



A GEOMORPHOMETRIC ANALYSIS OF POLAND BASED ON THE SRTM-3 DATA*

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Abstract

The paper presents a range of geomorphometric analyses of Polish territory using both classical and new approaches. The classical outcomes include maps of hypsometry, relative altitude, angle of slope and exposure, as well as altitudes broken down into ranges and angle of slopes in percentages broken down by administrative province. The new approach included the presentation of land relief through standard deviations of relative elevation in regular geometric fields. Maps of hypsometry, elevation difference, angle of slope, exposure and standard deviation were also presented. The survey involved elevation data from the SRTM-3 satellite with a resolution of 3×3' (60-65×90 m), which were converted for research purposes into a grid of 125×125 m and then into hexagons with a surface area of 0.14 and 3 km². This level of detail makes the data particularly useful in morphometric analyses, including in applied research. Certain terrain coverage elements, such as forests, especially in lowland and flatland areas, affected the data and would have to be filtered out in applications requiring even higher accuracy.

Key words

morphometry • geomorphometry • topographic quantification • land relief • land-surface parameters • SRTM • cartographical analyses • Poland

Introduction

The chief tasks faced by landform researchers include identification of morphological units using three-dimensional data (length, width and height/depth) and performing a morphometric analysis of either individual landforms or of a continuous surface area. Until relatively recently, the contour map, sometimes enhanced by the researcher's own land survey or by aerial photo exercises, were the main and often the sole source of data. This method has recently been made all but obsolete

with the arrival of remote sensing, photogrammetry and information systems. The growing level of detail and the expanding body of data on the Earth's surface, combined with the development of GIS instruments, have paved the way for research which hitherto had been technically unfeasible or very difficult. Siwek (2008) observed a paradox whereby classical cartometry went into decline at a time when the development of computer technology created perfect conditions for its development.

In its simplest form morphometric analysis of three-dimensional landforms is based on differences of relative and absolute elevations assuming a 'flat' Earth. For this reason geometry is the

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prime tool for landform analysis. It is not by accident that geographic literature has experienced a wave of methodology studies on the subject published by mathematicians (Steinhaus 1947a, b). An exhaustive review of methods and indicators of spatial morphometric variability was written by Shary et al. (2002) who mention the famous mathematician Gauss as the proponent of the earliest such indicator (Gauss 1902). Among the latest studies in the area is one by Hengl and Reuter (2009) and papers by Drągę et al. (2011), Evans et al. (2012), Bishop et al. (2012) and James et al. (2012).

Morphometric terrain analysis is commonly used in geomorphology, geology and related earth sciences for it allows not only the visualisation, but also a preliminary explanation of the processes shaping abiotic environments. For this reason the ability to perform morphometric analysis is an obligatory skill among physical geographers (Richling 2007).

Considering all that, topography and cartography textbooks offer surprisingly little cartometry. The question could therefore be asked whether morphometric terrain analysis belongs more to cartography and land surveying or to geomorphology and geology (Ławniczak 2003). It seems logical that there is a broad field of common interest, but even a cursory review of the literature shows that cartographers are less attracted to the subject. Interestingly, it is the older, rather than the newer, cartography textbooks that devote their attention to the topic. For example, Józef Szaflarski in his "Outline of cartography" (1965) has a chapter on morphometry where he discusses such examples of applications as typical geometric analysis (angle of slope, relative elevations and 'relief energy'), landform density (e.g. valleys and summit surfaces) and hydrographical elements. Siwek (2008) ascertains that morphometry lies outside the scope of cartography because its methodology was developed in the late 19th century and in the first decades of the 20th century, when calculations were tedious, 'manual' operations. For these reasons several important issues presented by the Earth's surface morphology were abandoned without a solution. Solutions would eventually be provided using different methods (e.g. physical-geographical regionalisation).

There are few methodological and overview studies on morphometry available in the Polish research literature published after the World War II

(Szumowski 1967; Żyszowska 1978; Lach et al. 1980; Kozieł 1990; Ławniczak 2003; Siwek 2008; Wieczorek & Żyszowska 2011). Additionally, all these studies covered relatively small areas due to the inherent labour intensity of the method. The earliest efforts in the field were published before the World War I (Eugeniusz Romer), but the field developed particularly strongly between the wars (Julian Czyżewski, Stanisław Pawłowski, Jerzy Smoleński, Bogdan Zaborski et al.; see: literature review in Ławniczak 2008). The most detailed map of relative altitudes at the national level was the 1:2,000,000 map included in Atlas of the Republic of Poland (Dębowska 1973). Morphometry studies are far more prominent in geomorphology and geology (including the latest by Zuchiewicz 1999; Szubert 2005; Ławniczak 2008; Dmowska 2008; Placek 2008; Sobczyk 2008, Migoń et al. 2009; Kasprzak & Traczyk 2010).

With the progress of computer technology morphometric analysis is becoming ever more prominent in the broadly understood GIS literature. This includes a highly recommendable and exhaustive Polish review of methodologies, technologies and applications written by Kurczyński et al. (2007). The fact that morphometric analysis has flourished in the field of GIS is far from a coincidence. Indeed, 3D terrain modelling is one the most efficient and therefore most methodologically interesting applications of this approach. For this reason many computer applications are equipped with modules designed to perform the analysis of more than just the basic morphometric indicators, such as relative height, slope and exposure, but also more complicated tasks including, for example, visibility analysis (Ołdak 1992; Śleszyński 1998). However, there still seems to be a deficit of this sort of analysis published in Poland. The publication of "Hipsometric atlas of Cracow" by Jędrychowski (2008), which combined strict research and a methodological approach and was based on detailed laser scanning, was a step towards filling this gap.

The facts discussed so far suggest that geomorphometry has become a very important subdiscipline of geomorphology (Evans 1972; Pike 2000), which is confirmed by the recent publication of a number of textbooks (El-Sheimy et al. 2005; Li et al. 2005; Zhou et al. 2008; Hengl & Reuter 2009). The rapid growth of this field of research is best illustrated by a literature review by Pike (2002), which includes more than 6,000 items on terrain morphometry analysis. Indeed, the

expanding body of detailed satellite data on the Earth's morphology combined with the progress of computer technology have spurred a rapid expansion of this subdiscipline of research.

Taking this into account the paper investigates the potential of using detailed satellite elevation data to perform morphometric analyses of Polish territory. An attempt was made to perform a number of classical tasks, including a hypsometric map, map of angle of slopes, etc., but some new methods were also proposed to measure the variation in land relief. The study involved the most detailed, yet freely available, satellite data available on Poland from the Shuttle Radar Topography Mission (SRTM). Other even more precise digital sources of a similar kind are available (LPIS, SMOK, TBD, VMAP), but they do not cover the entire territory of the country.

SRTM data have been commonly used worldwide, but have only recently come into focus in Poland. In the natural sciences they have been employed primarily by geologists (Nita et al. 2007; Wojewoda 2007), foresters (Wężyk & Świąder 2004; Stachura 2006) and geomorphologists (Dmowska 2008; Giętkowski & Zachwatowicz 2008). It is important to note that due to this high level of detail the SRTM data are particularly useful for medium-scale analysis, i.e. below 1:100,000, which makes them particularly valuable for geographers.

