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Vertical Accuracy Assessment of Various Digital Elevation Models Using Remote Sensing, and RADAR Techniques

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Abstract

This study examines the importance of using remote sensing in road design, especially in regions prone to flooding or irregular terrain. These technologies rely on digital elevation models to provide data on topography and elevations. DEMs also contribute to hydrological studies and identifying areas of water accumulation, aiding in better flood risk assessment and management, improved road design, saving time and effort, and ensuring traveler safety.

Different DEMs, such as NASA DEM, SRTM, AW3D30, Sentinel-1, and ALOS, were evaluated in the Ras Ghareb and Zaafaran regions and El Monte Galala in the Ain Sokhna region. The results showed varying accuracy, with NASA DEM proving to be the most accurate. GPS reference elevations indicated that the RMS values were ±6.5 m for NASA DEM, ±8.8 m for SRTM, ±9.7 m for AW3D30, ±21.1 m for Sentinel-1, and ±22.3 m for ALOS. In addition, elevation data from topographic maps showed that NASA DEM had the best accuracy with an RMS value of ±5.6 m. In comparison, the RMS values for the other DEMs were ±5.8 m for AW3D30, ±6.6 m for SRTM, ±17.1 m for ALOS PALSAR, and ±17.2 m for Sentinel-1. This range in accuracy is critical to consider when using DEMs for road design and other applications in these study areas.

Keywords: GDEM, SRTM, ALOS PALSAR, Sentinel-1, NASADEM, AW3D30, RMS, Vertical accuracy assessment, Hydrology, Remote sensing, RADAR techniques.

1 Introduction and background

It has been stated that if obtaining elevation levels on the Earth's surface through traditional surveying proves difficult, we can use high-resolution maps or DEMs to determine accurate elevations for different regions [1]. Digital Elevation Models represent the terrain's height and are generated through various techniques. These techniques include using GPS points, aerial photography, LiDAR, and Radar data. Traditionally, field surveying and aerial photogrammetry were the primary methods for acquiring elevation data. However, these methods are resource intensive and subject to environmental restrictions. Satellite remote sensing offers an efficient alternative, providing a cost-effective means to generate

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DEMs with a broader coverage area [2]. When comparing these techniques, factors such as cost, accuracy, density, and pre-processing requirements are considered. Remote sensing is increasingly preferred over direct surveying for DEM generation. DEMs are widely used in various applications, including GIS, environmental modeling, urban planning, and geological studies [2], [3], [4], [5]. They facilitate tasks such as site selection, flood modeling, and infrastructure planning.

The vertical accuracy refers to the reliability and precision of this elevation data. GDEM varies in accuracy[6]. The importance of a common reference point and a consistent vertical datum to assess accuracy through RMS values when comparing models is emphasized [4], [7]. However, open access GDEMs with 30 to 90-meter spatial resolutions are frequently used [7]. Their accuracy can be inconsistent, particularly in mountainous and desert regions. Despite ongoing improvements in the precision of DEMs, challenges persist, especially in complex terrains. Several research studies have been carried out to evaluate the accuracy and precision of GDEMs. Additionally, Dawod & Amin have contributed to improving the accuracy and enhancing the reliability of DEMs[8].

Previous studies have indicated that several researchers have assessed the accuracy of GDEM across various locations by employing Ground Control Points measured by GPS or by using elevations from topographic maps. The elevation data from ASTER v.3, ACE 2, SRTMGL1 v.3, and NASA DEM, which varied across different regions. Variations were observed in both flat and moderate-topography areas. In the Nile Delta, the results indicated that the RMS error ranged from ±2.5 to ±5.1 meters, while in the Makkah area, it ranged from ±5.1 to ±8.0 meters [9]. A study where elevation values recorded using GPS and LiDAR measurements with elevations below 7 m over the island of Hispaniola, in the West Indies were used for the assessment of ASTER, SRTM, ALOS AW3D30, and TanDEM-X (TDX) DEMs. The results concluded that RMSE for ASTER, SRTM, ALOS, and TDX DEMs were 8.44, 3.82, 2.08, and 1.74, respectively[5]. The elevation of SRTM and ASTER was compared with GPS elevations and the topographic map in Najran City, Saudi Arabia. The results concluded that the GPS reference elevations provided ±5.94 meters and ±5.07 meters accuracy for SRTM and ASTER DEMs, respectively. When using topographic map elevations as references, accuracies were ±6.87 meters and ±7.97 meters for SRTM and ASTER DEMs in the study area [6]. The elevation of AW3D30, SRTM 1, and ASTER GDEM 2 was performed using GPS/leveling points distributed all over Cameroon. The results concluded that the RMS were 13.06 meters for AW3D30, 13.25 meters for SRTM, and 18.87 meters for ASTER[4]. An accuracy assessment on various DEMs, including SRTM, ASTER, and AW3D30, in northeastern Mindanao, Philippines. The results showed that AW3D30 had the lowest RMSE of 5.68 meters, 8.28 meters for SRTM, and 11.98 meters for ASTER [10].

