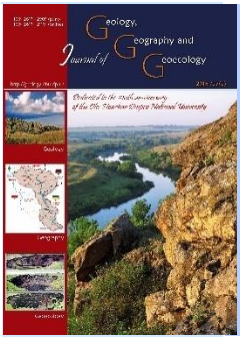

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Assessment of open source digital elevation models (SRTM-30, ASTER, ALOS) for erosion processes modeling

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Abstract. The relief has a major impact on the landscape`s hydrological, geomorphological and biological processes. Many geographic information systems used elevation data as the primary data for analysis, modeling, etc. A digital elevation model (DEM) is a modern representation of the continuous variations of relief over space in digital form. Digital Elevation Models (DEMs) are important source for prediction of soil erosion parameters. The potential of global open source DEMs (SRTM, ASTER, ALOS) and their suitability for using in modeling of erosion processes are assessed in this study. Shumsky district of Ternopil region, which is located in the Western part of Ukraine, is the area of our study. The soils of Shumsky district are adverselyaffected by erosion processes. The analysis was performed on the basis of the characteristics of the hydrological network and relief. The reference DEM was generated from the hypsographic data (contours) on the 1:50000 topographical map series compiled by production units of the Main Department of Geodesy and Cartography under the Council of Ministers. The differences between the reference DEM and open source DEMs (SRTM, ASTER and ALOS) are examined. Methods of visual detection of DEM defects, profiling, correlation, and statistics were used in the comparative analysis. This research included the analysis oferrors that occurred during the generation of DEM. The vertical accuracy of these DEMs, root mean square error (RMSE), absolute and relative errors, maximum deviation, and correlation coefficient have been calculated. Vertical accuracy of DEMs has been assessed using actual heights of the sample points. The analysis shows that SRTM and ALOS DEMs are more reliable and accurate than ASTER GDEM. The results indicate that vertical accuracy of DEMs is 7,02m, 7,12 m, 7,60 mand 8,71 m for ALOS, SRTM 30, SRTM 90 and ASTER DEMs respectively. ASTER GDEM had the highest absolute, relative and root mean square errors, the highest maximum positive and negative deviation, a large difference with reference heights, and the lowest correlation coefficient. Therefore, ASTER GDEM is the least acceptable for studying the intensity and development of erosion processes. The use of global open source DEMs, compared with the vectorization of topographic maps, greatly simplifies and accelerates the modeling of erosion processes and the assessment of the erosion risk in the administrative district.

Keywords: digital elevation model (DEM), SRTM, ASTER GDEM, ALOS

Оцінка придатності відкритих цифрових моделей рельєфу (SRTM-30, ASTER, ALOS) для моделювання ерозійних процесів

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Анотація. Рельєф має великий вплив на гідрологічні, геоморфологічні і біологічні процеси, що відбуваються в ландшафті. Тому багато геоінформаційних систем використовують його як основну інформацію для аналізу чи моделювання різних процесів.Цифрові моделі рельєфу є однією з сучасних форм представлення рельєфу. Тому метою дослідження є оцінювання потенціалу цифрових моделей рельєфу (ЦМР), зокрема SRTM, ASTER, ALOS та їх придатності для їх використання у моделюванні ерозійних процесів. Оскільки модель є відображенням реального об'єкта, системи чи поняття у певному вигляді, то їй властиві похибки. Дані ЦМР часто використовуються без кількісного визначення цих похибок. Тому дослідження передбачало аналіз похибок, які виникають при побудові ЦМР. Досліджувана територія – Шумський район Тернопільської області (Україна), ґрунтовий покрив якого зазнає негативного впливу ерозійних процесів. Виконаний на основі врахування характеристик рельєфу та гідрологічної мережі аналіз свідчить, що ЦМР SRTM і ALOS є надійнішими і точнішими, ніж ASTER. Здійснено порівняння референтної ЦМР, створеної нами в результаті векторизації рельєфу, відображеного на топографічній карті (1: 50000) з ЦМР SRTM, ASTER і ALOS. Визначено, що точність відображення висот земної поверхні за моделями становить 7,02 м, 7,12 м, 7,60 м і 8,71 м для ALOS, SRTM 30, SRTM 90 і ASTER відповідно. Найбільші абсолютну, відносну і середньоквадратичну похибки дає ЦМР ASTER, що в сукупності з іншими найгіршими показниками (найбільше максимальне додатне і від’ємне відхилення, велика різниця з референтними висотами, найменший коефіцієнт кореляції) робить цю модель найменш придатною для дослідження інтенсивності розвитку ерозійних процесів. Використання даних ЦМР, порівняно з векторизацією топографічних карт, значно спрощує і прискорює моделювання ерозійних процесів та оцінювання ризику їх прояву на території адміністративного району.

