POLISH JOURNAL OF SOIL SCIENCE
VOL. LIV/1 2021 PL ISSN 0079-2985

DOI: 10.17951/pjss/2021.54.1.123

MAŁGORZATA RADŁO-KULISIEWICZ*

DIGITAL TERRAIN MODEL DERIVATIVES ANALYSIS WITH THE AIM OF IDENTIFYING SPECIFIC SOIL TYPES IN YOUNG POST-GLACIAL TOPOGRAPHY WITH A VECTOR APPROACH

Received: 19.03.2021
Accepted: 31.05.2021

Abstract. This article discusses a study conducted in order to analyse selected Digital Terrain Model (DTM) derivates in diverse young post-glacial topographic profiles with the aim of identifying terrain features that could be related to the soils that formed there. The area under investigation is within the reach of the youngest Vistulian Glaciation, in the north-east of Poland. The main goal of the study was to reveal indirect relationships between a lithological soil type and terrain forms, which transpire from DTM derivatives. This can directly help to assign the type of soil in the area to one of the three soil types: a) made of sand, b) made of loam, c) wet-soils. The starting point for the research undertaken was the landscape approach to soil modelling and the article deals with medium scales. Derivatives were analysed using vector data notation, focusing on selected derivative values and their spatial location in relation to one another. The results obtained indicate the possibility of using this approach as an auxiliary approach in soil mapping of areas for which the quality of source materials (such as precipitation geometry) is low. Thus, they can be of assistance in improving the existing soil maps of selected scales. The trend revealed in the obtained results of DTM analysis can be considered as a contribution to realisation of assumptions of a study in digital soil mapping with the use of selected methods of AI.

Keywords: DTM derivatives, soils made of sand, soils made of loam, wet-soils, digital soil mapping

---

* Warsaw University of Technology, Department of Photogrammetry and Remote Sensing. 1 Politechniki Sq., 00-661 Warsaw. E-mail: Malgorzata.Radlo@pw.edu.pl

INTRODUCTION

In geological and geomorphological respect, the area of Poland is diversified. This diversified topography plays a great and exceptional role in soil forming (Miklaszewski 1901, Jenny 1941, Białousz 1969, Gerrard 1992, Deumlich 2010). The importance of this role results from indirect influence of terrain forms on the amount of water penetrating the soil (deriving directly from precipitation or accumulated in places with limited run-off) as well as its influence on the amount of solar energy (light and air temperature) reaching the soil. The uniqueness of the topography results from the diversity of terrain forms, characterised by various parameters such as: solar exposition of slopes, their length, steepness, or curvature shapes (convex, concave or flat forms), combination of which leads to a multiplicity of possible factor systems impacting the soil being formed. Among all the topography types in Poland, the young post-glacial topography is the best option for this examination, due to its highly characteristic and noticeable terrain forms. These forms, due to the glacial period they originated in, are also diversified both geologically and petrographically. Quantitative methods of terrain description came into use in geomorphology at the beginning of the 1950s (Stahler 1957) and later, with digitalisation development, they found their way into GIS software. The process of quantitative terrain description with terrain parameters, called "terrain parameterization", was initially implemented by adopting morphological, hydrological and ecological algorithms as well as algorithms concerning its other aspects with the use of DTM (Dobos *et al.* 2006). The literature mentions numerous terrain parameters, also called "topographic attributes" (Wilson and Gallant 2000) or "terrain derivatives" (Schillaci *et al.* 2015), and in DTM – "DTM derivatives". Primary attributes are values computed directly from DTM, while secondary attributes (also called "compound attributes") include combinations of basic features being the basis for characterisation of spatial diversification variability of the processes occurring in the given terrain. These solutions found its way into soil science in the 1990s, as they model selected soil characteristics with the use of selected terrain parameters (Table 1), with a large spectrum of field resolution. According to Dobos *et al.* (2002), soil types were modelled using the first and the second DTM derivatives with different pixel sizes: 50 m (Thomas 1999) and 1,000 m (Dobos *et al.* 2000, 2001). After 2000, with the increasing availability of satellite imagery and elevation data from various platforms, and thanks to the ever-evolving GIS applications, but, above all, the need for regional soil information, digital soil modelling products began to fill digital soil databases (e.g. SOTER, SOVEUR, EGSDB). In the last decade, machine learning methods such as random decision forest (RF) (Vaysse and Lagacherie 2017, Wadoux *et al.* 2019a, Ellili-Bargaoui *et al.* 2020) and, more recently, artificial neural networks of deep learning (DL) (Behrens *et al.* 2018, Wadoux *et al.* 2019b) have become principal methods of digital soil mapping. These methods emphasize interdependence between environmental and topographic variables, referring to the holistic (ecological) approach in classical soil modelling, which makes use of filtering terrain attributes based on different neighborhood sizes, as well as identification of topographic features in varied scales utilising so-called octaves (a multiscale approach). Using such advanced methods in modelling soil cover, partial solutions are sought that will improve the accuracy of parameters used in soil modelling algorithms. This research is an attempt to contribute to such partial solutions that can then serve as a basis for the development of more efficient models. Co-relations between terrain attributes and soil attributes have been frequently used to model soil coverage in the last 30 years and the highest degree of co-relation have been found for slope gradients and soil moisture index (Qiyong *et al*. 2014, Malone *et al*. 2009, Debella-Gilo and Etzelmüller 2009, Ziadat 2005, Gessler *et al*. 2000, Moore *et al*. 1993). The vector approach described in this work, making use of a combination of individual features (curvature values) and spatial features (proximity of adjacent cells) has not occurred in the available literature before. The main goal of the study was to reveal indirect relationships between a lithological soil type and terrain forms, which transpire from DTM derivatives. This research is an attempt to contribute to partial solutions that can then serve as a basis for the development of models in digital soil modelling.