Ras Gharib experienced devastating floods in 2016, leading to significant road damage. The importance of using DEMs in flood management, especially considering the floods that caused significant road damage in the study area, is emphasized in the study [11].

2 Problem definition and objectives

2.1 Problem definition

Civil engineers and designers require accurate elevation data to design effective infrastructure. However, traditional methods like field surveying face significant challenges regarding time, effort, safety, and financial constraints, especially in complex terrains. Additionally, environmental limitations delay the surveying process.

Different DEM models are crucial for obtaining topographical data, but they vary in accuracy, particularly in complex terrains. They are also affected by technical limitations inherent in each DEM technology, including spatial accuracy and data acquisition methods.

The existing road between Ras Ghareb and Zaafaran is prone to varying intensities of floods, leading to road collapses and endangering travelers' safety.

2.2 Objectives

1- Assess the accuracy of different DEM models, including NASA DEM, SRTM, AW3D30, Sentinel-1, and ALOS, in providing elevation data for road design in Ras Ghareb, Zaafaran, and El Monte Galala regions.
2- Assess the time and effort saved by utilizing remote sensing techniques compared to traditional field surveying methods.
3- Use remote sensing to identify flood-prone areas along the Ras Ghareb-Zaafaran road, improving flood risk assessment and management. Conduct hydrological studies to detect water accumulation areas and basins posing risks to the road infrastructure.
4- Investigate the feasibility and reliability of acquiring elevation data without physically visiting the site.

3 Methodology and data collection

The data collection stage involves identifying the study area and the sources that help in assessing horizontal and vertical accuracy. The main objectives are achieved through the following steps:

- Step 1: Obtain various DEMs
- Step 2: Preparation of reference elevation data
- Step 3: Vertical accuracy assessment
- Step 4: Hydrology analysis
- Step **5**: Horizontal accuracy assessment

