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Nagwa El-Ashmawy[1], Essam Al-Krargy[2]

Enhancing the GDEMs of Egypt Using a Surface Subtraction Approach

Abstract: This paper proposes an enhancement approach to improve the accuracy of global Digital Elevation Models (GDEMs) in Egypt. The proposed approach is an empirical one that depends on subtracting the heights error from the original DEM. The research includes the evaluation and enhancement of SRTM-1 (SRTM v4.1), ASTER GDEM v2, and AW3D30 v2 GDEMs, in Egypt, using 980 well distributed GPS/levelling points, that cover the entire country. The GPS/levelling points are divided into 500 control and 390 check points. The results show that the root mean square error (RMSE) in the SRTM, ASTER and AW3D30 are 3.99 m, 8.81 m, and 2.98 m respectively.

For enhancing purposes, two different approaches are used: a linear regression analysis approach, and the proposed empirical surface subtraction approach. The results of the linear regression analysis approach show that the accuracies are improved by 3%, 16%, and 3% for SRTM, ASTER and AW3D30 respectively. However, the accuracies are improved by 5%, 23%, and 16% for SRTM, ASTER and AW3D30 respectively when the proposed approach is followed. After using the proposed approach, the obtained accuracy of the enhanced DEM reached 2.5 m.

Keywords: global DEM, DEM enhancement, empirical approach, linear regression analysis, Egypt

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[1] Drainage Research Institute, National Water Research Center, Cairo, Egypt, email: nagwa_el-ashmawy@nwrc.gov.eg, https://orcid.org/0000-0002-3191-3641

[2] Survey Research Institute, National Water Research Center, Cairo, Egypt, email: essamalkrargy@yahoo.com, https://orcid.org/0000-0002-6640-6113

1. Introduction

Comprehensive information about the elevation of ground points is of profound importance for many fields of civil works including; gravity field modelling, topographic mapping, imageries ortho-rectifying and hydrological modelling studies. Planning irrigation networks, determining optimal dam locations, simulating floods, calculating cut and fill volumes, determining storage capacity of reservoirs, and many more are among the applications in water resource management works that require ground elevation information [1]. The Digital Elevation Model (DEM), as a digital representation of the Earth's surface and a description of its height, is a common source of ground level information [2]. DEMs have become increasingly important and their production is a main concern for many national surveying organizations. This is because these models enable computer processing to quickly solve problems and deal efficiently with the natural ground. Based on the application that the DEM is required for, the requisite accuracy of the DEM is specified. Not all applications require highly accurate DEMs, especially those for planning purposes, but the accuracy of the DEMs' is critical when it comes to their use in geophysics and water related applications. Nevertheless, the more accurate the DEM of any model is, the more accurate the outputs obtained.

Besides the local DEMs of each country, there are some DEMs available that cross national borders and cover almost the entire world. These are called Global DEMs and several are available via the internet free of charge. The available GDEMs do not have the same characteristics (e.g., geo-reference, resolution, accuracy, etc.) nor are they produced by means of the same instrument/technology. The following subsections describe three of the GDEMs that are available for Egypt.

1.1. Shuttle Radar Topography Mission (SRTM)

The National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency (NGA) launched the Space Shuttle Radar Topography Mission (SRTM) in February 2000 [3]. The SRTM payload was fixed to a space shuttle that collects data using dual radar antennas, sensitive to C-Band and X-Band. The collected data are used to generate a Digital Elevation Model based on the interferometric synthetic aperture radar (inSAR) technique. SRTM observations cover around 80% of the Earth's landmass between 56°S and 60°N Latitudes, which means that the SRTM mission covered Egypt, between 22°N and 31°N latitudes. The United States Geology Survey (USGS) created several DEMs with different ground sampling of 1″, 3″, and 30″, which are around 30 m, 90 m, and 900 m spatial resolutions respectively. (SRTM-1: 1″/30 m; SRTM-3: 3″/90 m; SRTM30: 30″/900 m) [4]. The radar C-Band used penetrated canopy cover and hit the ground, yet SRTM still struggled in sloping regions with foreshortening, layover, and shadows [5, 6]. In September 2014, the USGS released the SRTM-1 global DEM. The dataset provides worldwide coverage of high-resolution, void-filled elevation data, that includes Egypt. Although there was an effort to improve the produced DEM by filling the voids, large numbers of voids are still contained in SRTM-1, especially in regions where the initial processing did not satisfy quality specifications, such as mountains [7]. In August 2016, the SRTM1-arc second data became freely available for Egypt (Fig. 1). The vertical error of the DEMs is reported to be less than 16 m for the SRTM [8].

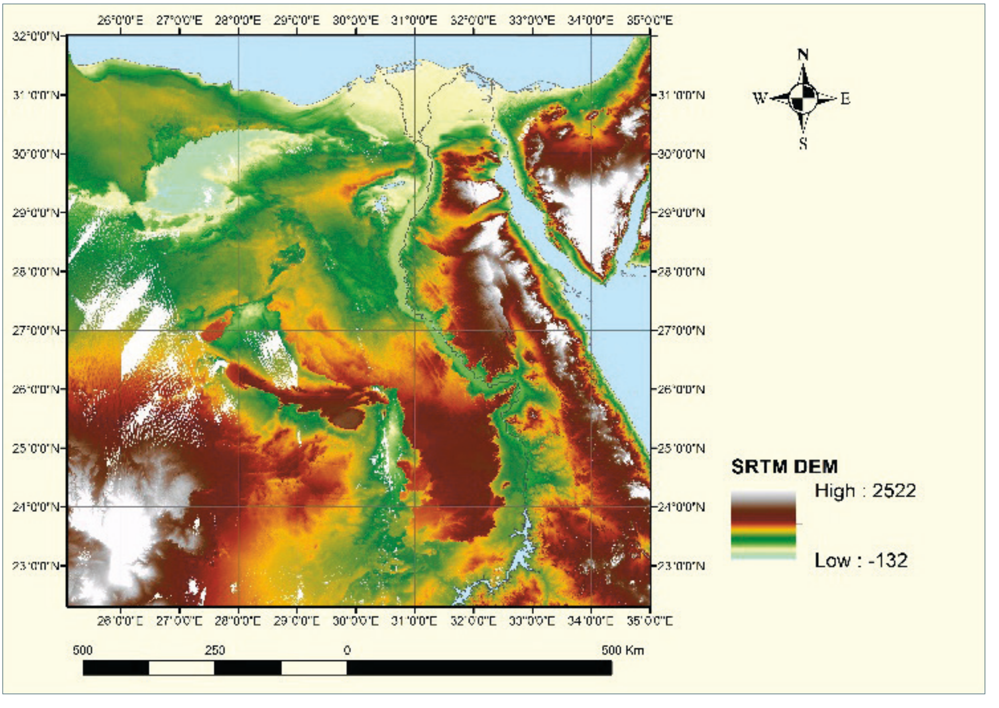

Fig. 1. Digital Elevation Model of SRTM GDEMs for Egypt

1.2. Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER)