Table 1. The selected most common terrain features used to model soil variables (Dobos *et al*. 2002, modified)

Authors	Soil variables	Terrain parameters	Resolution DTM [m]
Gessler *et al*. (1995)	A-horizon depth, solum depth, E-horizon presence or absence	plan curvature CTI	20
Bell *et al*. (1992)	Soil drainage classes	slope, slope-curvature ratio, elevation above local stream, slope gradient to local stream, distance to local stream, distance to local drainage way	30
Bell *et al*. (1994)	A-horizon and carbonate depth	slope gradient, curvature, drainage path, specific catchment area, elevation, wetness index, stream power, drainage	10
Moore *et al*. (1993)	A-horizon thickness, organic matter content, pH, extractable P, and silt and sand contents	slope and wetness indices	15, 24
Gessler *et al*. (2000)	C and soil mass	Flow direction, flow accumulation, slope gradient, profile and plan curvature, CTI	2, 4, 6, 8, 10
Thomas *et al*. (1999)	soil types	altitude, slope, aspect, profile and plan curvature, distance to the thalweg	50
Dobos *et al*. (2000, 2001)	soil types	PDD, slope, elevation	1,000

The study uses the experience from the research conducted as part of the doctoral dissertation (Radło-Kulisiewicz 2019), which investigated the use of DTM derivatives in modelling the soil cover in the young glacial landscape for a database of soils with a level of generalization corresponding to maps on a scale of 1:250 000. There, various sources of altitude data (in terms of spatial resolution and geometric accuracy) were tested in four research fields within the Masurian Lake District. From the range of possible DTM resolutions, which resulted from the geometrical detail of the additional materials (lithogenetic map 1:50 000 and auxiliary geomorphological sketches 1: 100 000) and reference (soil and agricultural map 1:100 000), a set of altitude data from a LPIS (land parcel identification system) with a spatial resolution of 20 m, was selected. It should be noted that generally available altitude data with lower resolution such as models generated from SRTM, from other satellite data or aerial photographs, are often land cover models, not land surface models, so they take into account the heights of field objects such as forests and they introduce into calculations errors of elevation. In the recommendations of the European Soil Bureau for the European Soil Database (SGDBE 1:1 mln), the model generated from digitized contour lines on topographic maps at the scale of 1:50 000 is indicated as the source of altitude data; DTED2, with a spatial resolution of 30 m (Białousz 2015). Due to the processing results obtained in the above-mentioned study, in this article the author focuses on one selected area for which the most interesting results were obtained (Fig. 1).

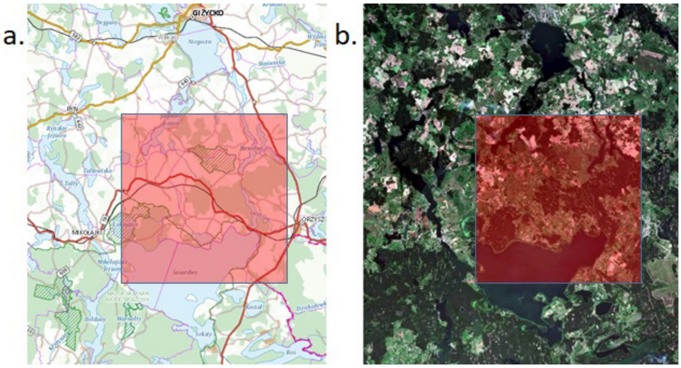

Fig. 1. Selected research area (a) against the background of a topographic map (b) against an orthophotomap (source: Geoportal)

MATERIALS AND METHODS

The area selected for examination is part of Pojezierze Mazurskie, located near Śniardwy Lake, stretching from Łuknajno Lake in the south-west to Miłki village in the north-east, inscribed in the 17 km × 17 km square. The examined area is within the reach of Pomeranian phase of Vistulian Glaciation, where the dominant forms are undulating plains of ground moraines of height ranging from 114 to 179 m, and slope gradients within the range of 0–8°. Loams of glacial origin, gravel sand of supraglacial and glacial origin, as well as swamp peats are dominant in the geological composition of the subsoil. Knowledge of the morphometric co-relations between geomorphological forms and geological composition of subsoils makes it possible to use selected DTM derivatives to extract pixels whose values and location in relation to one another determine the examined relation. The research was carried out considering the three co-relations (couples) of geomorphology and geology which dominate in the examined terrain. DTM derivatives were examined considering the occurrence of three types of soil characteristic of such conditions: soils made of sand (terminal moraine sands), soils made of loam (ground moraine loam) and wet-soils (swamp peat in catchment areas). A numerical terrain model developed for the purposes of orthorectification in order to develop a digital orthophotomap of a 20 m field resolution, which was used in a LPIS, was used as source data.