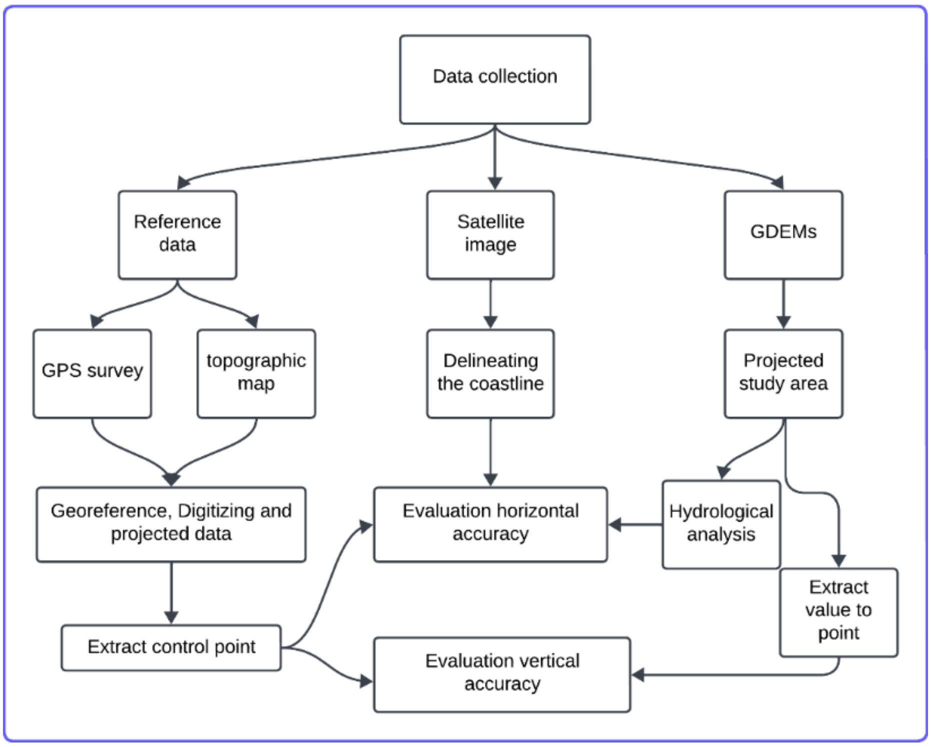

Figure. 1. Methodology for estimating DEM accuracy and hydrology analysis.

3.1 Study area

1) The digital elevation models were extracted to fit a study area of 2,960 square kilometers, which covers the region between Ras Gharib (28° 21' 30" N and 33° 04' 42" E) and Zaafaran (29° 7' 0.12" N and 32° 39' 0" E), with the Ras Gharib-Zaafaran road spanning about 112 kilometers.

2) Additional extraction was done for a 2.3 square kilometer area covering El Galala City, located in the Ain Sokhna region, where El Galala City is located in coordinates (29° 30' 7.2" N and 32° 24' 38.88" E).

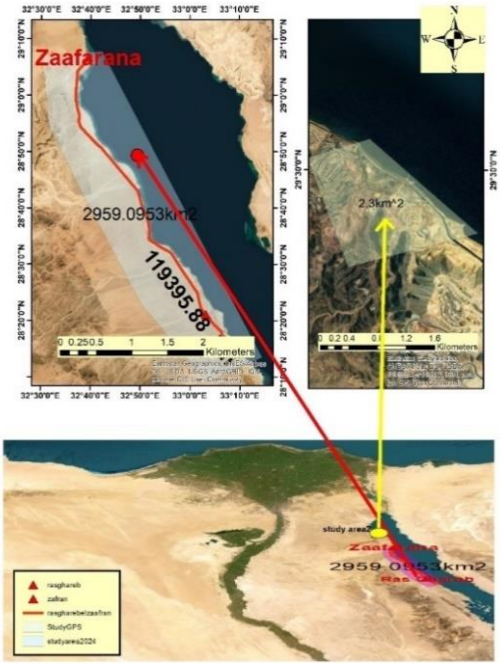

Fig. 2. Location of study area.

3.2 DEM sources

1) **SRTM:** The Shuttle Radar Topography Mission is a NASA mission. The SRTM dataset has a spatial resolution of 1 arc second. A maximum absolute vertical accuracy of approximately ±16 meters[1] and a relative vertical accuracy of ±10 meters according to the National Aeronautics and Space Administration, as found on their CMR Earth data [12]. The study area is covered by the following three tiles (1x1 degree) and downloaded from (https://earthexplorer.usgs.gov/).

- n28_e032_1arc_v3.tif
- n29_e032_1arc_v3.tif
- n28_e033_1arc_v3.tif

2) **AW3D30:** The Advanced Land Observing Satellite (ALOS) is a Japanese satellite mission that resulted in the development of ALOS World 3D (AW3D30), with a spatial resolution of 1 arc second. The vertical accuracy of AW3D30 is reported to be within ±5 meters [4]. The study area is covered and located at the following three tiles (1x1 degree) and downloaded from (https://www.eorc.jaxa.jp/ALOS/en/dataset/aw3d30/aw3d30_e.htm).

- ALPSMLC30_N028E033_DSM.tif
- ALPSMLC30_N028E032_DSM.tif
- ALPSMLC30_N029E032_DSM.tif

3) **NASA DEM:** It is primarily produced by reprocessing the SRTM radar data and merging it with refined ASTER GDEM elevations, the improved SRTM elevations in NASADEM result from better vertical control of each SRTM data swath via reference to ICE Sat elevations. The spatial resolution of 1 arc second [13], [14]. and downloaded from (https://dataverse.jpl.nasa.gov/dataverse/jor).