Another example of a GDEM is the ASTER Global Digital Elevation Model, which is based on stereo pairs measurements collected by the NASA Terra satellite. ASTER stands for Advanced Space-borne Thermal Emission and Reflection Radiometer, and it is a joint operation between NASA and the Japanese Ministry of Economy, Trade and Industry (METI). It covers almost the entire surface of the Earth. ASTER captures optical images in stereoscopic pairs that are acquired with different angles taken from the same pass. Digital image correlation methods are used to generate a DEM with about 30-meter spatial resolution. ASTER GDEM version 1.0, released on June 29, 2009, was compiled from over than 1.2 million scene-based DEMs covering the surface between 83°N and 83°S latitudes, with 1″ spatial resolution. In contrast to the SRTM C-Band, the visible and near-infrared bands of ASTER are affected by cloud cover. Over time, ASTER GDEM data has improved its products with artefact corrections of their own for cloudy and shaded areas in the second version of the DEM. In mid-October 2011, ASTER GDEM v2 was released. The ASTER GDEM v2 contains significant improvements of version 1 in terms of spatial coverage, refined horizontal resolution, increased horizontal and vertical accuracy, water masking, and the inclusion of additional scenes to supplement the voids and to reduce artefacts [9]. GDEM1 has an overall accuracy of between 10 m and 25 m, however, there was around −5 m overall bias observed in the GDEM1 that was removed in GDEM2 [9]. Figure 2 shows the DEM Aster model for Egypt.

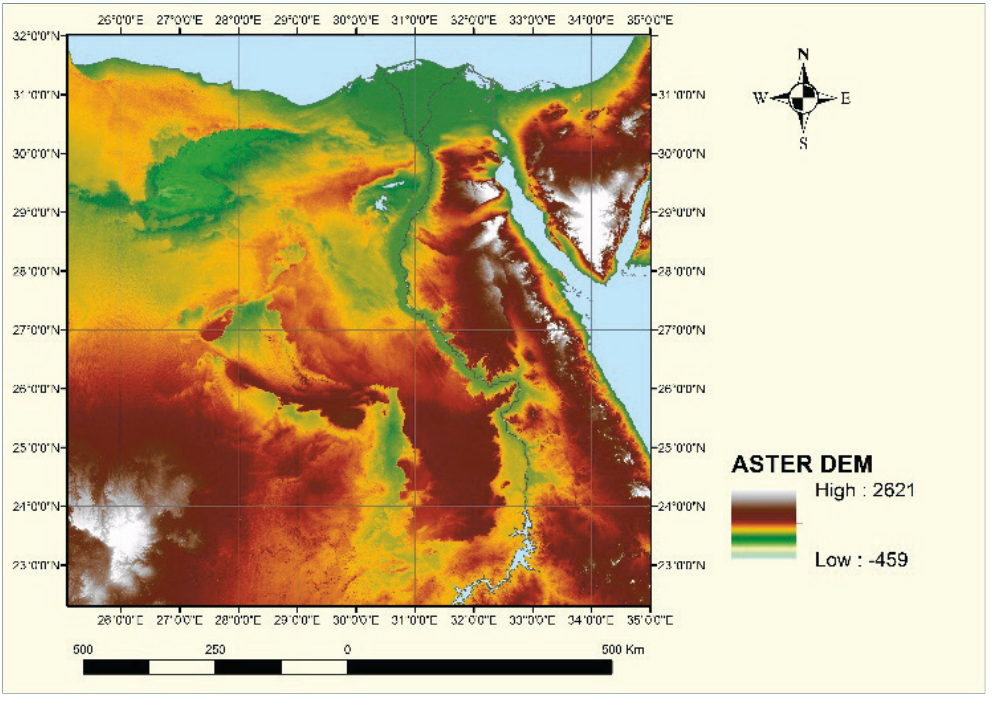

Fig. 2. Digital Elevation Model of the ASTER GDEMs for Egypt

1.3. ALOS Global Digital Surface Model – "ALOS World 3D – 30m (AW3D30)"

The ALOS World 3D – 30m DEM (AW3D30) is another global DEM with a horizontal resolution of 1″ (around 30 m). The DEM is produced using the Panchromatic Remote-sensing Instrument for triple Stereo Mapping (PRISM) on board of the Advanced Land Observing Satellite (ALOS). The Japan Aerospace Exploration Agency (JAXA) released the AW3D30 in May 2015 [10].

The AW3D30 data version 1.0 had voids (areas of no-data) and some areas were of low-quality. In March 2017, the areas from 60°N to 60°S, were filled in by version 1.1. In April 2018, version 2.1 was released, which covers the areas from 60°N to 60°S. The northern region over 60°N is included in version 2.2 which was released in April 2019. The AW3D was tested in four test sites with varying terrain features, and the results showed that the height accuracy was better than 5 m. Takaku et al. [11] assessed the DEM and concluded that the Root Mean Square Error (RMSE) of the produced DEM is almost 4 m based on comparisons with various datasets including the airborne LiDAR Digital Surface Model (DSM) and ground control points (GCPs). Additionally, assessment conducted by Tadono et al. confirmed that the RMSE of the ALOS DEM is 4.10 m [12]. Takaku and Tadono [13] determined both the horizontal and vertical accuracy of the AW3D30 GDEM and declared that both are within 5 m accuracy. Figure 3 shows the DEM AW3D30 model for Egypt.

