Accuracy of SRTM-X and ASTER Elevation Data and its Influence on Topographical and Hydrological Modeling: Case Study of the Pieniny Mts. in Poland

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Abstract

Satellite sensors provide currently reliable elevation data over large areas, with spatial resolutions below 100 m and reported accuracies of approximately 10 m. However, the vertical accuracy of these quasi-global digital elevation models (DEM) varies depending on the terrain and land cover, decreasing in mountain areas, and may influence the quality of products derived from these data, like stream channel network or relief forms. In this paper, we investigated two global elevation data sets: SRTM-X DEM and ASTER GDEM, assessing their vertical accuracy and reliability of terrain features extracted automatically from the elevation data. The research was carried out in the Pieniny Mts., a small mountain range in southern Poland, with elevations ranging from about 400 m to 1000 m a.s.l. One particular attribute of this mountain range that may create several problems in deriving accurate terrain features is a deep, narrow and windy gorge of the Dunajec river. We found that the vertical accuracy of SRTM-X DEM is significantly better than of the ASTER GDEM (Root Mean Square errors of 12.05 m and 17.43 m, respectively). Both DEMs allow to extract terrain features with a similar accuracy in areas of moderately steep and gentle slopes, yet fail to properly represent the floor of the Dunajec gorge as relative vertical errors along the river may exceed 100 m. Therefore, we conclude that while both models provide statistically reliable description of the terrain surface, they require additional corrections for hydrological or terrain modeling.

1. Introduction

Satellite sensors provide currently reliable elevation data over large areas, with spatial resolutions below 100 m and reported vertical accuracies of 10-20 m. Examples of widely used elevation data sets are Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM; ASTER, GDEM Validation Team, 2009) and Shuttle Radar Topography Mission (SRTM) digital elevation models (Wagner, 2003 and Rodriguez et al., 2005) (Table 1). The ASTER instruments were designed and built by Ministry of Economy, Trade, and Industry (METI) of Japan and launched on board of US National Aeronautics and Space Administration (NASA) TERRA spacecraft in 1999. Elevation data were received from stereo pairs acquired from nadir and backward looking sensors located on the satellites, in three spectral bands, from visible to near-infrared wavelengths. The first version of ASTER GDEM was made available to the public in 2009 (ASTER GDEM Validation Team, 2011). The elevation data cover land surface between 83°N and 83°S latitudes and are available as 1° by 1° tiles in the GeoTIFF file format, with a resolution of 1 arc second. The SRTM was a cooperative effort between NASA, National Geospatial-Intelligence Agency (NGA), Agenzia Spaziale Italiana (ASI) as well as Deutsches Zentrum für Luft und Raumfahrt (DLR). The space shuttle Endeavour with the set of SIR-C/X-SAR (Shuttle Imaging Radar - type C / X-band Synthetic Aperture Radar) collected data in three microwave bands (L, C and X) in February 2000 (Rabus et al., 2003, Farr et al., 2005 and Jarvis et al., 2008). The X-SAR instrument collected data with higher resolution (1 arc second), but with reduced coverage, allowing to build the SRTM X-band digital elevation model (SRTM-X DEM) based entirely on finer X-band data. It has been made available through the FTP service of DLR / ASI since 2010 (DLR, 2010).

Table 1: Characteristics of ASTER GDEM and SRTM-X DEM

	ASTER GDEM ver. 2*	**SRTM-X DEM DLR/ASI****
Data supplier	METI/NASA	NASA/NGA/DLR/ASI
Version and acquisition date	ver. 2, 2011	ver. 1, 2011
Period of data collection	2000-2010	11 days in 2000
Acquisition technics	stereo pairs, visible and near infrared	radar interferometry
Main distortion factor	clouds	radar shadows and echo
Datum (horizontal)	WGS1984	WGS1984
Datum (vertical)	EGM96 geoid	WGS1984 ellipsoid
Horizontal resolution	1 arc second	1 arc second
Horizontal accuracy	±30 m (abs.) 95% Circular Error (CE)	±20 m (abs.) 90% CE
Vertical accuracy	±20 m (abs.) 95% Linear Error (LE)	±16 m (abs.) 90% LE
Data format	GeoTIFF, 16-bit signed integer	DTED-2, 16-bit signed integer