As source data, a numerical terrain model with the Delaunay triangulation algorithm was used, in a sheet cut with the rectangular plane coordinate system PUWG1992 in the scale of 1:10 000, with GSD = 20 m and an average height position mh<0.8–2.0>[m]. The model was created for the purposes of ortho-rectification of a digital orthophotomap for the identification system of agricultural parcels, which was created using aerial photos taken as part of the PHARE project. The data was obtained free of charge from the Central Geodetic and Cartographic Documentation Center (CODGIK) in the TIN format (25 files). They were linearly interpolated to be converted to GRID format and combined into a mosaic of rasters. The lithogenetic map of Poland in the scale of 1:50 000 in the form of WMS provided by the Polish Geological Institute (PIG), as well as auxiliary geomorphological sketches in the scale of 1:100 000 downloaded from the PIG website in PDF format were used as additional data. They were converted to .PNG format in ArcMap, and transformed from pixel coordinate system to PUWG 1992 using affine calibration based on field details.

As reference data was used a soil-agricultural map of 1:100 000 scale, verified for lithological data with the use of a geological map of 1:50 000 scale and the pine forest contour from the data basis of State Forests. Refining the soil data was essential due to the spatial resolution of the DTM source data transformations (20 m), corresponding to bigger scales. Original soil data in bigger scales were not available for that particular area.

Group I: soils made of sand

The basic assumption for the first group was that terrain forms made of sand, occurring in terminal moraine, are often of oval shape and often have elongated and regular slopes. AB type soils (agricultural soil map legend term for soils made of sand) may occur at various heights and elevations, both in terrain hollows and elevations. The variability of the forms made of sand in a given section is lower than when compared with loam forms. This characteristic is clear in a curvature image. Curvature shows the rate of change of the first derivative of heights (slope gradient) in a specified direction: profile curvature in the direction perpendicular to the ground and plan curvature in the direction parallel to the ground, while the sum of their values constitutes standard curvature. **In this study it is not the value of curvature itself that is of importance, but its graphic notation; adjacency of pixels which can be aggregated according to their signs and approximated value** (concerning one slope of a terrain form). Curvature values were reclassified in order to obtain two classes representing concavities and convexities of terrain. This form was converted into a vector, and then the class representative of the form sought underwent spatial selection. Figure 2 shows the scheme of the analysis.

Group II: soils made of loam

Reversing the results of the first study, namely an attempt to use the curvature image to extract small groups of pixels of similar values, which would imply short and irregular terrain forms did not bring the expected results. The reason for this were numerous microforms in the sand and silt of terminal moraine and in other geomorphological forms. That is why **the starting point for the second study was the variability characteristics of the forms of ground moraine.** Ground moraine terrain forms are often not very high or long and irregular. That is why the assumption of the study was that an averaged curvature value in the area with various geomorphological forms will assume lower values in the ground moraine than it does in terminal moraine, and, at the same time, higher than in flat areas. Figure 3 shows the scheme of the analysis carried out. A vector structure of adjacent squares of sides equal triple the size of a DTM source terrain pixel was developed. The difference between the extreme values of the curvature inside each square of the new structure was computed, thus, obtaining a spatially generalised raster, whose values are statistical values resulting from the raster record in a structure of other data set. Then, pixels of selected values, relating to the form variability that should be characteristic of loam in ground moraine were determined by reclassifying the raster, converting it to a vector form and selecting by attributes.

Group III: wet-soils

The assumption for study three was that hollows provide favourable conditions for wet-soils to form. One of the humidity indicators commonly used in modeling hydrological processes is the topographic humidity index (TWI; CTI), in GIS systems calculated by the formula: $\Omega = \ln (As / \tan \beta)$ (Wilson and Gallant 2000), where, As is catchment area, and β – terrain slope.

This approach assumes that: the determined surface runoff is the average for the entire local catchment area, the local hydraulic gradient can be approximated by the local slope, the saturated hydraulic conductivity of the soil is an exponential function of depth, therefore, the Ω index can be taken as an image of the spatial distribution of soil moisture. However, it does not give significant values in places where the terrain is flat (which is due to the formula where the tangent of the slope appears in the denominator). In order to avoid this situation, the TWI values for the tested DTM were extrapolated and the resulting index was named IDW (as the abbreviation for Inverse Distance Weighted). It was assumed that it can be used to identify both dry (minimum values) and water-storing places (maximum values), but in both cases it should be treated as supplementary information, and also requiring verification.