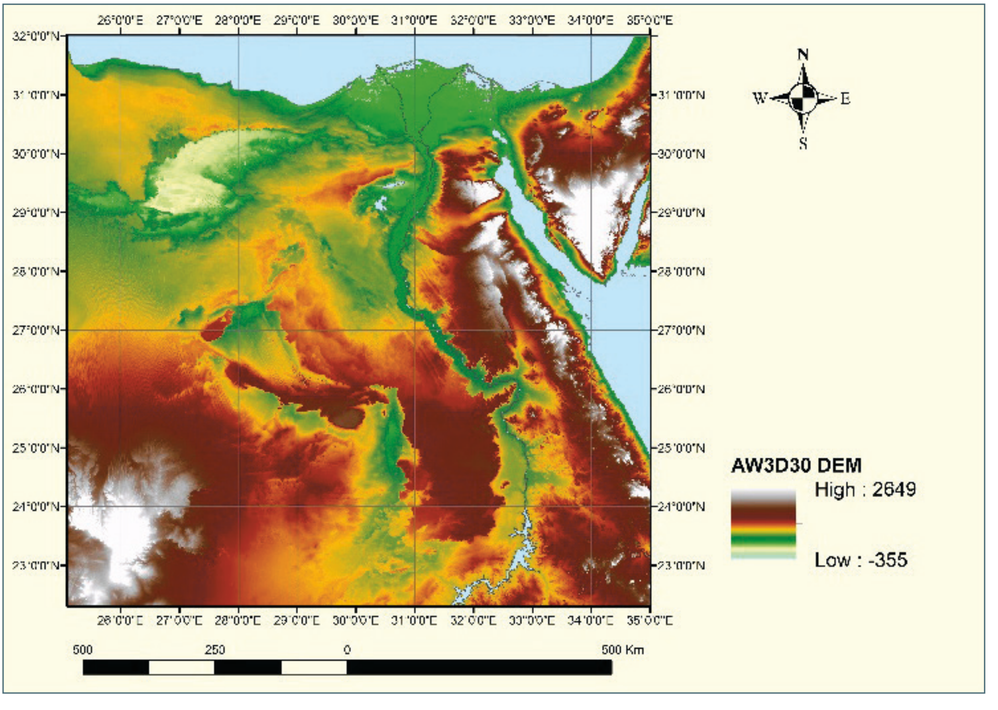

Fig. 3. Digital Elevation Model of AW3D30GDEMs for Egypt

The aim of this paper is to evaluate the available GDEMs for Egypt and enhance the most accurate one to obtain a more accurate DEM for Egypt. The more detailed objectives of this paper are to evaluate the accuracy of the three available GDEMs, named SRTM v4.1, ASTER GDEM v2, and AW3D30 v2, using levelling points that are jointed and related to the National Benchmarks Network of Egypt. Proposing an approach for enhancing the GDEMs is another aim of this paper. The results of the proposed enhancement approach are compared to the results of a linear regression model enhancing approach. The proposed approach depends on reducing the errors in the DEM with different values based on the spatial distribution of the DEM.

2. Background Studies

Since the beginning of the twenty first century and the release of the first global DEMs, researchers have investigated their quality. Rodríguez et al. [14, 15] analyzed and verified SRTM performance for the whole globe. The assessment of SRTM accuracy was conducted for each continent separately using kinematic GPS points. It was found that the 90% error of the absolute geolocation and the absolute height errors for Africa are 11.9 m and 5.6 m respectively. In addition to the kinematic GPS points, a Digital Terrain Elevation Data with a cell size the same as the resolution of the SRTM was used to assess the height accuracy of the SRTM. There were five cells in Africa, and it was found that the height has an average error of 2.44 m with standard division of 4.68 m and the 90% error in height is 8.8 m.

Gorokhovich and Voustianiouk [16] evaluated the SRTM-Consultative Group on International Agricultural Research Consortium for Spatial Information (SRTM-CGIAR) in two areas: one in the USA (the Catskill Mountains) and one in Thailand (Phuket) using 73 and 182 GPS points respectively. The results show that the accuracy of the SRTM-CGIAR is 7.58 m ±0.6 m and 4.07 m ±0.47 m for the Phuket and Catskill areas respectively. Another analysis based on the slope and aspects of the DEM has been done. It was found that when the slope is less than 10° the accuracy become 5.03 m ±0.41 m for the Phuket and 3.83 m ±0.35 m for the Catskill area. Meanwhile, when the slope is greater than 10°, the accuracy of the DEM decreased to 12.37 m ±1.31 m for the Phuket and 19.2 m ±2.7 m for the Catskill area.

Mouratidis et al. [17] conducted an extensive campaign to collect 60,000 kinematic GPS points to assess the accuracy of the four versions of SRTM-3 DEM for the city of Thessaloniki (northern Greece). It was found that the standard division of the absolute elevation errors in the four versions of the SRTM-3 are: 6.4 m, 6.4 m, 7.3 m, and 6.4 m respectively.

Hirt et al. [18] investigated the quality of three DEM for Australia:

1) national GEODATA DEM-9S v3 from Geoscience Australia and the Australian National University with 9″ resolution;
2) the SRTM v4.1 from CGIAR-CSI with 3″ resolution;
3) the ASTER-GDEM v1 from NASA/METI with 1″ resolution.

The three DEMs were evaluated using 6,392 levelled benchmarks. The results obtained show that the RMSE for the DEM-9S, SRTM v4.1 CGIAR-CSI), and ASTER GDEM v1 are 9 m, 6 m, and 15 m respectively [18].

Li et al. [19] evaluated the accuracy of the ASTER GDEM v1 and v2, and CGIAR-CSI SRTM v4.1 using GPS ground control points in five different sites in China. The results show that the mean for ASTER GDEM v1, ASTER GDEM v2 and CGIAR-CSI SRTM v4.1 are −21 m, −13 m, and −17 m respectively, however, the RMSE are ±26 m, ±19 m, and ±23 m. The authors compared the ASTER GDEM v2 to the CGIAR-CSI SRTM v4.1 pixel by pixel and concluded that the mean of the difference approached to zero (0.2 m) in GDEM v2, and the RMSE value fell off from 22.0 m in GDEM v1 to 20.6 m in GDEM v2 [19].

Yao et al. [20] evaluated the accuracy of the SRTM-3 v4.1 and the ASTER GDEM v2 in the Tibetan Plateau, China, based on GPS points. The GPS points were collected in six mountainous areas with 8242 points. By comparing the GPS elevation data with the DEMs elevations it was found that the standard division of the elevation error in the ASTER GDEM v2 was 18.56 m and 10.39 m for the SRTM-3 v4.1.