4) **Sentinel-1:** is a satellite program developed by the European Space Agency (ESA) in collaboration with the European Union (EU) for Earth observation and environmental monitoring. With a spatial resolution of 10 meters. In the process of creating a DEM from Sentinel-1 data downloaded from (https://scihub.copernicus.eu/).

- S1A_IW_SLC_15DV_20221202T155638_20221202T155705_046155_05868B_CFA0.SAFE
- S1A_IW_SLC__1SDV_20221226T155637_20221226T155704_046505_05927D_87FB.SAFE

5) **ALOS PALSAR**: Phased Array type L-band Synthetic Aperture Radar (PALSAR) instrument, deployed on the Advanced Land Observing Satellite (ALOS). This data is part of a mission by the Japan Aerospace Exploration Agency (JAXA) and has a spatial resolution of 12.5 meters. The study area is covered and located at the following three tiles and downloaded from (https://asf.alaska.edu/datasets/daac/alos-palsar/).

- AP_10689_FBS_F0550_RT1.dem.tif
- AP_07582_FBD_F0570_RT1.dem.tif
- AP_07582_FBD_F0560_RT1.dem.tif

Table 1. Characteristics of DEM datasets

Data	SRTM	AW3D30	NASADEM	Sentinel-1	ALOS PALSAR
Production agency	USA /NASA	Japan /(JAXA)	USA /NASA	EU /ESA	Japan/ (JAXA)
Data acquisition period	Launched in 2000	2006 to 2011	February 2020	Sentinel1A3-4-2014	from 2006 to 2011
Released period	2014-09-23	Jan 2021	1-2-2020	2-12-2022.	2008-01-26
Pixel Size	~30M	~30M	~30M	~10 M	~12.5M
Horizontal Datum	WGS1984	WGS1984	WGS1984	WGS1984	WGS1984
Vertical datum	EGM96	EGM96	EGM96	EGM96	EGM96
DEM format	Geo TIFF	Geo TIFF	Geo TIFF	Geo TIFF	Geo TIFF

3.3 Reference elevation data

All reference data were transformed to the UTM zone 36 north projection system, with WGS 1984 as the datum and ellipsoid. The vertical datum used was the mean sea level, Helmert 1906. To ensure consistency and compatibility among data sets, the ArcGIS 10.8 software was employed for data transformation and preparation.

Reference data for this thesis were obtained from a 1:50,000 scale topographic map produced by the Egyptian Survey Authority using aerial photography from 1989. The map was digitized into JPEG format, providing a horizontal accuracy of about 20 to 25 meters in some regions. As for vertical accuracy, the precision is approximately 10 meters, and 5 meters when auxiliary contour lines are present.

GPS data were randomly collected using a Sokkia GRX2 device. The device has a horizontal accuracy of 3mm + 0.8ppm and a vertical accuracy of 4mm + 1ppm [15].

3.4 Hydrology analysis of the study area

Detection of areas prone to flooding is obtained using the Arc Hydro tool, part of the ArcGIS software, which is used for hydrological analysis. Hydrological processes rely on algorithms related to point elevations within the DEM, including determining flow direction to find the steepest slope and calculating flow accumulation to determine the number of contributing cells per cell, identifying water accumulation areas. This process facilitates the extraction of the hydrological stream order network.

In this study, 20 points are plotted on the topographic map with a 1: 50,000 scale to delineate water accumulation areas. These points are compared with the hydrological network generated from the hydrological analysis conducted on three DEMs (NASA, AW3D30, and SRTM) using the "Near" tool in ArcGIS. This comparison aims to evaluate the accuracy of the digital elevation models in representing streamlines and identifying hydrological network locations.

3.5 Shoreline detection

- **Step 1:** To delineate the shoreline, the study area is covered by a satellite image from Sentinel-2 with a 10-meter resolution (Fig. 3) the specific images in TIFF format can be downloaded from (https://scihub.copernicus.eu/).