SRTM satellite data and their processing

In 2000, a mission of the Space Shuttle Endeavour involved the scanning of the Earth's surface using radar. This produced more than 12 terabytes of data on absolute elevations at very high levels of horizontal and vertical resolution ($x=1''$, $y=1''$, $z=1$ m). About 80% of the Earth's surface was scanned covering the area between parallels 54°S and 60°N thus excluding polar areas. A detail technical description of the exercise is available in the form of an on-line paper published by the American geological services (Rodriguez et al. 2005; in Poland see: Karwel & Ewiak 2006a, b). With this in mind technical aspects will be left aside here apart from three areas important for the analysis of Polish territory:

1) at Polish latitudes the horizontal resolution of the data is such that the level of detail is greater along the parallels than along the meridians;

- 2) the vertical accuracy of one metre does not ensure good interpretation of flatlands, especially on the Baltic coast and it is also the reason why parts of the original model involve the land cover rather than the land relief as such, which is particularly important in lowlands and urbanised areas (this study used a version that largely corrected that deficiency, especially in urban areas). In reality the margin of error in Poland is slightly greater than the one metre assumed, especially in areas with greater angle of slopes (in rolling and hilly areas 2.7 m; see: Karwel & Ewiak 2006a);
- 3) some data are missing in 0.05% of the area primarily due to weather and hydrological conditions (e.g. due to the reflection of radio waves by water).

Files available in the public domain have a horizontal resolution of 3", which translates to 60-65×90 m in Poland. This level of detail not only permits accurate 3D digital terrain modelling (DEM/DTM), but also quite advanced morphometric analyses. Six years after the publication of the database in 2003, there are a large number of examples of its use, especially in on-line sources. Nearly all of these applications are of the simplest kind, such as DEMs and hypsometric maps. For example there are many, often non-commercial (freeware), applications for SRTM-3 data processing producing terrain models and interpolating contours (incl. MicroDEM, 3DEM and Landserf).

The original three-second data granularity was found unnecessarily fine for certain analyses of Poland's morphology. This was addressed by converting the body of data in two ways (Fig. 1). The first involved maintaining a relatively high level of meridional and parallel detail at 125 m. This was performed by interpolating the original NASA binary files with the 3×3" grid from 60-65 m (parallel) and 90 m (meridional) to 125×125 m. This means that the latitudinal generalisation involved a factor of two, while the longitudinal generalisation involved a factor of 1.5. The exercise produced a base of 20 million elevation points covering the territory of Poland.

The other method involved performing calculations on the said input data to give a map at a scale of 1:5,000,000. A hexagonal division was adopted for full coverage of the national territory and because the hexagon is a good approximation of a circle and thus is well suited to represent the natural environment. A primary division involved

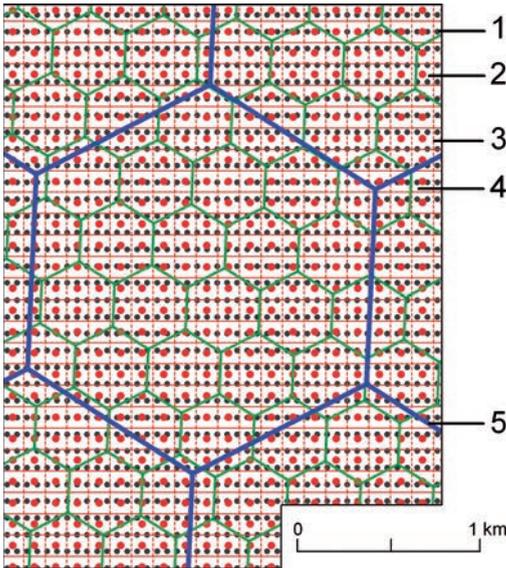


Figure 1. Transformation methods, relationships between grid points and hexagons and fields where the calculations are presented on the maps.

The area depicted is located near the points of longitude 22°12'E and latitude 54°46'N. 1 - original set of points (3×3", or 60-65×90 m; depicted in grey); 2 - grid of points 125×125 m from interpolation of data from the original set (red points); 3 - square reference fields for absolute elevation data from Figure 3; 4 - hexagons with an area of 13.81 ha within which average absolute elevations and angle of slopes calculated on the 125×125 m grid are presented (Fig. 2 and 5); 5 - hexagons with an area of 3 km² in which elevation differences and standard deviations of elevations from the 125×125 m grid were calculated and presented (Fig. 4 and 7).

hexagons with a side of length 400 m (area of 13.81 ha) where each cell contained on average 10 altitude points. A second division with a cell area of 3 km² (more than 100,000 cells within Poland) was adopted to provide a greater sample of points required by a methodology involved in the analysis of standard deviations.

The analyses were performed with various computer applications, including primarily Global Mapper 9.0 (by Global Mapper Software LLC) and Vertical Mapper (MapInfo Corporation/Pitney Bowes, Inc.). The final maps were edited using MapInfo Professional 7.8.

Morphology maps

Hypsometry map

Elevation data is typically applied in building digital elevation models (DEMs) and elevation maps.

The hypsometry map shown in Figure 2 is produced at a scale of 1:5,000,000, which is too general to represent the full level of detail available in the input database. Indeed, each millimetre on the map printed at 300 dpi contains nearly 12 pixels each representing more than 400 metres, which offer approximately 10 times less detail than in the base of points in the 125×125 m grid. For this reason Figure 3A presents a small part of the Polish territory (the Warsaw Basin) prepared with the use of the base of points in the 125×125 m grid and the method used in Figure 1 (see also detailed maps on Figure 3B-D). This shows clearly that it still has some influence on the elevation values despite filtering the terrain coverage out because, while the built environment has been nearly completely eliminated, the forests have not. On the SRTM-based map the highest point in Warsaw is only 4 meters higher than the height given on the topographic map. The boundaries of forest complexes within the Kampinos Forest are also visible, which is only partly explained by their location on overgrown dune hillocks.

As has already been mentioned, the building of a hypsometric map is the simplest application of the SRTM data. It is simply obvious that a 3D terrain model can radically shorten the time used to prepare such maps using traditional methods. In this context it is encouraging to see the potential for such mainstay morphometric analysis as the hypsographic curve and hypsographic statistics of areas such as voivodships (Tab. 1). In the calculations each elevation point from the 125×125 m grid represented an area of 0.015625 km² (1.5625 ha).

Elevation differences

In Earth surface morphometry the analysis of relative elevations is one of the most frequently used research methods. It offers answers to questions about age and development dynamics and hence maps of relative elevations are also referred to as maps of relief energy. In this particular case SRTM-3 data make it easy to derive elevation difference indicators.

The simplest of these indicators is the difference of absolute elevations within an area, which is used to develop the map of relative elevation differences. One way to perform this task is to divide an area into identical polygons (e.g. triangles) and calculate the difference between the maximum