Ключові слова: цифрова модель рельєфу (ЦМР), SRTM, ASTER GDEM, ALOS

Introduction. Erosion plays main role among factors that leads to loss of soil fertility, decreasing agricultural production efficiency and causes deterioration of agroecological and hydroecological situations in conditions of erosion-hazardous relief. In Ukraine, according to The State Service for Geodesy, Cartography and Cadastre of Ukraine (Stratehiia udoskonalennia …, 2017) the area of agricultural lands affected by water erosion is 13.3 million hectares (32%), including 10.6 million hectares of arable land. In most of the Ukrainian forest steppe zone, especiallyat the West-Ukrainian and Dniester-Dnieper physiographic provinces, soil loss due to erosion reaches 31-36 t/ha per year, and sometimes exceeds 200 t/ha per year (allowable level of 4-6 t/ha per year) (Hudz et al, 2010). The erosion situation in the Ternopil region in many areas is critical and requires specialized research the potential for erosion development, as well as the extent of its detection and environmental consequences.

Relief data playan important role for assessing the intensity of soil erosion. The source of such data is topographic maps and digital elevation models (DEMs). According to the Set of Standards «Topographic Database» (SOU 742–33739540, 2010), DEM is a digital representation of spatial objects (surfaces, facets of relief) in a form of three-dimensional models that visualize a set of altitudes or depth marks and other indicators in the nodes of the triangles irregular network or as a set records of information about contour lines or other isolines. DEM is a continuous surface of altitudes, which makes possible to derive the following main morphometric characteristics: 1) relative elevation; 2) horizontal terrain roughness; 3) slopes steepness; 4) slopes aspect; 5) plan and/or profile curvature; 6) frequency and density of objects placement, etc. (Bairak, 2014). The more accurate DEM data will be better in possibility to recognize these characteristics. Remote sensing data with high accuracy (spatial resolution up to 10 meters) are still costly, which limits their use in research. Therefore, it is worth to analyze the potential of mentioned free data available. DEMs such as SRTM (Shuttle Radar Topography Mission), ALOS (Advanced Land Observation Satellite), ASTER GDEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model), are now freely available, but the choice of data for a particular project remains a difficult decision. Therefore, assessment of SRTM, ALOS and ASTER DEMs in the administrative district level is an important task.

The main aim of this paper is to analyze global open source DEMs (ALOS World 3D - 30 m v.2.1, ASTER GDEM2 and SRTM v.4.1) and their comparison to DEM obtained by vectorizing topographic maps of scale 1: 50000 into the territory of administrative district.

The study is conducted at Shumsky administrative district, it is located in the North-East of Ternopil region (West of Ukraine) (Fig. 1). Its total area is 838 km².

Most of the district belongs to the Podilian Upland, only in the extreme north the Lesser Polissia is located. The surface is characterized by elevated wavy upland, deeply dissected by valleys and ravines (Svynko, 2007). The highest areas are situated in the northwest of the district, there are the Kremenets mountains with an average heights of 340-400 m. There are 7 rivers in the study area. The largest of these are the Viliya River, which crosses the district from the west to the northeast. Viliya River is a tributary of Horyn River, which flows through Ukraine and Belarus. The valley of Viliya River has the lowest hypsometric indices, 220-240 m average. The amplitude of heights is 180 m. A significant vertical and horizontal dismemberment of the relief determine the active development of erosion processes and is an important factor used in modeling the effect of relief on erosion.

Analysis of publications. Assessments of DEMs accuracy, application for geomorphological studies, including the purpose of soil erosion modeling, have been studied over the past three decades (J.F. O'Callaghan, D.M. Mark, L.E. Band, S.K. Jenson, I.D. Moore, H. Mitasova, J. Hofierka, I.V. Florinsky, J.P. Walker and G.R. Willgoose). These results confirm that the different spatial resolution of the DEM allows obtaining the characteristics of the relief with different accuracy (Gerrard, 1971). Typically, lower spatial resolution DEM result in larger errors in reflecting the morphology of the relief, altitudes (Chang & Tsai, 1991; Gao, 1998; Kienzle, 2004). Short, steep slopes and other small local features of the relief are not shown, which results in an increase in the slopes length and the catchment area, and therefore affects the distribution and intensity of erosion development.

Fig. 1. Geographical location of Shumsky district of Ternopil region (Ukraine)

Recent studies are concerned with modeling the Earth's surface in Asia (China, India, Philippines) (Hu et al., 2017; Mondal et al., 2017; Santillan & Makinano-Santillan, 2016), Africa (Ghana, Morocco) (Bannari et al., 2018; Forkuor & Maathuis, 2018) and America (Mexico) (Courty et al., 2018), and dangerous hydrological and erosion processes were the subject of study. These studies also compare global DEM (SRTM, ASTER, and ALOS) and evaluate their accuracy.

Modeling and analysis of relief using mathematical and geoinformation tools is a rather long-standing and traditional direction of research scientists from the geomorphological scientific school of the V. N. Karazin Kharkiv National University, especial Chervanov I.H., Kostrikov S.V (Chervanov, 2012).

The use of DEMs for the modeling of water erosion in Ukraine was studied by such scientists as Dmytruk Yu.M., Cherlinka V.R. (Dmytruk, Cherlinka, 2012), Kovalchuk I.P., Mkrtchian O.S. (Kovalchuk, Mkrtchian, Lobanska, 2008; Mkrtchian, 2004, 2006).