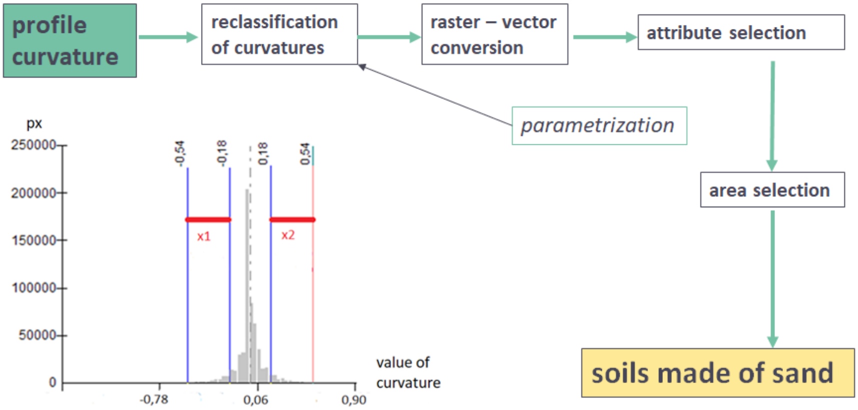

Fig. 2. Scheme of analysis in study 1

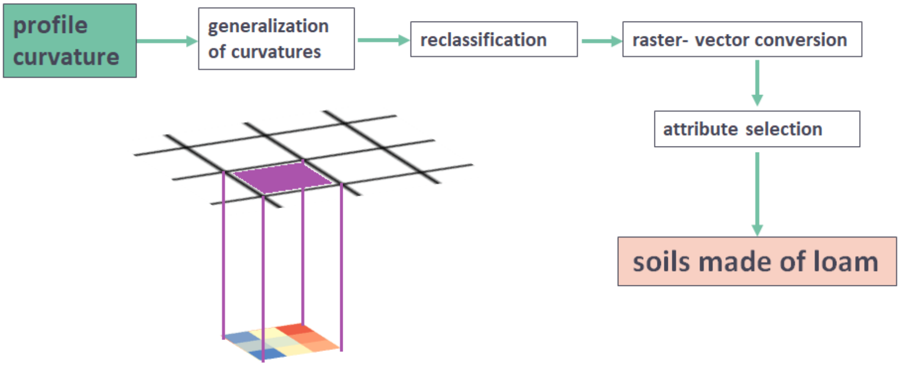

Fig. 3. Scheme of analysis in study 2

RESEARCH RESULTS

Fig. 4. Consecutive DTM transformations in study 1; A – a full range of curvature values; B – curvature classes; C – the selected class in vector record

The results of sequential processing of a curvature image to the vector form in study 1 are shown in Fig. 4. From among all the results in vector record, as intended, groups of adjacent pixels (separation surface > 1 ha, the value selected empirically), corresponding to big terrain forms with low variability, were selected. A fragment of the selected results superimposed on a lithological map of 1:50 000 scale and on a soil-agricultural map of 1:100 000 scale is shown in Fig. 5.

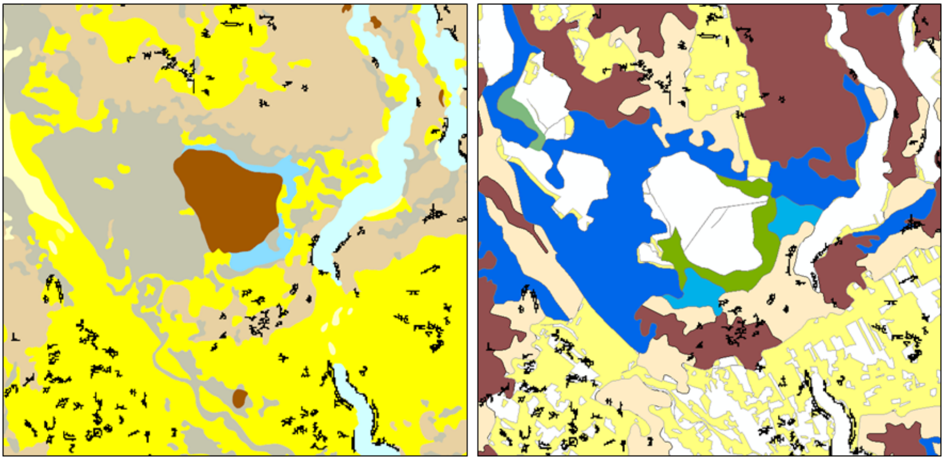

Fig. 5. The results of group 1 (black pixels) superimposed on lithological data (on the left) and on a soil-agricultural map (on the right)

The fact that the result has a "point" characteristics is partially caused by the input DTM resolution (20 m), sensitive to microtopography and capable of resulting in a high variability of curvature around 0 value. However, it is worth noting that the majority of the obtained results for lithological subsoils are in the area of silt-sand (yellow) of terminal moraine. The results superimposed on a soil-agricultural map are in the area of AB soils (beige) and within the pine forest contour (light yellow). An analysis of the result percentage share of study 1 for particular soil classes was carried out, with the use of a soil-agricultural map and assuming that the soil under pine forest is sandy; therefore, the missing contours of pine forests in the soil-agricultural map were added and combined with the AB type soil contours. The results are shown in a diagram (Fig. 6) – 66% of the obtained results in study 1 are in the AB + L_S type, 31% are brown soils and 2% – peat.

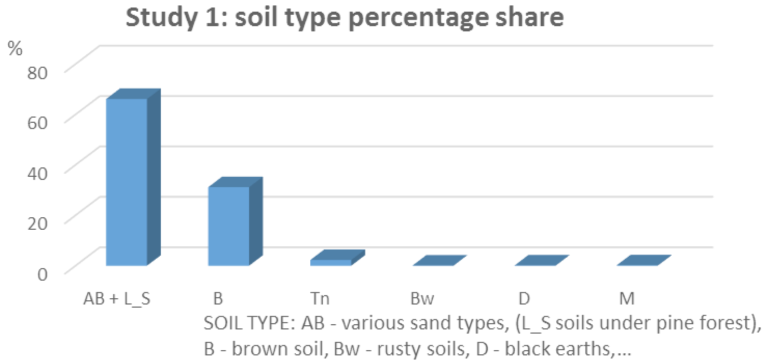

Fig. 6. Diagram showing the percentage share of study 1 results
(soil classes in a soil-agricultural map)

