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ORIGINAL ARTICLE

A new digital elevation model over South Africa based on ground and satellite data

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Abstract:

This study makes contributions toward development of accurate DEM from ground and satellite data over South Africa. This is achieved by preparing recent satellite-based DEMs (AW3D30, SRTM, ASTER, TanDEM-X, and MERIT), assessing their vertical accuracy, selecting candidate DEMs, modelling errors for the candidate DEMs and fusing candidate DEMs. Following removal of outliers from each DEM, a different number of ground levelling data are used in the assessment of the DEMs (AW3D30 – 26,364 points, SRTM – 25,727, ASTER – 23,773, TanDEM-X – 25,964 and MERIT– 24,485). The standard deviations of the differences between ground levelling and DEMs heights are ±5.09, ±7.03, ±9.20, ±4.99 and ±8.36 m for AW3D30, SRTM, ASTER, TanDEM-X and MERIT, respectively. AW3D30 and TanDEM-X are therefore selected for fusion. The two candidate DEMs are improved by applying a combination of linear regression, multiple regression, and adaptive terrain-dependent methods using 17,307 model data points. A fused DEM is developed from improved candidate DEMs using a combination of different fusion methods and assessed using 8,657 data points (distinct from the model points). The standard deviation of the height differences between ground levelling and the fused DEM is ±4.290 m, and it is more accurate than all satellite based DEMs considered in this study.

Keywords: digital elevation model; vertical accuracy; DEM fusion; ground levelling.

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1. Introduction

A digital elevation model is one of the basic and most frequently used topographic digital representations and has many applications, including but not limited to view-shed visibility analysis, landscaping, water modelling, marine observation, and geological land observation (ElSayed and Ali, 2016; Tian et al., 2018). It is also one of the important datasets for geodetic survey applications such as classification of topography for earthquake motion assessment, flood overflow modelling, soil erosion, and sediment yield prediction (Yamazaki et al., 2017). Techniques for generating DEMs include ground surveying, photogrammetry, airborne laser scanning, and satellite remote sensing (ElSayed and Ali, 2016). Ground field surveying, photogrammetry, light detection and ranging (LiDAR), and very high-resolution satellite data generate DEMs with high accuracies and resolutions (Tran et al., 2014; Tian et al., 2018). However, these techniques can be very costly especially for larger coverages (Gómez et al., 2012; Tran et al., 2014).

The satellite based DEMs generated, either from InSAR or optical stereoscopy, are the most used DEMs, especially in studies that require global coverage. Until now, the most popular near-global DEMs that are available at resolution of about 30 m include the Shuttle Radar Topography Mission (SRTM), TerraSAR-X add-on for Digital Elevation Measurement (TanDEM-X), Advanced Land Observing Satellite World 3D (AW3D) and Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER). These DEMs have been used by many scientists for different scientific studies (O'Loughlin et al., 2016). However, some of them are subjected to incomplete results and errors (Karkee et al., 2008). Many authors (Uuemaa et al., 2020; Santillan and Makinano-Santillan, 2016; Mahesh et al., 2021; Han et al., 2021) have conducted DEM validation studies in various parts of the world. The results from these studies indicate that the AW3D30 has the highest vertical accuracy compared to all other freely available satellite based DEMs. The results also indicate that the ASTER DEM shows the worst performance compared to all the free satellite based DEMs. Similar results have been obtained in the western part of South Africa (Malindi and Odera, 2021).

There have been several attempts for enhancing quality of these free satellite based DEMs. Some authors (Shortridge and Messina, 2011; Su and Guo, 2014; Su et al., 2015; ElSayed and Ali, 2016; Ali et al., 2018; Tian et al., 2018; Gorokhovich and Voustianiouk, 2006) have attempted to model satellite-based DEM errors using simple and multiple linear regression in studies carried out in various parts of the world. Zhou et al. (2020) also proposed an adaptive terrain method for modelling satellite-based DEM errors over mountainous areas. Because of the redundancy of DEM data and the need to further reduce errors in satellite based DEMs, fusion techniques have been developed (Tian et al., 2018). In several studies, several methods for DEM fusion have been proposed and examined. Many authors (Papasaika et al., 2011; Tran et al., 2014; Bagheri et al., 2018; Mohamed and Saleh, 2018; Roth et al., 2002; Reinartz et al., 2005) have proposed simple techniques such as weighted averaging, and the simple averaging of input DEMs. A variety of advanced techniques for DEM fusion have been proposed, these include but not limited to linear combination (Pham et al., 2018), frequency domain fusion (Karkee et al., 2008), multi scale fusion (Tian et al., 2018), active surface fusion (Kass et al., 1988), Ordinary cokriging (Johnston et al., 2001; Setiyoko et al., 2019), modified *k*-means clustering fusion (Fuss et al., 2016), sparse representation (Papasaika et al., 2011), and self-consistency fusion (Schultz et al., 2002). After considering computing capacity and data structure requirements against the minimal gain in the accuracy between simple and advanced fusion methods, this study adopted the simple fusion techniques due to a lack of accurate continuous reference DEM and computing capacity required to implement advanced fusion techniques over large areas.

South Africa has some national DEMs that have been used in scientific research. They include the Chief Directorate: National Geo-Spatial Information (CD: NGI) DEM, Stellenbosch University Digital Elevation Model (SUDEM) which is part of the efforts made in South Africa to produce a high-resolution national DEM that reduces anomalies in satellite based DEMs, and Computamaps™ South African Digital Terrain Model (SADTM). The CD: NGI

DEM is available for free, while the SUDEM and SADTM are available at a cost. As far as the authors are aware, the publicly available free 25 m resolution DEM provided by the CD: NGI does not provide the full coverage of the country, some tiles are missing, some tiles contain pixels with incorrect height information. In addition, The LiDAR data available for non-commercial work only covers certain locations such as the City of Cape Town.

The South African ground levelling (trigonometrical beacon) data heights have a precision of about ± 0.1 m and are more capable of representing the terrain height accurately. However, the data points are farther apart, making it difficult to accurately represent the topography over South Africa as a continuous surface. On the other hand, the satellite based DEMs over South Africa provide moderately accurate surface representation but are associated with speckle noise, strip noise, voids, and vegetation errors, limiting their applications. Now the challenge is how to ground levelling data and satellite-based DEMs to develop a more accurate DEM over South Africa that draws from the strengths of the two data sets (ground and satellite-based data) and reduces errors to improve its applications.

Since freely available local DEMs are less accurate and have limited coverage while relatively more accurate commercial DEMs are more costly beyond the reach of many users, there is a need to develop an accurate DEM based on freely available satellite based DEMs and ground levelling data for the whole of South Africa for various applications, at no cost. This paper proposes an approach to develop an accurate digital elevation model over South Africa. This is achieved by preparing satellite-based DEMs, assessing the quality of the satellite-based DEMs, selecting candidate DEMs for fusion, modelling errors in the candidate DEMs, and fusing selected DEMs.

2. Study area and datasets

2.1 Study area

The study site is the whole of South Africa, and it is located between latitudes 22–35°S and longitudes 17–33°E. It has an area of approximately 1.22 million km^2. The region consists of high, middle, and low terrain elevation with a mountain height range of up to 3,475 m. The physical features range from grasslands, forests, deserts, bushveld, mountain peaks and coastal wetlands. Figure 1 shows the spatial location of the study area.

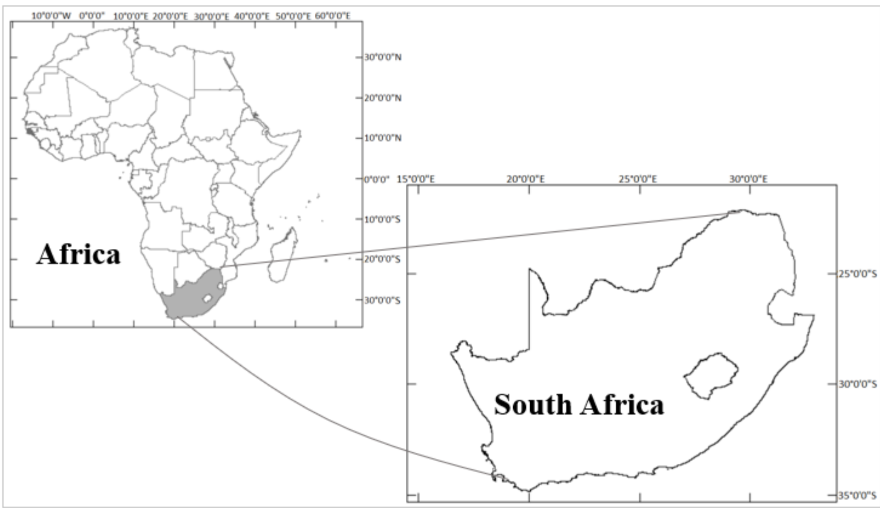

Figure 1: Spatial location of the study area.

2.2 Datasets

The data sources for satellite based DEMs are given in Table 1. The South African hybrid quasigeoid model of 2010 (SAGEOID10) was used for converting ellipsoidal height to spheroidal orthometric height where necessary while South African National Land Cover for 2018 (SANCL2018) was applied in the accuracy assessment of DEMs. In addition, the ground levelling (trigonometrical beacon) data was used as reference for validation, error modelling and fusion parameter derivation. The vertical accuracy for the ground levelling data is ±0.1 m and there are 27,350 ground levelling data points over South Africa (Figure 2).

Table 1: DEM types, sources, spatial resolution, and accuracies.