- S2B_MSIL1C_20230108T083229_N0509_R021_T36RVT_20230108T090814
- S2B_MSIL1C_20230108T083229_N0509_R021_T36RVS_20230108T090814
- S2B_MSIL2A_20240110T082229_N0510_R121_T36RWS_20240110T095820

- **Step 2:** A contour line of zero elevation is extracted from various DEM for comparison. Then, 30 points are plotted along the shoreline from the Sentinel-2 satellite image. These 30 points are compared with the contour line of zero elevation using the "Near" tool in ArcGIS.

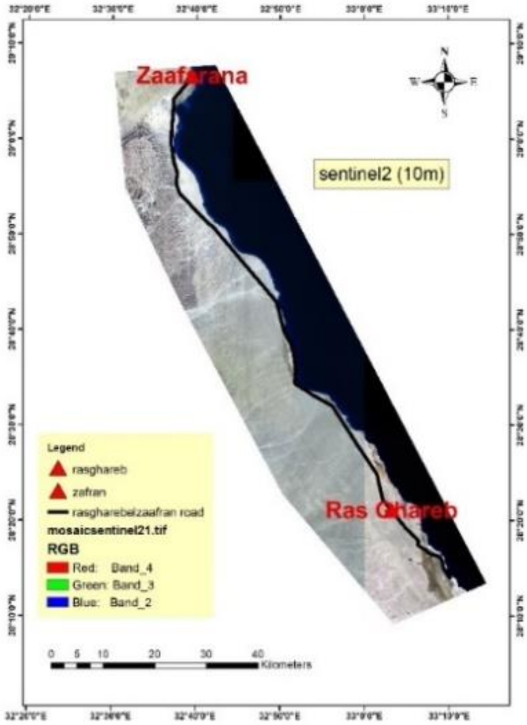

Fig. 3. Sentinel 2 Satellite images with 10m resolution for the study area 1.

4 Results and discussion

The following results show vertical accuracy by comparing the DEM with reference points, and horizontal accuracy by comparing the locations of valleys with the hydrological network.

4.1 Geolocation error estimation

After georeferencing the topographic map, the result of the root mean square (RMS) error was (2 meters), based on the four corners of the map. The georeferenced map was used to extract (370 checkpoints) at different locations. These points include both spot heights and contour lines as shown in (Figure 4).

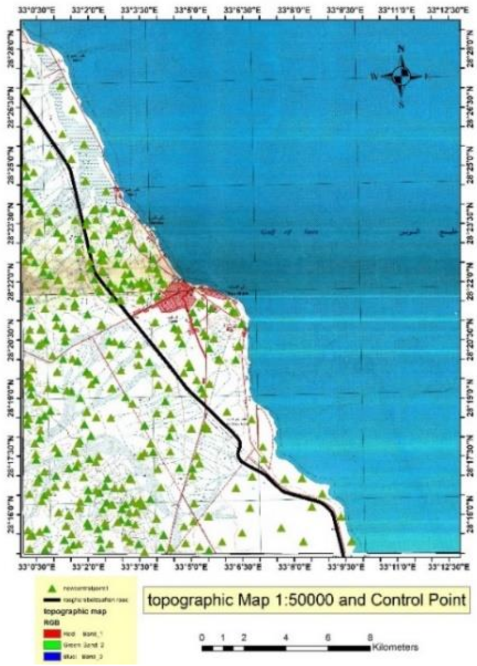

Fig. 4. Distribution of checkpoints.

4.2 Assessment of vertical accuracy

A comparison was conducted between the DEMs and checkpoints from the topographic maps and GPS points, as shown.

Topographic map

The results, as shown in (Table 2), reveal significant elevation differences in the study area. The performance of GDEMs was compared using 370 checkpoints, revealing that the NASA DEM was the best, with an RMS of ±5.6 meters, followed by AW3D30 (±5.8 meters), SRTM (±6.6 meters), ALOS PALSAR (±17.1 meters), and Sentinel-1 (±17.2 meters). The results also highlight the differences between DEM elevations and elevations from the topographic map, as indicated by the minimum and maximum values. The mean, median, and range provide additional insights into the data distribution. NASA DEM offers the best elevation accuracy among the GDEMs, showing the least errors in its data. However, the large ranges should be considered, as they indicate substantial variations in elevation data.