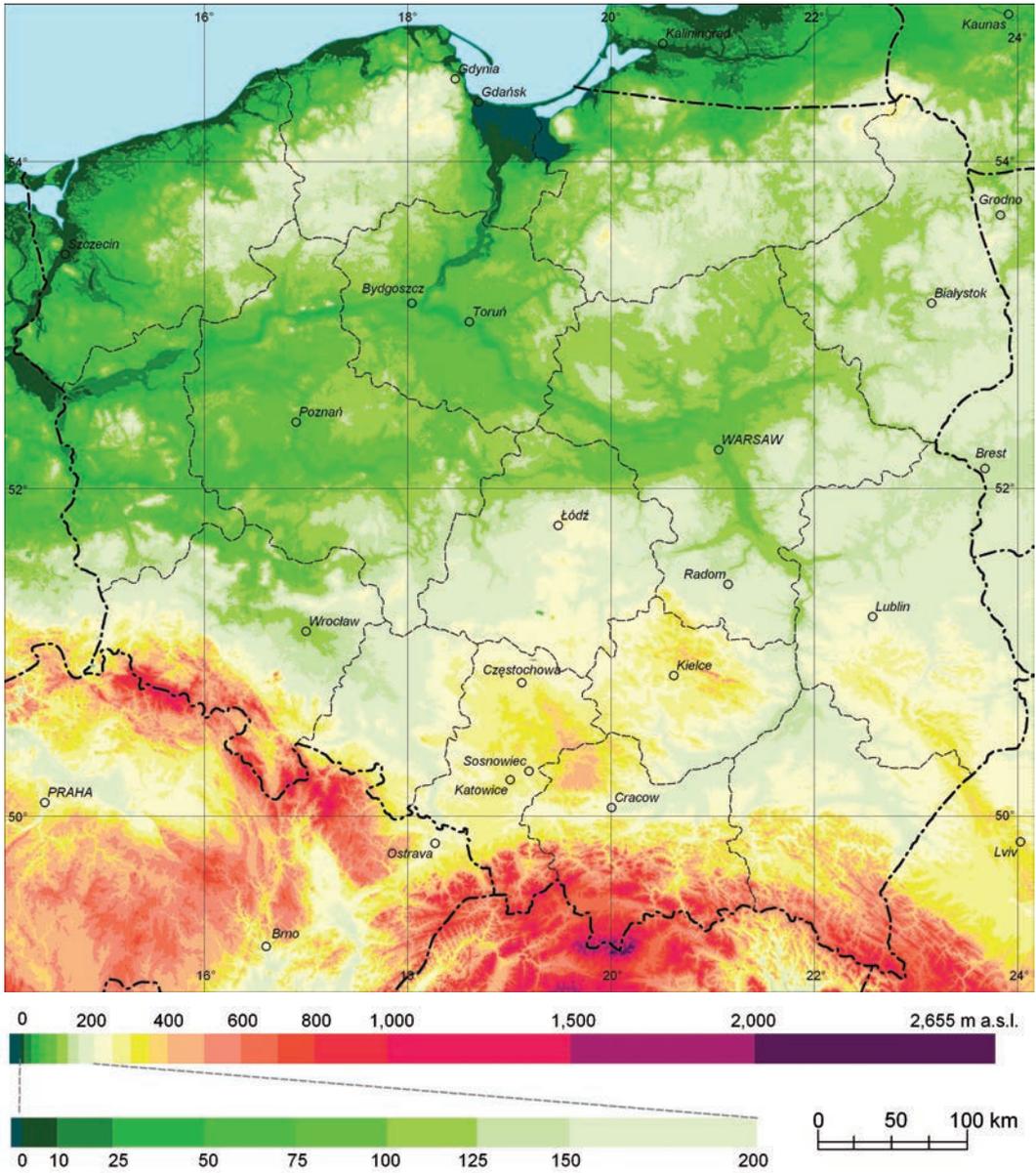


Figure 2. Hypsometric map of Poland based on the 125×125 m grid (for publication purposes the data were averaged within larger hexagons (13.81 ha). Large anthropogenic features (brown coal mine at Kleszczów near Bełchatów) and elevation discrepancies in low areas (Żuławy) are clearly seen.

and minimum elevation within them, i.e. the maximum relative elevation in that area (Fig. 4). A disadvantage of this approach is that the polygons are in a random configuration *vis-à-vis* morphological units, such as valleys or slopes. At the scale of an entire country this may be of negligible importance, but when a small area is considered it is necessary to match the polygons with types of relief. In this study the hexagonal grid was chosen

to calculate the elevation differences with each cell having an area of 3 km² (148,000 cells including 104,000 covering the area of Poland).

The overall range of elevation differences in Poland is vast, but a majority of the country's territory falls within the 10-40 m band. The map reflects well the division of the country into the basic types of physical geographical units, including lake districts, lowlands, uplands, foothills and

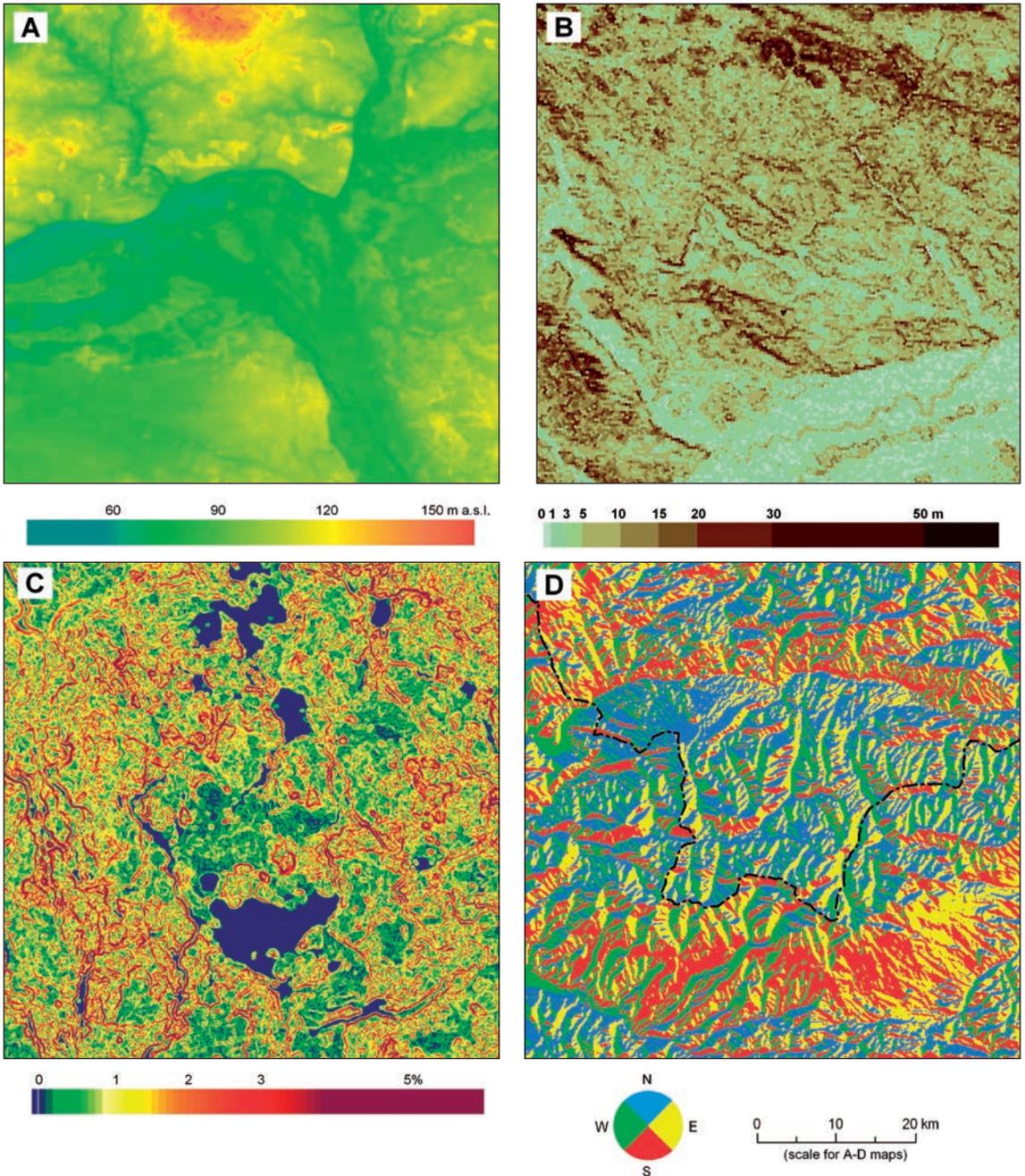


Figure 3. Relief variability maps of Poland based on the 125×125 m grid or on 13.81 ha hexagons. A - hypsometric map (Warsaw Basin, grid of points); B - map of elevation differences (Świętokrzyskie Mts. and Nida Basin based on hexagons); C - angle of slopes (part of the Mazury region, grid of points); D - slope exposure (Tatra Mts. and surroundings, grid of points).

Table 1. Hypsometric characteristics of Polish voivodships.