Dataset	Spatial resolution	Source	Vertical accuracy specifications
SRTM	30 m	USGS (https://www.usgs.gov/)	< ±16 m absolute & < ±6 m relative
ASTER	30 m	Earthdata(NASA) (https://search.earthdata.nasa.gov/search)	< ±16 m absolute & < ±6 m relative
AW3D30	30 m	JAXA (https://eorc.jaxa.jp/ALOS/en/aw3d30/data/index.htm)	< ±5 m absolute
TanDEM-X	30 m	Geoservice (https://download.geoservice.dlr.de/TDM90/)	< ±10 m absolute
MERIT	90 m	Yamazakilab (http://hydro.iis.utokyo.ac.jp/~yamadai/MERIT_DEM/)	< ±12 m absolute

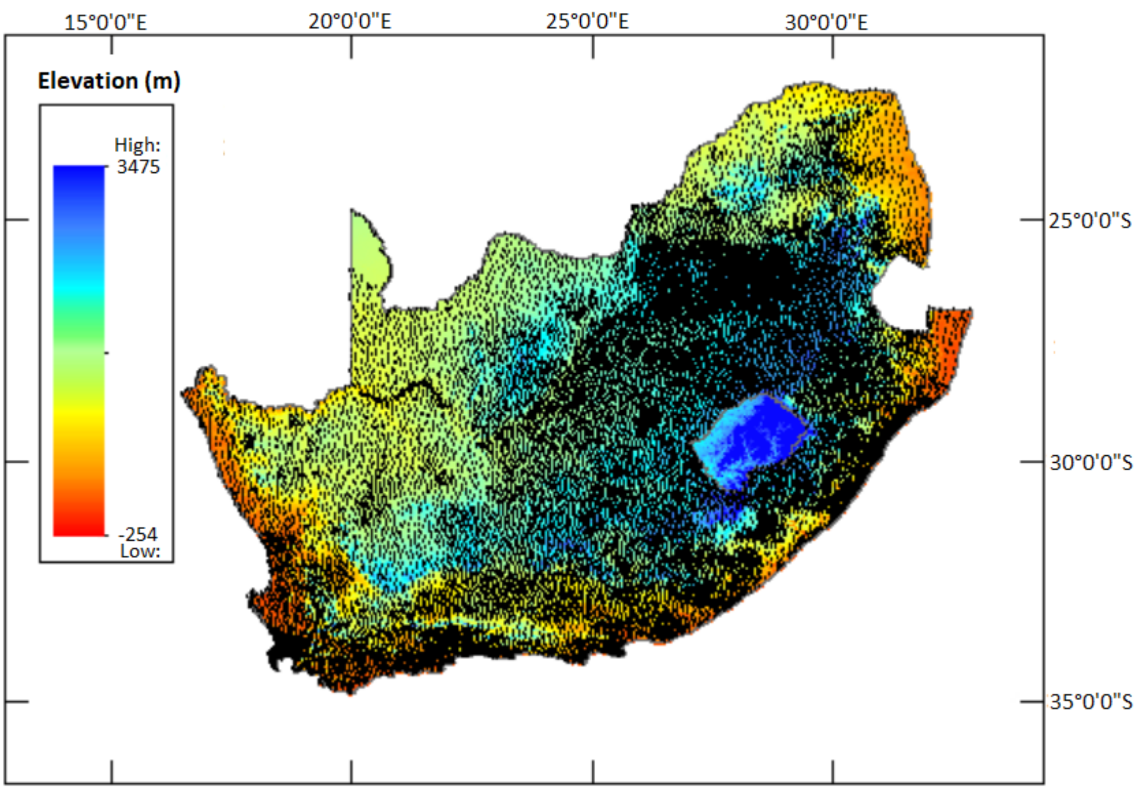

Figure 2: Distribution of 27,350 levelling data points with black dots representing levelling data points.

The SRTM, ASTER, AW3D30, TanDEM-X, and MERIT data offer worldwide coverage. The horizontal positions for SRTM, ASTER, AW3D30 and MERIT data are referred to WGS84 while vertical positions are based on EGM96. Although the horizontal datum for TanDEM-X is WGS84, the heights are ellipsoidal, hence the need for conversion to spheroidal orthometric heights used in South Africa. The South African quasigeoid model of 2010 (SAGEOID10) is a 2.5 x 2.5 arc-minutes hybrid quasigeoid model covering the whole of South Africa. The data was downloaded as an ASCII data file containing 128,017 quasigeoid height points. The SAGEOID10 model is estimated to have an accuracy of better than 10 cm and was generated using satellite altimetry, global DEM, land-based gravity measurements, the Earth Gravity Model 2008, and GPS/levelling datasets (Chandler and Merry, 2010). The SAGEOID10 height anomalies for 128,017 grid points were downloaded from the ISG website (https://www.isgeoid.polimi.it/Geoid/geoid_rep.html).

The South African National Land Cover for 2018 (SANCL2018) has a 20 m resolution and covers the full extent of South Africa. The dataset was generated from a multi-seasonal 20 m resolution Sentinel 2 satellite imagery. The imagery used represents the complete temporal range of accessible imagery attained by Sentinel 2 through the period 01 January to 31 December 2018 (https://www.environment.gov.za/mapsgraphics).

2.3 Data pre-processing

Each freely available satellite-based DEM comes in several raster tiles. Therefore, a mosaic of the raster data tiles is done. Mosaicking of tiles combines all the raster tiles to produce one continuous raster. This process is achieved using a data management tool from the ArcMap (ArcGIS 10.7.1) by first creating a blank raster dataset followed by combination of the tiles of the raster data using the raster mosaic tool, then the continuous mosaiced output raster is stored within the directory of the blank raster dataset. A conversion of TanDEM-X heights from ellipsoidal to spheroidal orthometric height is done using height anomaly as follows,

$$H = h - \zeta \tag{1}$$

where, H is the spheroidal orthometric height, h is the ellipsoidal height (TanDEM-X height), and ζ represents the height anomaly (SAGEOID10 quasigeoid undulation in this case).

It should be noted that orthometric height system used in South Africa is spheroidal orthometric, which is more consistent with the quasigeoid than geoid model (Mphuthi and Odera, 2022). The SAGEOID10 is a hybrid quasigeoid model obtained by fitting a gravimetric quasigeoid model onto the GPS/levelling quasigeoid over South Africa. The accuracy of this hybrid quasigeoid model is ± 7.0 cm as reported by Chandler and Merry (2010). Therefore, transformation of ellipsoidal to spheroidal orthometric heights is considered accurate enough for the current study. However, it is worth noting that the SAGEOID10 may not be so accurate in the high mountainous areas, this may slightly affect accuracy of spheroidal orthometric height obtained from ellipsoidal height. A total of 128,017 quasigeoid height points from SAGEOID10 are used in interpolating a 30 m resolution raster surface using the inverse distance weighted (IDW) technique to facilitate conversion of ellipsoidal height to spherical orthometric height for the TanDEM-X. Voids detected on SRTM DEM only are filled using the Arc GIS Elevation Void Fill function. To determine the presence of voids for each satellite-based DEM, a conditional map algebra expression is used in classifying the data into two classes (with value and no value). The Arc GIS Elevation Void Fill function is used to create pixels in DEMs where holes exist then the Plane Fitting/ IDW method is applied to fill the voids. The value of the missing pixel is calculated by taking the average of eight neighbouring pixel values, then the plane fitting method is applied, in case the error of the plane fitting method is too large, an inverse distance weighted (IDW) algorithm is applied.

3. Methods

An accurate DEM based on satellite and ground data over South Africa is developed using the following steps. Firstly, assessment of satellite based DEMs (AW3D30, SRTM, ASTER, TanDEM-X, and MERIT) using ground levelling data and selection of candidate DEMs for fusion. Secondly, modelling errors in the candidate DEMs. Finally, fusing the error-modelled candidate DEMs.

3.1 Assessment of satellite-based digital elevation models

The assessment of the DEMs includes validation of the vertical accuracy of DEMs over South Africa by determining the absolute differences in heights between the DEMs and ground levelling points starting with all data points (27,350) and removing outliers. Outliers are removed using a method that focuses on a percentage of height differences with respect to ground levelling data heights (taking > 3% to be outliers). This method is a more thorough approach of identifying outliers because it can identify outliers that cannot be visually identified by plotting data and using common sense or global statistics (mostly mean and standard deviation). The method also ensures that elevation data in high areas that are normally less accurate on DEMs are not arbitrarily removed while errors in more accurate elevation data in low areas are detected and removed. Several tests were conducted using different percentages before arriving at 3% for application in this research. The method is applied to each DEM, then remaining points are used in the subsequent validation processes. The percentage difference is computed as follows,

$$H_{error} = \frac{|\Delta H| \times 100}{H^{Trig}} \tag{2}$$

where $\Delta H = H^{Trig} - H^{DEM}$. Height error values corresponding to more than 3% are considered outliers and are removed. The statistics of the height differences of the remaining points (AW3D30 – 26,364, SRTM – 25,727, ASTER – 23,773, TanDEM-X – 25,964 and MERIT– 24,485) are then computed for each DEM.

To study the Influences of elevation and slope on heights differences, extracted elevations and slopes corresponding to the ground levelling data are divided into different ranges, and statistical parameters for the height differences in each range are computed to assess the vertical accuracies. The slope raster used is generated using ArcMap (ArcGIS 10.7.1) spatial analysis surface tool for the full extent of South Africa using the SRTM DEM (Figure 3). The slope raster is generated from east-west and north-south gradients.

To study the influence of land use/cover on height differences, the land use/cover corresponding to the ground levelling data points is extracted, differences in heights in each land use/cover are determined, and statistical parameters for the height differences are computed. The influences of elevation and slope change on the vertical accuracy of each DEM over each land use/cover is assessed. Regarding land use/cover, the South African National land use/cover is reclassified into 3 classes of land use/cover (low, medium, and high) as shown in Figure 4. The low land use/cover is composed of bare land, grassland, shrub-land, water bodies, and wetlands. The medium land use/cover is composed of agricultural/cultivated land while the high land use/cover is composed of forestland and built-up areas.

3.2 Error modelling for the candidate DEMs

Based on the slope ranges (0–2.5°, 2.5–5.5°, 5.5–7.5°, 7.5–10°, 10–20° and >20°), a selection of different error modelling methods that have high effect in improving the vertical accuracy of the candidate DEMs (AW3D30 and TanDEM-X) in each slope range is made after empirical investigations using model data (Figure 5) and test data (Figure 6). It should be noted that AW3D30 is first co-registered to the TanDEM-X grid lines. A sample of 66.7% of ground levelling data points from each region are randomly selected as model data points using random sampling techniques and considering slope variations (Figure 5) while the remaining 33.3% data points are selected as test data points (Figure 6) to test both corrected/improved and fused DEMs. The numbers of model and test data points in each of the six regions are given in Table 2. The selected methods for each range are combined to generate final correction models applied to the candidate DEMs (AW3D30 and TanDEM-X) in each of the six regions. Original candidate DEMs are also used in very few instances where correction models do not provide improvements. The correction models used in the current study include simple linear regressions (SLR), multiple linear regressions (MLR), and adaptive terrain-dependent method (ATM) with parameters determined using ordinary least squares (OLS) and robust least squares (M-estimator). These models are used to estimate spatial relationship between slope and DEMs height errors at model data points to facilitate height error prediction at any other point within a region. The specific correction models applied in each region are provided in the subsequent paragraph.