Table 2. Results of the comparison using topographic maps and GDEMs

DEM	Min	Max	RMS	Mean	Median	Range
NASA	-15	16	±5.6	-1.8	-1	31
AW3D30	-13	21	±5.8	3.1	3	34
SRTM	-15	21	±6.6	3.8	4	36
ALOS PALSAR	-1	34	±17.1	16.2	16	35
Sentinel-1	3.2	33.7	±17.2	16.5	16.6	30.5

The following histogram shows the number of points representing the differences in elevation between the DEM and the elevations from the checkpoints. Given that the vertical accuracy of the topographic map is ±10 meters, the number of points within the ±10meter range for the SRTM is 90% of the 370 points. For the NASA DEM, the number of points within this range is 93.5%, and for the AW3D30, it is 94.8%.

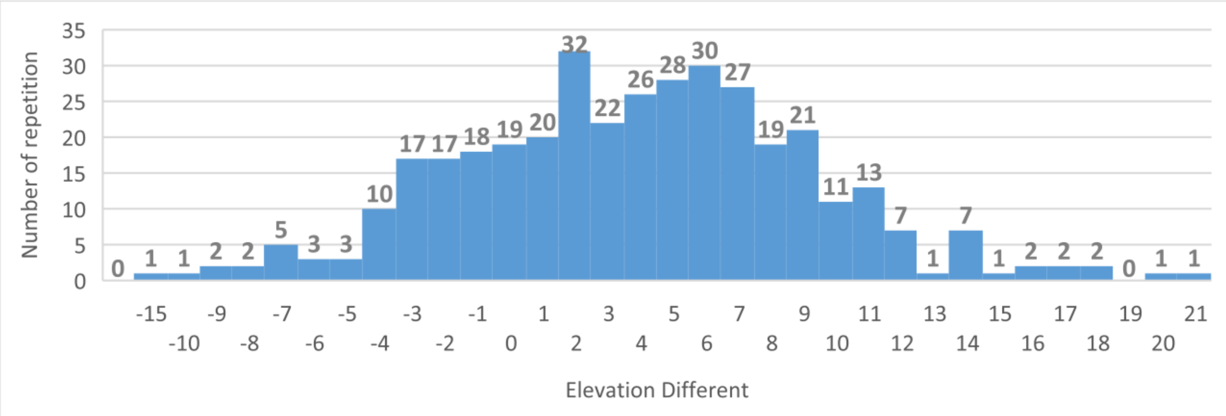

Fig. 5. SRTM vs. topographic map.

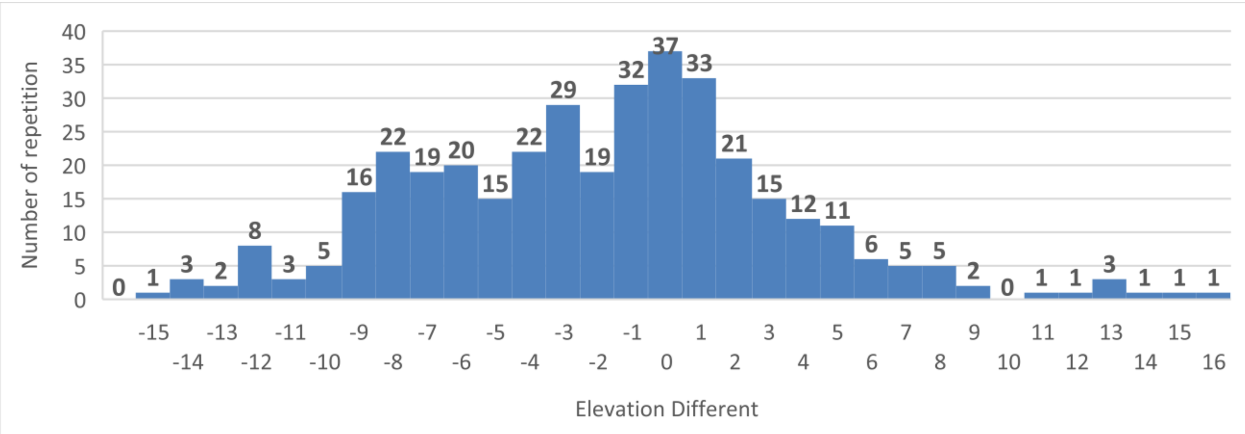

Fig .6. NASA vs. topographic map.