The possibility of using DEMs in Ukraine was studied by O.O. Svitlychny, A.A. Postelnyak, M.T. Protsyk, K.V. Burshtynska, O.S. Mkrtchian, A.D. Smaliichuk, V.R. Cherlinka, V.I. Zatserkovny, D.V. Svidzinska and others. Most scientists have analyzed the applicability and accuracy of SRTM and ASTER DEMs for different parts of the territory within Ukraine (Postelniak, 2013; Smaliichuk, 2016; Svidzinska, 2014b). At the same time, there are few studies devoted to the analysis of the possibilities of the ALOS DEM, which appeared not so long ago in open access. Therefore, an important task is to approbate these DEMs for the territory of Ukraine and to determine the possibilities for their application in erosion processes modeling.

Data and methodology. All assessed DEMs (SRTM, ALOS and ASTER) are freely available after free of charge registration. After receiving the data, they were pre-processed in the open source software SAGA (System for Automated Geoscientific Analyses). All the tiles of DEMs were mosaiced and saved in GeoTIFF format and reprojected to UTM coordinate system, zone 35N, on WGS-84 ellipsoid (World Geodetic System 1984). Different filters (Simple Filter, Fill Sinks) have been used to eliminate defects (noise, artifacts, sinks). To eliminate the noise applied the Simple Filter tool, which calculates the new values of the raster cells by the formula. That mean it recalculates the value of the central cell based on the neighbor cells values (Svidzinska, 2014a). The main task of filtration of this kind is directed to maximum possible elimination of noise with the preservation of characteristic features of the relief. It was also important to make a hydrological correction, because for the

DEMs obtained by the remote sensing method a presence of false depressions is typical, this can cause significant errors, especially in assessing the redistribution of surface runoff. Therefore, the Fill Sinks tool, based on the algorithms by Planchon and Darboux (Planchon & Darboux, 2002) was applied for the hydrological correction. Corrected DEMs are more accurate and suitable for further work.

DEM of Shumsky district was created by us on the basis of vectorization of topographic maps of scale 1: 50000 using ArcMap 10.5 software by ESRI. For this study, this DEM was chosen as reference data to assess SRTM, ASTER GDEM, ALOS and the calculation of their errors.

Also, on the basis of all DEMs with ArcMap 10.5 slope maps were created. Slope steepness indicators were also used to assess the quality of DEMs and their suitability for modeling erosion processes.

Results and discussion. DEM reflects the morphology of the Earth's surface in digital form. Data of remote sensing, photogrammetric processing data, materials of satellite positioning systems, ground geodetic surveys, results of intermediate works and echo sounding, laser scanning of terrain, cartographic models, etc. can serve as information sources for DEM generation (Zatserkovnyi et al., 2017). The listed sources provide different precision of DEM. The spatial distribution and the number of errors may vary depending on the spatial resolution of image.

Depending on tasks and research details, different types of the Earth's surface mapping can be used: in form of a regular square matrix where each pixel is an elevation (GRID) or a triangulated irregular network (TIN) (Svitlychnyi, Plotnytskyi, 2006). The surface, created on the basis of TIN, is «broken». It complicates work, and in some cases (river valleys and slightly sloping relief) makes impossible to provide correct hydrological analysis (Cherlinka, 2013). The smoothed and flat forms of relief are better displayed with a regular network. Despite some disadvantages associated with the fact that the correctness of an image in a GRID model depends on the size of the raster cell, the very description of the surface in the form of a regular network is the most popular (Ivanov et al., 2014; Postelniak, 2013). The greatest advantage of GRID models is their high computational efficiency. Thus, in our study we used DEMs based on the GRID spatial data model.

Global and national models of heights are usually based on a GRID model. The GRID model is the basis of free global DEMs that we will analyze: ALOS, ASTER and SRTM. Let's consider them in more detail.

In 2000, SRTM (Shuttle Radar Topography Mission) collected data from over 80% of the Earth's surface - from 60º N to 56º S. They were processed to create global DEM with a spatial resolution of 30 m (for USA territory) and 90 m (for the rest of the territory) (Rabus et al., 2003). As a result, the most complete for that time digital topographic base of the Earth with high resolution was created. The SRTM data were downloaded from the CGIAR CSI website (SRTM …, 2018) and Earth Explorer (Earth Explorer, 2018).

The ASTER GDEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model), which appeared in 2009, is the most complete reflection of the earth's surface. The coverage of the first version of ASTER GDEM covers from 83° N to 83° S, 99% of the Earth's surface (ASTER…, 2018). Depending on the band, the ASTER GDEM has a spatial resolution of 15m, 30m and 90m, but for the territory of Shumsky district of Ternopil region data with spatial resolution of 30m were available. Data from ASTER GDEM were downloaded from Earth Explorer (Earth Explorer, 2018).

