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Vertical Accuracy of Digital Elevation Models Based on Differential Global Positioning System

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Abstract

The Digital Elevation Model (DEM) has been known as a quantitative description of the surface of the Earth, which provides essential information about the terrain. DEMs are significant information sources for a number of practical applications that need surface elevation data. The open-source DEM datasets, such as the Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER), the Shuttle Radar Topography Mission (SRTM), and the Advanced Land Observing Satellite (ALOS) usually have approximately low accuracy and coarser resolution. The errors in many datasets of DEMs have already been generally examined for their importance, where their quality could be affected within different aspects, including the types of sensors, algorithms, terrain types, and other features. Ground control points (GCPs) used in this study were observed through the utilization of differential global positioning system (DGPS) with dual frequencies. Statistical indices were used to compare, evaluate, and validate the DEMs data against DGPS data. Statistical analysis of DEMs pointed out that SRTM accuracy was higher, with Root Mean Square Error (RMSE) of $\pm 6.276\text{m}$ as compared to the other DEMs. ASTER showed the biggest residual error with an RMSE of $\pm 10.241\text{m}$. Nevertheless, ALOS was noticeably improved by having an RMSE of $\pm 6.988\text{m}$.

Keywords: Terrain analysis, Digital elevation model, Open source, Accuracy assessment, Vertical Accuracy, Data pre-processing.

الدقة الرأسية لنماذج الارتفاع الرقمية بالأعتماد على نظام تحديد المواقع العالمي التفاضلي

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الخلاصة

يُعرف نموذج الارتفاع الرقمي بأنه الوصف الكمي لسطح الأرض الذي يوفر معلومات أساسية عن التضاريس. تعتبر نماذج الارتفاعات الرقمية مصادر معلومات مهمة لعدد من التطبيقات العملية التي تحتاج إلى بيانات ارتفاع السطح. عادة ما تكون نماذج الارتفاعات الرقمية مفتوحة المصدر المتاحة مجاناً لجميع المستخدمين والتي توفرها الوكالات الفضائية مثل ASTER و SRTM و ALOS والتي تكون ذات دقة منخفضة تقريباً. لأهمية نماذج الارتفاعات الرقمية تم فحص الأخطاء في العديد منها لتحديد أسباب تلك الأخطاء حيث يمكن أن تتأثر جودتها في جوانب مختلفة، مثل أنواع المستشعرات والخوارزميات وأنواع التضاريس وميزات الأخرى. نقاط التحكم الأرضية المستخدمة في هذه الدراسة رصدت باستخدام نظام تحديد المواقع العالمي التفاضلي (DGPS) ذات التردد المزدوج. تم استخدام المؤشرات الإحصائية لمقارنة وتقييم والتحقق من بيانات DEMs مقابل بيانات DGPS. أشار التحليل الإحصائي لـ DEMs إلى أن دقة SRTM

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كانت أفضل مع خطأ متوسط الجذر التربيعي $\pm 6.276\text{m}$ مقارنةً بالنماذج الأخرى حيث أظهر ASTER أكبر خطأ متبقي مع $\pm 10.241\text{m}$. على أي حال فقد أظهر ALOS تحسناً ملحوظاً من خلال تسجيل خطأ متبقي مقداره $\pm 6.988\text{m}$.