In region 1, the correction model for AW3D30 is a combination of ATM for slope less than 2.5° and greater than 7.5°, and MLR for slope 2.5–7.5° while the correction model for TanDEM-X is a combination of ATM for slope less than 2.5° and greater than 20°, ATM for slope 2.5–5.5° and 7.5–10°, SLR for slope 5.5–7.5°, and MLR for slope 10–20°. In region 2, the correction model for AW3D30 is a combination of SLR for slope less than 2.5°, MLR for slope 2.5–7.5° and ATM for slope greater than 7.5° while the correction model for TanDEM-X is a combination of SLR for slope less than 2.5°, MLR for slope 2.5–7.5°, original TanDEM-X for slope 7.5–10°, and ATM for slope greater than 10°. In region 3, the correction model for AW3D30 is a combination of MLR for slope less than 7.5°, and ATM for slope greater than 7.5° while the correction model for TanDEM-X is a combination of MLR for slope less than 10°, SLR for slope 10–20°, and ATM for slope greater than 20°. In region 4, the correction model for AW3D30 is a combination of SLR for slope less than 2.5°, MLR for slope 2.5–5.5° and 7.5–10°, and ATM for slope 5.5–7.5° and greater than 10° while the correction model for TanDEM-X is a combination of MLR for slope less than 5.5° and 7.5–20°, and ATM for slope 5.5–7.5° and greater than 20°. In region 5, the correction model for AW3D30 is a combination of ATM for slope less than 2.5° and 10–20°, MLR for slope 2.5–7.5°, ATM for slope 7.5–10°, and original AW3D30 DEM for slope greater than 20° while the correction model for TanDEM-X is a combination of ATM for slope less than 5.5°, and slope 5.5 –7.5°, MLR for slope 7.5–10°, SLR for slope 10– 20°, and original TanDEM-X DEM for slope greater than 20°. Finally, in region 6, the correction model for AW3D30 is a combination of ATM for slope less than 5.5° and greater than 7.5°, and SLR for slope 5.5–7.5° while the correction model for TanDEM-X is a combination of ATM for slope less than 10° and greater than 20°, and MLR for slope 10–20°.

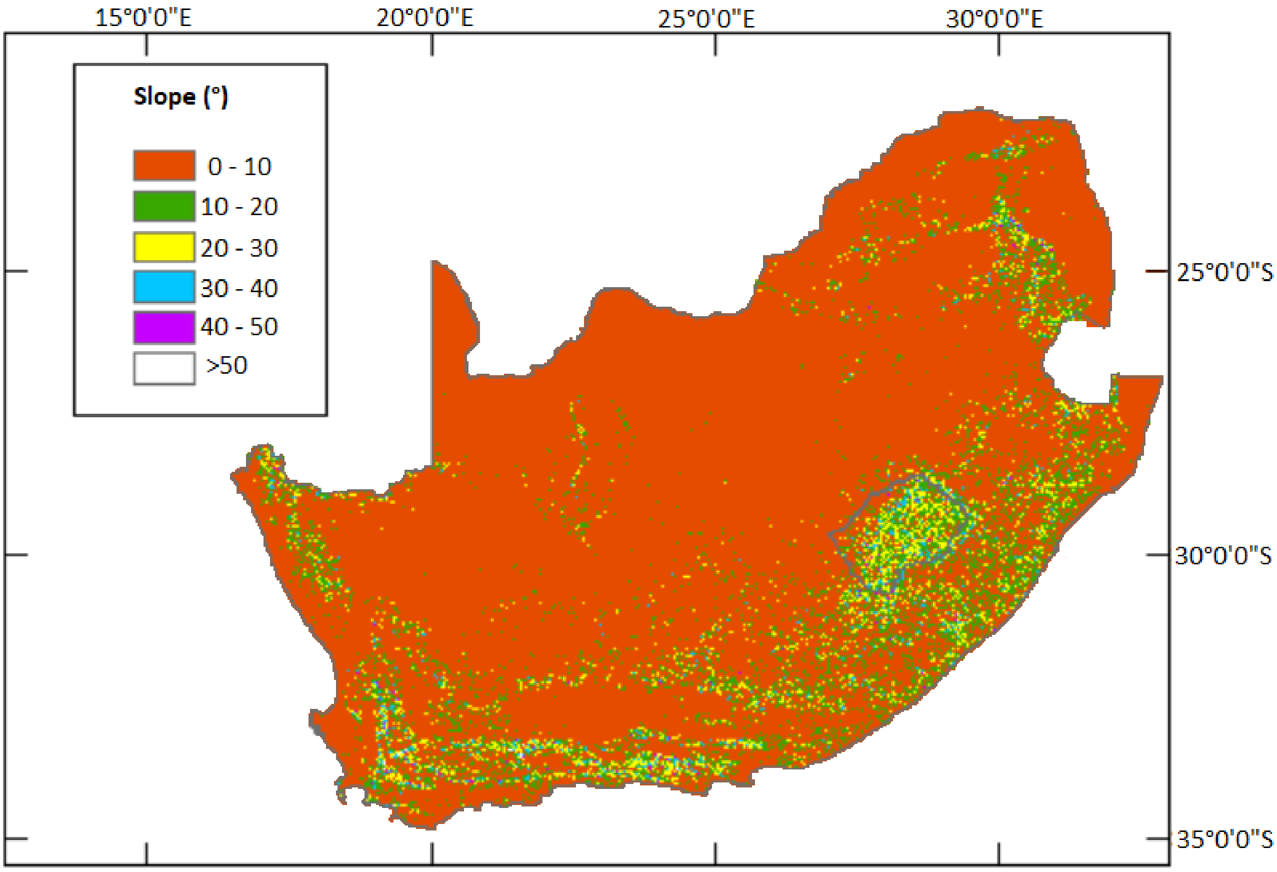

Figure 3: Categorised slope representation over South Africa based on SRTM data (units are in angular degrees).

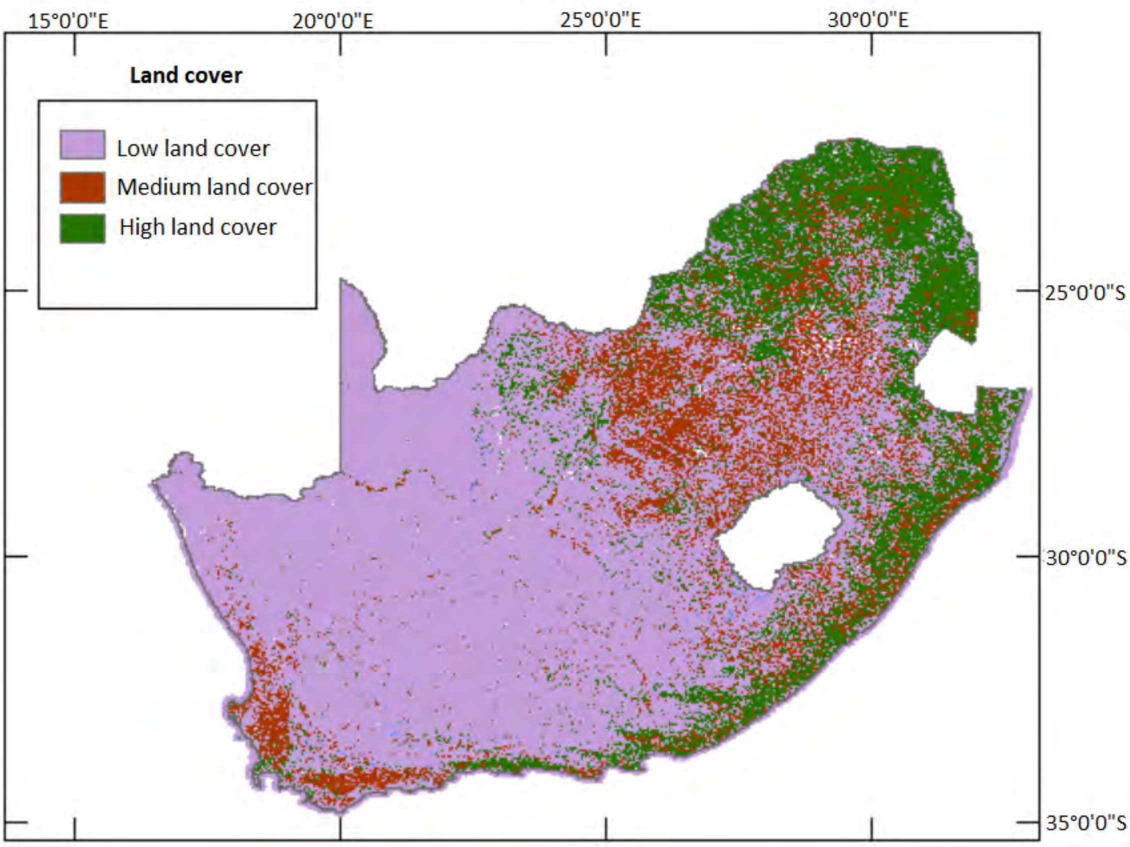

Figure 4: Categorised land use/cover over South African.