Today's newest data - the Advanced Land Observation Satellite (ALOS) Global Digital Surface Model (DSM) «ALOS World 3D-30m» from Japan Aerospace Exploration Agency (JAXA), which began operating in 2015 (ALOS …, 2018). On web-site (ALOS …, 2018) is information available for the entire Earth's surface with a spatial resolution of 30 m, which was generalized from DEM with 5-meter resolution (Tadono et al., 2014). These data became available for free in 2016. They can be obtained from the pre-registration by the link (ALOS …, 2018).

Each of the models is constantly updated and refined. So, SRTM version 3 was created in 2012 by combining SRTM and ASTER GDEM. The third version of the SRTM was improved, gaps were filled with data from ASTER GDEM2, USGS GMTED (Global Multi-Resolution Terrain Elevation Data) and USGS NED (National Elevation Dataset) (NASA …, 2018). Latest version 4.1 (SRTM …, 2018) also uses extra auxiliary DEMs to fill the voids and SRTM30 for large voids. Interpolation algorithms have also been changed. The upgraded version of the ASTER GDEM V2 adds 260000 additional stereo-pairs improving coverage and reducing the occurrence of artifacts, that degrade the model's quality. It also provides improved spatial resolution, increases horizontal and vertical accuracy, etc. (ASTER…, 2018). In the recently released version of ALOS World 3D-30m 2.1, water masks and low correlation pixels were also filled with existing DEMs (except for pixels of clouds and snow between 60º N and 60º S).

The main characteristics of the DEMs have been summarized in table 1.

Table 1. The main characteristics of global open-access DEMs (SRTM, ASTER, ALOS) (ALOS …, 2018; ASTER…, 2018; Rodriguezet al., 2005; SRTM …, 2018; Tachikawa et al., 2011; Tadono et al., 2014)

	SRTM	ASTER	ALOS
Full name of DEM	Shuttle Radar Topography Mission	Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model	Advanced Land Observation Satellite
Organization	U.S. National Aeronautics and Space Administration (NASA)	U.S. National Aeronautics and Space Administration (NASA) and Japan's Ministry of Economy, Trade, and Industry (METI)	Japan Aerospace Exploration Agency (JAXA)
Website	http://srtm.csi.cgiar.org	https://asterweb.jpl.nasa.gov	http://www.eorc.jaxa.jp/ALOS/en/index.htm
In free access from	2000	2009	2016
The latest version issued	2016	October 2011	April 2018
Last update	January 2017	October 2011	May 2018
Coverage	60º N - 56º S	83º N - 83º S	82º N - 82º S.
Spatial resolution for the study area	3'' (≈90 m) 1''(≈30 m)	1''(≈30 m)	1''(≈30 m)
Nominal vertical accuracy, m	16	17	5
Nominal horizontal accuracy, m	20	30	5

For a detailed analysis of these models fragments of the territory with a contrasting relief were selected (Fig. 2). The visual analysis of the investigated DEMs indicates that the SRTM 90 (Fig. 2b) is the most similar to the reference DEM (Fig. 2a). The mesorelief is correctly reflected on it, but the smaller features of the relief are too generalized. Resolution of SRTM 90 is much worse than in other models. This suggests that the use of SRTM in erosion research will negatively affect the accuracy of modeling of erosion. Although, in medium-scaled studies of erosion processes that spatial resolution is admissible. Therefore, for further research, the SRTM with the best resolution of 30 m was taken (SRTM 30) (Fig. 2e). At first sight, it seems that heights at the SRTM 30 are slightly lower than those of other DEMs, but further studies do not confirm this. ALOS is also quite similar to the reference DEM, but has some artifacts (Fig. 2d) that could not be removed by pre-processing. But it is noticeable while zooming that in cases of rough surface ALOS DEM shows more detail than SRTM DEM. The quality of ASTER GDEM is worse in comparison to the SRTM and ALOS DEMs. The image is very granular, contains a lot of noise and artifacts (Fig. 2c) that were not removed by filters. Because of these specifics, ASTER GDEM isolines are not similar to their configuration on the reference DEM. Nevertheless, all investigated DEMs reflected mesorelief equally well.

However, it would be wrong to assess the DEMs only visually. Therefore, further comparison was made by the use of such techniques:

1) determination of elevation errors at control points;

2) statistical analysis of the distribution of heights at these points;

3) construction of the hypsometric profile of the terrain.

Studies of precision DEMs constructed on the basis of satellite data involves calculating the statistical parameters of elevation deviations obtained from DEMs (SRTM, ASTER, ALOS) and elevations of the reference DEM. Comparison of elevations of the same point on different models allows us to determine the scale of their deviations from the real values. The obtained values were used to calculate the statistical accuracy parameters of the analyzed DEMs. It is worth to mention that the values of all DEMs' pixels are difficult to display on the map, because each DEM contains more than a million of pixels. For this reason, about 21000 points/pixels with the same coordinates were randomly selected from each DEM. On the basis of this sampling, a correlation analysis was carried out, its results are shown on Fig. 3. Using the scatter plots, the linear relationship between the elevation at the topographic maps and the elevation values displayed on the SRTM, ASTER, and ALOS

DEMs, respectively, may be observed. In general, all correlation coefficient values are greater than 0.95, which indicates a close direct linear relationship between the elevations on the reference DEM and the assessed DEMs. Nevertheless, linear relationship is strongest between the reference values and heights of the ALOS (0,976) (Table 3).