Later, when the ALOS PRISM data were released, scholars assessed the global DSM (AW3D). By comparing the AW3D DSM to the ICESat (Ice, Cloud, and land Elevation Satellite) data, ground control points, and LiDAR data, the accuracy of the AW3D DSM was within 5 m RMSE [21]. Additionally, Santillan and Makinano-Santillan [22] evaluated the AW3D DSM, ASTER GDEM2 and SRTM3 over north-east Mindano, Philippines based on 274 control points. They concluded that the AW3D DSM has the lowest RMSE of 5.68 m, followed by SRTM3 which has 8.28 m RMSE, and the lowest accuracy GDEM is ASTER GDEM2 of 11.98 m RMSE. However, Takaku et el. [23] were interested in enhancing the DSM (AW3D) by filling the voids in the DSM depending on the SRTM DEM [23].

Other research works have focused on the enhancement of Global DEMs. Arefi and Reinartz [24] enhanced the ASTER GDEM using ICESat laser altimetry data to remove its systematic errors. The accuracy of the GDEM was improved from 15.36 m to 7.98 m RMSE. Ebaid [25] enhanced the accuracy of SRTM and ASTER GDEM using Weight Estimation Regressing Models for two areas in Egypt (Delta region, and the West Desert and Qena region). The RMSE of the SRTM and ASTER GDEM were 11.69 m and 11.76 m, improved to 5.9 m, and 8.52 m respectively [25]. Rabah et al. [26] enhanced the SRTM1 for Egypt by exchanging the contribution of the global geopotential model from EGM96 to GECO. The results show an improvement of 0.06 m in RMSE after changing the geopotential model.

3. Materials and Methods

3.1. Study Area and Datasets

This research considered the entire area of Egypt (Fig. 4). Egypt is located in the northeastern corner of Africa. This zone is considered to be an arid/semi-arid zone, therefore most of the area (more than 90%) is covered by desert. The Nile passes from the Egyptian-Sudanese border in the south to the Mediterranean Sea in the north, forming the Nile valley and delta, and dividing the desert territories into the Eastern and Western Deserts. Besides, there is Sinai Peninsula between the Suez Gulf and the Aqaba Gulf (gulfs of the Red Sea) and the Mediterranean Sea at the north. The Western Desert is almost entirely flat, while the Eastern Desert is mostly hilly, while Sinai is flat in the north and hilly in the middle and the south. The elevation throughout the entire area of Egypt ranges between −130 m in the Western Desert to around 2,600 m in the Sinai Peninsula [27]. The slope ranges between 0% in most areas and 35% in some areas in the Eastern Desert and the Sinai Peninsula, with very small areas where the slope reaches around 88%.

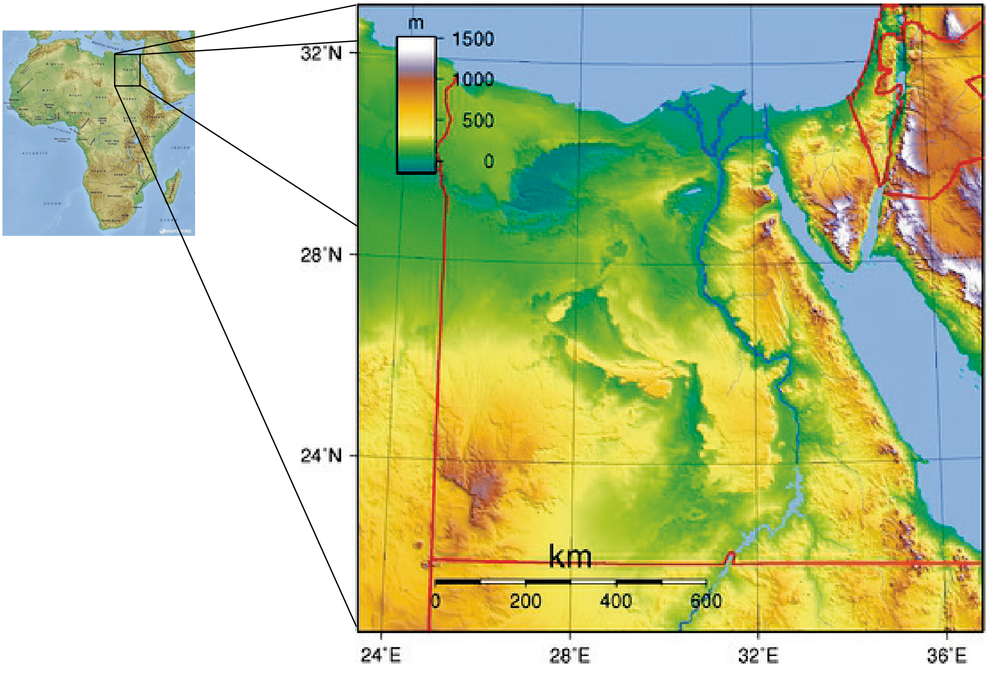

Fig. 4. The study area
Source: Wikipedia

Two types of data are used for this research: DEM datasets, and GPS/levelling points. For the DEM datasets, three GDEMs were selected to be evaluated and enhanced; SRTM v4.1 (Fig. 1), ASTER GDEM v2 (Fig. 2), and AW3D30 v2 (Fig. 3). Based on the Egyptian vertical datum (Old Egyptian Datum of 1907), 1,042 GPS/levelling points have been collected throughout the whole country by means of several research projects since 1996. Based on the requirements of these projects, most of the points are located in the Nile valley, Nile delta, and the coastal areas of Mediterranean and Red seas, which are considered flat areas. Figure 5 illustrates the distribution of the measured GPS/levelling points.