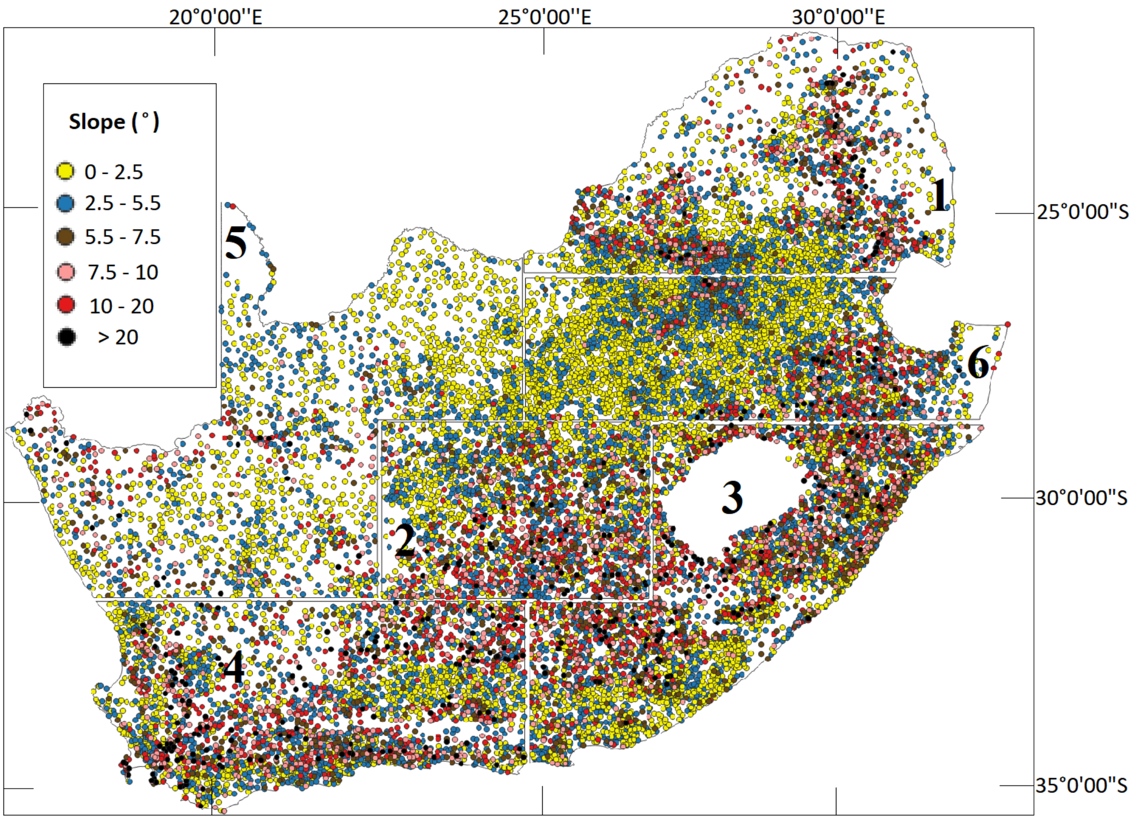

Figure 5: Spatial distribution of 17,307model data points falling in different slope ranges over the six regions. Units for the slope range are in angular degrees.

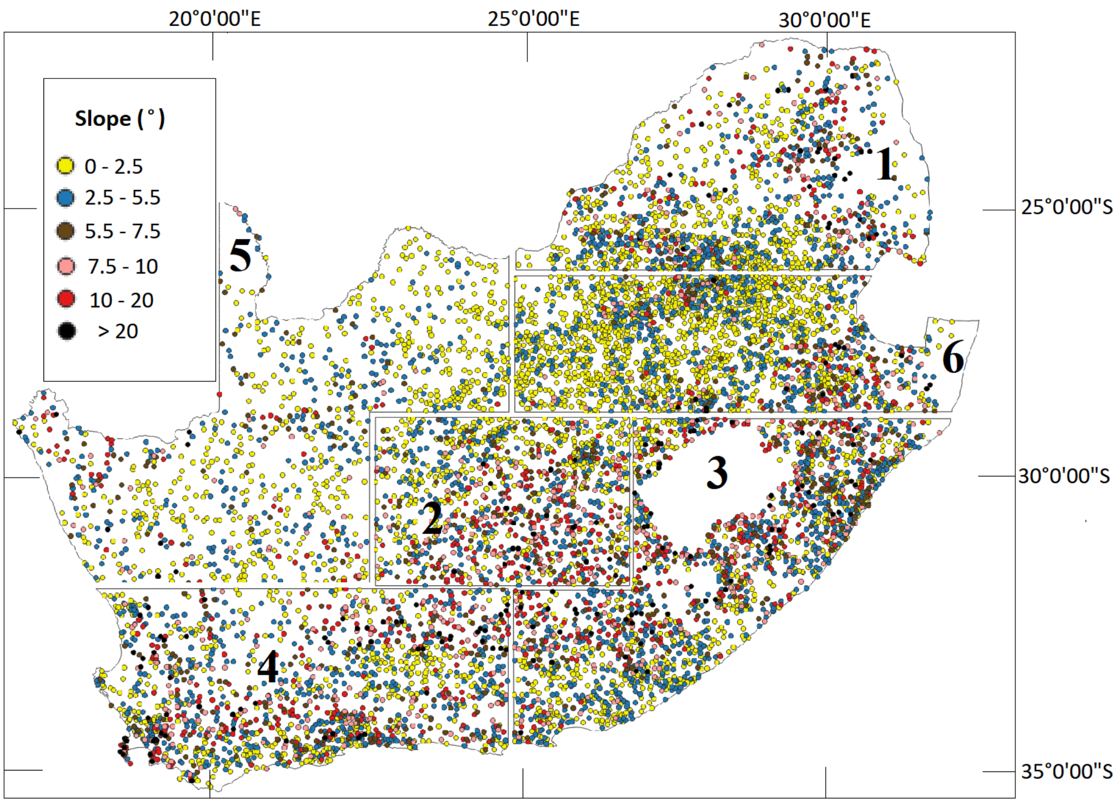

Figure 6: Spatial distribution of 8,657 test data points falling in different slope ranges over the six regions. Units for the slope range are in angular degrees.

Table 2: Number of model and test points in the six regions.

Region	1	2	3	4	5	6	Total
Model data	2,437	2,191	3,801	2,999	1,929	3,950	17,307
Test data	1,219	1,095	1,901	1,500	965	1,977	8,657
Total	3,656	3,286	5,702	4,499	2,894	5,927	25,964

3.3 Fusion of the candidate DEMs

The DEM fusions are between the corrected AW3D30 and TanDEM-X DEMs using model ground levelling data to derive fusion parameters in the six regions (Figures 5 and 6). The fusions methods applied include the linear combination, weighted averaging and averaging of the DEMs. Corrected candidate DEMs are also used in very few instances where no direct fusion methods tested provide improvements. Th selection of fusion methods is based on empirical evaluations. The final fusion in region 1 consists of linear combination for slope less than 2.5° and greater than 20°, corrected TanDEM-X for slope 2.5–5.5° and 10–20°, averaging for slope 5.5–7.5°, and weighted averaging for slope 7.5–10°. The final fusion in region 2 consists of linear combination for slope less than 5.5°, and corrected TanDEM-X for slope greater than 5.5°. The final fusion in region 3 consists of linear combination for slope less than 2.5° and 10–20°, corrected TanDEM-X for slope 2.5–7.5°, averaging for slope 7.5–10°, and corrected AW3D30 for slope greater than 20°. The final fusion in region 4 consists of linear combination for slope less than 2.5° and 7.5–20°, corrected TanDEM-X for slope 2.5–7.5°, and corrected AW3D30 for slope greater than 20°. The final fusion in region 5 consists of linear combination for slope less than 2.5°, corrected TanDEM-X for slope 2.5–10°, and weighted averaging for slope greater than 10°. The final fusion in region 6 consists of linear combination for slope less than 2.5° and 10–20°, and corrected AW3D30 for slope 2.5–10° and greater than 20°.

The validation of the fused DEM is achieved using test points in each of the six regions (Figure 6). The process includes finding the height differences between the ground levelling data and the fused DEM. The original DEMs (TanDEM-X, SRTM, ASTER, MERIT, AW3D30, and co-registered AW3D30) and corrected candidate DEMs are also compared to the fused DEM. The comparison is done using height differences between 8,657 ground levelling test data points and the DEMs. It should be noted that these are independent test data not used in the error modelling and fusion processes.

4. Results and discussion

4.1 Validation results for the original satellite based DEMs

Statistical results for the absolute height differences between the DEMs and the ground levelling data after removing outliers are presented in Table 3.

Table 3: Absolute height differences between the DEMs and ground levelling data over South Africa (Units are in m).

	AW3D30	SRTM	ASTER	TanDEM-X	MERIT
N	26364	25727	23773	25964	24485
Min	-34.90	-37.80	-40.70	-28.83	-18.62
Max	74.30	66.20	63.20	73.95	72.29
Mean	2.94	3.81	9.35	4.27	7.91
SD	5.09	7.03	9.20	4.99	8.36

The absolute height differences after removing outliers between the DEMs (AW3D30, SRTM, ASTER, TanDEM-X, and MERIT) and ground levelling data have standard deviations of ±5.09, ±7.03, ±9.20, ±4.99, and ±8.36 m, respectively with mean values of 2.94, 3.81, 9.35, 4.27, and 7.91 m, respectively (Table 3). These results indicate that the TanDEM-X achieves better absolute vertical accuracy compared to all other DEMs followed by the AW3D30, SRTM, MERIT, and ASTER, respectively in that order. The standard deviations for TanDEM-X and MERIT are within the vertical accuracy specifications of better than ±10 and ±12 m, respectively. The SRTM and ASTER vertical accuracy specifications of better than ±16 m is met and the AW3D30 original specification of better than ±5 m is marginally met.

The variations of standard deviations of the differences between ground levelling and satellite based DEMs over varying elevations and slopes are presented in Tables 4 and 5, respectively. In general, there is a relationship between the standard deviation of the height differences with elevation and slope. As the elevation and slope increases, the standard deviation also increases meaning deterioration in the vertical accuracy. In Table 4, the lowest standard deviations for all the DEMs are found in the height range (0 to 500 m). The highest standard deviation for AW3D30, SRTM, TanDEM-X, and MERIT are found in the height range greater than 3000 m. However, it should be noted that results for elevation more than 3000 m may not be accurate due to very few numbers of test points. Although the standard deviations depict a relationship, a very weak linear (positive) correlation between the elevation and height differences for all DEMs is indicated by the low correlation coefficient (R^2).