Voivodship	Percentage of area in altitude bands of above sea level						
	<100	100-200	200-300	300-600	600-1000	>1000	total
Dolnośląskie	8.0	50.1	17.1	18.8	5.5	0.5	100.0
Kujawsko-Pomorskie	64.7	35.3	0.0	0.0	0.0	0.0	100.0
Lubelskie	0.0	59.8	38.3	1.9	0.0	0.0	100.0
Lubuskie	72.6	27.3	0.2	0.0	0.0	0.0	100.0
Łódzkie	6.5	68.1	25.3	<0.1	0.0	0.0	100.0
Małopolskie	0.0	9.8	28.7	41.1	18.2	2.2	100.0
Mazowieckie	19.1	78.7	2.0	0.3	0.0	0.0	100.0
Opolskie	0.0	54.5	41.7	3.7	<0.1	0.0	100.0
Podkarpackie	<0.1	28.6	35.4	28.7	6.9	0.4	100.0
Podlaskie	1.1	95.8	3.1	0.0	0.0	0.0	100.0
Pomorskie	45.5	49.7	4.8	<0.1	0.0	0.0	100.0
Śląskie	0.0	2.1	66.7	24.2	6.4	0.6	100.0
Świętokrzyskie	0.0	20.2	68.8	10.9	<0.1	0.0	100.0
Warmińsko-Mazurskie	21.1	76.1	2.8	<0.1	0.0	0.0	100.0
Wielkopolskie	53.4	45.9	0.7	0.0	0.0	0.0	100.0
Zachodniopomorskie	70.9	28.8	0.3	0.0	0.0	0.0	100.0
Total of Poland	25.5	50.9	15.7	6.0	1.7	0.2	100.0
Total of Poland according to Staszewski and Uhorczak (1966; based on unpublished calculations by Zofia Rachwalska)	26.0	49.3	16.5	7.9		0.3	100.0

mountains. It offers a vivid representation of landform that permits the identification of the main directions of morphogenetic processes linked with upthrusts (Carpathian Mts.), tectonic faults (Sudety Mts.), the Pleistocene glacier (the lake districts), periglacial processes (central Polish lowlands) and Holocene-age valley erosion and accumulation (Vistula valley).

Map of angle of slopes

Angle of slope analysis involves the determination of slope directions and the maximum angles between elevation points, whether taken from a regular grid or selected as characteristic points of a landform, e.g. summit vs. valley floor. The limitation of the grid approach is that the actual landforms are covered randomly. However the high resolution of this particular grid means that it is far more likely that each landform is covered by more than one cell than that there are multiple landforms between each two points. This means that the 125×125 m grid reflects the main relief features, but filters out smaller ones.

Maps of angle of slopes are useful in a number of analyses involving slope energy, sheet flow and erosion, which make significant contributions to soil studies and landscape investigations. Maps of angle of slopes were among some of the earliest applications of GIS in geomorphology and have been known since the arrival of solutions using 3D digital terrain models. Numeric techniques reduced radically the time and labour intensity involved in making angle of slope maps with traditional contour maps. Therefore, while the map presented here represents no methodological innovation, it shows how to convert elevation data to achieve satisfactory results.

The map (Fig. 5) is supplemented by voivodship data (Tab. 2). The 125×125 m grid of elevation points also formed the base of this map as in the previous ones, but the final output was based on a small hexagonal grid with cell size of 13.81 ha. Two smaller areas were also chosen for detailed analysis (Fig. 3C and 3D). The calculations were performed with the Vertical Mapper application. The output includes not just the average angle of slope, but also its direction ranging from 0 to 360°.

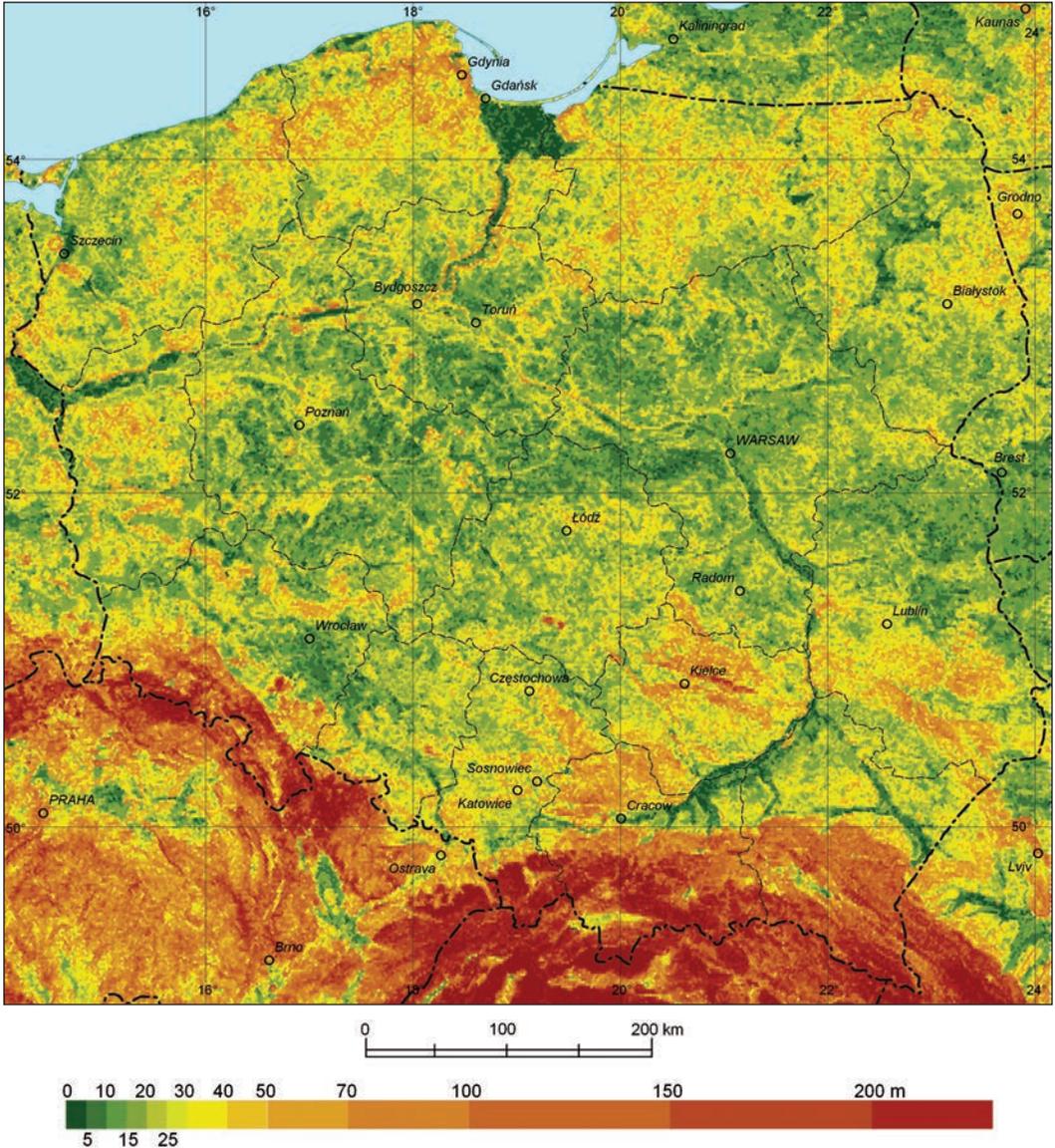


Figure 4. Map of elevation differences based on 3 km^2 hexagons and the $125 \times 125 \text{ m}$ grid.

The map of angle of slopes shares many similarities with the map of elevation differences, but the final image is far more detailed. It shows not just larger hills, but also individual dunes in the lowlands. This analysis was also overlapped with the Polish physico-geographical mesoregional division proposed by Kondracki and Richling (1994; Fig. 6). It is a fact that is generally well known that northern exposure is most frequent in Poland, but the SRTM data allow a detailed calculation of the various exposures (N, E, S, W) for any size of area.

