. dev.	17.4	1.0	12.7	1.1	26.4	0.9	1.4	1.6	21.4	0.5
Skewness	3.0	1.1	1.1	1.5	1.7	1.2	1.2	1.7	1.4	1.4
Kurtosis	20.5	1.7	2.5	3.0	6.6	1.6	1.3	5.7	3.9	3.2

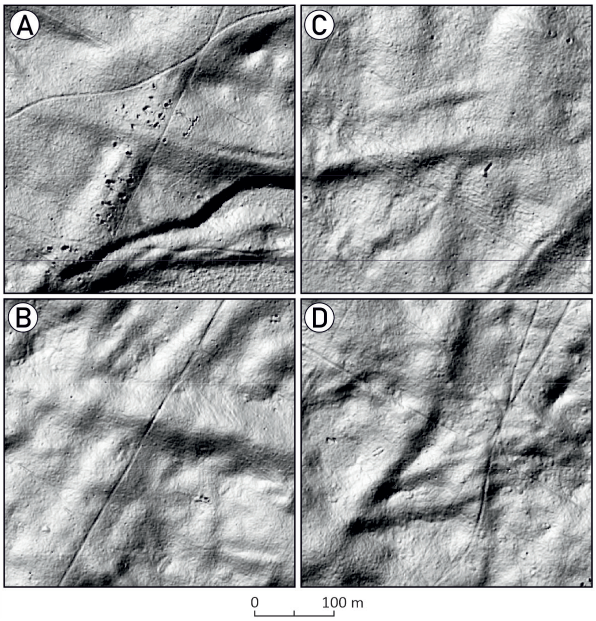

Fig. 4. Examples of superimposed dunes in the vicinity of Serwy Lake

(Fig. 7A). The associations between asymmetry and steepness indexes calculated for megadunes near the Serwy Lake are also weak, as the data on the scatter plot form a cluster with values in the ranges 0.4–3.25 and 10–100, respectively (Fig. 7D). The dependency of stoss slope inclination on lee slope angle of analysed megadunes also displays the existence of a data cluster (ranging up to 8° for both slopes), but, even though they are weakly correlated, there is a visible tendency for the stoss slope inclination to increase with increased lee slope angle (Fig. 7B).

Discussion

The complex pattern of 254 megadunes recognised in the area of an unconfined outwash plain displays successive bedforms overlapping (superimposing) (Fig. 4), which makes such an arrangement unique on a global scale. Bedforms overlapping was noted for subglacial features (see Dunlop and Clark 2006) or in riverbeds (e.g., Jackson 1976; Rodrigues et al. 2015; Wintenberger et al. 2015). Based on classification proposed by Ashley (1990), subaqueous dunes identified near Serwy Lake represent large, two-dimensional bedforms (length 10–100 m, height 0.75–5 m) (Table 1; Figs 5 and 6). However, not all the data meet the criteria of L and H relation proposed by Flemming (1978), because bedforms of length over 100 m (which should be defined as "very large") do not have enough height (mostly below 5 m; Fig. 7A). At the same time, Ashley (1990) states that megadunes are created from deposition of coarse sand (grain size over 0.15 mm), which, according to our preliminary study, matches the sediments forming megadunes in the vicinity of Serwy Lake. Another evidence for the GLOF-related origin of the whole population of bedforms near Serwy Lake is that they form a continuum of landforms without discrete