Table 4: Variation of standard deviation of the differences between ground levelling and satellite based DEM heights with elevation over South Africa. Both elevation range and standard deviation are in m.

DEM	Elevation range	0 - 500	500 - 1000	1000 - 1500	1500 - 2000	2000 - 2500	2500 - 3000	> 3000	R^2
AW3D30	N	3184	4629	10854	7105	540	49	3	0.01
	SD	2.63	4.04	5.19	5.99	7.01	6.15	15.05	
SRTM	N	2722	4516	10818	7082	537	49	3	0.01
	SD	3.09	5.45	6.84	8.30	11.44	12.16	13.44	
ASTER	N	1200	4209	10709	7069	536	48	2	0.02
	SD	4.79	7.15	8.75	10.51	13.24	10.50	2.40	
TanDEM-X	N	2943	4605	10781	7065	519	48	3	0.02
	SD	2.15	3.32	4.54	6.42	9.67	10.79	19.39	
MERIT	N	1923	4197	10710	7073	530	49	3	0.03
	SD	3.16	6.02	8.02	9.78	12.95	14.32	14.85	

Table 5: Variation of standard deviation of the differences between ground levelling and satellite based DEM heights with slope over South Africa. Units for slope range are in angular degrees while standard deviations are in m.

DEM	Slope range	0° - 2°	2° - 4°	4° - 6°	6° - 8°	8° - 10°	> 10°	R^2
AW3D30	N	9433	7121	3245	1927	1332	3306	0.05
	SD	4.54	5.14	5.02	4.90	4.63	5.84	
SRTM	N	9371	7033	3171	1856	1266	3030	0.30
	SD	4.97	5.83	6.20	6.29	6.06	8.75	
ASTER	N	8669	6427	2893	1728	1186	2870	0.11
	SD	7.82	8.39	9.15	9.09	9.38	10.55	
TanDEM-X	N	9342	7038	3203	1892	1307	3182	0.11
	SD	4.34	4.76	4.49	4.45	3.55	6.79	
MERIT	N	9145	6745	2961	1718	1165	2751	0.32
	SD	5.21	6.48	7.21	7.56	7.97	10.27	

In Table 5, all the DEMs have the lowest standard deviations in areas with the slope range (0° to 2°). The highest standard deviations for all the DEMs are found in the slope range greater than 10°. Although the standard deviations depict a relationship with slope, the coefficient of determination (R^2) indicates a very weak linear (positive) correlation between the slope and height differences for the AW3D30, ASTER, and TanDEM-X, and a moderate positive correlation for the SRTM and MERIT. It can be deduced that all DEMs applied in this study are relatively less accurate in steep slope and high elevation areas compared to gentle slope and low elevation areas.

The variations of standard deviations of the differences between ground levelling and satellite based DEMs over varying elevations and slopes in low, medium, and high land use/cover areas are presented in Tables 6 to 11. In Tables 6 and 8, the standard deviations for the height differences increase with an increase in elevation, meaning deterioration in the vertical accuracy. From these results, it can be deduced that vertical accuracies of DEMs degrade with an increase in elevation in low and high land use/cover areas. In all DEMs, areas with a height range (0 to 250 m) have the lowest standard deviations, and areas with a height range greater than 1750 m have the highest standard deviations. It is worth noting that the correlation coefficients indicate a very weak linear (positive) correlation between the elevation change and height differences for all DEMs.

Table 6: Variation of standard deviation of the height differences with elevation in low land use/cover areas over South Africa. Units for elevation and standard deviation are in m.

DEM	Elevation range	0 - 250	250 - 500	500 - 750	750 - 1000	1000 - 1250	1250 - 1500	1500 - 1750	1750 - 2000	>2000	R^2
AW3D30	N	689	898	1117	2258	3120	4512	4014	1368	580	0.01
	SD	1.78	3.06	3.58	3.65	4.08	4.41	4.82	5.24	7.06	
SRTM	N	541	756	1051	2222	3108	4495	3999	1356	577	0.01
	SD	2.00	3.57	5.15	5.51	5.99	6.91	7.39	8.69	11.60	
ASTER	N	137	364	887	2156	3075	4455	3995	1357	574	0.01
	SD	3.19	4.91	6.16	7.19	7.71	9.07	9.73	11.13	13.25	
TanDEM-X	N	585	874	1104	2256	3115	4484	3999	1351	558	0.01
	SD	1.34	2.37	2.97	3.25	3.53	4.00	4.94	6.44	9.92	
MERIT	N	363	579	925	2115	3060	4464	3993	1359	570	0.04
	SD	1.90	3.28	5.24	6.48	7.25	8.48	9.07	10.69	13.20	

Table 7: Variation of standard deviation of the height differences with elevation in medium land use/cover areas over South Africa. Units for elevation and standard deviation are in m.

DEM	Elevation range	0 - 250	250 - 500	500 - 750	750 - 1000	1000 - 1250	1250 - 1500	1500 - 1750	>1750	R^2
AW3D30	N	409	252	116	96	161	760	751	78	0.00
	SD	1.63	2.10	2.13	2.86	3.88	2.76	2.61	1.86	
SRTM	N	357	249	115	96	161	760	751	78	0.16
	SD	1.91	2.74	3.57	3.21	4.46	2.50	2.67	2.14	
ASTER	N	99	132	111	96	161	759	750	78	0.00
	SD	2.81	4.62	6.24	6.95	6.90	7.30	8.25	7.93	
TanDEM-X	N	377	251	116	96	161	760	751	78	0.00
	SD	1.01	1.47	1.62	2.27	3.20	1.87	2.10	1.48	
MERIT	N	290	221	109	95	161	760	751	78	0.06
	SD	1.62	3.12	3.37	3.59	5.13	2.68	2.74	2.60	

Table 8: Variation of standard deviation of the height differences with elevation in high land use/cover areas over South Africa. Units for elevation and standard deviation are in m.

DEM	Elevation range	0 - 250	250 - 500	500 - 750	750 - 1000	1000 - 1250	1250 - 1500	1500 - 1750	>1750	R^2
AW3D30	N	473	454	484	532	1008	1207	719	123	0.07
	SD	1.89	3.43	4.50	5.75	6.10	7.78	10.02	11.84	
SRTM	N	370	439	476	530	1000	1201	719	120	0.03
	SD	2.27	3.65	5.28	5.85	6.25	8.58	11.02	12.91	
ASTER	N	177	287	422	511	995	1180	715	122	0.07
	SD	2.96	4.91	6.89	8.00	8.54	10.05	12.01	14.38	
TanDEM-X	N	405	442	479	526	999	1186	717	119	0.07
	SD	1.77	2.92	3.44	4.13	5.46	7.21	11.02	12.69	
MERIT	N	167	298	410	530	998	1190	714	122	0.06
	SD	2.23	3.53	5.06	6.43	7.53	8.88	11.46	12.84	

From the results in Table 7 it can be deduced that in medium land use/cover the AW3D30, SRTM, TanDEM-X, and MERIT vertical accuracies degrade with an increase in elevation in elevation range 0 to 1250 m. The ASTER vertical accuracy in medium land use/cover generally degrades with an increase in all elevation ranges. The coefficients of determination indicate a weak linear (positive) correlation between the elevation and height differences for the AW3D30, ASTER, TanDEM-X, and MERIT and a moderate positive correlation for the SRTM. From the results in Table 9, it can also be deduced that in all the DEMs in low land use/cover it is more likely for steeper areas to have lower vertical accuracies compared to flat areas. The coefficients of determination also indicate a weak linear correlation between the slope and height differences for the AW3D30 and ASTER, low positive correlation for the TanDEM-X, and moderate positive correlation for the SRTM and MERIT.

Table 9: Variation of standard deviation of the height differences with slope in low land use/cover areas over South Africa. Units for slope and standard deviation are in m and angular degrees, respectively.

DEM	Slope	0° - 2°	2° - 4°	4° - 6°	6° - 8°	8° - 10°	> 10°	R^2
AW3D30	N	5973	4933	2350	1468	1054	2778	0.09
	SD	3.66	4.06	4.04	3.82	4.24	5.71	
SRTM	N	5930	4895	2310	1428	1004	2538	0.38
	SD	4.40	5.06	5.58	5.68	5.95	8.90	
ASTER	N	5566	4560	2151	1342	959	2422	0.13
	SD	7.34	7.88	8.81	8.85	9.31	10.59	
TanDEM-X	N	5923	4899	2337	1459	1035	2673	0.19
	SD	3.34	3.43	3.63	3.52	3.47	7.08	
MERIT	N	5829	4772	2210	1350	940	2327	0.36
	SD	4.80	5.98	6.92	7.32	7.95	10.36	

Table 10: Variation of standard deviation of the height differences with slope in medium land use/ cover areas over South Africa. Units for slope and standard deviation are in m and angular degrees, respectively.

DEM	Slope	0° - 2°	2° - 4°	4° - 6°	6° - 8°	8° - 10°	> 10°	R^2
AW3D30	N	1683	716	129	49	24	22	0.02
	SD	2.41	2.76	3.08	4.65	2.67	2.82	
SRTM	N	1676	686	118	45	20	22	0.20
	SD	2.48	3.14	4.11	3.32	4.87	4.77	
ASTER	N	1473	551	91	36	15	20	0.01
	SD	7.28	7.58	8.99	7.99	7.40	8.70	
TanDEM-X	N	1678	698	125	44	23	22	0.01
	SD	1.71	2.33	2.37	2.01	1.73	1.62	
MERIT	N	1651	648	98	36	16	16	0.24
	SD	2.26	3.29	4.38	4.55	5.26	9.83	

Table 11: Variation of standard deviation of the height differences with slope in high land use/cover areas over South Africa. Units for slope and standard deviation are in m and angular degrees, respectively.