Introduction

The Digital Elevation Model (DEM) has been known as a quantitative description of the surface of the Earth, which provides essential information about the relief or terrain [1]. DEMs are significant information sources for a number of practical applications that need surface elevation data and they have been utilized as sources of elevation data in several geospatial applications and studies, including plant cover research, urban studies, tsunami assessments, geomorphology, glacier observations, topography, and archaeology [2]. They can be classified into two groups: Digital Surface Models (DSMs), which display the surface of the Earth and contain all natural and man-made objects, and Digital Terrain Models (DTMs), where there are no types of objects like trees and buildings [3]. The datasets of DEMs could be generated through the use of different mechanisms, such as techniques of air-borne (e.g. Light Detection and Ranging (LiDAR) and photogrammetric), conventional methods of surveying techniques (e.g. leveling and Global Positioning System (GPS)) and space-borne interferometry (e.g. satellite imagery and Radar altimetry) [4]. These data sources could be assessed in four various ways, namely the pre-processing, accuracy, resolution, and cost. Furthermore, every aforementioned mechanism includes both benefits and drawbacks [5]. Recently, research has always utilized the DEMs, which could be gained by techniques of remote sensing, instead of the mechanisms of direct measurement. This is due to the increasing quantity of satellite observations accompanied by increased spatial and temporal resolution with stereo abilities, homogeneous data quality, and wide coverage [6]. Also, the low production cost of modern DEMs is an additional advantage. DEMs can be seen in a format of raster data, that are arrays of square cells [7].

The open-source DEM datasets, that are freely accessible, such as the ASTER, the SRTM, and ALOS, usually have approximately low accuracy and coarse resolution [8]. The errors in many datasets of DEMs have already been generally examined for their importance, where their quality could be effected within different aspects, including the types of sensors, algorithms, terrain types, grid spacing, and other features [9]. As those of ASTER and SRTM, the data of ALOS are available to everyone. A plethora of studies have been concerned with examining the accuracy through the use of various mechanisms for validation. Nonetheless, the assessment of DEMs' accuracy necessitates a measurement of GPS data, including the regional ground-truth data, with an increased degree of precision, to validate the accuracy of DEM datasets [10].

Related Works

Recently, immense literature have been conducted on the generation of DEM data from images sent by satellite and the evaluation of their quality. Mukherjee *et al.*, 2013, evaluated open-source DEMs (ASTER and SRTM) and their derived features, utilizing DEM high posting Cartosat and height information of Survey of India (SOI). Their results revealed that terrain characteristics' representation has been influenced by DEM coarse postings. The total vertical accuracy analysis revealed that RMS error values of $\pm 17.76\text{ m}$ and $\pm 12.62\text{ m}$ for SRTM and ASTER DEMs, respectively, compared with Cartosat DEM [1]. Khalid *et al.*, 2016, made a comparison to evaluate the accuracy of SRTM, ASTER, and GMTED10 by using earth real data from the Global Positioning System (GPS). SRTM vertical accuracy displayed better findings against GMTED10 and ASTER, with an RMSE of $\pm 6.054\text{ m}$ [11]. Rabah *et al.*, 2017, utilized the ellipsoidal observed heights of 601 points, compared to the ASTER and SRTM DEMs. The findings revealed that the most accurate one was the SRTM; it produced mean height differences and standard deviation values equal to $\pm 2.89\text{ m}$ and $\pm 8.65\text{ m}$, respectively [12]. Elkhrachy, 2018, assessed the quality of DEMs gained by ASTER and SRTM. The levels of reference provided by topographic maps and elevations of GPS were utilized to evaluate the vertical accuracy of ASTAR and SRTM in Najran city, Saudi Arabia. The DGPS elevations showed RMSE values of $\pm 5.94\text{ m}$ and $\pm 5.07\text{ m}$ using SRTM and ASTER, respectively. Moreover, the gained accuracy values were $\pm 7.97\text{ m}$ and $\pm 6.87\text{ m}$ for ASTER and SRTM, respectively, through the use of elevation from the topographic map as a reference elevation [13]. Wessel *et al.*, 2018, provided a unique assessment of the accuracy of the last TanDEM-X global DEM, utilising reference datasets of GPS point, toward the total characterization of the absolute height error. These comparisons proved a

vertical Mean Error (ME) less than ± 0.20 m and an RMSE less than ± 1.4 m for TanDEM-X DEM [14].