Map of standard deviations of elevation

The availability of elevation data in a regular grid allows indices to be derived that would be impossible or very difficult to obtain using regular contour maps. The analysis of standard deviations of elevation is among the simplest, but most effective uses of a morphometric database. This measure shows the deviation from the arithmetical mean, i.e. what is the variability of all values. In other

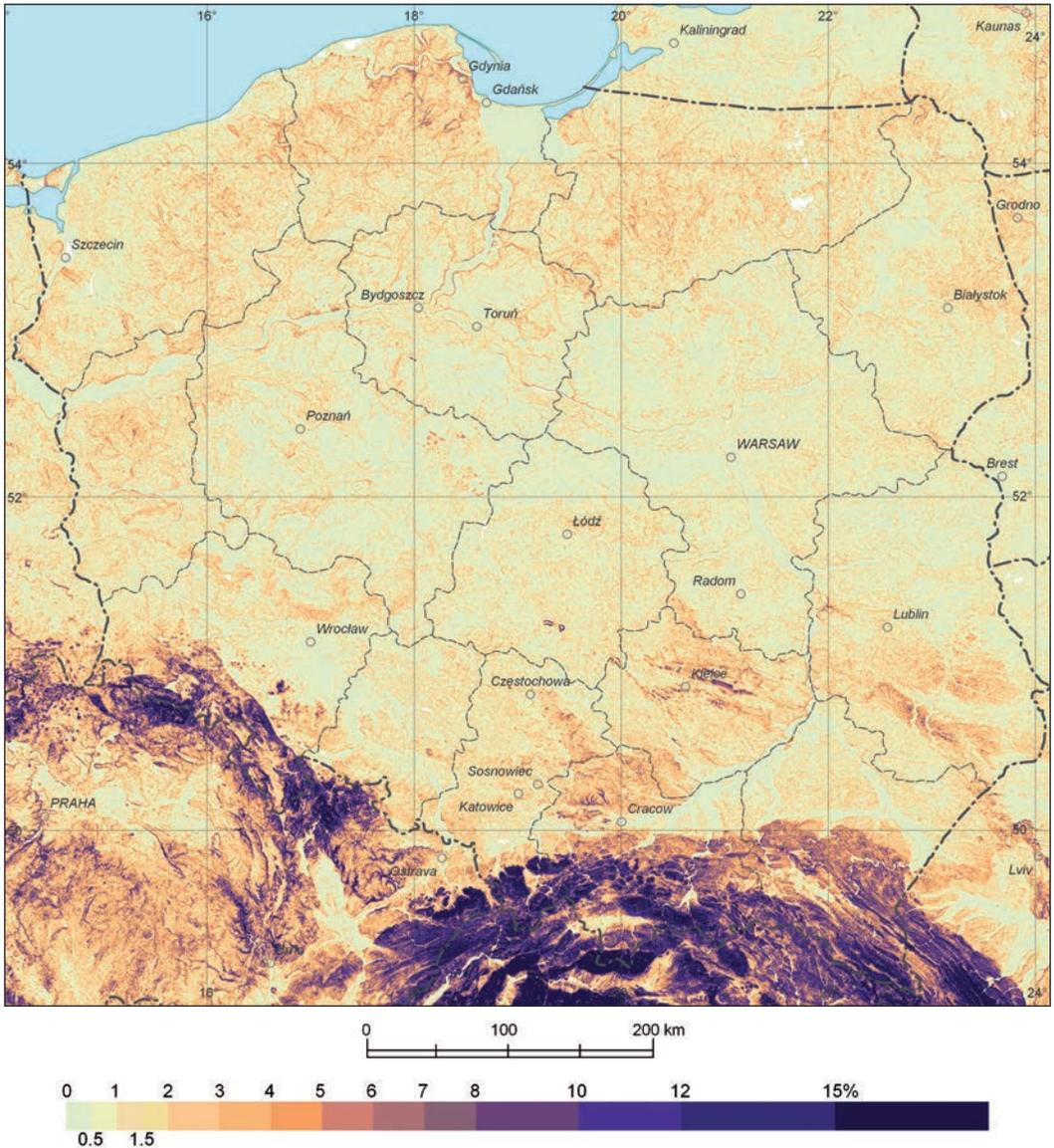


Figure 5. Map of angle of slopes based on the 125×125 m grid (for publication purposes the data were averaged in hexagons with an area of 13.81 ha).

words the standard deviation measures the distribution of all values in relation to the mean value, which gives a good description of the variability of a given data set.

The standard deviation calculations were performed on the larger 3 km² hexagonal grid (Fig. 7). There were more than 100,000 hexagons covering the territory of Poland and each contained about 100 points of the 125×125 m grid. This is the first analysis of the territory of Poland with this level of detail.

The map helps determine the patterns of regional distribution of standard deviations of absolute and relative elevations. Their value was found to range between 1 and 273 m across the grid. Interestingly, not all high values were recorded in mountains and uplands. Other regions with relatively highly varied relief included lake districts, especially the Kaszuby Lake District. The level of detail in the elevation data allowed the edge of river valleys, including that in the lower course of the Vistula River, to be distinguished.

Table 2. Angle of slope of Polish voivodships.

Voivodship	Percentage of area in angle of slope bands							total
	<1%	1-2%	2-3%	3-5%	5-7%	7-10%	>10%	
Dolnośląskie	42.8	22.6	11.3	9.3	4.2	4.0	5.8	100.0
Kujawsko-Pomorskie	65.9	22.0	7.5	3.7	0.7	0.2	<0.1	100.0
Lubelskie	54.9	27.9	10.6	5.4	1.0	0.3	0.1	100.0
Lubuskie	50.1	29.7	12.6	6.4	1.0	0.2	<0.1	100.0
Łódzkie	66.2	25.0	6.7	2.0	0.1	0.1	<0.1	100.0
Małopolskie	19.3	12.9	10.9	15.7	11.0	11.5	18.7	100.0
Mazowieckie	70.7	22.1	5.4	1.6	0.1	<0.1	<0.1	100.0
Opolskie	54.8	27.9	11.4	4.9	0.6	0.2	0.1	100.0
Podkarpackie	32.5	18.6	10.1	11.7	9.0	9.0	9.1	100.0
Podlaskie	57.3	29.7	9.0	3.6	0.3	0.1	<0.1	100.0
Pomorskie	46.2	28.6	13.4	8.8	2.2	0.7	0.1	100.0
Śląskie	36.5	30.1	13.5	7.9	2.4	2.1	7.4	100.0
Świętokrzyskie	35.3	32.6	16.7	11.2	2.6	1.1	0.3	100.0
Warmińsko-Mazurskie	46.4	31.8	13.2	7.2	1.2	0.2	<0.1	100.0
Wielkopolskie	67.9	21.3	7.4	2.9	0.4	0.1	<0.1	100.0
Zachodniopomorskie	50.4	29.7	12.1	6.4	1.1	0.2	<0.1	100.0
Total of Poland	52.8	25.6	10.2	6.1	2.0	1.5	2.0	100.0

SRTM data in human geography and applied research

Relief data might seem out of the scope of human geography, but should it extend its focus to human-nature relationships (following either the ecological or environmental paradigm), it would find SRTM-3 data offering a greater potential, especially in the area of local history and agrotechnical conditions.

Many avenues seem to open up in the areas of population and settlement geography. For example, one can analyse population distribution within areas with specific features of relief, such as specific angle of slopes or elevation differences. This type of information seems to offer more than 'anecdotal' value and may serve in various types of population analyses linked to the natural environment, settlement typology (primarily in the countryside) or in rates of population movement.