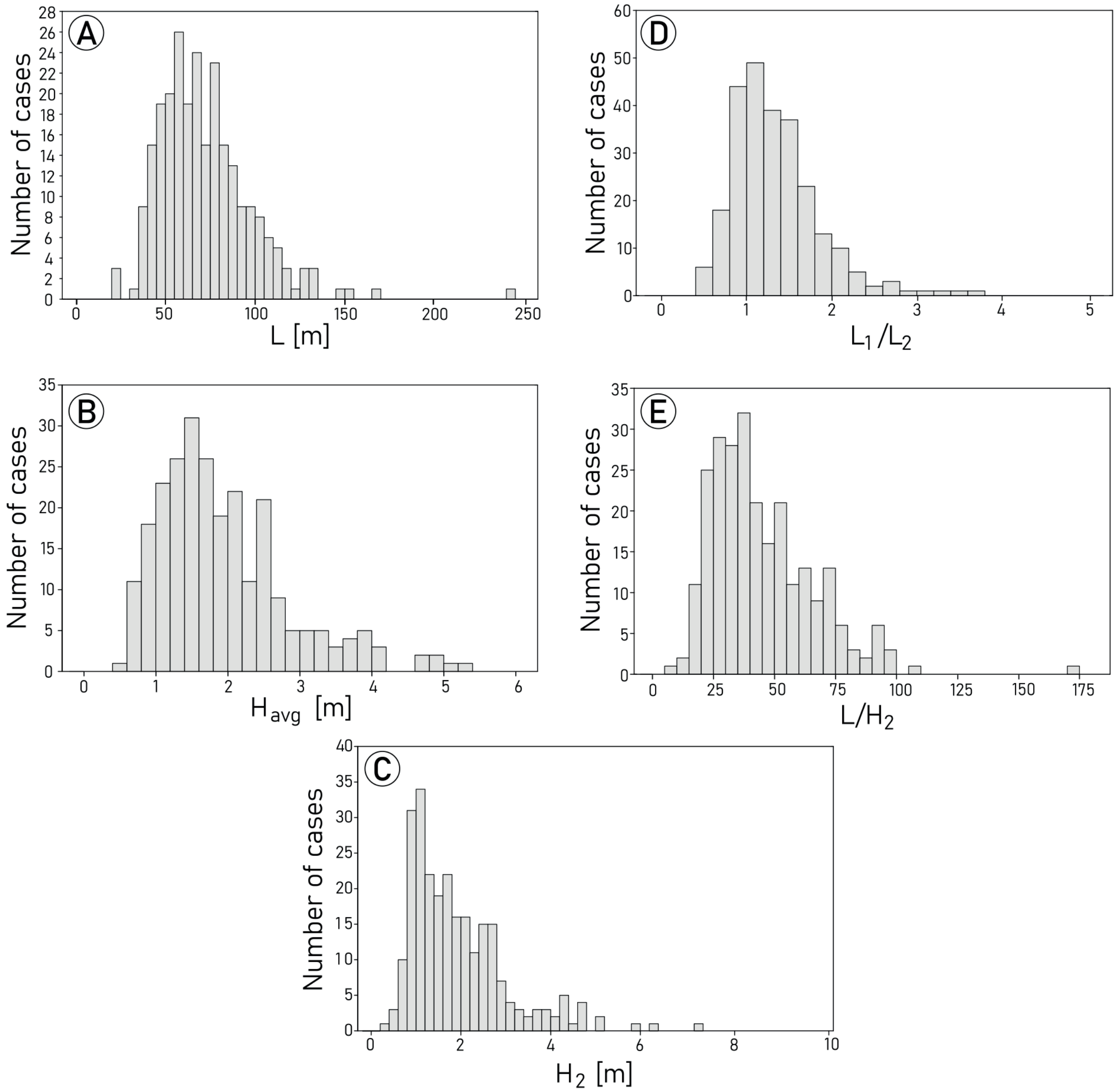

Fig. 5. The distribution of megadunes' length (A), average height (B), lee slope height (C), asymmetry index (D) and steepness index (E)

subpopulations, analysing the relationships between H_2 and L (Fig. 4A).

The link between the development of megadunes near Serwy Lake and a high-energy glaciofluvial environment (e.g., GLOFs) is also confirmed by comparison of their length, height and slope inclination (23.6–241.8 m, 0.6–5.4 m and 0.8–12.7, respectively; Table 1) against the morphometry of megadunes recognised in the Altai Mountains (Herget and Carling 2004; Table 1). Furthermore, the megadunes from wide Kuray Basin originated in mostly unconfined setting (Herget 2005). The spatial distribution of bedforms in our study area seems also to be similar to the ones in a western Channelled Scabland near the town of Odessa (Baker 1973; Baker et al. 2016), where the pattern of giant subaqueous dunes is characterised by alternating bedforms of different morphometries and dimensions. The only difference is that features in the vicinity of Serwy Lake (Fig. 2), do not have the uniform crest orientation exhibited by those in the Channelled Scabland. Moreover, bedforms created during the Lake Missoula Flood, which consist mostly of gravels, are characterised by similar gradients of lee and stoss slopes (Herget