This research aims to utilize notions of the Global Navigation Satellite System (GNSS) to validate the open DEMs accuracy. This is required to analyse remote sensing data and confirm that free available data provide a critical possibility for analysing spatial data and perform measurements for geomorphologic and topographic purposes.

Study Area and Data

A. Study Area

The research was conducted in the southeastern region of Iraq, as shown in Figure-1(A), located between the geographic coordinates of $31^{\circ} 59' 37.19''$ - $32^{\circ} 59' 31.64''$ N and $45^{\circ} 05' 09.81''$ - $45^{\circ} 59' 08.22''$ E. The study area varied in terms of terrain. Geomorphologically, its eastern side was adjoining the mountain range, which represents the border of Iraq – Iran. Therefore, the northern part of the study area was higher than the southern part, which was a level territory with slight variety in heights. The Tigris River passes from the north to the south-east through the area of study.

B. Digital Elevation Model

The National Aeronautics and Space Administration (NASA) and the Japanese Ministry of Economy and Trade have developed the “The Advanced Space borne Thermal Emission and Reflection Radiometer” (ASTER). Its sensors have an along-track stereoscopic ability, through the use of near-infrared spectrum sensors. DEMs are generated with spatial resolution of 30m. The ASTER complete vertical accuracy is 20 m with a confidence level of 95% [15].

The National Imagery and Mapping Agency (NIMA) and NASA made the “Shuttle Radar Topography Mission” (SRTM) to gather the world elevation dataset. The SRTM data of elevation were taken from the Interferometric Synthetic Aperture Radar (InSAR). Data of SRTM are available at 90 m posting for the whole world and 30 m posting for USA. The data showed that the most complete vertical height accuracy was 16 m [11].

Japan Aerospace Exploration Agency (JAXA) launched the “Advanced Land Observing Satellite” (ALOS) which is a global digital elevation model that started functioning since 2006. ALOS is consisted of three panchromatic radiometers that procured along-track stereo images. The model has a 2.5 m spatial resolution in the nadir-looking radiometer and achieved coverage of the whole globe, producing a suitable potential candidate for exact global generation of digital elevation models [8].

C. Ground Reference Data

In the current research, DGPS survey data were utilized as ground truth data, which is capable of producing the highest accuracy of DEMs on land. As shown in Figure-1(B), the 219 (GCPs) used in this study were observed through the utilization of DGPS with dual frequencies, by using the mechanism of static observation, accompanied by vertical accuracy of $0.015 \text{ m} + 2.5 \text{ ppm}$ and horizontal accuracy of $0.012 \text{ m} + 2.5 \text{ ppm}$ [12]. These data were gained through field surveys by the companies of oil and gas topographical survey functioning in Wasit district. Table-1 shows a sample of 25 points from all GCPs with its data.