Elevation data can also be used to analyse transport. Three-dimensional terrain models have long been used for planning road and railway networks. An example is the use of SRTM-3 data in building road velocity models (Śleszyński 2009b). An index of ground relief was used as a variable influencing travel time. Road segments were classified according to their ground relief calculated

using standard deviations and elevation differences. This was based on the premise that roads in areas with more varied ground relief were less likely to follow a straight and horizontal line, reducing the average travel speed through both road traffic regulations (signposts) and more difficult driving conditions. These restrictions were assumed to be affecting local roads more than higher-grade roads, such as motorways and other dual carriageways. The model also employed a population distribution variable, i.e. population density and its absolute number within a certain radius, which influenced traffic density and therefore also speed.

Summary

The examples of applications presented here suggest that SRTM data offer great potential. Morphometric analysis in physical geography would be an obvious first choice, but there are possibilities also in a range of topics in the study of settlement, transport and spatial management in general. In classical morphometric analysis much hope is pinned on data mining and cluster analysis in general, which help discover unobvious, but very significant patterns in the variability of terrain morphometry. These in turn can help explain

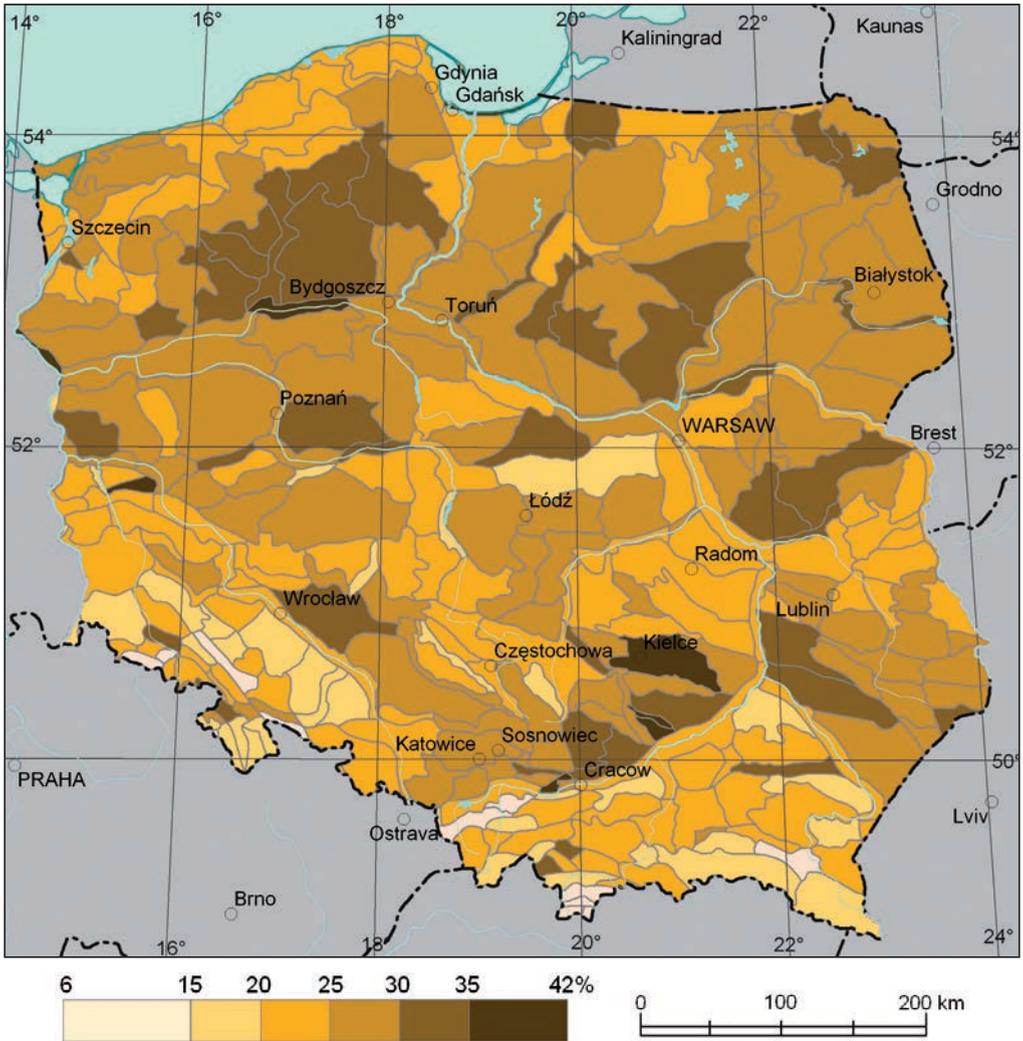


Figure 6. Proportion of southern exposure (135-225°) in the area of physico-geographical mesoregions (proposed by Kondracki & Richling 1994; based on the 125×125 m grid calculated within the borders of Poland).

morphogenetic and landscape forming processes. Interesting recent examples of such studies in Poland include Dmowska (2008) and Giętkowski and Zachwatowicz (2008), who morphometrically classified mesoregions and lower-ranking geomorphological units using DTMs (but not SRTM).

Finally, it is worth focusing attention on the advantages, disadvantages and other methodological aspects involved in the use of SRTM data from the geographer's standpoint. The data are clearly superior to earlier terrain morphometry databases. The satellite data are in the public domain and their processing for specific analytical purposes is relatively easy, effective and for basic applications requires no additional expenditure. There is

a vast range of freeware applications designed to process SRTM elevation data. The results can then be imported into GIS and other applications (a DEM file has a simple three-column structure representing the x , y coordinates and the elevation z).

The main limitation of satellite data is their accuracy, both horizontal and vertical. Horizontally the data are mostly useful down to the scale of 1:100,000-1:200,000 and smaller. This is entirely sufficient for most regional analyses. The vertical accuracy limitation is far more serious, because it rules out certain elevation-critical analyses, including flood risk analysis and watershed identification.