DEM	Slope	0° - 2°	2° - 4°	4° - 6°	6° - 8°	8° - 10°	> 10°	R^2
AW3D30	N	1698	1421	742	403	248	488	0.00
	SD	7.03	7.74	6.91	7.13	5.99	6.46	
SRTM	N	1683	1396	715	376	236	449	0.07
	SD	6.99	7.93	7.56	8.08	6.33	7.38	
ASTER	N	1552	1270	628	343	206	410	0.03
	SD	9.19	9.94	9.60	9.38	9.20	9.73	
TanDEM-X	N	1662	1394	718	384	243	472	0.00
	SD	7.10	7.96	6.70	6.89	3.84	4.48	
MERIT	N	1589	1282	637	328	204	389	0.12
	SD	7.14	8.30	8.13	8.40	7.89	9.39	

Table 10 shows lower vertical accuracies for SRTM and MERIT in medium land use/cover areas with steeper slopes compared to gentle and flat slopes. However, for AW3D30, TanDEM-X, and ASTER, this is not the case as there is an unclear variation in vertical accuracies as slope changes. There is also a weak linear correlation between the slope and height differences for the AWD30, ASTER, and TanDEM-X, and a moderate positive correlation for the SRTM and MERIT in medium land use/cover areas. For AW3D30 and TanDEM-X in high land use/cover, it is more likely for steeper areas to have higher vertical accuracies compared to flat areas. However, for the MERIT, SRTM, and ASTER, it is more likely for steeper areas to have lower vertical accuracies compared to flat areas. The results in Table 11 also indicate a weak linear correlation between the height differences of these DEMs and slope. We note degradation of vertical accuracy of DEMs in low slope areas due to high land use/cover.

In all the evaluations of the satellite based DEMs against ground levelling data, the ASTER shows the lowest vertical accuracy, followed by the MERIT and SRTM. These DEMs also provide very low accuracies in areas with the highest elevations and slopes. The AW3D30 and TanDEM-X provide relatively high vertical accuracies in most elevation and slope ranges. Therefore, they (AW3D30 and TanDEM-X) are selected as candidate DEMs for fusion over South Africa based on the results of the empirical evaluations.

4.2 Assessment results for the corrected candidate DEMs

Tables 12 and 13 show the statistical results of the vertical accuracies of the corrected/improved candidate DEMs. The correction models used in modelling AW3D30 and TanDEM-X errors are shown in Figures 7 and 8, respectively. The corrections (Figures 7 and 8) have maximum values of 101.82 and 88.05 m with minimum values of -33.65 and -41.38 m, for AW3D30 and TanDEM-X, respectively. High correction values are found in high slope areas.

Table 12: Statistics of absolute height differences between the DEMs and ground levelling data at 8,657 test points before and after applying corrections (units are in m).

	Original DEMs		**Corrected DEMs**	
	AW3D30	**TanDEM-X**	**AW3D30**	**TanDEM-X**
Min	-34.900	-23.079	-37.954	-28.338
Max	62.200	73.320	50.458	62.921
Mean	3.867	4.250	-0.073	0.213
SD	5.745	5.073	4.995	4.582

Table 13: Absolute height differences in different slope ranges between the DEMs and 8,657 ground levelling test data before and after applying corrections. Units for slope are in angular degrees while mean and standard deviation are in m.

DEM	Slope	0° - 2.5°	2.5° - 5.5°	5.5° - 7.5°	7.5° - 10°	10° - 20°	> 20°
Original AW3D30	N	3920	2448	666	593	824	206
	Mean	2.22	3.70	5.27	5.69	7.70	12.09
	SD	4.58	5.42	5.30	5.17	6.51	10.37
Original TanDEM-X	N	3920	2448	666	593	824	206
	Mean	3.31	3.97	4.59	5.19	6.30	13.47
	SD	4.17	4.69	4.27	4.69	4.12	13.28
Corrected AW3D30	N	3920	2448	666	593	824	206
	Mean	-0.269	0.041	0.837	-0.173	-0.241	0.34
	SD	4.420	5.126	5.224	4.759	5.700	8.79
Corrected TanDEM-X	N	3920	2448	666	593	824	206
	Mean	0.427	0.065	0.034	-0.040	-0.484	1.99
	SD	4.037	4.491	4.173	4.434	3.953	12.27

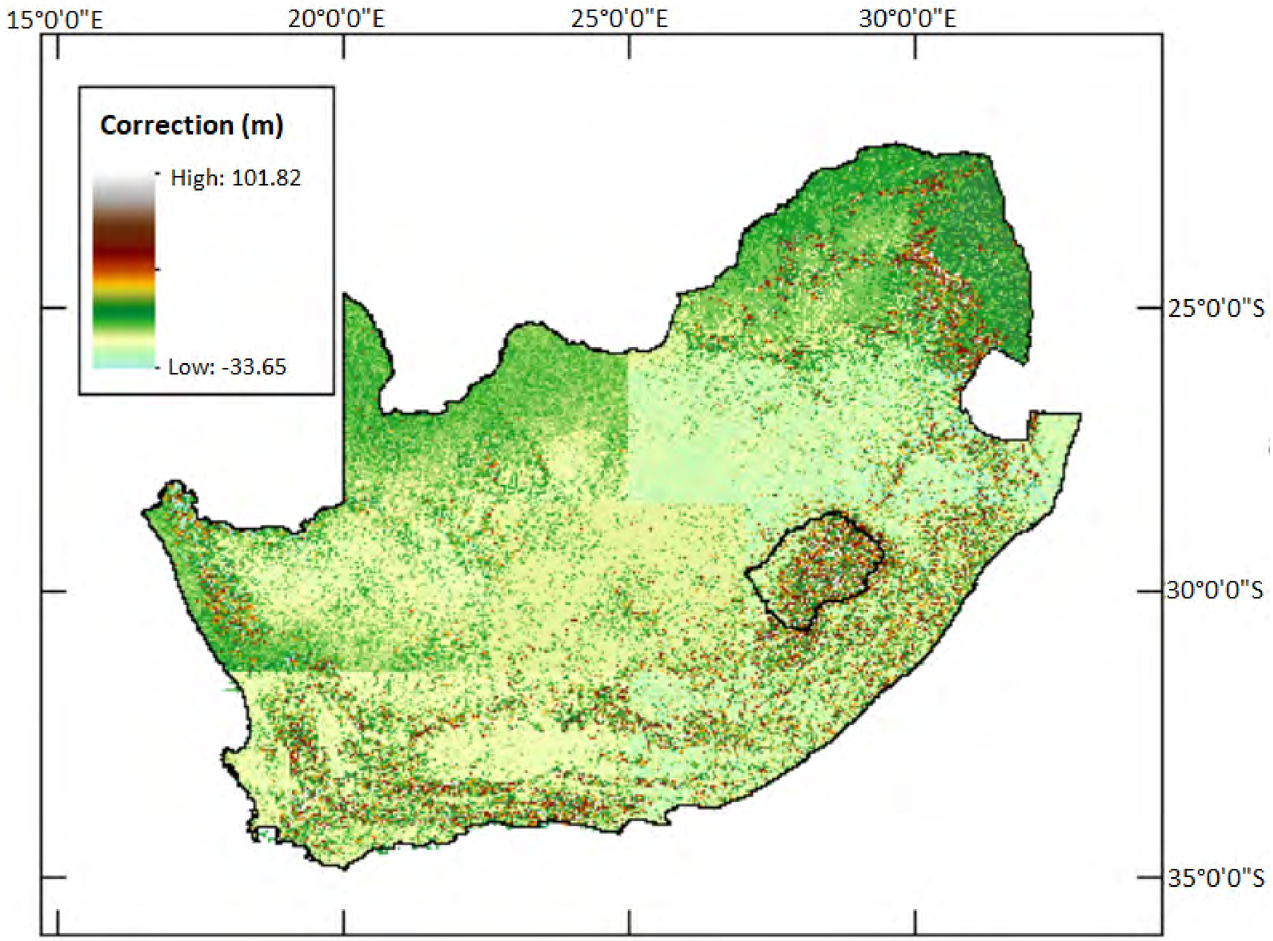

Figure 7: AW3D30 final corrections model over South Africa (units are in m).