*ASTER GDEM Validation Team, 2009; 2011

**Wagner, 2003; DLR, 2010

Several studies investigated the vertical accuracy of both elevation data sets, comparing them to elevation data from various sources: stereo-pairs (Nikolakopoulos et al., 2006), elevation data obtained from national resources (Ludwig and Schneider, 2006 and Frey and Paul, 2012) or field measurements (Gorokhovich and Vostianiouk, 2006). This studies prove that the vertical accuracy of global elevation data depends on the terrain and land cover, decreasing especially in rugged mountain areas of high terrain complexity (Gorokhovich and Vostianiouk, 2006, Hoffmann and Walter, 2006, Ludwig and Schneider, 2006, Hirt et al., 2010, Jacobsen and Passini, 2010, Mouratidis et al., 2010 and Frey and Paul, 2012). Vertical errors of DEMs propagate into various derived products, like slope gradients, aspects, stream channel network or relief forms, and may cause unexpected artifacts putting into question the usefulness of these data for further analysis. Several studies have tackled this question, showing that terrain attributes are sensitive to DEM accuracy and cell size (Bolstad and Stowe, 1994, Thompson et al., 2001, Erskine et al., 2007, Jacobsen and Passini, 2010 and Grohmann and Sawakuchi, 2012), however, knowledge on the accuracy of terrain feature extraction from these two relatively new DEMs: ASTER GDEM and SRTM-X DEM is limited. Therefore, in this paper we aimed to investigate various aspects of accuracy of SRTM-X DEM and ASTER GDEM. The study was carried out in a small mountain range in Poland with an extremely rugged relief. We assessed vertical accuracy of both data sets using standard error measures, and proposed various means to estimate reliability of terrain features extracted automatically from the elevation data.

2. Methods

2.1 Study Area

The study was confined to the section of the Pieniny Mountains in Poland within the boundaries of the Pieniny National Park (PPN, Figure 1). Although the elevation in the PPN does not exceed 1,000 m (Trzy Korony 982 m a.s.l.), this section of the Pieniny range belongs to one of the most spectacular mountain sites in Poland due to the gorge of the Dunajec river which cuts through its very middle (Figure 1, Supplement, Annex 1). The relative elevations around the Dunajec gorge reach up to 500 m, its walls are in some places extremely steep, and the course of the river is winding, resulting in serious difficulties in proper estimation of elevation for any aerial data acquisition technology.

2.2 Elevation Data Sets and their Preparation

2.2.1 SRTM-X and ASTER GDEM data

For this study, SRTM-X DEM data file (E0201500N491500_SRTM_1_DEM.dt2) was downloaded from the website https://centaurus.caf.dlr.de:8443. The data are stored in DTED format, in geographic coordinate system (WGS 84) and WGS 84 vertical datum. ASTER GDEM data set (ASTGTM2_N49E020_dem.tif) in version 2 released in 2011 was obtained from the website http://reverb.echo.nasa.gov/reverb. This version was improved with respect to the previous one due to better data processing algorithm and additional data used during the processing. However, the revised version still contains anomalies and artifacts which are particularly important in local studies (ASTER GDEM Validation Team, 2009). Data are in geographic coordinate system (WGS 84) with EGM 96 vertical datum.