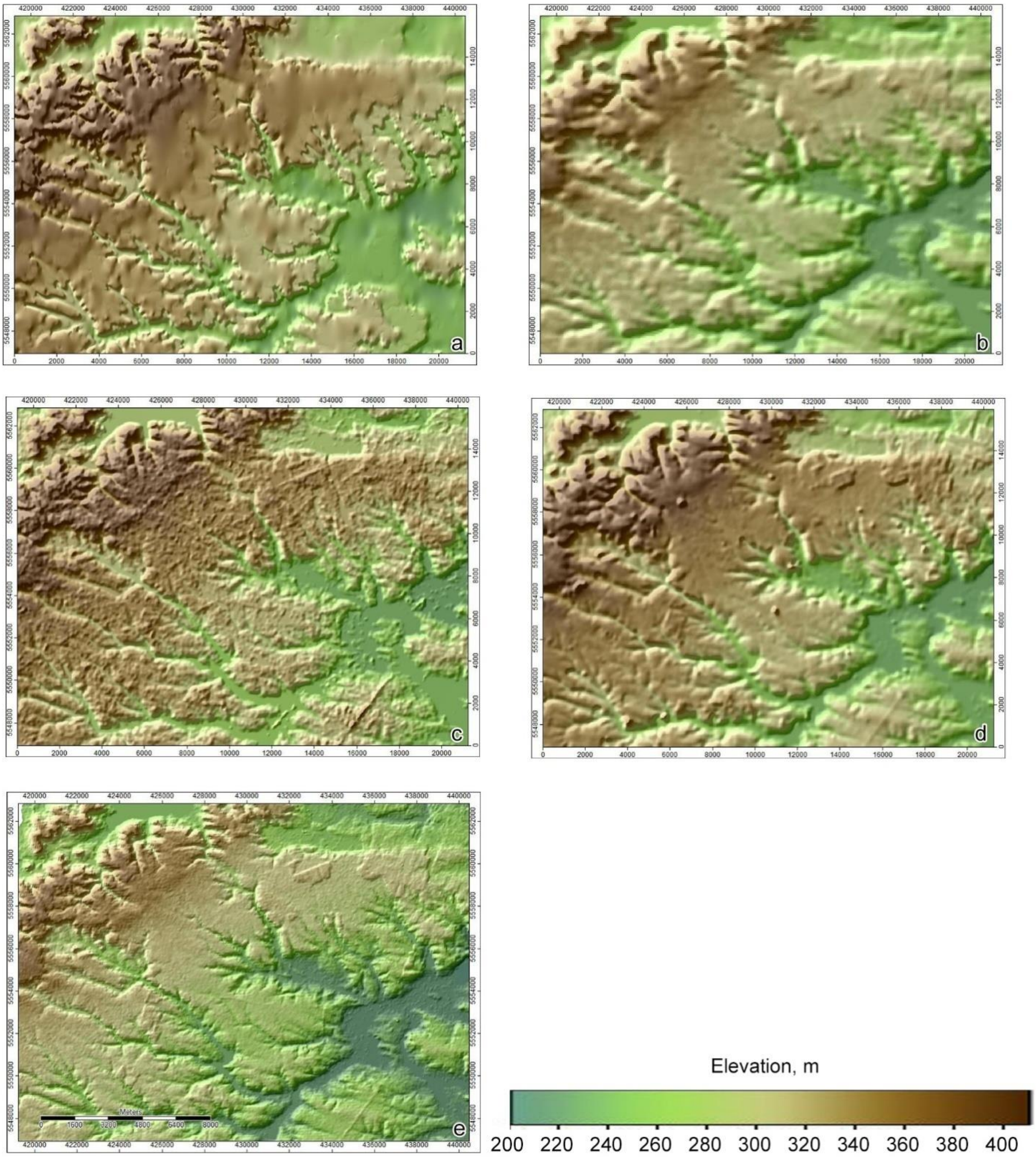

Fig. 2. Fragment of the DEM of Shumsky district, obtained from: a - vectorized topographic map, b – SRTM 90, c - ASTER, d – ALOS, e – SRTM 30.

Further assessment of the accuracy of the investigated DEMs involved statistical analysis of elevations and steepness of slope. Tables 2 and 3 present comparative statistics for DEMs. The results showed, that the maximum elevation values for all DEMs were larger and exceeded reference values of 12,43 m , 8,56 m, 27,34 m, 11,07 m, and the minimum heights were lower (4,89 m, 2,78 m, 30,35 m, 4,60 m) in SRTM 30, SRTM 90, ASTER and ALOS DEMs respectively. The largest amplitude of the difference in absolute heights was found in the ASTER GDEM (160,75 m). The average altitudes are not very different, however, the largest difference with the reference values was of the ASTER GDEM (1,6 m).