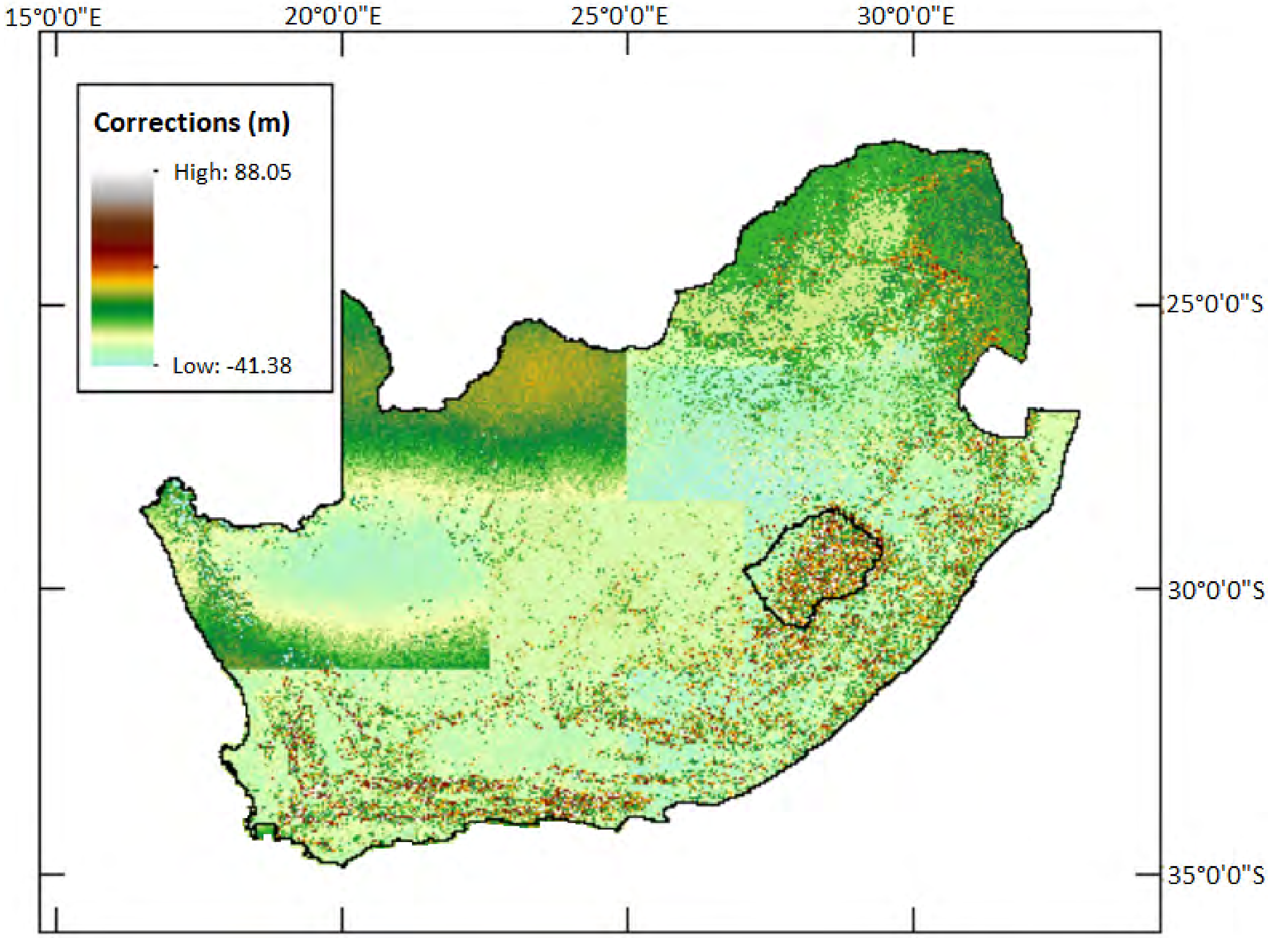

Figure 8: TanDEM-X final corrections model over South Africa (units are in m).

Table 12 shows a remarkable decrease in mean values of absolute height differences in different slope ranges between the DEMs and ground levelling for the corrected AW3D30 and TanDEM-X. A decrease in standard deviation is also observed (±4.582 and ±4.995 m for TanDEM-X and AW3D30, respectively). The mean and standard deviations decrease for all slope ranges (Table 13), indicating that corrected AW3D30 and TanDEM-X perform better than the original versions. Steeper slopes experience higher standard deviations of the height errors for all the DEMs before and after correction, but there is a decrease for corrected compared to the original DEMs. The corrected TanDEM-X has a better performance in slopes ranging from 0° - 20° while corrected AW3D30 has better performance in slopes greater than 20°.

4.3 Assessment results for the final fused DEM

The final fused DEM is presented in Figure 9 while Tables 14 and 15 show the statistical results for the comparison of the corrected DEMs and final fused DEM using 8,657 ground levelling test data over South Africa. The fused DEM has smaller standard deviation compared to the corrected DEMs over South Africa (Table 14). Comparisons within slope ranges also show superiority of the fused DEM in relation to the corrected candidate DEMs (Table 15). Although the vertical accuracies of the corrected candidate DEMs and fused DEM still decrease at steeper slopes, the fused DEM shows better performance compared to the corrected candidate DEMs. Finally, all DEMs (original, corrected and fused) are compared at 8,657 test points over South Africa. The statistics of the height differences between ground levelling and DEMs at the test points are given in Table 16. The results in Table 16 show that the fused DEM has smaller range, mean, standard deviation, and RMSE over South Africa compared to all other DEMs applied in this study. These results indicate that the final DEM fusion achieves better absolute vertical accuracy (±4.294 m) compared to all other DEMs followed by the corrected TanDEM-X, corrected AW3D30, original AW3D30, TanDEM-X, co-registered AW3D30, SRTM, MERIT, and ASTER, in the order of decreasing vertical accuracy.

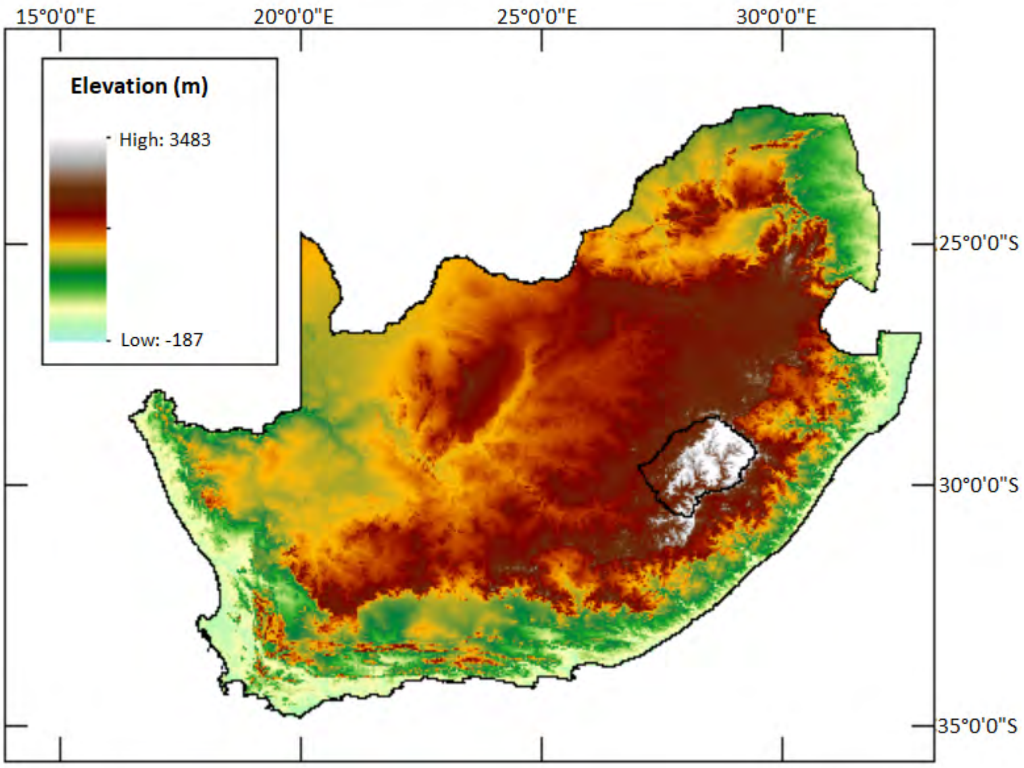

Figure 9: Final fused DEM for South Africa (units are in m).

Table 14: Vertical accuracy comparison of the corrected and fused DEM at 8,657 ground levelling test data over South Africa. Units are in m.

	Corrected AW3D30	**Corrected TanDEM-X**	**Final DEM fusion**
Min	-37.95	-28.34	-28.70
Max	50.46	62.92	48.56
Mean	-0.073	0.213	0.173
SD	4.995	4.582	4.290

Table 15: Vertical accuracy comparison of the corrected and fused DEM in different slope ranges using 8,657 ground levelling test data over South Africa. Units for mean and standard deviation are in m while slope are in angular degrees.

DEM	Slope range	0° - 2.5°	2.5° - 5.5°	5.5° - 7.5°	7.5° - 10°	10° - 20°	> 20°
Corrected AW3D30	N	3920	2448	666	593	824	206.00
	Mean	-0.269	0.041	0.837	-0.173	-0.241	0.336
	SD	4.420	5.126	5.224	4.759	5.700	8.790
Corrected TanDEM-X	N	3920	2448	666	593	824	206.00
	Mean	0.427	0.065	0.034	-0.040	-0.484	1.986
	SD	4.037	4.491	4.173	4.434	3.953	12.272
Fused DEM	N	3920	2448	666	593	824	206.00
	Mean	0.334	0.050	0.578	-0.188	-0.440	0.756
	SD	4.016	4.417	4.200	4.014	3.887	8.224

Table 16: Statistics of the height differences between all the DEMs and the ground levelling data at 8,657 test points over South Africa. Units are in m.

	ASTER	SRTM	MERIT	AW3D30 before co-registration	AW3D30 after co-registration	TanDEM-X	Corrected AW3D30	Corrected TanDEM-X	Final DEM Fusion
Min	-35.50	-37.80	-12.82	-34.90	-34.90	-23.08	-37.95	-28.34	-28.70
Max	91.50	91.40	116.43	66.00	62.20	73.32	50.46	62.92	48.56
Mean	9.995	3.851	8.497	2.768	3.867	4.250	-0.073	0.213	0.174
Range	127.00	129.20	129.25	100.90	97.10	96.40	88.41	91.26	77.26
SD	9.732	7.293	9.275	4.784	5.745	5.073	4.995	4.582	4.290
RMSE	13.950	8.247	12.579	5.528	6.925	6.618	4.996	4.587	4.294

5. Conclusion

This study aimed at contributing to the development of an accurate digital elevation model using satellite based DEMs and ground levelling data over South Africa. This is achieved by preparing the satellite based DEMs (AW3D30, SRTM, ASTER, TanDEM-X, and MERIT), assessing the quality of the DEMs, selecting candidate DEMs for fusion, modelling errors inherent in the candidate DEMs and fusing candidate DEMs using a combination of different methods. The findings indicate that the absolute height differences have standard deviations of ±5.09 m for AW3D30 implied heights, ±7.03 m for SRTM, ±9.20 m for ASTER, ±4.99 m for TanDEM-X, and ±8.36 m for MERIT. The results for AW3D30 and TanDEM-X show better performance while ASTER show the worst performance compared to all other DEMs considered in this study.

Variations in elevation and slope affect accuracy of satellite based DEMs. As elevation increases, the vertical accuracy of the DEMs decreases. As the slope increases, only the vertical accuracy of ASTER and MERIT decreases, while there are no clear trends in the other DEMs. Most high accuracies are achieved by these DEMs in areas with an elevation below 500 m and flat areas with slope angles between 0° to 2°. Lowest accuracies are observed in steepest slope and highest elevation areas. Assessments in land use/cover categories show significant decrease in the vertical accuracy of DEMs with increase in elevation in the low and high land use/cover areas. In medium land use/cover, only the ASTER vertical accuracy decreases as elevation increases, the rest of the DEMs show unclear trends that may be attributed to the smaller number of ground levelling data available, especially in higher elevation areas. In low land use/cover, all the DEMs vertical accuracies decrease as the slope becomes steeper. In medium land use/cover, only the SRTM, ASTER, and MERIT vertical accuracies are affected by slope change. In high land use/cover, the MERIT vertical accuracy decreases as the slope becomes steeper, and for the AW3D30 and TanDEM-X, higher vertical accuracies are found in steeper slopes. This indicates the negative effect of high land use/cover on the accuracy of satellite based DEMs in low slope areas where most land development activities occur. The absolute vertical accuracy of the AW3D30 and TanDEM-X varies less compared to all other DEMs over all land use/cover.