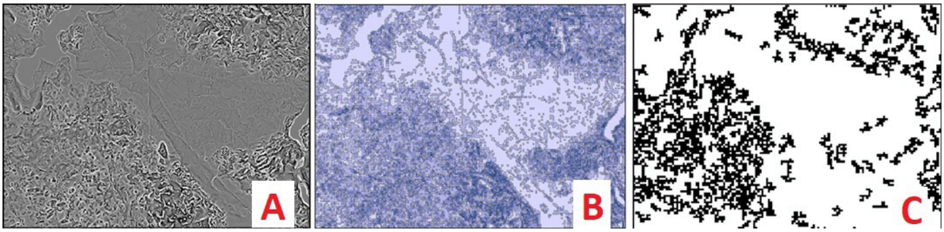

Fig. 7. Consecutive DTM transformations in study 2: A – a full range of curvature;
B – generalised curvature values; C – selected values in vector record

Figure 7 illustrates curvature transformations in study 2: A) a full range of curvature, B) a variability range for the generalised structure, C) curvature values signifying frequent changes of the derivative value within a small area. Superimposing the results on the lithological data of 1:50 000 scale and on the soil-agricultural map of 1:100 000 scale is shown in Fig. 8. In comparison with study 1, the result characteristics is fuller and more spatial, which results from the methodology adopted – enhanced fields resolution of the processed curvature (from 20 to 60 m). The majority of the results of study 2 (occurrence of soils made of loam) overlap with loams in the lithological subsoil (brown colour), and on the soil-agricultural map – with type B soils.

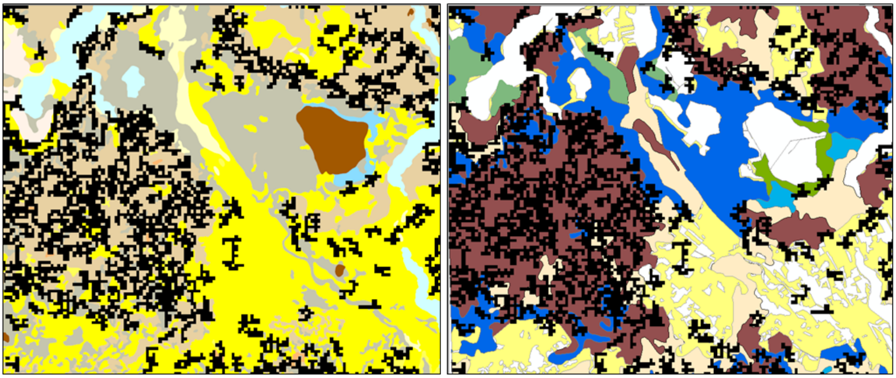

Fig. 8. The results of study 2 (black pixels) superimposed on the lithological data (on the left) and on the soil-agricultural map (on the right)

Similarly to study 1, the obtained results were analysed for percentage compatibility with the data on the soil-agricultural map, which is shown in a diagram (Fig. 9). 54% of the results fall into the B type, 19% into the AB (+ L_S) category, 14% into peat. Study 2 was also carried out with the use of slope gradients. The obtained results and their analysis were very similar to the results obtained with the use of curvature.

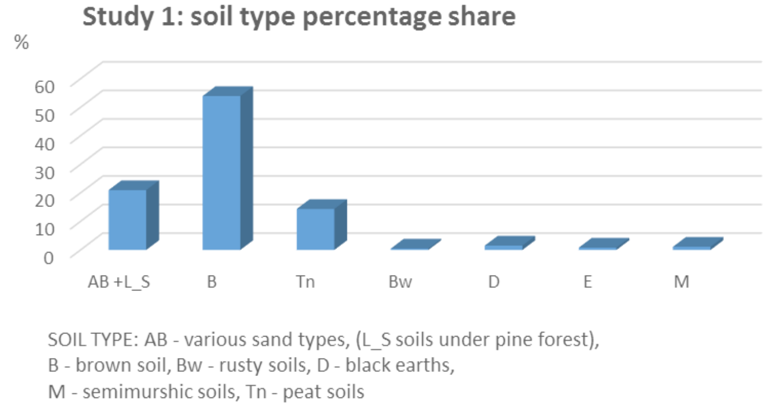

Fig. 9. Diagram showing the percentage share of study 2 results (soil classes in a soil-agricultural map)

The results of study 3 are shown in Fig. 10. It can be seen how important the scale is: the results based on DTM with the field resolution of 20 m fit in well with the contours of other lithological types in loam (most frequently peat, but sand as well), showing small hollows, mapped in the scale of 1:50 000 or not mapped. The results superimposed on the soil-agricultural map of the 1:100 000 scale fit in with the generalised contours of soil classes. That is why the percentage share of the results in the soil-agricultural map, even as a demonstration tool, is not shown here. The effectiveness of this approach will be confirmed further, in the quantitative analysis.