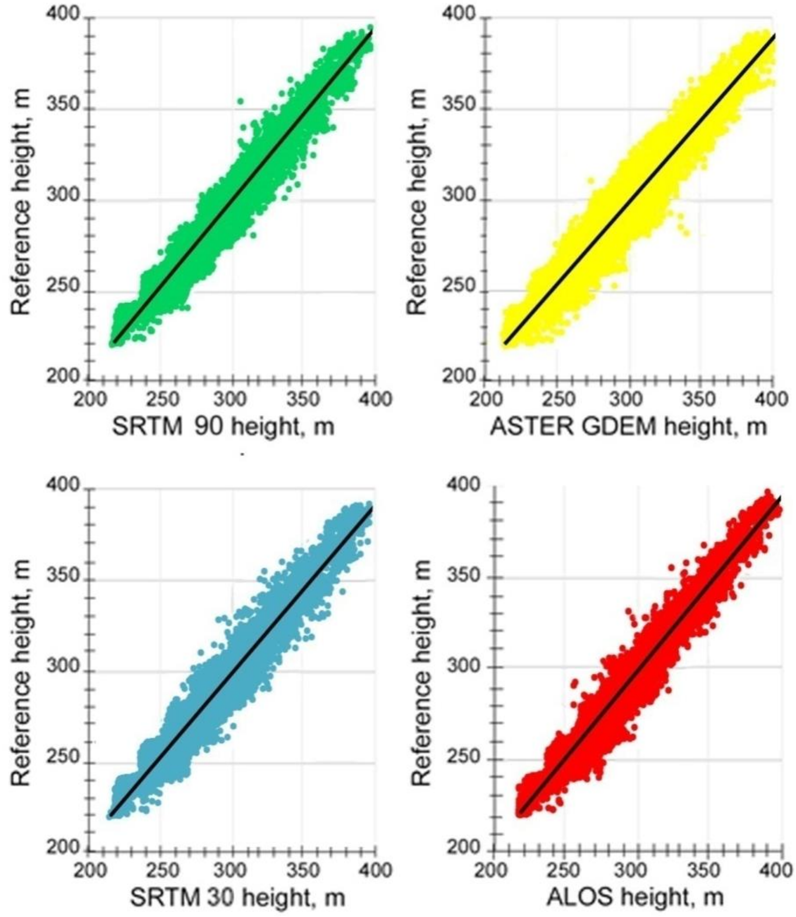

Fig. 3. Scatter plots of the points elevation values for models: a- SRTM 90, b- ASTER, c- SRTM 30, d – ALOS in relation to the reference DEM.

As for the steepness of the slopes, the situation is as follows. All the minimum values obtained from the investigated DEM are close to zero. But all the maximum values of slopes steepness are greater than the referent value. The closest to referent value is the value from SRTM 90. The average values of slopes steepness also exceed the reference value. The average value from SRTM 90 is the nearest to the reference value.The average value from SRTM 30 is higher than the referent value more than twice.

In general, SRTM 90 is the most close to the reference DEM for all the indicators. But most likely, that such "proximity" is achieved due to the same degree of generalization of SRTM 90 and a series of maps of scale 1: 50000, which taken as the basis of reference DEM. Therefore, more attention should be paid to DEM, which is the most different from the reference and this is ASTER GDEM.

Table 2. Characteristics of the relief of Shumsky district, obtained as a result of DEMs analysis

Indices of heights of the Shumsk district	The parameters of relief obtained as a result of the DEMs analysis				
	SRTM 30	SRTM 90	ASTER	ALOS	Reference
Maximum height, m	408,46	404,59	423,37	407,1	396,03
Minimum height, m	213,30	215,41	187,84	213,59	218,19
Average height, m	285,98	285,98	283,94	286,19	285,84
Maximum steepness of the slopes, °	40,85	14,68	34,38	24,80	13,25
Minimum steepness of the slopes, °	$9,24 * 10^{-5}$	$3,50 * 10^{-5}$	$2,99 * 10^{-5}$	$8,52 * 10^{-5}$	$6,30 * 10^{-5}$
Average steepness of the slopes, °	3,63	1,83	2,9	2,49	1,67

Table 3 shows the accuracy of the assessed DEMs. As can be seen in Table 3, the largest most positive and most negative deviations from the reference values are given by the ASTER GDEM (68,74 m and -45,27 m, respectively). The absolute errors of elevation of SRTM 30, SRTM 90 and ALOS DEMs are small (± 0,14 m, ± 0,14 m and ± 0,35 m, respectively). The absolute error of ASTER GDEM is greater (± 1,90 m). The relative error of the SRTM 30, SRTM 90 altitudes is the smallest

(0,05%), which is almost the same in ALOS (0,12%). The highest relative error is calculated in ASTER GDEM (0,67%).

The most commonly used techniques for investigating the relationship between assessed DEMs and reference DEM are calculation of correlation and determination coefficients. It is known, that the closer these coefficients to 1, the closer the relationship. Therefore, in general, all investigated DEMs have a close correlation with the reference DEM, since the correlation coefficient is greater than 0,96 and the determination is greater than 0,93. The highest values of the coefficients in the ALOS are 0,976 and 0,95 respectively.