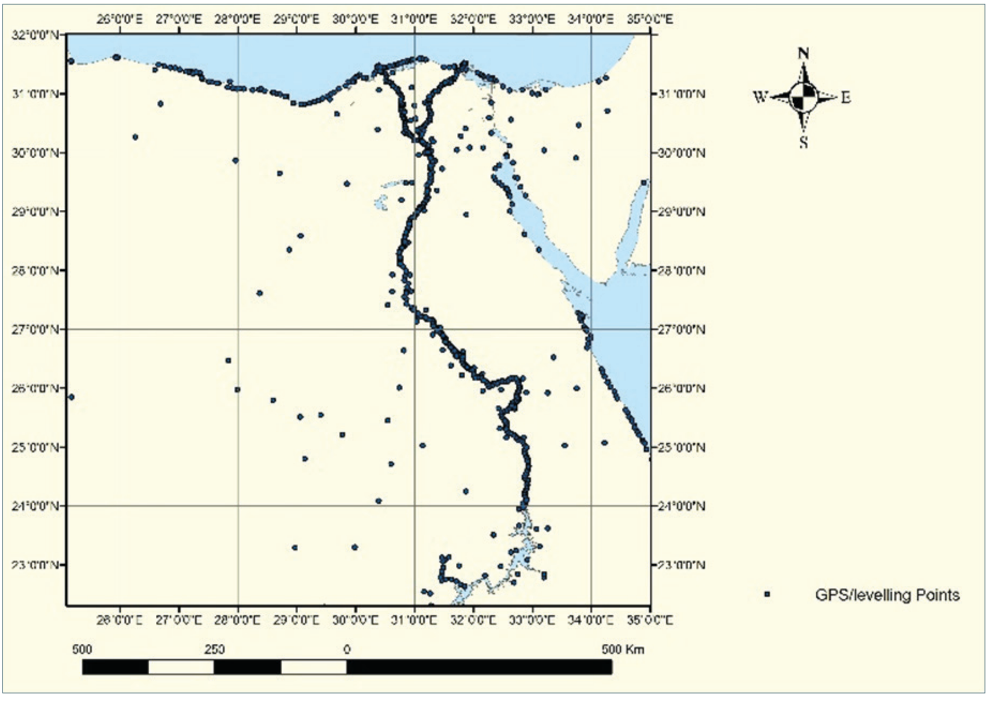

Fig. 5. Distribution of GPS/levelling points

3.2. Research Methodology

In this research, two different approaches are followed to enhance the GDEMs, namely the simple linear regression approach and a new proposed empirical approach. The proposed approach depends on the elevation, as well as the location of the GDEM points. Therefore, the regression model will not only depend on the elevation value but on the location of the points as well, for more credibility in the comparison between the results of the two approaches. The linear regression analysis approach is used to determine the enhanced orthometric height (*H*) for each pixel/point of the GDEM based on the location (latitude φ and longitude λ) and the GDEM elevation (*Z*) of the GDEM pixels. To use this approach, control point data are used to form the regression equation, where the φ, λ, and *Z* are the independent variables, and the *H* is the target (dependent value). Other points are used to assess the accuracy of the formed regression equation:

$$H_{\mathrm{enh}} = \beta_0 + \beta_1\varphi + \beta_2\lambda + \beta_3 Z \tag{1}$$

where:

H_{enh} – enhanced orthometric height (dependent value),
φ, λ, Z – latitude, longitude, and elevation (independent variables),
$\beta_0, \beta_1, \beta_2$ – parameters of the regression equation.

Figure 6 shows the procedure of the regression equation approach. Firstly, the collected points at the field (φ, λ, H_{ob}) are located on the GDEM, then the corresponding GDEM elevation values are determined (Z). By dividing the collected points into control and check points, the parameters of the regression equation are calculated based on the values of the control points. Finally, the regression equation is evaluated using the data of the check points (validation data).

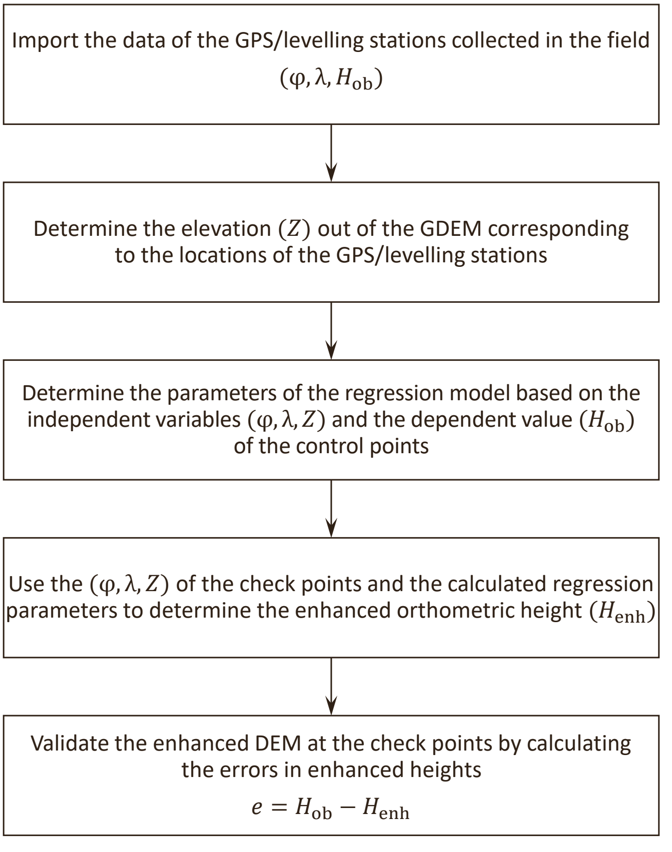

Fig. 6. Workflow of the regression analysis approach for enhancing GDEMs

The second approach is a proposed empirical approach that depends on subtracting the errors in the DEM data based on their locations. The idea behind this empirical approach is that if the error in the DEM is known at each pixel, subtracting these error values will produce an accurate, enhanced, DEM. However, these values are largely unknown and only errors at certain points (the collected GPS/levelling stations) are available. Since these stations do not represent the entire area pixel by pixel, predicting the height error at each pixel of the DEM is required. Therefore, based on a number of error values (at control points), a surface representing the errors in the height values of the entire area can be interpolated. This surface not only represents the height errors at the control points, but at each pixel of the DEM as well. To determine the errors in height data at the control points, the residuals between the observed orthometric heights and the corresponding elevation data (out of the DEM) are calculated. Then, a surface of the residuals is created using a selected interpolation technique. By subtracting this surface from the original DEM, an enhanced DEM can be obtained. Figure 7 illustrates the procedure of the proposed approach.