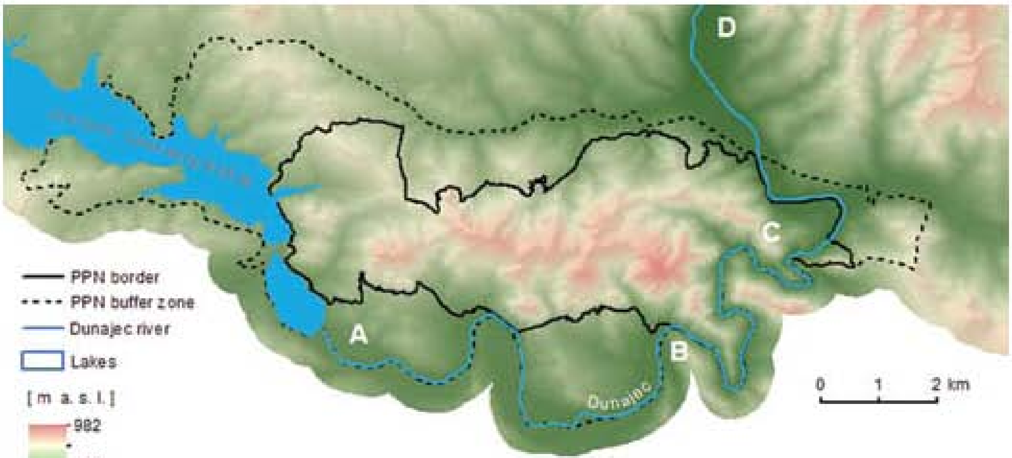


Figure 1: Study area

Both models have no voids in the study area, nevertheless the quality of elevation data differs significantly and degrades in the most rugged part of the Pieniny Mts. and over the water bodies (Supplement, Annex 2). As in the study area the average undulation of the EGM 96 datum in relation to the WGS 84 datum equals 40.46 m (based on the reference point values and tests done with datum convertors, e.g., EGM 96 GeoidCalculator by National Geospatial Intelligence Agency, http://earthinfo.nga.mil/GandG/wgs84/gravitymod/-egm96/intpt.html), elevations of the SRTM-X DEM were recalculated by subtracting an integer value of 40 m. Both models were then resampled to the Polish co-ordinate system '1992' using the nearest neighbor method and output resolution of 20 m, and clipped finally to the extent of the study area.

2.2.2 Reference data sets

Digitizing elevation data from topographic maps was often used in the past to create digital elevation models (Arrighi and Soille, 1999 and Urbański, 2011). Due to the unavailability of Airborne Laser Scanning (ALS) data, for this study the reference data were extracted from the Polish topographic maps in 1:10,000 scales. These maps were made in national planar coordinate system "1992" based on the "Kronsztad 86" vertical reference system. First, height values from the primary geodetic horizontal network were digitized. They have the average position error of ±0.1 mm at the map scale that is ±1 m (GUGiK, 1987). In addition, height values from the supplemental geodetic vertical network were used. Their positional accuracy may vary from ±0.5 mm to ±0.75 mm. As the failure to read the position of points on the map is about 0.5 mm (Longley et al., 2008), the total horizontal error for the reference points should not exceed 9 m. The vertical precision of elevation for the reference points is 0.1 m. For the study area, a total of 278 ground control points were acquired, most of them represented the primary geodetic horizontal network. These points were later considered as the reference point data set. The topographic maps were used also to compute a high-resolution reference DEM for the study area. In addition to geodetic points, contour lines with an interval of 2.5 m, height spots placed on characteristic terrain forms, discontinuities and water lines were vectorized from the topographic maps. As the density of contours was high, and their positional error as compared to ground control points should not exceed two thirds of the contour interval for slopes higher than 20º (GUGiK, 1980), the accuracy of the reference DEM should be higher than that of SRTM-X DEM and ASTER GDEM. In addition, the model is supposed to accurately represent river and ridge networks, hence providing a sound reference for the topographical and hydrological modeling. All elevation data vectorized from the maps were interpolated to a Triangulated Irregular Network (TIN) model and then converted into a regular grid with 10 m cell size to retain all details of the surface, using a natural neighbor method, and finally resampled to 20 m using nearest neighbor assignment to allow a direct comparison with SRTM-X DEM and ASTER GDEM. This reference elevation model was later referred to as TopoDEM. In order to assess results of hydrological modeling, the stream network (rivers, streams and creeks) was also vectorized from the same 1:10,000 maps. The actual position of streams was confirmed with orthorectified airborne imagery.

2.3 Accuracy Assessment

Accuracy assessment started with the analysis of mean error (equation 1) and root mean square errors (equation 2) of both data sets using the reference point data set:

$$ME = \frac{\sum_{i=1}^{n}(x_i - h_i)}{n}$$

Equation 1

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_i - h_i)^2}{n}}$$

Equation 2

Where x_i denotes elevation measured at DEM being evaluated, and h_i is the reference elevation, at point i. River network was generated on both DEMs using standard ArcGIS tools (hydrological modeling). First, sinks were filled, then flow accumulation network was computed based on the flow direction raster, finally, streams were delineated. Distances between vertices of computed river features and the reference stream line digitized from topographic maps (points to line distances) were calculated only for the Dunajec river; distance discrepancies for other streams were evaluated visually. As for the Dunajec river, the vector line digitized from the topographic maps was used also to generate vertical profiles along the river course and to calculate the vertical errors along the river. Elevation anomalies were described as the difference between elevation measured on the tested DEMs and the river bed elevation extracted from the TopoDEM. Terrain features were computed on all models using the Topographic Position Index (TPI) proposed by Weiss (2001). TPI in general allows to classify landscape into discrete landform categories by comparison of individual cell heights with an average height of neighboring cells.