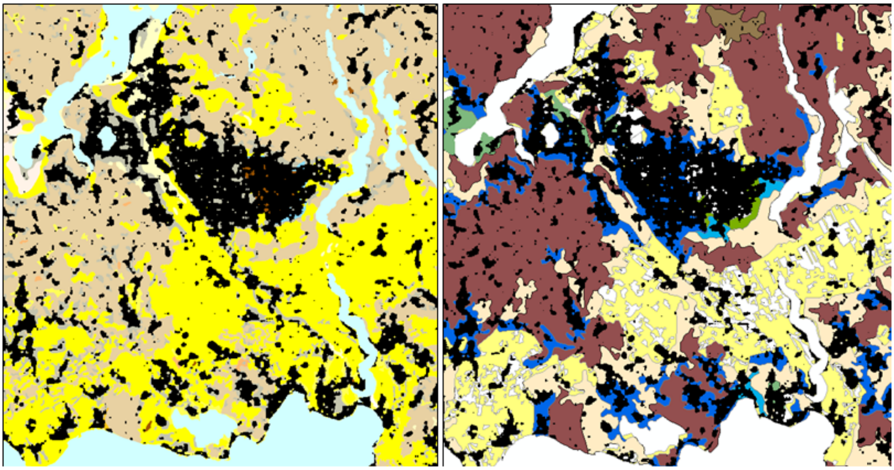

Fig. 10. The results of study 3 (black pixels) superimposed on the lithological data (on the left) and on the soil-agricultural map (on the right)

Juxtaposition of the results of the three transformations led to overlapping of the results for the investigated groups in some places. The two overlapping end-results of transformations: soils made of loam and wet-soils or soils made of sand and wet-soils or the third combination – soils made of loam and soils made of sand are correct from the geological subsoil point of view, because in a situation where there is no clear borderline between geological forms, there appears the problem of a diffused border and transitional forms. Places where all the three transformation groups overlap yield falsified results and need to be verified. The reason for this might be terrain with low variability of topography or heterogeneity of geological subsoil (microtopography). The image of the juxtaposition of the three result groups is shown in Fig. 11, with the colour convention used to denote such soil classes in maps retained: yellow – soils made of sand, brown – soils made of loam, blue – wet-soils. Next to the juxtaposition, reference data can be found – soil classes from the soil-agricultural map.

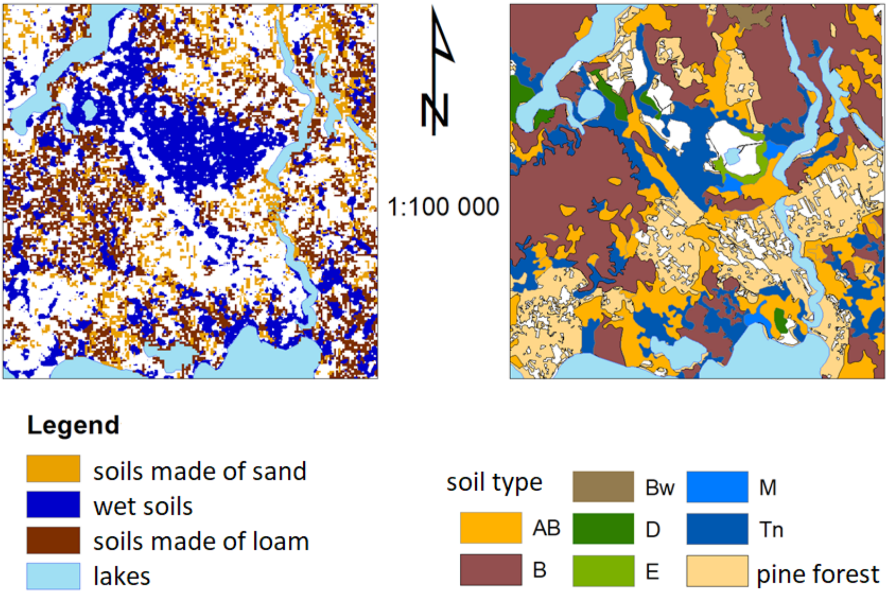

Fig. 11. Juxtaposition of the results of the three studies (on the left) and reference data (on the right)

DISCUSSION

In order to carry out an analysis of the accuracy of the obtained results, 500 control points were set, assuming a sampling strategy in which the points were randomly set within all the soil classes, proportionately to the surface area of each class. On the user's side, the group from the first study was defined as class I (C_1), the group of soils made of loam was defined as class II (C_2), and the group of wet-soils as class III (C_3). The soil-agricultural map was used as reference data, where the following classes were defined on the developer's side: class I – comprising contours of AB soils and, additionally, contours of pine forests, class II – comprising types B and Bw, class III – comprising types D, E, M and Tn. A confusion / an error matrix was computed (Table 2).

Table 2. An error matrix for the results of all the three studies

Class	C_1	C_2	C_3	Total	U_Accuracy
C_1	76	30	1	107	0.71
C_2	67	133	20	220	0.60
C_3	29	14	130	173	0.75
Total	172	177	151	500	0
P_Accuracy	0.44	0.75	0.86	0	0.68

The most accurate results were obtained for class III, with the user and developer accuracy 75% and 86%, respectively, for class II – 60% and 75%, while for class I – 71% and 44%. The overall accuracy of classification amounted to 68%. The results of the quantitative analysis are shown in the form of a map in Fig. 12. The points which were classified accurately are marked with circles as follows: red for the wet-soils group, blue for soils made of loam, green for soils made of sand. The points which were classified inaccurately are marked with a two-colour square, where the colour of the rim signifies the developer's class and the middle – the user's class (e.g. a blue rim and green middle is a point within the area of B/Bw type, classified as the group of soils made of sand). It was noted that the highest concentration of the points classified inaccurately – as the group of soils made of loam, while they are sands in reality – is located in those areas where the dominant forms are gentle slopes (up to 2°) and *vice versa*: the points classified as soils made of sands, while they are located within B/Bw type contours, are located in areas with slope gradient of above 2°. All the points classified inaccurately were analysed for their slope gradient. Table 3 shows the percentage share of the points that were overestimated and those that were underestimated in juxtaposition with the five gradient classes. The analysis of the table leads to a conclusion that the reason for inaccurate classification of these points might be an error resulting from the systematics of research; points generated on steep lake shores were classified as class I, while points on flat tops of elevations and hills as class III.