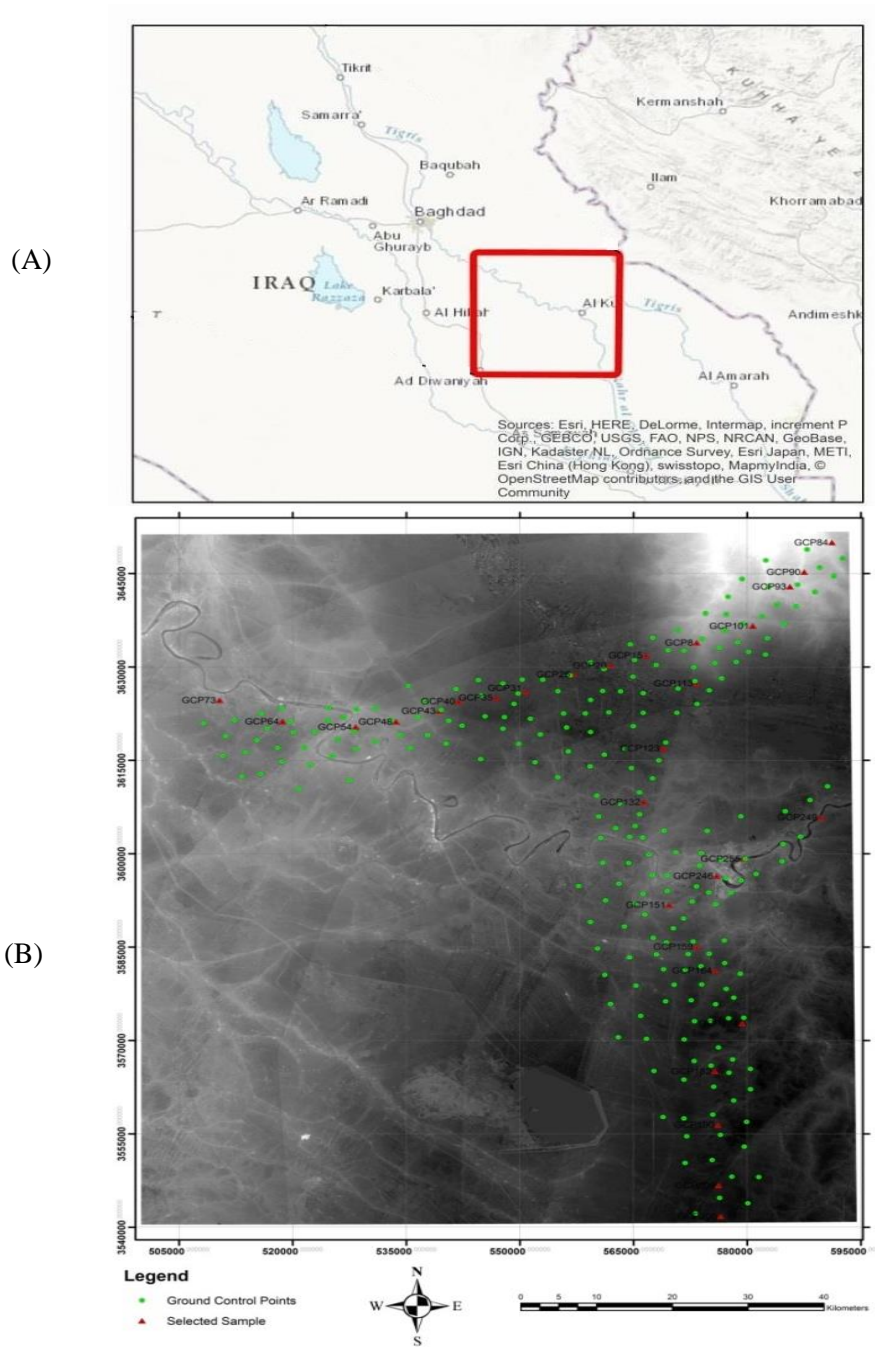


Figure 1- (A) Study area, (B) Selected DEM with the ground control points.

Methodology

A. Data Pre-processing

The World Geodetic System (WGS84) was used to project digital elevation models and make cuts to the extent of every testing area [16]. Then, the three digital elevation models were selected with ortho-metric heights regarding the computed geoid model, utilizing EGM2008. The elevation value extraction of the digital elevation model was carried out by the use of the Arc-Map Software's export functionality.

Nevertheless, the observation data of DGPS provided the default vertical datum for computation purposes of relative heights. By the use of the software of Geodetic Datum Transformation Suite (GDTS), the digital elevation models were transformed into WGS84. After that, DEM elevation was changed to an ortho-metric height. Thus, the geometric height of DGPS was then changed to the ortho-metric height by subtracting the height of the geoid at the position of every point of DGPS. The fundamental formula for these transformations is [17], as shown in Figure-2:

$$H = h - N \quad (1)$$

where H is the vertical distance between geoid and topographic surface, h is the vertical distance between ellipsoid and topographic surface, and N is the vertical height of geoid from ellipsoid [17]. This change was made to the whole open-source DEMs which utilized a comparable reference (EGM2008) for vertical datum. The sample of 25 points with its coordinates and DEMs elevations is illustrated in Table-1.