To calculate TPI, neighborhood search radius has to be carefully tested to classify terrain features; comparison of results received with various search radii may show the relation between terrain forms of different scales and hierarchies (Jenness, 2006). In this study, the landforms were computed using a 480 m radius (the value was selected using trial and error approach). All necessary work was performed using Jenness TPI-based classification extension in ArcGIS (Jenness et al., 2012). Based on calculated TPI values, all DEMs were classified into valleys, gentle slopes, steep slopes and ridges. The terrain forms received from the SRTM-X DEM and ASTER GDEM were then compared to the map of terrain forms generated from the TopoDEM using standard cross-tabulation procedures for qualitative maps.

3. Results

3.1 Vertical Errors for SRTM-X DEM and ASTER GDEM

If both models (SRTM-X DEM and ASTER GDEM) are compared to each other, 72% of the study area has the absolute elevation difference below 10 m, and 94% below 20 m. Area where larger uncertainty exists is located in the south-eastern, most dissected part of the mountain region, and the maximum height difference between the models equals 114 m. ME for SRTM-X DEM was -2.48 m, RMSE was 12.05mfor all reference points (10.15mfor positive values and 6.49mfor negative values; Figure 2). ME for the ASTER GDEM was 0.69 m, RMSE was equal to 17.43m for all reference points (14.30 m for positive values and 9.97m for negative values; Figure 2). Absolute errors were the highest for both models in the most rugged part of the mountain range; the extreme values (above 50 m) occur most frequently on steeper slopes (Supplement, Annex 3).