Table 3. The percentage share of points inaccurately classifed in slope gradient classes

Slope	Class	B.sand	AB.loam	Tn.loam	AB.wet	B.wet
0–2°	1	24	60	80	86	92
2–5°	2	56	39	20	10	8
5–10°	3	12	1	0	3	0
10–15°	4	2	0	0	0	0
>15°	5	5	0	0	0	0

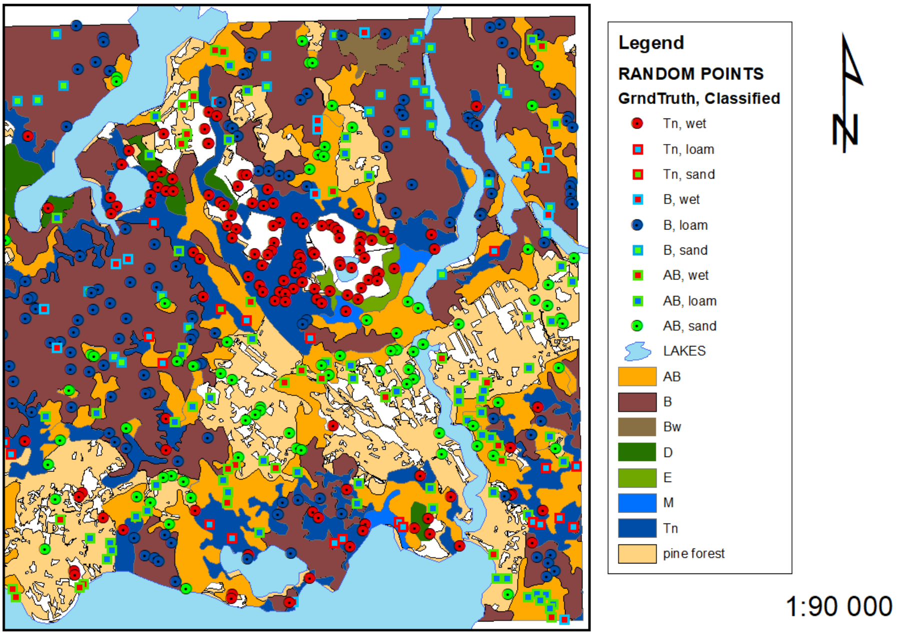

Fig. 12. Location of control points (random) and their class assessment

CONCLUSIONS AND COMMENTS

Three independently conducted studies in the research described, yielded results that were varied quantitatively and qualitatively. Their discontinuous and spatially diffused character does not allow to obtain high correspondence with reference data of continuous nature and unique values (soil class contours in the soil-agricultural map), which is exemplified by overall accuracy of classification amounting to 68%. Yet, the qualitative analysis (visual one) clearly shows a good correlation between the obtained results of the research and lithological types in the area of the youngest glacial period, and consequently, the group of the soil formed there. The study was limited to testing the proposed methodology of DTM derivatives transformation and it did not include the problem of diffused borders. One of the valid conclusions of the study conducted is an indication that the choice of the field resolution of the DTM source should be adjusted to the reference scale in which the soil coverage is modelled. Altitude models of high resolution yield data including terrain microforms, which loses its significance in presentation of soil coverage in smaller scales. Nevertheless, such DTM after generalisation of the required pixel size yields good results in derivatives transformations whose aim is to identify soil groups.

REFERENCES

[1] Behrens, T., Karsten, S., MacMillan, R.A., Rossel, A., 2018. *Multi-Scale Digital Soil Mapping with Deep Learning*. Scientific Reports, 8, article no. 15244.

[2] Bell, J.C., Cunningham, R.L., Havens, M.W., 1992. *Calibration and Validation of a Soil-Landscape Model for Predicting Soil Drainage Class*. Soil Society of America Journal, 56(6): 1860–1866.

[3] Bell, J.C., Cunningham, R.L., Havens, M.W., 1994. *Soil Drainage Class Probability Mapping Using a Soil-Landscape Model*. Soil Society of America Journal, 58(2): 464–470.

[4] Białousz, S., 1969. *The Impact of the Morphogenesis of the Masurian Lake District on the Formation of Soils and the Conclusions for the Geodetic Shaping of the Boundaries of Agricultural Economy Units* (in Polish), PhD dissertation.

[5] Białousz, S., 2015. *Support in Updating and Harmonization of the European Soil Database and Map*. Joint Research Centre, European Commission, ISPRA, pp. 1–101.

[6] Debella-Gilo, D., Etzelmüller, B., 2009. *Spatial Prediction of Soil Classes Using Digital Terrain Analysis and Multinomial Logistic Regression Modeling Integrated in GIS: Examples from Vestfold County, Norway*. CATENA, 77(1): 8–18.