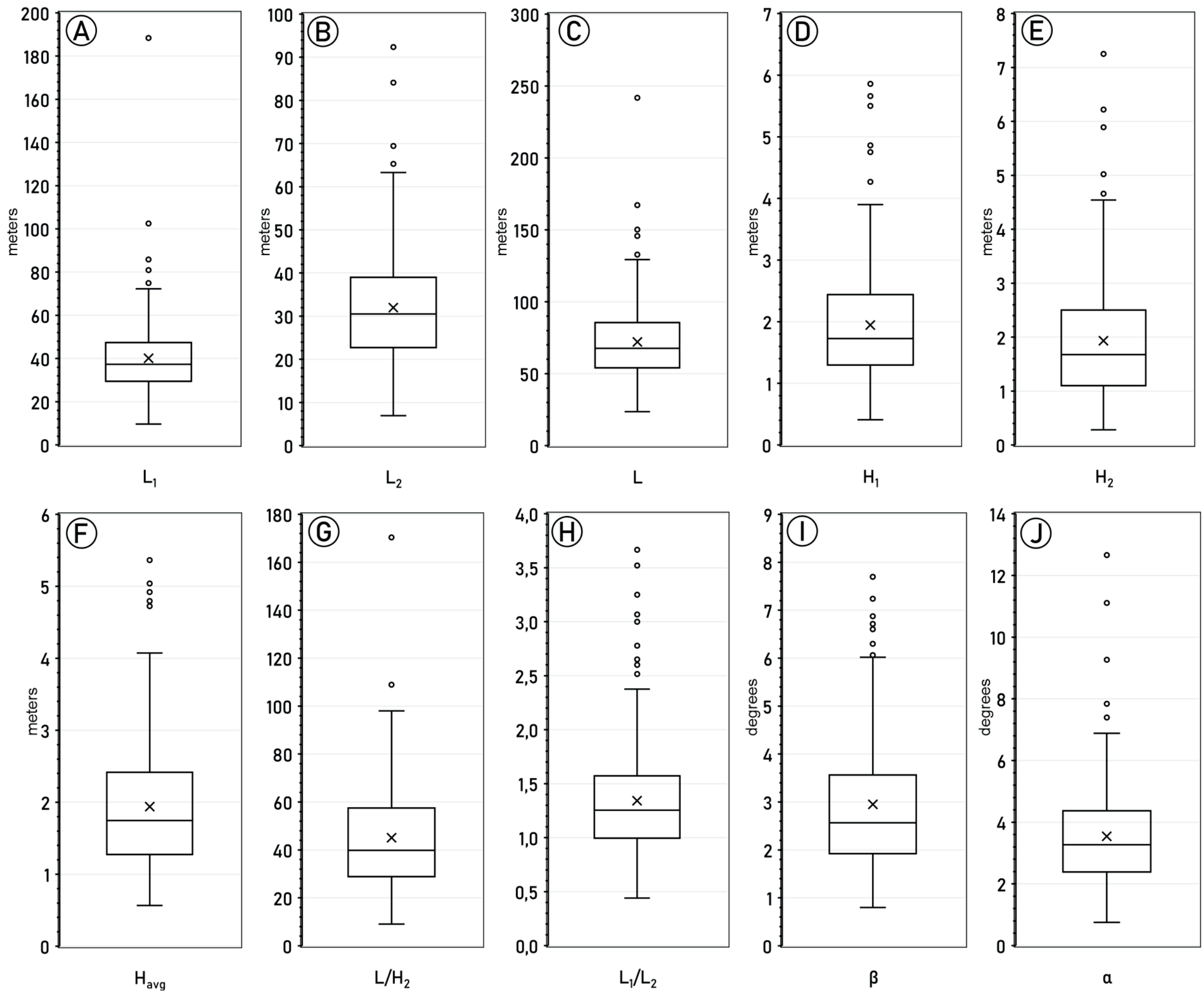

Fig. 6. Morphometric characteristics of megadunes near Serwy Lake: A – stoss slope length, B – lee slope length, C – length, D – stoss side height, E – lee side height, F – average height, G – steepness index, H – asymmetry index, I – stoss slope gradient, J – lee slope gradient

and Carling 2004) to bedforms around the Serwy Lake (Table 1; Fig. 7D). Moreover, the comparison of relationships between L and H2 of bedforms located near Serwy Lake against those described by Baker (1973) and Ashley (1990) reveals possible differences in their development (Fig. 7A).