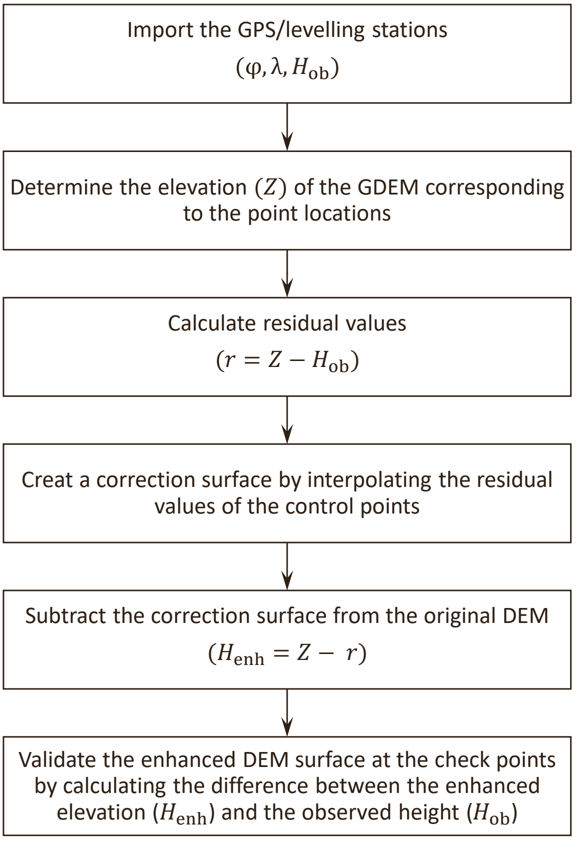

Fig. 7. Workflow of the proposed surface subtraction approach for enhancing GDEMs

4. Experimental Work and Results

Before applying the two enhancement approaches, the observed points were located on the DEM and the elevation values were determined at each point. Having the levelling data of the observed points, the differences between the observed levelling data and the DEM values were calculated (residual of height values). Based on the entire data (1,042 points), the means (μ) and the standard deviations (σ) of the residuals (between observed levelling and the DEMs values) were calculated. The outlier points based on 3σ were extracted, with 890 points remaining. Figure 8 shows the location of the outliers and the locations of the remaining points used.

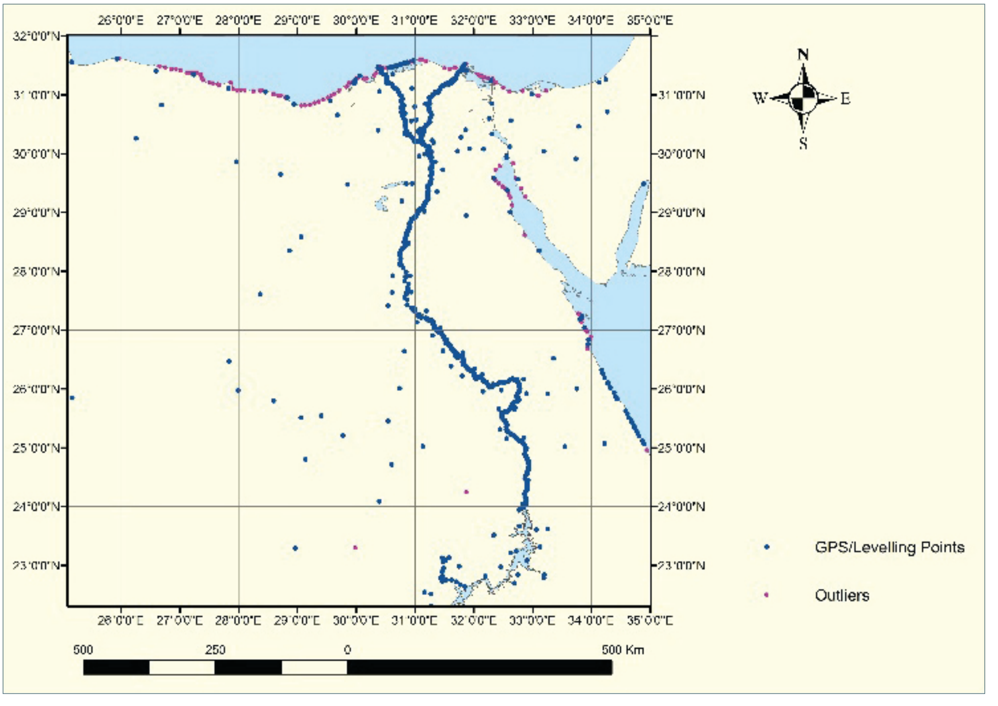

Fig. 8. The location of the extracted outlier data and the remaining 890 points

After removing the outliers, the remaining points (890) were divided into control and check points; 500 points were randomly selected to be used as control points, and the remaining 390 served as check ones. Figure 9 illustrates the distribution of the control and check points over the entire area. Before applying the enhancement approaches, the three selected GDEMs were evaluated using the 390 selected check points. Table 1 illustrates the calculated univariate values of the residuals in the three GDEMs.

Table 1. Univariates of residuals in the three available GDEMs based on 390 check points

	SRTM	ASTER	AW3D30
Max	12.38	43.04	11.45
Mean	1.30	3.54	−0.02
Min	−12.81	−19.95	−7.53
RMSE	3.99	8.81	2.98