The approach for modelling DEM errors implemented in this study provides a remarkable improvement in the vertical accuracies of the candidate DEMs (AW3D30 and TanDEM-X). After validating the DEMs using 8,657 ground levelling test data over South Africa, there is a decrease in the mean and standard deviation values. The standard deviations of the discrepancies decrease from ± 5.745 to ±4.995 m for AW3D30 and ±5.073 to ±4.582 m for TanDEM-X, and the correction models have more effect over slope ranges greater than 10°. The fused DEM achieves the best accuracy of 4.290 m over South Africa.

The fused DEM can be applied in all elevation and slope ranges. However, better terrain representation is achievable in areas with slopes less than 20°. The fused DEM is expected to be used in scientific research and geospatial applications. These include but not limited to geological and geomorphological studies, geodetic and geophysical studies, water resources and hydrology, evaluation of natural hazards, vegetation surveys and gravity modelling, among other applications.

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AUTHOR´S CONTRIBUTION

Mihlali Malindi and Patroba Odera conceptualised and designed the research. Mihlali Malindi carried out computations, modelling and drafted the manuscript. Patroba Odera carried out interpretation of results and designed the manuscript layout. Both authors read, revised, and approved the final manuscript.

REFERENCES

Ali, M.E.N.O., Fathy, I., Shaker, M. and Saba, N.M., 2018. Enhancement of SRTM and ASTER elevations using GPS control points and polynomial regression model. Al-Azhar University Civil Engineering Research Magazine, 40(2), pp.68–79.

Bagheri, H., Schmitt, M. and Zhu, X.X., 2018. Fusion of TanDEM-X and Cartosat-1 elevation data supported by neural network-predicted weight maps. ISPRS Journal of Photogrammetry and Remote Sensing, 144, pp.285–297. https://doi.org/10.1016/j.isprsjprs.2018.07.007

Chandler, G. and Merry, C.L., 2010. The South African Geoid 2010: SAGEOID10. PositionIT, pp.29–33.

ElSayed, M.S. and Ali, A.H., 2016. Improving the accuracy of the SRTM Global DEM using GPS data fusion and regression model. International Journal of Engineering Research, 5(3), pp.190–196.

Fuss, C.E., Berg, A.A. and Lindsay, J.B., 2016. DEM Fusion using a modified k-means clustering algorithm. International Journal of Digital Earth, 9(12), pp.1242–1255. https://doi.org/10.1080/17538947.2016.1208685

Gómez, M.F., Lencinas, J.D., Siebert, A. and Díaz, G.M., 2012. Accuracy assessment of ASTER and SRTM DEMs: A case study in Andean Patagonia. GIScience and Remote Sensing, 49(1), pp.71–91. https://doi.org/10.2747/1548-1603.49.1.71

Gorokhovich, Y. and Voustianiouk, A., 2006. Accuracy assessment of the processed SRTM-based elevation data by CGIAR using field data from USA and Thailand and its relation to the terrain characteristics. Remote Sensing of Environment, 104(4), pp.409–415. https://doi.org/10.1016/j.rse.2006.05.012

Han, H., Zeng, Q. and Jiao, J., 2021. Quality assessment of TanDEM-X DEMs, SRTM and ASTER GDEM on selected Chinese sites. Remote Sensing, 13(7), 1304; https://doi.org/10.3390/rs13071304

Johnston, K., Ver Hoef, J.M., Krivoruchko, K. and Lucas, N., 2001. Using ArcGIS geostatistical analyst. Environmental Systems Research Institute, Redlands, USA, p.300.

Karkee, M., Steward, B.L. and Aziz, S.A., 2008. Improving quality of public domain digital elevation models through data fusion. Biosystems Engineering, 101(3), pp.293–305. https://doi.org/10.1016/j.biosystemseng.2008.09.010

Kass, M., Witkin, A. and Terzopoulos, D., 1988. Snakes: Active contour models. International Journal of Computer Vision, 1, pp.321–331. https://doi.org/10.1007/BF00133570

Mahesh, R., Sarunjith, K.J., Rajakumari, S., Muruganandam, R. and Ramesh, R., 2021. Quality assessment of open-sourced digital elevation models in southeast coast of India. The Egyptian Journal of Remote Sensing and Space Sciences, 24(3), pp.745–754. https://doi.org/10.1016/j.ejrs.2021.03.006

Malindi, M. and Odera, P.A., 2021. An assessment of SRTM, ASTER and LiDAR digital elevation models in the western part of South Africa. Journal of Geomatics, 15(2), pp.115–120.

Mohamed, M.H. and Saleh, S.S., 2018. Fusion of SRTM and ASTER GDEM2 DEMs based on height error weighted average technique. Australian Journal of Basic and Applied Sciences, 12(6), pp.23–29. https://doi.org/10.22587/ajbas.2018.12.6.5

Mphuthi, M.S. and Odera, P.A., 2022. Comparison between orthometric, normal and spheroidal orthometric heights over South Africa. Applied Geomatics, pp.1–9 https://doi.org/10.1007/s12518-022-00443-1

O'Loughlin, F.E., Paiva, R.C.D., Durand, M., Alsdorf, D.E. and Bates, P.D., 2016. A multi-sensor approach towards a global vegetation corrected SRTM DEM product. Remote Sensing of Environment, 182, pp.49–59. https://doi.org/10.1016/j.rse.2016.04.018

Pham, H.T., Marshall, L., Johnson, F. and Sharma, A., 2018. A method for combining SRTM DEM and ASTER GDEM2 to improve topography estimation in regions without reference data. Remote Sensing of Environment, 210, pp.229–241. https://doi.org/10.1016/j.rse.2018.03.026

Papasaika, H., Kokiopoulou, E., Baltsavias, E., Schindler, K. and Kressner, D., 2011. Fusion of digital elevation models using sparse representations. In Proceedings of the 2011 ISPRS conference on Photogrammetric image analysis, 6952, pp.171–184. https://doi.org/10.1007/978-3-642-24393-6_15

Reinartz, P., Müller, R., Hoja, D., Lehner, M. and Schroeder, M., 2005. Comparison and fusion of DEM derived from SPOT-5 HRS and SRTM data and estimation of forest heights. Proceedings of the EARSeL workshop on 3D-remote sensing, 6-11 June 2005, Porto, Portugal.

Roth, A., knöpfle, W., Strunz, G., Lehner, M. and Reinartz, P., 2002. Towards a global elevation product: Combination of multi-source digital elevation models. Symposium on Geospatial Theory, Processing and Applications, 3, pp.1699–1702.

Santillan, J. and Makinano-Santillan, M., 2016. Vertical accuracy assessment of 30-m resolution ALOS, ASTER, AND SRTM Global DEMs over north-eastern Mindanao, Philippines. ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLI-B4, pp.149–156. https://doi.org/10.5194/isprs-archives-XLI-B4-149-2016

Schultz, H., Hanson, A.R., Riseman, E.M., Stolle, F.R., Zhu, Z. and Dong-Min, W., 2002. A Self-consistency technique for fusing 3D information. Proceedings of the fifth IEEE international conference on information fusion, 2, pp.1106–1112. https://doi.org/10.1109/ICIF.2002.1020936

Setiyoko, A., Arymurthy, A.M. and Basaruddin, T., 2019. DEM fusion concept based on the LS-SVM cokriging method. International Journal of Image and Data Fusion, 10(4), pp.244–262. https://doi.org/10.1080/19479832.2019.1664647

Shortridge, A. and Messina, J., 2011. Spatial structure and landscape associations of SRTM error. Remote Sensing of Environment, 115(6), pp.1576–1587. https://doi.org/10.1016/j.rse.2011.02.017

Su, Y. and Guo, Q., 2014. A practical method for SRTM DEM correction over vegetated mountain areas. ISPRS Journal of Photogrammetry and Remote Sensing, 87, pp.216–228. https://doi.org/10.1016/J.ISPRSJPRS.2013.11.009

Su, Y., Guo, Q., Ma, Q. and Li, W., 2015. SRTM DEM correction in vegetated mountain areas through the integration of spaceborne LiDAR, airborne LiDAR, and optical imagery. Remote Sensing, 7(9), pp.11202–11225. https://doi.org/10.3390/rs70911202

Tian, Y., Lei, S., Bian, Z., Lu, J., Zhang, S. and Fang, J., 2018. Improving the accuracy of open-source digital elevation models with multi-scale fusion and a slope position-based linear regression method. Remote Sensing, 10(12), 1861. https://doi.org/10.3390/rs10121861

Tran, T., Raghavan, V., Masumoto, S., Vinayaraj, P. and Yonezawa, G., 2014. A geomorphology-based approach for digital elevation model fusion; case study in Danang City, Vietnam. Earth Surface Dynamics Discussions, 2(1), pp.255–296. https://doi.org/10.5194/esurfd-2-255-2014

Uuemaa, E., Ahi, S., Montibeller, B., Muru, M. and Kmoch, A., 2020. Vertical accuracy of freely available global digital elevation models (ASTER, AW3D30, MERIT, TanDEM-X, SRTM, and NASADEM). Remote Sensing, 12(21), 3482. https://doi.org/10.3390/rs12213482

Yamazaki, D., Ikeshima, D., Tawatari, R., Yamaguchi, T., O’Loughlin, F., Neal, J., Sampson, C., Kanae, S. and Bates, P.D., 2017. A high-accuracy map of global terrain elevations. Geophysical Research Letters, 44, pp.5844–5853. https://doi.org/10.1002/2017GL072874

Zhou, C., Zhang, G., Yang, Z., Ao, M., Liu, Z. and Zhu, J., 2020. An adaptive terrain-dependent method for SRTM DEM correction over mountainous areas. IEEE Access, 8, pp.130878–130887. https://doi.org/10.1109/ACCESS.2020.3009851