The origin of large-scale bedforms near Serwy Lake as representing high-energy meltwater outflow, can also be confirmed by comparing them (in terms of location and morphometry) to megadunes located near Wigry Lake (Weckwerth et al. 2019). The latter developed due to a GLOF with discharge assessed as up to 2×106 m^3s^{-1} and are located adjacent to the same outwash-plain-like bedforms near Serwy Lake, but developed having different floodwater sources (Fig. 1). Moreover, in terms of megadune height, the bedforms near Wigry Lake were split into two groups, the first comprising bedforms with heights below 3.5 m and the second with heights above 4 m. This means that the megadunes described in this study are similar to those representing the first group developed near Wigry Lake, having a height in the range 0.4–2.2 m and being shorter than those described by Weckwerth et al. (2019) in more than 50% cases (Table 1; Fig. 5b, c). The similarity between these two fields of megadunes extends to their amalgamation and the existence of crestal depressions, which assures us of their fluvial origins (Figs 2 and 4).

The next similarity in morphometry between the megadunes near Wigry Lake (Weckwerth et al. 2019) and the 2-D dunes in the vicinity of

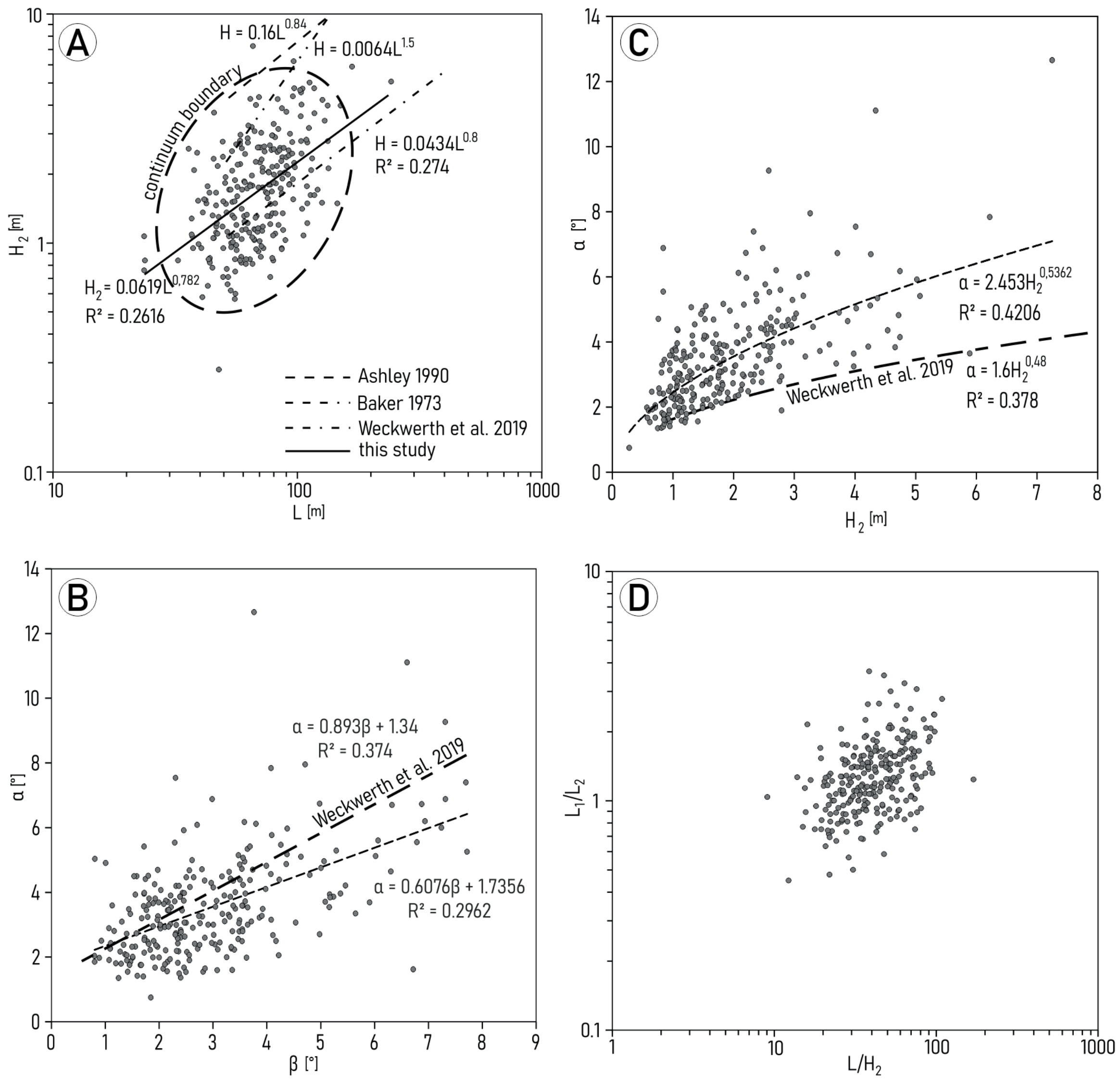

Fig. 7. Relationships between selected megadunes morphometric parameters: A – bedform length (L) and lee slope height (H_2) with L to H_2 relation given by equations proposed by Baker (1973), Ashley (1990), Weckwerth et al. (2019) and this study; B – lee and stoss slope gradients; C – lee slope gradient and lee slope height; D – asymmetry and steepness indexes

Serwy Lake is shown by the equations defining the distributions of megadune lengths and lee slope heights (Fig. 7A). The graphs of these functions are closely parallel to each other and to the function proposed by Ashley (1990). However, all data from NE Poland scatter widely below functions developed by Baker (1973) and Ashley (1990). Considering these facts, the morphological similarity characterising megadunes in NE Poland may indicate their consistent development. This refers to stable flow dynamics resulting in the creation of 2-D megadunes like in the sites of Akturu, Kuray or Platovo (Altai Mountains) more than the bedforms in the Missoula region (Carling 1996a) (Fig. 7A). Analysing the changes in the lee slope gradients and their heights, the relationships between these parameters are even more significant for megadunes near Serwy Lake than for those located near Wigry Lake (Fig. 7C). Moreover, the majority of bedforms developed in the vicinity of Serwy Lake are symmetrical (Fig. 7B), which may indicate Froude-supercritical flow