Table 3. The calculated errors of heights of the analyzed DEMs

Errors of the elevation of the Shumsky District	The values of the elevation errors obtained as a result of the analysis of the investigated DEMs			
	SRTM 30	SRTM 90	ASTER	ALOS
Maximum positive deviation, m	49,89	48,00	68,74	38,33
Maximum negative deviation, m	-40,10	-50,63	-45,27	-40,04
Absolute error, m	±0,14	±0,14	±1,90	±0,35
Relative error,%	0,05	0,05	0,67	0,12
RMSE, m	7,60	7,12	8,71	7,02
Correlation coefficient	0,973	0,974	0,964	0,976
Coefficient of determination	0,94	0,95	0,93	0,95

It is worth noting also, that the elevation values of the study area taken from SRTM and ASTER DEMs correspond to the vertical accuracy of 16 m and 17 m, respectively, established in previous studies (Chang & Tsai, 1991;Fujisada et al., 2005; Tachikawa et al., 2011) and information from official sites of these DEMs (ASTER…, 2018; Rodriguez et al., 2005; SRTM …, 2018). SRTM 30 and SRTM 90 had a higher vertical accuracy (in terms of RMSE) than ASTER GDEM (7,60 m and 7,12 m compared to 8,71 m). The official site (ALOS …, 2018; Tadono et al., 2014) states that ALOS vertical accuracy is about 5 m, and in the recent study (Bayik et al., 2018) a value of 1,78 m was received. However, for the territory assessed, vertical accuracy of ALOS is slightly worse (7,02 m), which is still the best result among other DEMs assessed.It should be noted that the reference DEM also has its own indicators of accuracy. According to the "Osnovni ..." (Dohtiar, Protasov & Protsenko, 1999), for maps of the given scale of 1: 50000 for plain, crossed and hilly regions with prevailing slopes of the area to 6 ° the average errors for heights can reach 4 m. But when we created DEM from maps, than accuracy deteriorated.

A further analysis of DEM involves the comparison of hypsometric profiles in two directions, which are best reflect the diversity of relief forms for the study area: from north to south and from west to east (Fig. 4). It was found that the mean ASTER GDEM elevations are lower than the reference DEM elevations, while SRTM and ALOS elevations were higher. The obtained results confirm previous statistical calculations (tables 2, 3). The ASTER GDEM elevation varies with great amplitude and often does not reflect actual changes in elevation. Although ASTER GDEM elevations on the profile (Fig. 4) are lower than at the reference DEM (with a maximum deviation of 15 m) at the highest points of the profile, the values of ASTER GDEM exceed the values of reference DEM by 15-30 m. It was found that the closest to the reference elevations are values from ALOS and SRTM DEMs. The maximum deviation was 10-15 m. That is, the value of the overestimation in SRTM and ALOS DEMs is less than ASTER GDEM underestimation value. This again confirms that SRTM and ALOS DEMs have an accuracy higher than ASTER GDEM.

Based on the analysis, it was found that among three assessed DEMs of Shumsky district, ALOS DEM was the most accurate in reflecting the absolute altitudes of the Earth's surface, since this DEM has the smallest root mean square error, the best correlation with the reference DEM and the best detailing of the Earth's surface. Also, the slope steepness values obtained from the ALOS DEM have some of the smallest deviations from the reference values. Therefore, it is perfect for detailed study of the distribution and development of erosion processes and their modeling.SRTM 90 has the values of heights and slopes steepness nearest to the reference values. However, SRTM 90 has the worst spatial resolution among investigated DEMs, which leads to a generalization of the characteristic features of the relief, and makes this DEM unsuitable for further modeling of erosion processes at the district level. SRTM 30 with better resolution has slightly worse indicators but better detail. In addition, values of slope steepness obtained from SRTM 30 are the highest among other DEMs and are overestimated. Both SRTM 30 and 90 have the lowest absolute and relative error values. ASTER GDEM was the worst DEM in analysis, and it did not meet the needs of our modeling.