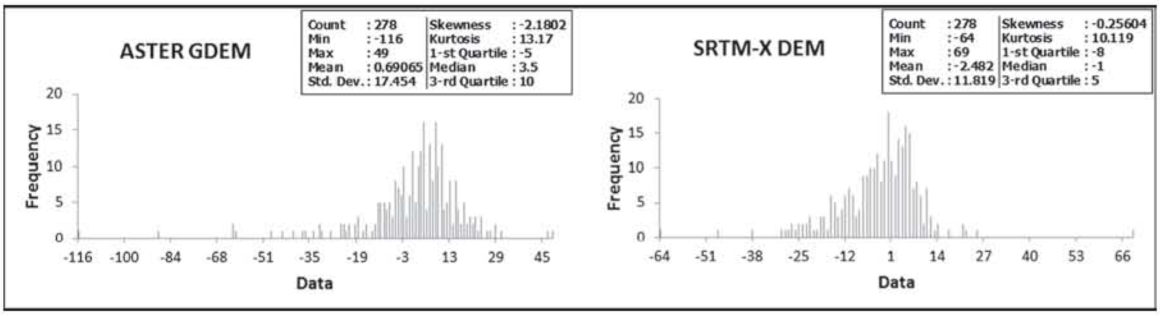


Figure 2: Elevation errors of SRTM-X DEM and ASTER GDEM

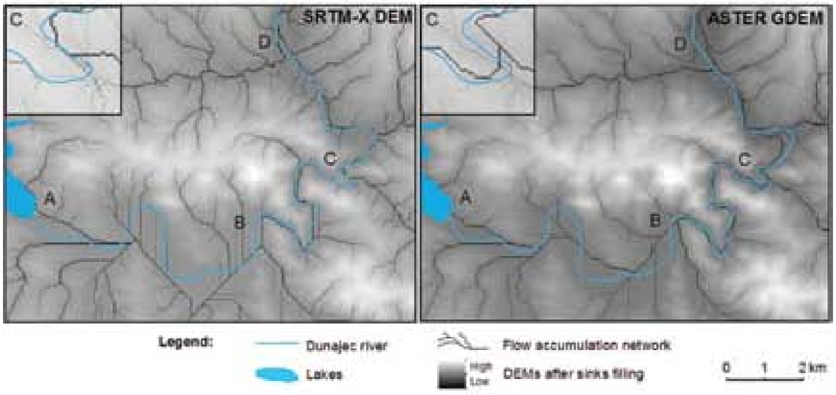


Figure 3: Horizontal delineation errors for the Dunajec River

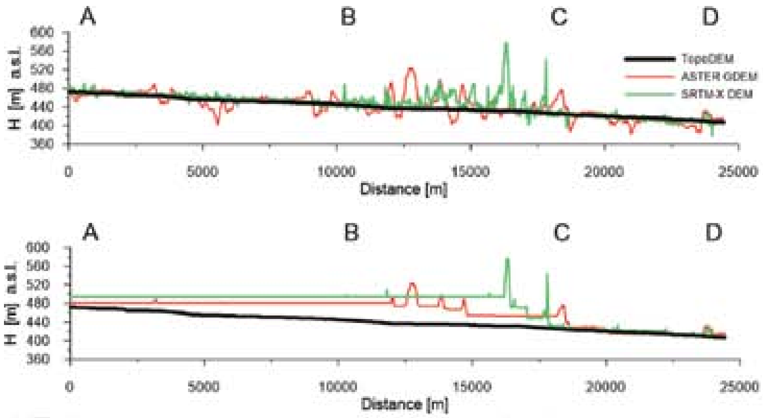
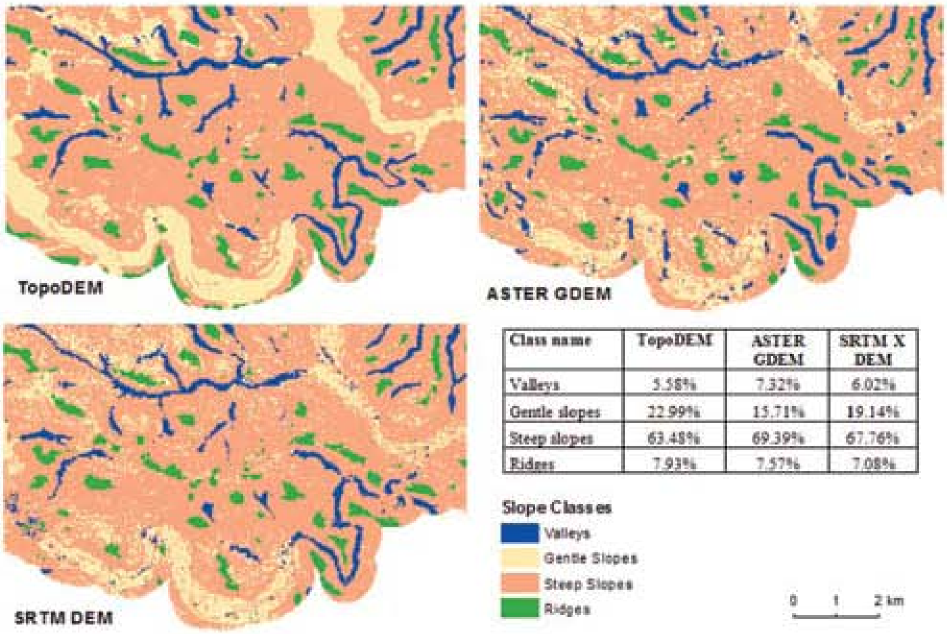


Figure 4: Vertical profiles along the Dunajec River. Upper panel: before; lower panel: after applying the Fill Sinks function



Class name	TopoDEM	ASTER GDEM	SRTM X DEM
Valleys	5.58%	7.32%	6.02%
Gentle slopes	22.99%	15.71%	19.14%
Steep slopes	63.48%	69.39%	67.76%
Ridges	7.93%	7.57%	7.08%

Figure 5: TPI-based landform classification and proportion of four delineated classes