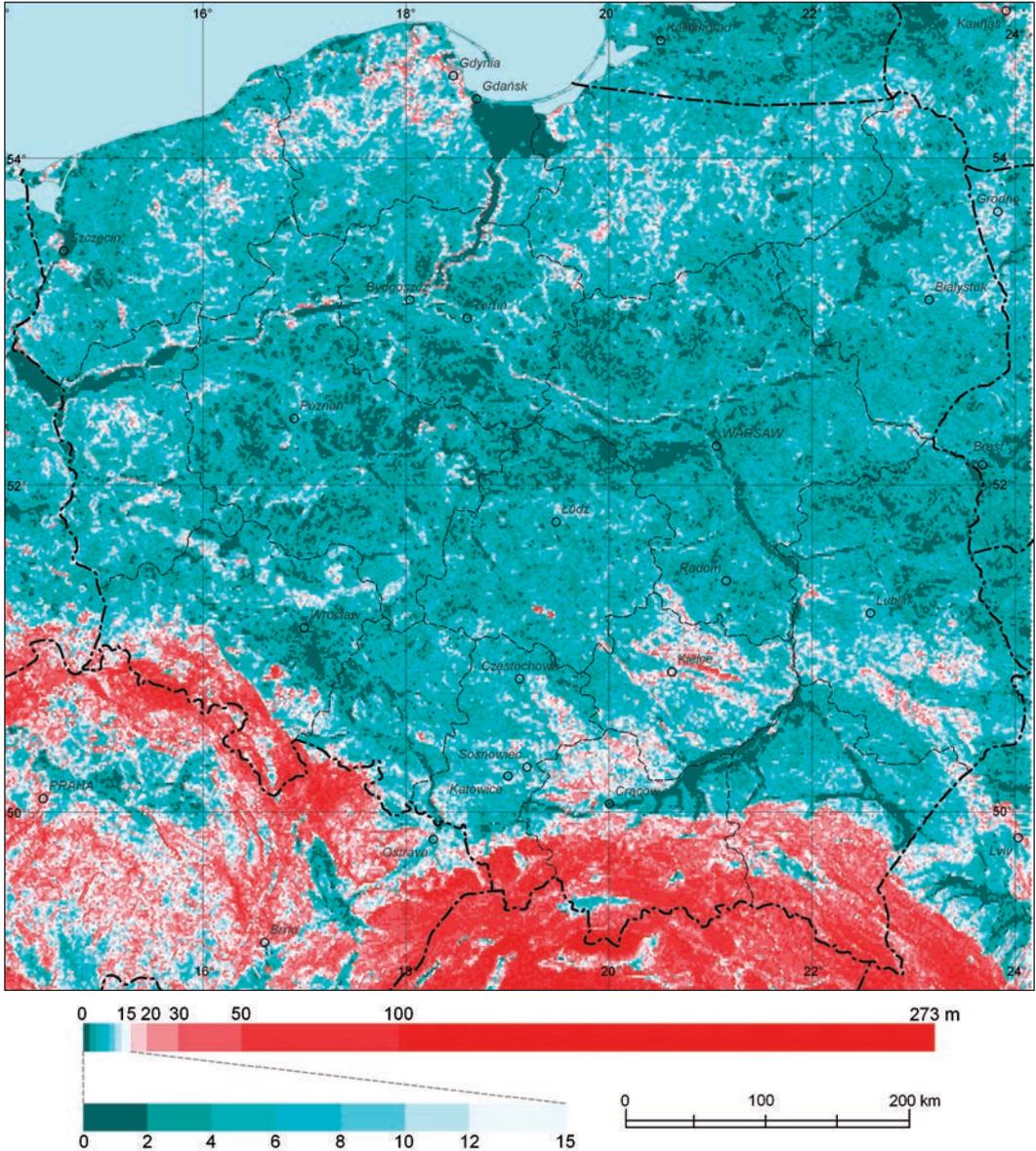


Figure 7. Map of standard deviations of elevation in Poland based on the 125×125 m grid in hexagons with an area of 3 km².

The chief methodological problem in SRTM data analysis is the selection of basic fields, especially in calculating composite indicators, such as those discussed in this paper. This, however, is a common problem in studies involving the continuity or discontinuity of geographical data, their representativeness, etc.

In conclusion, SRTM data are easily superior to traditional, extremely tedious methods of terrain

data collection in most typical applications. This gap is expected to widen as more accurate terrain databases are made available free of charge.

Editors' note:

Unless otherwise stated, the sources of tables and figures are the author(s), on the basis of their own research.

References

- BISHOP M.P., JAMES L.A., SHRODER J.F. JR., WALSH S.J., 2012. *Geospatial technologies and digital geomorphological mapping: Concepts, issues and research*. Geomorphology, vol. 137, iss. 1, pp. 5-26.
- DĘBOWSKA S., 1973. *Wysokości względne* [in:] Narodowy Atlas Polski, map sheet no. 17, scale 1:2,000,000, Warszawa: Instytut Geografii PAN.
- DMOWSKA A., 2008. *Klasyfikacja Pojezierzy Południowobałtyckich i Pojezierzy Wschodniobałtyckich w oparciu o kryterium morfometryczne* [in:] W. Florek, J. Kaczmarzyk (eds.), *Współczesne problemy geomorfologii*, Landform Analysis, vol. 9, pp. 345-347.
- DRĄGUT L., EISANK C., STRASSER T., 2011. *Local variance for multi-scale analysis in geomorphometry*. Geomorphology, vol. 130, iss. 3-4, pp. 162-172.
- EL-SHEIMY N., VALEO C., HABIB A. (eds.), 2005. *Digital terrain modeling. Acquisition, manipulation and applications*. Ser. Artech House Remote Sensing Library, Boston-London: Artech House, 257 pp.
- EVANS I.S., 1972. *General geomorphometry, derivatives of altitude and descriptive statistics* [in:] R.J. Chorley (ed.), *Spatial Analysis in Geomorphology*, London: Methuen, pp. 17-90.
- EVANS I.S., 2012. *Geomorphometry and landform mapping: What is a landform?* Geomorphology, vol. 137, iss. 1, pp. 94-106.
- GAUSS K.F., 1902. *General investigations of curved surfaces of 1827 and 1825*. Princeton: The Princeton University Library, 136 pp. [first published: Gauss K.F., 1828. *Disquisitiones generales circa superficies curvas*. Commentationes societatis regiae scientiarum Gottingensis recentiores, Commentationes classis mathematicae, vol. 6, pp. 99-146].
- GIĘTKOWSKI T., ZACHWATOWICZ M., 2008. *Klasyfikacja rzeźby w oparciu o pochodne Numerycznego Modelu Wysokości i jej potencjalne zastosowania w badaniach krajobrazowych* [in:] T.J. Chmielewski (ed.), *Struktura i funkcjonowanie systemów krajobrazowych: meta-analizy, modele, teorie i ich zastosowania*, Problemy Ekologii Krajobrazu, vol. 21, pp. 111-125.
- HENGL T., REUTER H.I. (eds.), 2009. *Geomorphometry. Concepts, Software, Applications*. Developments in Soil Science, no. 33, Amsterdam-Oxford-Boston: Elsevier, 772 pp.
- JAMES L.A., WALSH S.J., BISHOP M.P., 2012. *Geospatial technologies and geomorphological mapping*. Geomorphology, vol. 137, iss. 1, pp. 1-4.
- JĘDRYCHOWSKI I. (ed.), 2008. *Hipsometryczny atlas Krakowa*. Kraków: Biuro Planowania Przestrzennego, Urząd Miasta Krakowa, 318 pp.
- KARWEL A., EWIAK I., 2006a. *Ocena dokładności modelu SRTM na obszarze Polski*. *Archiwum Fotogrametrii, Kartografii i Teledetekcji*, vol. 16, pp. 289-296.
- KARWEL A., EWIAK I., 2006b. *Ocena przydatności danych wysokościowych z misji SRTM do generowania NMT na obszarze Polski*. *Prace Instytutu Geodezji i Kartografii*, vol. 52, no. 110, pp. 75-87.
- KASPRZAK M., TRACZYK A., 2010. *Geomorfometria granitowej części Karkonoszy* [in:] T. Kalicki, J.B. Szymańda (eds.), *Aplikacyjne metody badań geomorfologicznych*, Landform Analysis, vol. 13, pp. 33-46.
- KONDRACKI J., RICHLING A., 1994. *Regiony fizyczno-geograficzne* [in:] Atlas Rzeczypospolitej Polskiej, map sheet no. 53.3, scale 1:1,500,000, Warszawa: Główny Geodeta Kraju, Instytut Geografii i Przestrzennego Zagospodarowania PAN, Polskie Przedsiębiorstwo Wydawnictw Kartograficznych.
- KOZIEŁ Z., 1990. *Zmiany struktury kartograficznego obrazu energii rzeźby wywołane różnymi układami i nałożeniami sieci pól odniesienia*. *Polski Przegląd Kartograficzny*, vol. 22, no. 3, pp. 57-66.
- KURCZYŃSKI Z., GOTLIB D., OLSZEWSKI R., KACZYŃSKI R.M., BUTOWIT J., UCHAŃSKI J., 2007. *Numeryczny Model Terenu – podstawy, budowa i wykorzystanie* [in:] M. Kunz (ed.), *Systemy informacji geograficznej w praktyce (studium zastosowań)*, Toruń: Wydawnictwo Naukowe Uniwersytetu Mikołaja Kopernika, pp. 59-109.
- LACH J., TABOR J., ŻYCHOWSKI J., 1980. *Współczynnik rozwinięcia powierzchni jako wskaźnik syntetycznego przedstawienia rzeźby*. *Rocznik Naukowo-Dydaktyczny WSP w Krakowie*, vol. 71, *Prace Geograficzne*, no. 8, Kraków: Wyższa Szkoła Pedagogiczna, pp. 159-166.
- LI Z., ZHU Q., GOLD CH. (eds.), 2005. *Digital terrain modelling. Principles and methodology*. Boca Raton: CRC Press, 323 pp.
- MIGOŃ P., PLACEK A., ŻYSZKOWSKA W., 2009. *Steep slopes in the Sudetes and their morphotectonic interpretation*. *Geological Quarterly*, vol. 53, no. 2, pp. 219-232.
- ŁAWNICZAK R., 2003. *Próba zastosowania kartograficznej metody badań do określania morfometrycznych cech rzeźby terenu*. *Polski Przegląd Kartograficzny*, vol. 35, no. 3, pp. 191-198.
- ŁAWNICZAK R., 2008. *Morfometryczne cechy rzeźby a geneza wybranych zespołów form Polski Północno-Zachodniej*. Ser. Geografia, no. 80, Poznań: Wydawnictwo Naukowe Uniwersytetu im. Adama Mickiewicza, 129 pp.
- NITA J., MAŁOLEPSZY Z., CHYBIORZ R., 2007. *Zastosowanie numerycznego modelu terenu do wizualizacji*