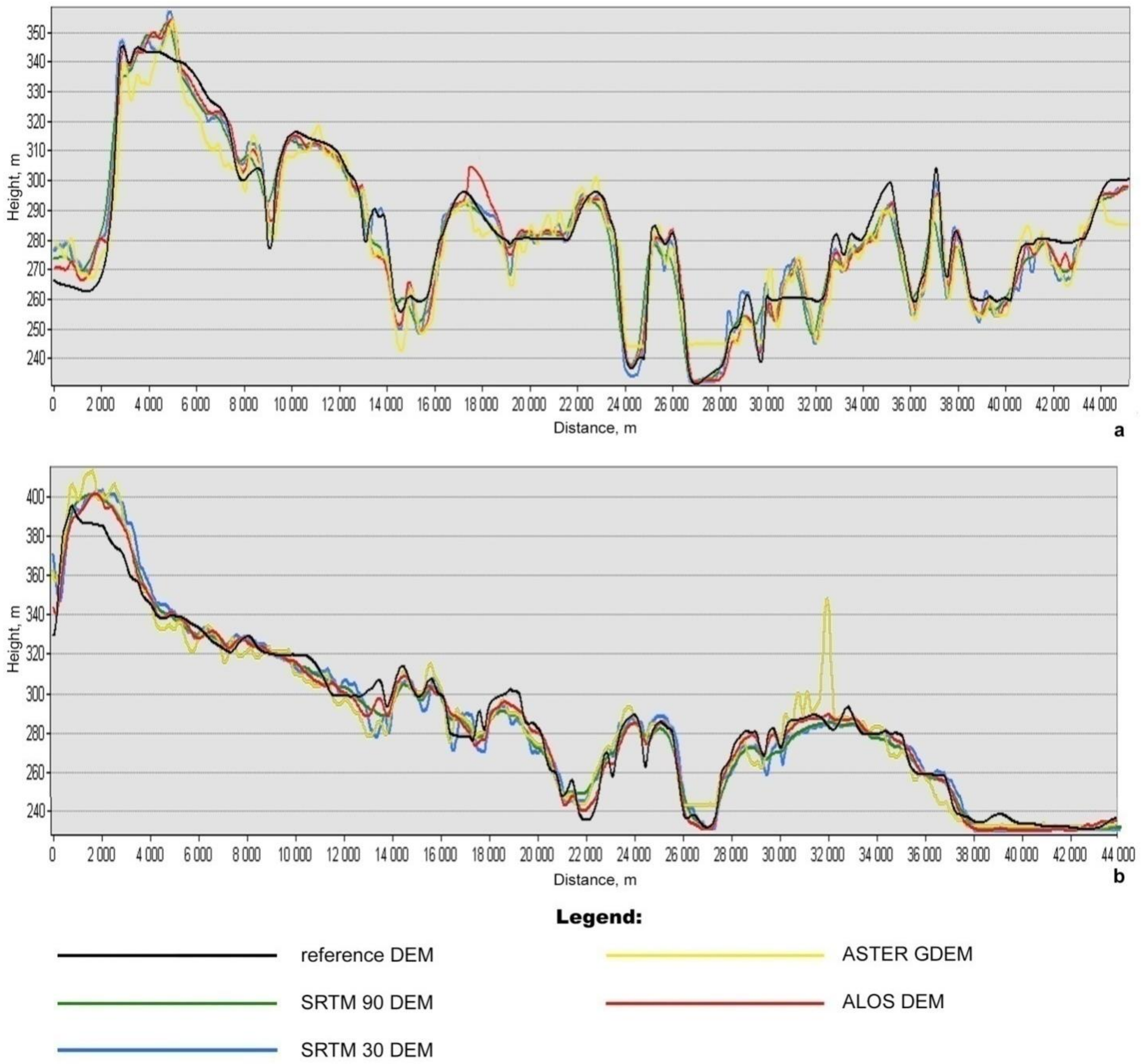

Fig. 4. Hypsometric profiles of the Shumsky district, which reflect the complexity of the relief on various DEMs: a - from north to south; b - from west to east

Conclusions. This study analyzed four global DEMs - SRTM 30, SRTM 90, ASTER, ALOS, and compared them to reference DEM. The reference DEM is created by vectorizing topographic map of scale 1: 50000. In the comparison methods of visual detection of DEM defects, computation of statistics, profiling, correlation were used.

The obtained results have confirmed vertical accuracy for SRTM and ASTER DEMs. The SRTM 30, SRTM 90, and ASTER DEMs for the study area have vertical accuracy of 7,60 m, 7,12 m and 8,71 m, respectively. The vertical accuracy of ALOS DEM is slightly different from the declared values (5.00 m) and was 7,02 m, however that's the best value among the assessed DEMs.

Furthermore, ALOS, SRTM 30, SRTM 90 DEMs a little bit overestimates the height, which may be due to the fact that they record the reflecting surface and, therefore, may be prone to overstatement in areas of distribution of woody plants. In ASTER GDEM the heights changes with a large amplitude (even after pre-processing), which adversely affects the correctness of the modeling.

ALOS DEM is the most accurate in reflecting the absolute altitudes of the Earth's surface, because it contains the smallest root mean square error.SRTM 90 was also similar to the reference DEM. However, analysis show that SRTM 90 cannot be applied for modeling of erosion processes in district level, because its spatial resolution is not acceptable. SRTM 90 will be more appropriate for a smaller scaled area. SRTM 30, as well as SRTM 90, has the lowest absolute and relative errors, but the values of slope steepness are overestimated, and its can be negative effects on modeling of erosion processes. The worst was ASTER GDEM.

Still, all assessed DEMs are useful and are a good substitute for DEMs, created on the basis of topographic maps of 1: 50000 scale. Getting and preparing for the use of open sources DEMs takes less time than vectorization of topographic maps and their further processing. The availability of high-resolution DEM in open access and further improvement of their processing algorithms will promote their more active use in multidisciplinary research, including modeling of erosion processes. In further research, the derivatives of the DEMs maps will be created (slope steepness, exposure, length, shape of the slope). Also the influence of other factors on modeling of erosion processes is considered in more detail.

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