3.2 Accuracy of the Stream Network Delineation

Maximum horizontal distance between vertices of the Dunajec river path generated from global DEMs and the reference river line reached up to 1036 m in case of SRTM-X DEM and 530 m in case of ASTER GDEM (Figure 3), and mean values of horizontal distance were 121.6 m and 117.2 m, respectively. Most problems were identified in the valley of the Dunajec river between points A and B, as the delineation of the river path was not consistent with the actual one, and both models performed here equally bad. In the Dunajec river gorge, between point B and C, the distances between delineated river courses and the reference line did not exceed 160 m (SRTM-X DEM) and 110 m (ASTER GDEM). Both models failed to represent correctly elevations along the course of the Dunajec river (Figure 4). Although they depicted a clear trend down the river course as represented by elevation data taken from TopoDEM (elevations decrease by approximately 60 m, from 470 m a.s.l. down to 410 m a.s.l), the elevation in the most narrow part of the gorge varied significantly, with elevation anomalies ranging from -39 m to 145 m in case of SRTM-X DEM, and -52 m to 88 m in case of ASTER GDEM. The Fill Sinks function available in ArcGIS did not allow to solve all the problems with the elevation models, and the smoothed river profile still contained significant errors (artificial dams and barriers; Figure 4). These effects caused displacements of the Dunajec channel, especially between points A and B where the flat valley floor is wider and also its discontinuity in the middle of the gorge in case of SRTM-X DEM. North of the Dunajec gorge both models allowed to delineate stream network that is much more consistent with results received using the reference TopoDEM (Figure 3).

3.3 Delineation of Terrain Features

Based on the TPI classification, four elementary topographic forms were extracted from all DEMs. Valleys, gentle slopes, steep slopes and ridges had similar distribution for both global DEMs, yet they were significantly different from the reference TopoDEM (Figure 5). In particular, TopoDEM had a much higher share of 'gentle slope' class which included also broad valley floors; this class was less pronounced in both SRTM-X DEM and ASTER GDEM due to small scale elevation variability, contributing to the visually pronounced 'salt and pepper' effect.

4. Discussion and Conclusions

For most of the study area, SRTM-X DEM and ASTER DEM exhibit low differences (less than 20 m) for more than 90% of the studied area. However, their vertical errors measured with 278 reference points exceeded the values provided in their specifications (Wagner, 2003; ASTER GDEM Validation Team, 2009; ASTER GDEM Validation Team, 2011; DLR, 2010). As it was expected, the largest errors occurred in the most rugged part of the Pieniny National Park, where processing quality of both DEMs was lower than in other parts of the study area. These errors, together with small scale variability propagate into various derivatives of both DEMs. Standard tools of hydrological modeling of ArcGIS software allowed to extract stream line network with sufficient accuracy over most of the study area. The only exception was the Dunajec Valley. First, in the flat and relatively wide (around 500 m) section of the valley the automatic delineation of the stream line failed, as both ASTER GDEM and SRTM-X did not capture such a small scale feature like the river channel, incised into the flat valley floor by less than 5 m. Here, filling sinks likely contributes to a major uncertainty in the delineation of the river course, as this procedure eliminates local elevation minima that represent the river channel. On the other hand, in the narrow part of the Dunajec gorge the vertical errors were severe and in case of SRTM-X DEM exceeded 100 m. Filling sinks at least partially eliminated these errors and was efficient for the ASTER GDEM, allowing to delineate the continuous river course with a good accuracy, it failed however for the SRTM-X DEM. Hence it seems that using global DEMs for stream channel delineation in the complex mountain terrain with flat valley floors and deeply incised river gorges is not a recommendable solution. Rather, existing stream network should be used to correct the DEMs via 'burning' proper river profiles into the DEMs or, alternatively, elevation data with higher resolution and better accuracy should be used for hydrological modeling (Gichamo et al., 2011). Small-scale elevation variations of both SRTM-X DEM and ASTER GDEM contributed to errors in terrain forms classification that were visible as 'salt and pepper' appearance of qualitative maps (Figure 5). This effect was much less visible for the TopoDEM: in this case, smooth interpolated surface received from contours and elevation points outperforms both global DEMs. These disparities contribute to significant differences in the proportion of two classes (gentle and steep slopes) between global DEMs on one side, and the reference DEM on the other. As in case of hydrological modeling, smoothing of global DEMs might be a good choice before performing terrain classification, yet it should be simultaneous with updating the DEMs with elevation values of river channels and ridges elevations. The findings of this study confirm that global DEMs (SRTM-X DEM and ASTER GDEM) are a good approximation of the variability of Earth surface except for extremely steep and rugged mountain relief. However, these models do not represent correctly the topology of valley and ridge networks, as is the case of topographic maps that explicitly contain this type of information. These drawbacks, together with the small-scale elevation variability exclude the direct use of global DEMs in either terrain classification or hydrological modeling.

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NOTE:

The graphics referred as 'Supplement Annex 1, Annex 2 and Annex 3' in this paper are available online at: www.gis.geo.uj.edu.pl/ijg/supplement.pdf.