- rzeźby terenu i interpretacji budowy geologicznej. *Przegląd Geologiczny*, vol. 55, no. 6, pp. 511-520.
- OŁDAK A., 1992. *Możliwości oceny widzialności krajobrazu przy zastosowaniu Geograficznych Systemów Informacyjnych* [in:] *Metody oceny środowiska przyrodniczego*, *Gea*, no. 2, Warszawa-Płock-Murzynowo: Wydawnictwa Wydziału Geografii i Studiów Regionalnych UW, pp. 37-39.
- PIKE R.J., 2000. *Geomorphometry – diversity in quantitative surface analysis*. *Progress in Physical Geography*, vol. 24, no. 1, pp. 1-20.
- PIKE R.J., 2002. *A bibliography of terrain modeling (geomorphometry), the quantitative representation of topography – Supplement 4.0*. Open-File Report 02-465, Denver: U.S. Geological Survey, <http://geopubs.wr.usgs.gov/open-file/of02-465/of02-465.pdf> [13 December 2012].
- PLACEK A., 2008. *Zastosowanie numerycznego modelu terenu w geomorfologii strukturalnej na przykładach z obszaru Sudetów* [in:] W. Florek, J. Kaczmarzyk (eds.), *Współczesne problemy geomorfologii, Landform Analysis*, vol. 9, pp. 364-368.
- RICHLING A. (ed.), 2007. *Geograficzne badania środowiska przyrodniczego*. Warszawa: Wydawnictwo Naukowe PWN, 324 pp.
- RODRIGUEZ E., MORRIS C.S., BELZ J.E., CHAPIN E.C., MARTIN J.M., DAFFER W., HENSLEY S., 2005. *An assessment of the SRTM topographic products*. *Technical Report JPL D-31639*. Pasadena: Jet Propulsion Laboratory, http://www2.jpl.nasa.gov/srtm/SRTM_D31639.pdf [13 December 2012].
- SHARY P.A., SHARAYA L.S., MITUSOV A.V., 2002. *Fundamental quantitative methods of land surface analysis*. *Geoderma*, vol. 107, iss. 1-2, pp. 1-32.
- SIWEK J., 2008. *Wpływ generalizacji na obraz rzeźby terenu* [in:] W. Żyszkowska, W. Spallek (eds.), *Analizy przestrzenne w kartografii. Głównie problemy współczesnej kartografii 2008*, Wrocław: Instytut Geografii i Rozwoju Regionalnego Uniwersytetu Wrocławskiego, pp. 63-77.
- SOBCZYK A., 2008. *Rzeźba Rudaw Janowickich i Kotliny Kamiennogórskiej w świetle danych z cyfrowego modelu terenu i badań terenowych* [in:] W. Florek, J. Kaczmarzyk (eds.), *Współczesne problemy geomorfologii, Landform Analysis*, vol. 9, pp. 377-380.
- STACHURA K., 2006. *Wykorzystanie teledetekcji satelitarnej w ocenie bioróżnorodności lasu na poziomie regionalnym: wstępne rezultaty studium pilotażowego projektu Ocena wartości biologicznej lasów w Polsce* [in:] *Sposoby rozpoznawania, oceny i monitoringu wartości przyrodniczych w polskich lasach*, *Studia* i *Materiały Centrum Edukacji Przyrodniczo-Leśnej*, vol. 8, no. 4 (14), pp. 231-241.
- STASZEWSKI J., UHORCZAK F., 1966. *Geografia fizyczna w liczbach*. Warszawa: Państwowe Wydawnictwo Naukowe, 738 pp.
- STEINHAUS S., 1947a. *O wskaźniku stromości przeciętnej*. *Przegląd Geograficzny*, vol. 21, no. 1-2, pp. 107-108.
- STEINHAUS S., 1947b. *O wskaźniku ukształcenia pionowego*. *Przegląd Geograficzny*, vol. 21, no. 1-2, pp. 113-115.
- SZAFLARSKI J., 1965. *Zarys kartografii*. Warszawa: Państwowe Przedsiębiorstwo Wydawnictw Kartograficznych, 699 pp.
- SZUBERT M., 2005. *Geostatystyczne metody rekonstrukcji rzeźby podzwartorzędowej na przykładzie Wyżyny Woźnicko-Wieluńskiej* [in:] A. Kotarba, K. Krzemień, J. Świąchowicz (eds.), *VII Zjazd Geomorfologów Polskich. Współczesna ewolucja rzeźby Polski*. Kraków: Instytut Geografii i Gospodarki Przestrzennej UJ, pp. 439-442.
- SZUMOWSKI A., 1967. *Rozwój głównych kierunków morfometrii*. *Czasopismo Geograficzne*, vol. 38, no. 1, pp. 37-55.
- ŚLESZYŃSKI P., 1998. *Mapa zasięgu widoku okolic Pińczowa*. *Polski Przegląd Kartograficzny*, vol. 30, no. 3, pp. 173-184.
- ŚLESZYŃSKI P., 2009a. *Wykorzystanie danych georadarowych SRTM-3 w analizie zróżnicowania ukształtowania terenu Polski*. *Polski Przegląd Kartograficzny*, vol. 41, no. 3, pp. 237-252.
- ŚLESZYŃSKI P., 2009b. *Zaludnienie i zróżnicowanie rzeźby terenu w modelowaniu prędkości ruchu transportu drogowym*. *Przegląd Komunikacyjny*, vol. 64, no. 5, pp. 26-32.
- WĘŻYK P., ŚWIADER A., 2004. *Wykorzystanie numerycznych modeli terenu w aplikacjach z zakresu leśnictwa i ochrony przyrody*. *Archiwum Fotogrametrii, Kartografii i Teledetekcji*, vol. 14, pp. 515-526.
- WIECZOREK M., ŻYSZKOWSKA W., 2011. *Geomorfometria – parametry morfometryczne w charakterystyce rzeźby terenu*. *Polski Przegląd Kartograficzny*, vol. 43, no. 2, pp. 130-144.
- WOJEWODA J., 2007. *Neotectonic aspect of the intrasubduction shear zone*. *Acta Geodynamica et Geomaterialia*, vol. 4, no. 4 (148), pp. 31-41.
- ZHOU Q., LESS B., TANG G. (eds.), 2008. *Advances in digital terrain analysis*. Ser. *Lecture Notes in Geoinformation and Cartography*, Berlin-Heidelberg: Springer-Verlag, 462 pp.

ZUCHIEWICZ W., 1999. *Przydatność metod morfometrycznych w ocenie tendencji neotektonicznych Karpat polskich*. Przegląd Geologiczny, vol. 47, no. 9, pp. 851-854.

ŻYSZKOWSKA W., 1978. *Zastosowanie numerycznych modeli terenu do kartometrycznej analizy rzeźby*. Acta Universitatis Wratislaviensis, vol. 340, Prace Instytutu Geografii, Ser. A, pp. 163-175.