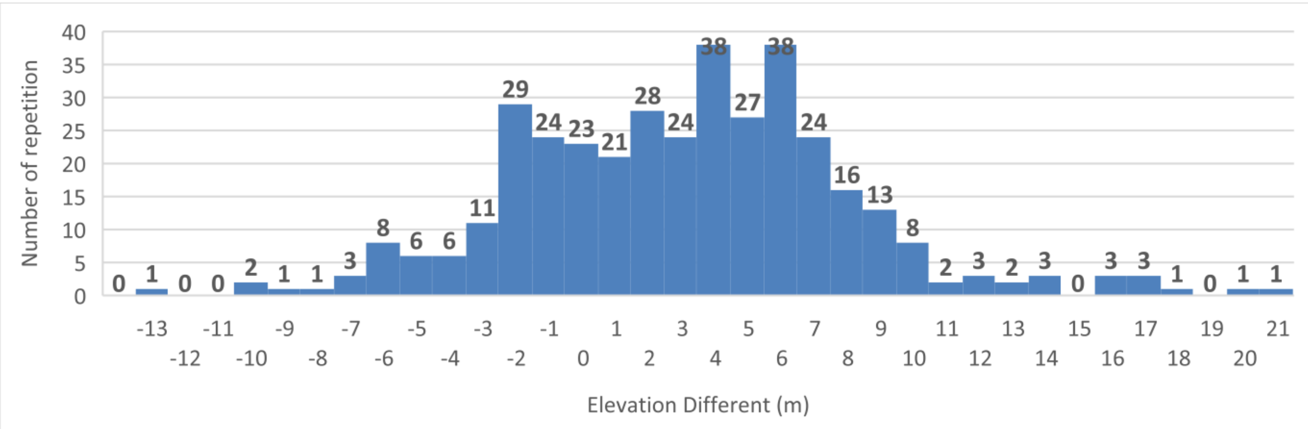

Fig. 7. AW3D30 vs. topographic map.

GPS points

The results show, as in (Table 3), significant elevation differences in the study area. The performance of global DEMs was compared against 17 checkpoints from GPS, revealing that the NASA DEM was the best, with an RMS of ±6.5 meters, followed by SRTM (±8.8 meters), AW3D30 (±9.7 meters), Sentinel-1 (±21.1 meters) and ALOS PALSAR (±22.3 meters). then the results also highlight the differences between the GDEM elevation and the elevation from the GPS survey, as indicated by the minimum and maximum values.

Table 3: Results of the comparison using GPS points and GDEMs

DEM	Min	Max	RMS	Mean	Median	Range
NASA	-16.9	10	±6.5	1.6	1.8	26.9
SRTM	-4.3	24	±8.8	5.6	3.8	28.3
AW3D30	-5.3	26	±9.7	5.7	4.4	31.3
Sentinel-1	13.3	31.7	±21.1	20.5	19.1	18.4
ALOS PALSAR	10.4	36.3	±22.3	21.1	20.4	25.9

The table demonstrates that NASA DEM has the lowest RMS value, indicating the best accuracy among the DEMs evaluated. Sentinel-1 and ALOS PALSAR exhibit the highest RMS values, reflecting greater discrepancies compared to the GPS survey data. The range, median, and mean values offer additional insights into the distribution and variation of elevation errors across the different DEMs.

Assessment of horizontal accuracy

A comparison was conducted to show horizontal accuracy using the DEMs by comparing with valleys in topographic maps and determining the shoreline location.

Comparison with drainage network

A comparison of the DEMs using ArcGIS 10.8 hydrological tools revealed important differences in the representation of stream order [16], [17] analyzed the hydrological characteristics of DEMs. When applying this analysis to GDEMs (NASA, SRTM, and AW3D30), the results revealed differences in terms of the average distance between the streamline and the topographic map, the average distance for the NASA model was 4.8 meters, making it the closest to the map, while the average distance for the SRTM model was 5.6 meters, and for the AW3D30 model, it was 34.7 meters, indicating variations in the accuracy. (Figure 8) shows the streamline for the NASA DEM.