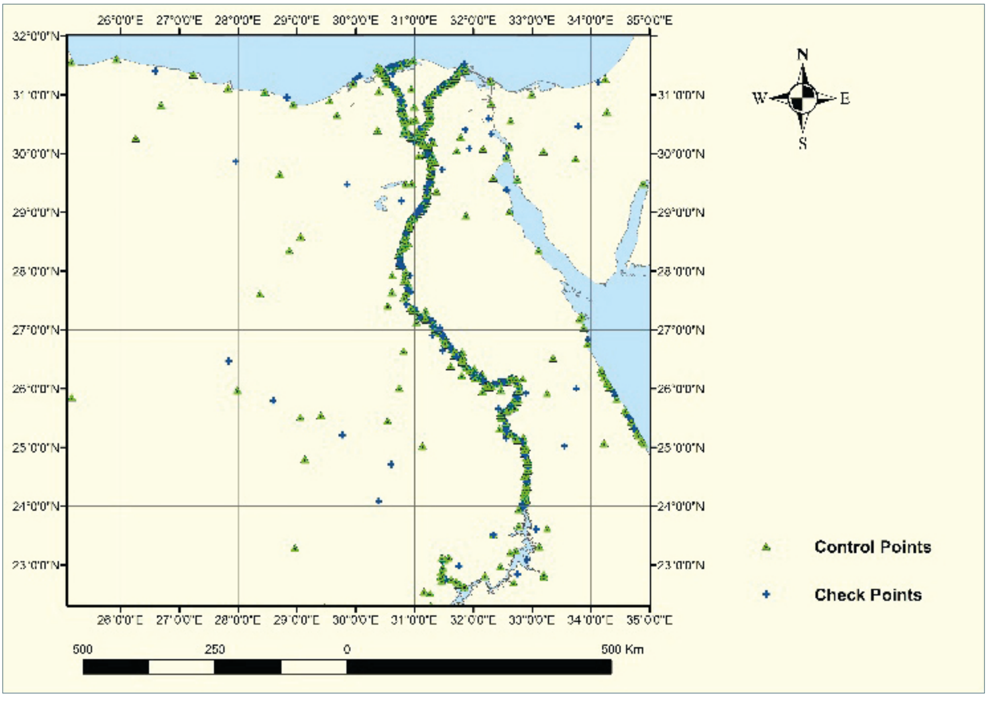

Fig. 9. Distribution of control and check points

To enhance the DEM, the regression analysis approach was first followed, with both the independent variables: location (φ, λ) and the elevation (*Z*) values, and dependent ones – height (*H*), of the control points being used to determine the parameters of the regression equation. The calculated parameters of linear regression were then used to create the enhanced DEM by applying the regression equation at each cell of the DEM (Equation (1)).

Table 2 illustrates the parameters of the regression models and the *R* square for the three GDEMs based on the 500 control points.

Table 2. Coefficients of the regression models for the three GDEMs

Coefficients	SRTM	ASTER	AW3D30
Intercept (β_0)	−3.835	61.942	−10.736
Latitude (β_1)	0.073	−2.555	−0.001
Longitude (β_2)	0.118	0.499	0.353
Elevation (β_3)	0.992	0.973	0.993
R square	0.998	0.987	0.999

The new height values (H_{enh}) at the 390 check points were determined for validation using Equation (1). The errors between the observed height values (H_{ob}) and the enhanced height values (H_{enh}) at the check points were calculated using Equation (2):

$$e = H_{ob} - H_{enh} \tag{2}$$

where:

e – error in enhanced height,
H_{ob} – observed orthometric height in the field,
H_{enh} – enhanced orthometric height by the enhancement model.

The maximum, minimum, mean, and RMSE of the errors based on the regression analysis enhancement approach are illustrated in Table 3.

Table 3. Evaluation results of the regression models for the three GDEMs using the 390 check points

	SRTM	ASTER	AW3D30
Max	10.94	32.69	10.84
Mean	−0.27	−0.49	−0.05
Min	−14.55	−26.19	−8.70
RMSE	3.86	7.44	2.90

In the second approach, the residual values between the elevation value extracted from the DEM (Z) and the observed height (H_{ob}) at the 500 control points were calculated for the SRTM, ASTER, and AW3D30 DEMs (Equation (3)). The maximum, minimum, mean, and RMSE values of the residuals based on the 500 control points are illustrated in Table 4. The calculated residuals at the 500 control points were used to create the surfaces of residuals using the natural neighbour interpolation technique, Figure 10 illustrates the created residual surfaces for the three DEMs:

$$r = Z - H_{ob} \tag{3}$$

Table 4. Univariates of residuals in the three available GDEMs at the 500 control points

	SRTM	ASTER	AW3D30
Max	10.48	82.28	11.14
Mean	−1.41	−4.39	0.07
Min	−11.88	−103.68	−11.45
RMSE	3.67	11.66	3.02

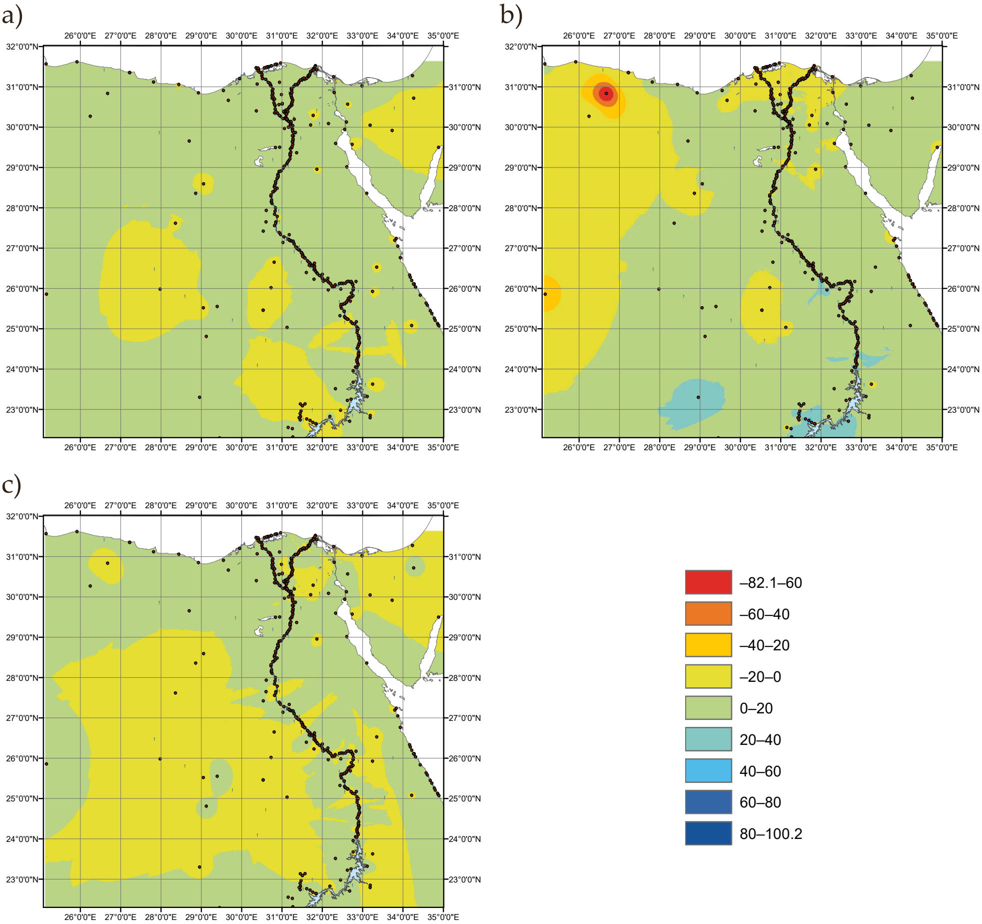

Fig. 10. The residual surfaces for the three GDEMs:
a) SRTM; b) ASTER; c) AW3D30

After that, the values of the residual surfaces at each pixel were subtracted from the original DEMs to produce the enhanced ones. To evaluate the enhanced DEMs, the new enhanced heights (H_{enh}) at the 390 check points were extracted from each of the enhanced DEMs. Then, the errors in the enhanced DEMs were calculated using the extracted values and the observed heights (H_{ob}), as in Equation (2). The maximum, minimum, mean, and RMSE of the errors based on the surface subtraction empirical enhancement approach are illustrated in Table 5. It can be seen that there are more improvements in the accuracies of the enhanced DEMs with respect to the accuracies of both the original ones and the enhanced DEMs using the regression analysis approach. Additionally, the fact remains that the AW3D30 is still the most accurate.