Table 1- DEMs elevations for the sample of 25 GCPs with its coordinates [8]

Point	GCPs Coordinates (m)			DEMs Elevations (m)		
	X	Y	Elv.	ALOS	ASTER	SRTM
GCP8	574242.105	3634284.054	24.992	23	13	26
GCP15	567614.987	3632067.177	18.821	19	13	19
GCP20	560916.702	3630029.123	17.324	17	12	17
GCP25	556184.526	3628410.522	17.035	15	13	17
GCP31	549744.644	3625749.594	17.878	19	12	18
GCP35	545851.463	3625058.979	18.225	19	14	18
GCP43	540147.999	3623502.740	18.341	10	13	18
GCP48	532784.380	3620771.424	20.794	22	12	23
GCP54	529177.680	3619967.224	20.826	19	16	20
GCP64	517738.454	3621516.889	22.010	24	26	23
GCP73	509455.545	3625059.557	23.551	27	19	26
GCP84	591803.388	3650728.201	31.320	30	19	29
GCP93	585050.479	3642088.103	29.972	29	20	28
GCP101	580196.448	3635738.636	22.872	21	17	23
GCP113	572729.170	3626510.143	16.618	15	13	16
GCP123	569227.232	3617859.592	15.903	17	10	16
GCP132	566014.956	3607331.667	16.095	15	11	17
GCP151	570573.538	3591348.906	16.659	18	20	16
GCP159	572850.605	3585910.924	14.503	16	19	15
GCP164	575520.217	3582182.003	15.328	17	12	16
GCP174	578325.774	3570961.479	13.039	15	10	14
GCP182	575871.4196	3566041.803	13.218	12	16	14
GCP190	576325.571	3557398.185	12.760	13	15	13
GCP200	576226.652	3547486.261	11.671	11	14	12
GCP205	576282.037	3542744.999	11.609	11	13	12

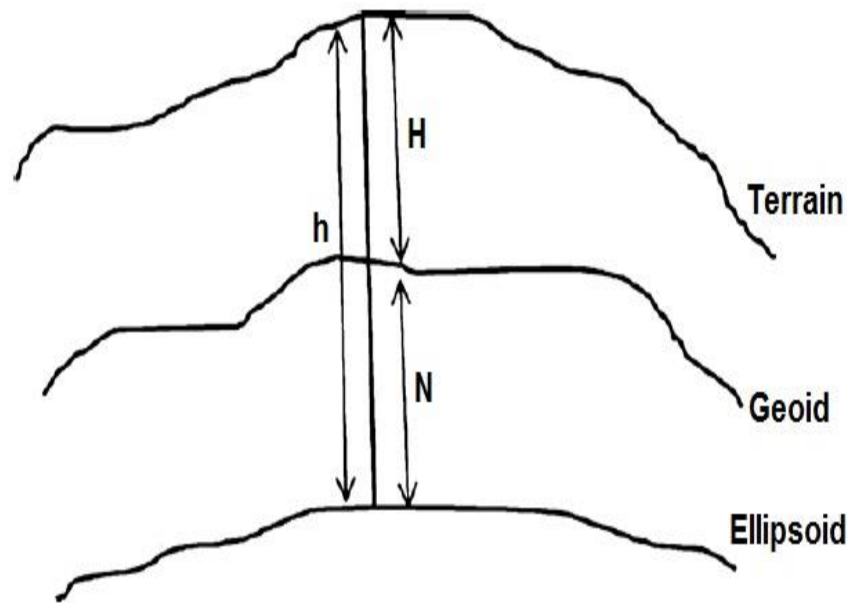


Figure 2- Height differences among topographic, geoid and ellipsoid surfaces [17]