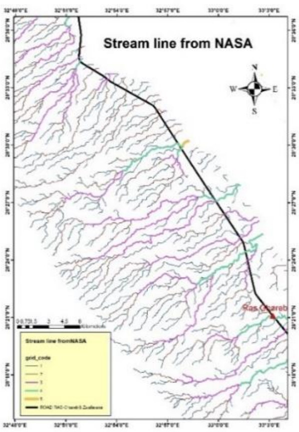

Fig. 8. Streamline extract from NASA DEM.

Comparison with shoreline

A comparison of the coastline from the Sentinel -2 satellite image with the zero contour from four DEMs highlighted variations in accuracy. The average distance between the coastline from the Sentinel-

2 satellite image and the zero-contour extract from GDEMs was 22.6 meters for AW3D30, indicating the closest match. In contrast, the NASA DEM had an average distance of 30.4 meters, SRTM had 33 meters, and Sentinel had 38 meters. This suggests that AW3D30 is the best model for accurately representing the coastline.

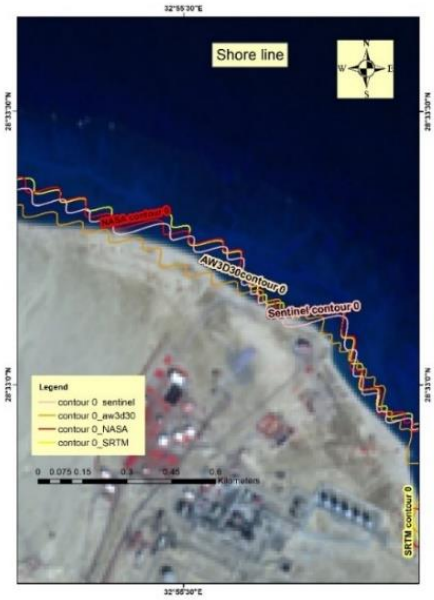

Fig. 9. Shoreline extracted from sentinel image and contour from different DEM.

5 Conclusions

- This study found that NASA DEM is the most accurate compared to SRTM, AW3D30, Sentinel-1, and ALOS DEMs, both when compared to GPS reference points and topographic map elevation data.
- GPS reference elevations showed RMS values of ±6.5 m, ±8.8 m, ±9.7 m, ±21.1 m, and ±22.3 m for the NASA, SRTM, AW3D30, Sentinel-1, and ALOS DEMs, respectively. Using topographic map data, the RMS values were ±5.6 m for NASA, followed by AW3D30 (±5.8 m), SRTM (±6.6 m), ALOS PALSAR (±17.1 m), and Sentinel (±17.2 m).
- The range, median, and mean values provide further insights into the distribution and variation of elevation errors across different DEMs. It is evident that NASA DEM offers the best accuracy in elevation measurements among all the DEMs.
- also assisted in evaluating the vertical accuracy of extracting the zero-contour line from different DEMs compared to the coastline from satellite imagery.
- Based on the horizontal accuracy assessment, AW3D30 was the most accurate DEM, with an average distance of 22.6 meters from the shoreline, followed by NASA at 30.4 meters, SRTM at 33 meters, and Sentinel at 38 meters. This indicates AW3D30's superiority in representing the coastline.
- In assessing streamline accuracy by examining the hydrology network with a topographic map, NASA had the closest alignment with an average distance of 4.7 meters, followed by SRTM at 5.6 meters, and AW3D30 at 34.7 meters, showing variability in horizontal accuracy.

In summary, NASA's model exhibits superior vertical accuracy and horizontal representation of streamline locations, whereas AW3D30 excels in horizontal accuracy for coastline delineation. Therefore, it is recommended to use the NASA DEM in this thesis.

6 Future Work

Future work in the field of DEMs should focus on improving horizontal and vertical accuracy, especially in mountainous areas where the terrain is complex.

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