[7] Deumilch, D., 2010. *A Multiscale Soil-Landform Relationship in the Glacial-Drift Area Based on Digital Terrain Analysis and Soil Attributes*. Journal of Plant Nutrition and Soil Science, 173(6): 843–851.

[8] Dobos, E., Micheli, E., Baumgardner, M., Biehl, L., Helt, T., 2000. *Use of Combined Digital Elevation Model and Satellite Radiometric Data for Regional Soil Mapping*. Geoderma, 97(3–4): 367–391.

[9] Dobos, E., Montanarella, L., Nègre, T., Micheli, E., 2001. *A Regional Scale Soil Mapping Approach Using Integrated AVHRR and DEM Data*. International Journal of Applied Earth Observation and Geoinformation, 3(1): 30–42.

[10] Dobos, E., Carré, F., Hengl, T., Reuter, H.I., Tóth, G., 2006. *Digital Soil Mapping as a Support to Production of Functional Maps*. EUR 22123 EN, p. 68. Office for Official Publications of the European Communities, Luxemburg.

[11] Dobos, E., Norman, B., Worstell, B., *et al*. 2002. *The Use of DEM and Satellite Data for Regional Scale Soil Databases*. Agrokémiaés Talajtan, 51(1–2): 263–272.

[12] Ellili-Bargaoui, Y., Malone, B.P., Michot, D., Minasny, B., Vincent, S., Walter, C., Lemercier, B., 2020. *Comparing Three Approaches of Spatial Disaggregation of Legacy Soil Maps Based on the Disaggregation and Harmonisation of Soil Map Units Through Resampled Classification Trees (DSMART) Algorithm*. SOIL, 6: 371–388.

[13] Gerrard, A.J., 1992. *Soil Geomorphology*. Chapman and Hall, London.

[14] Gessler, P.E., Moore, I.D., McKenzie, N.J., Ryan, P.J., 1995. *Soil-Landscape Modelling and Spatial Prediction of Soil Attributes*. International Journal of Geographical Information Systems, 9(4): 421–432.

[15] Gessler, P.E., Chadwick, O.A., Chamran, F., Althouse, L., Holmes, K., 2000. *Modeling Soil-Landscape and Ecosystem Properties Using Terrain Attributes*. Soil Science Society of America Journal, 64(6): 2046–2056.

[16] Jenny, H., 1941. *Factors of Soil Formation: A System of Quantitative Pedology*. McGraw-Hill Book Company, Inc., New York.

[17] Malone, B.P., Minasny, B., Mcbratney, A.B., 2009. *Mapping Continuous Soil Depth Functions in the Edgeroi District, NSW, Australia, Using Terrain Attributes and Other Environmental Factors*. Proceedings of Geomorphometry.

[18] Miklaszewski, S., 1901. *Soils of Polish Lands* (in Polish).

[19] Moore, I.D., Nielsen, G.A.E., Peterson, G.A., Gessler, P.E., 1993. *Soil Attribute Prediction Using Terrain Analysis*. Soil Science Society of America Journal, 57(2): 443–452.

[20] Qiyong, Y., Zhang, F., Jiang, Z., Li, W., Zhang, J., Zeng, F., Li, H., 2014. *Relationship Between Soil Depth and Terrain Attributes in Karst Region in Southwest China*. Journal of Soils and Sediments, 14: 1568–1566.

[21] Radło-Kulisiewicz, M., 2019. *The Use of DTM Derivatives in Modeling Soil Cover in a Young Glacial Landscape for a Database of Soils with a Level of Generalization Corresponding to 1:250 000 Scale Maps* (in Polish), PhD dissertation, Oficyna Wydawnicza PW, Warszawa.

[22] Schillaci, C., Braun, A., Kropáček, J., 2015. *Terrain Analysis and Landform Recognition*. In: Geomorphological Techniques, L. Clarke, J. Nield (eds.). British Society for Geomorphology (online edition).

[23] Stahler, A.N., 1957. *Quantitative Analysis of Watershed Geomorphology*. EOS Sciences News.

[24] Thomas, A.L., King, D., Dambrine, E., Couturier, A., Roque, J., 1999. *Predicting Soil Classes with Parameters Derived from Relief and Geologic Materials in a Sandstone Region of the Vosges Mountains (Northeastern France)*. Geoderma, 90(3–4): 291–305.

[25] Vaysse, K., Lagacherie, P., 2017. *Using Quantile Regression Forest to Estimate Uncertainty of Digital Soil Mapping Products*. Geoderma, 291: 55–64.

[26] Wadoux, A., Brus, D.J., Heuvelink, G.B.M., 2019a. *Sampling Design Optimization for Soil Mapping with Random Forest*. Geoderma, 355.

[27] Wadoux, A., Padarian, J., Minasny, B., 2019b. *Multi-Source Data Integration for Soil Mapping Using Deep Learning*. SOIL, 5(1): 107–119.

[28] Wilson, J., Gallant, J. (eds.), 2000. *Terrain Analysis*. *Principles and Applications*. John Wiley & Sons, Inc.

[29] Ziadat, F.M., 2005. *Analyzing Digital Terrain Attributes to Predict Soil Attributes for a Relatively Large Area*. Soil Science Society of America Journal, 69(5): 1590–1599.