and similarity to antidunes (Carling and Shvidchenko 2002). If so, the flooding must have occurred as a high-energy event with very short waning stage because, during this time, the antidunes are usually washed out (Carling and Shvidchenko 2002; Carling et al. 2009). The example in British Columbia shows similar bedforms in terms of the lee and stoss slope symmetries and dimensions (length 100–230 m, height 3–7 m; Johnsen and Brennand 2004) (Table 1; Fig. 7A-C).

Conclusions

Application of GIS tools and LiDAR data enables identification of hitherto unrecognisable indicative landforms for GLOFs. The central part of the Augustów plain has a distinct area of megadunes in the vicinity of Serwy Lake, where 254 objects were distinguished. The two-dimensional bedforms have lengths varying between 23.6 and 241.8 m and average heights ranging from 0.6 to 5.4 m. These characteristics create a continuum of bedforms as typical for subaqueous dunes. Morphometry of megadunes near Serwy Lake shows similarities: to GLOF-related large-scale bedforms in the vicinity of Wigry Lake in terms of L/H ratios; to bedforms originating from the Missoula and Altai flooding in terms of gradient of megadunes slopes; and to bedforms near the town of Odessa in Channelled Scabland in terms of spatial distribution. The similarity in terms of two-dimensionality, slope gradient and heights between dunes in Altai Mountains and Serwy Lake finds its confirmation in similar, unconfined flow and deposition conditions. Most of the bedforms are symmetrical, which indicates a high probability of having developed as antidunes. Demonstrated similarities show that GLOFs had a crucial impact on development of outwash plains in NE Poland and supplying ice-marginal river valley system of Europe.

The recognition of these landforms emphasises the need for further research about subaqueous bedforms developed in unconfined flow and deposition environments that are typical for European Lowland where huge outwash plains were formed during the Pomeranian phase of the Weichselian glaciation. That stays in contrast with previous phases of the last glaciation and with the most of documented places with confined setting. The main goals for the future are (1) establishing the pattern and causes of megadune overlapping and (2) the interpretation of their sedimentary successions.

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No potential conflict of interest was reported by the authors.

Author contributions

Study design: MS, PW; data collection: MS; statistical analysis: MS; result interpretation: MS, PW; manuscript preparation: MS, PW; literature review: MS, PW.

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