B. Validation of Data

Statistical indices were used to compare, evaluate, and validate the DEMs data against DGPS data. Based on the current statistical research, DEM vertical accuracy relies on error propagation and trends amongst the DGPS and DEMs datasets [18]. The elevation error was estimated for each point as the difference between reference data and those of the model using equation 2 [9]

$$E_{diff} = E_{model} - E_{ref} \quad (2)$$

where E_{model} is DEMs' elevations, E_{ref} is DGPS points' elevations, and E_{diff} is the error of the elevations. After that, the values of RMSE and ME for each model were estimated by utilizing equations 3 and 4.

$$ME = \frac{\sum E_{diff}}{n} \quad (3)$$

$$RMSE = \sqrt{\frac{\sum E_{diff}^2}{n}} \quad (4)$$

where n : number of points [9].

RMSE refers to surface quality measures and offers an understanding of the differences between two kinds of data (anticipated by the observed and model data) [19]. The agreement level of derived elevation values among SRTM, ASTER, and ALOS datasets, on one hand, and data of DGPS, on the other hand, was also assessed regarding correlation and linear regression through comparing the value of every DGPS validation point with the digital elevation model.

Results and Discussion

To evaluate the data obtained from open-source digital elevation model's data and ground truth data, 219 points were collected by DGPS and randomly distributed in the selected study area, which represents a flat land, coastal lines, and hilly land. Extracted DEMs elevation values were gained through the use of Arc Map software and validated using the DGPS points.

Nevertheless, regarding the validation of digital elevation models, the most accurate digital elevation model was demanded. Figure-3 illustrates the comparison of data of SRTM, ASTER, and ALOS against the ground-truth data around the study area. The correlation of the digital elevation models was calculated. By plotting the point between the heights of the digital elevation methods (SRTM, ALOS, and ASTER) and the ellipsoid height (DGPS), regression value findings are represented in Figure-4, indicating high confidence levels of correlation amongst the ellipsoid height values from DGPS, SRTM, and ALOS, and elevation height from ASTER. Weak or strong

relationships among the ortho-metric (DGPS) and DEM heights could be identified by referring to the findings of the regression model. These findings indicate that the strongest and most suitable model was selected as the best technique for the digital elevation model.