Table 5. Evaluation results of the surface subtraction approach for the three GDEMs using the 390 check points

	SRTM	ASTER	AW3D30
Max	13.94	21.35	12.69
Mean	−0.27	0.18	0.08
Min	−14.46	−29.33	−12.86
RMSE	3.78	6.75	2.50

5. Discussion

From the literature, the expected accuracies of the three GDEMs are 16 m for SRTM [8], from 5 m to 20 m for ASTER GDEM [9], and within 5 m for the AW3D30 [11–13]. An additional assessment was conducted on a continental basis for the SRTM that show an expected accuracy within 5.6 m as an absolute height error (90% error) for Africa [14, 15]. Other local studies conducted to evaluate the SRTM concluded that the expected error in height ranges between 4 m and 23 m [17–20, 22], and that the accuracies of the ASTER GDEM ranges between 13 m and 19 m [18–20]. Meanwhile, for the AW3D30 DEM, previous studies concluded that the expected accuracy was around 5 m [22].

Nevertheless, by analyzing the assessment results of the GDEMs for Egypt, it can be discerned that the RMSE of the residuals in the three GDEMs based on the 390 check points are 3.99 m, 8.81 m, and 2.98 m for SRTM v4.1, ASTER GDEM v2, and AW3D30 v2, respectively. These obtained accuracies are better than the accuracies of the three GDEMs in the literature. It is worth mentioning that the improvement of these accuracies might be because hilly and mountainous areas were not covered in this research work as no funding was available for such field measurements. Therefore, more field measurements covering the hilly and mountains areas will be required in the future, where the effect of the slope of the Earth's surface on DEM accuracy will be investigated.

Additionally, based on the results of the evaluation illustrated in Table 1, it can be seen that the AW3D30 GDEM is more accurate than both the SRTM and the ASTER GDEMs, with a root mean square error (RMSE) equal to 2.98 m. Conversely, the ASTER GDEM is the least accurate, with a RMSE of 8.8 m.

After enhancing the GDEMs using the regression model based on the 500 control points, and by analyzing the derived coefficients of the regression model, it is clear that in both the SRTM and the AW3D30 DEM, the latitude variable has minor effects in the prediction of height values (β_1 = 0.073, and −0.001 for the SRTM and the AW3D30, respectively). However, in the ASTER DEM, the Latitude variable has a considerable negative effect ($\beta_1 = -2.555$) this may be referred to the greater error in the ASTER DEM). At the same time, the Longitude variable has a considerable effect on the predicted Height value in the three DEMs (β_2 = 0.118, 0.499, and 0.353 for the SRTM, ASTER and AW3D30 DEMs respectively).

The evaluation of the enhanced DEMs by means of the regression model, as illustrated in Table 3, show an improvement in the accuracy of the DEMs. By comparing the results in Table 1 (the evaluation of the original DEMs) and Table 3 (the evaluation of the enhanced DEMs), it can be seen that there are slight improvements in the accuracies. Furthermore, the AW3D30 is still the most accurate.

According to the evaluation of the enhanced DEMs using the proposed surface subtraction approach, the results illustrated in Table 5 show further improvement. By collecting the results from Tables 1, 3, and 5, the improvement in the accuracies of the DEMs are illustrated in Table 6. Additionally, the calculated improvement of the accuracies as a result of using the two enhancement approaches compared to the original accuracies is shown. It can be noticed that the enhanced DEM using the new proposed approach are more accurate than the enhanced DEM using the regression analysis approach. The improvement in the accuracy when the regression analysis approach was used were; 3% in the SRTM, 16% in the ASTER, and 3% in the AW3D30 GDEMs. However, when the proposed surface subtraction approach was followed, the accuracy of the enhanced DEMs improved by 5%, 23%, and 16% for the SRTM, ASTER, and AW3D30 GDEMs respectively.

Table 6. Improvement of DEM accuracy using the regression model and the proposed enhancement approaches

	RMSE for original DEM	RMSE for enhanced DEM		Improvement in enhanced DEM [%]	
		regression model	proposed approach	regression model	proposed approach
SRTM	3.99	3.86	3.78	3	5
ASTER	8.81	7.44	6.75	16	23
AW3D30	2.98	2.90	2.50	3	16

6. Conclusions

The aim of this research was to enhance the GDEMs for Egypt, using the three different available GDEMs: SRTM v4.1, ASTER GDEM v2, and AW3D30 v2. These were all downloaded and assessed. By observing and analyzing the accuracies of the three available GDEMs for Egypt, it can be concluded that the AW3D30 DEM has higher accuracy than the SRTM and the ASTER, while the ASTER DEM is the least accurate. The RMSE of the residuals of the used 390 check points were: 3.99 m, 8.81 m, and 2.98 m for SRTM, ASTER GDEM, and AW3D30 respectively.

By using the enhancement approaches, the accuracies of the GDEMs were improved by 3% for SRTM, 16% for ASTER and 3% for AW3D30 GDEMs when the regression analysis approach was used. Moreover, more improvement in the accuracies was obtained when the proposed surface subtraction enhancement approach was applied, where the accuracies improved by 5%, 23%, and 16% for SRTM, ASTER and AW3D30 GDEMs respectively. The final accuracy of the AW3D30 DEM reached 2.5 m when the proposed error surface subtraction approach was used. Therefore, the proposed error surface subtraction approach has more advantages over the regression analysis approach.

It is worth mentioning that enhancing the GDEM for the entire country was applicable since a large number of collected GPS/levelling points could be obtained. Hence, it can be concluded that this approach is applicable in Egypt and for any other region if efficient data are available.

Author Contributions

Nagwa El-Ashmawy (first author): conceptualization, methodology, validation, formal analysis, writing – original draft preparation, writing – review and editing, visualization, supervision.

Essam Al-Krargy (second author): investigation, data curation, formal analysis, validation, writing – review and editing.

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