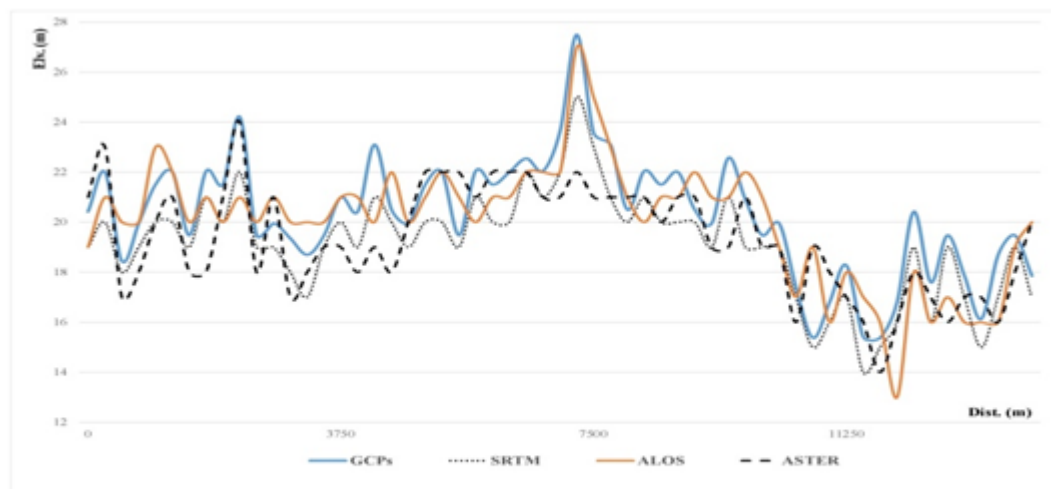


Figure 3- Difference in DEMs and GCPs elevations

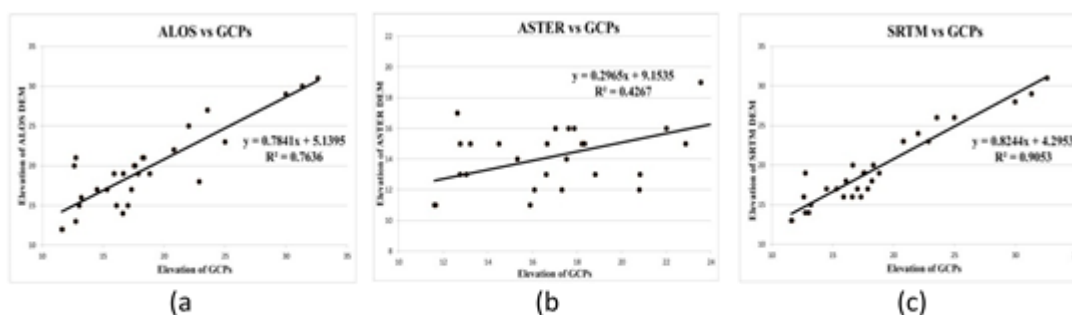


Figure 4- Correlation analysis and linear regression between GCPs data and (a) ALOS, (b) ASTER and (c) SRTM DEMs datasets.

The obtained results confirmed the vertical accuracy values for SRTM, ALOS, and ASTER DEMs, which have values of ± 6.276 m, ± 6.988 m, and ± 10.241 m, respectively, for the study area (see Table-2).

Table 2- Standard deviation SD, Mean Error and RSME of ASTER, ALOS and SRTM datasets in study area.

	ASTER	ALOS	SRTM
SD	± 8.620 m	± 4.790 m	± 4.550 m
RMSE	± 10.241 m	± 6.988 m	± 6.276 m
ME	± 8.437 m	± 4.782 m	± 4.262 m

Conclusions

Three digital elevation models were compared in terms of vertical accuracy that is calculated through the utilization of DGPS reference data. Eventually, the differences in digital elevation models were discussed based on the assessment of statistical test results.

After the removal of systematic and blunders errors, random errors were found to cause the distribution of the remaining errors. Regarding the accuracy of the evaluation data, results of statistical

tests were presented and the characteristics of errors were investigated in the three sources of digital elevation models. The overall results showed the correlation of SRTM at 0.905, while ALOS and ASTER showed correlations of 0.764 and 0.427, respectively. Statistical analysis of the digital elevation model pointed out that the accuracy of SRTM was higher, with an RMSE value of ± 6.276 m, as compared to the other digital elevation models (Table-2). ASTER showed the highest residual error value, with an RMSE of ± 10.241 m. However, ALOS was noticeably improved with an RMSE of ± 6.988 m.

Reviewing the study results is critical to comprehend the errors connected with the used digital elevation models. The spatial features of the digital elevation models error were also depicted for different slope, land cover, and terrain morphologies. The vertical accuracy of the digital elevation models is influenced by the features of terrain morphology, where the roughness of the terrain has affected the vertical accuracy in a negative way. Researchers recommend that DEMs are of crucial benefit in small scale regional level studies. Future research can be conducted to measure the vertical accuracy of open source digital elevation models. Moreover, it is recommended to investigate the variation of terrain attributes of the first and second order when computing with SRTM, ALOS, and ASTER DEMs.

Still, all the assessed DEMs are useful and confer a good substitute for those DEMs created based on topographic maps. Acquiring and preparing DEMs for the use at open sources takes less time than the vectorization of topographic maps and their further processing. The availability of high-resolution DEMs in open access and further improvement of their processing algorithms will promote more active use of DEMs in multidisciplinary research.

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