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Comparative Analysis of Satellite-Based Elevation Models and High-Resolution Terrain Data for Coastal Flood Risk Assessment in the Red Sea Region

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Abstract: This research conducts a comparative analysis of three Digital Elevation Models—developed High-Resolution Digital Elevation Model (HRDEM) as a reference, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), and Shuttle Radar Topography Mission (SRTM)—across the study region from Suez to Hurghada. Initially, elevation and slope characteristics are evaluated using elevation difference statistics, revealing that ASTER and SRTM exhibit broader elevation ranges and more rugged topographical features than the reference DEM. Subsequent statistical analysis identifies notable outliers, with ASTER and SRTM datasets showing high slope values that may necessitate additional quality assessments. Further examination using skewness and kurtosis metrics indicates a symmetrical distribution, highlighting a decline and slope bias toward lower values accompanied by significant outliers. Elevation differencing was then performed to generate error maps, uncovering significant discrepancies between ASTER and the reference, as well as between SRTM and the reference. Root Mean Square Error (RMSE) values demonstrate notable variations between ASTER and SRTM relative to the reference DEM, with the ASTER-reference comparison indicating a marginally reduced mean elevation bias compared to the SRTM-reference. ASTER and SRTM datasets exhibit significant skewness and kurtosis, signifying pronounced terrain fluctuations and noise. Ultimately, HRDEM presents a more balanced and reliable representation of the terrain, underscoring its reliability as a reference model for precise terrain modelling and the necessity for accurate terrain modelling while using ASTER and SRTM datasets as their intrinsic biases and elevated kurtosis can adversely affect geomorphometric analysis, coastal flooding assessments, and risk evaluations.
Keywords: High Resolution DEM, free DEMs, coastal flooding.

1. Introduction

Digital Elevation Models (DEMs) are essential for ensuring the accuracy of hydrodynamic models. Open-access DEM products have been extensively utilized in flood modelling and cartography. However, open-access DEMs' inadequate resolution and precision considerably restrict the capacity to assess flooding zones and associated dangers. Low-quality DEM data has been shown to cause significant biases in flood predictions, influenced mainly by the spatial resolution and vertical accuracy of Digital Elevation Models (DEMs). Inadequate spatial resolution impairs the identification of surface features and the precision of flood simulations. Vertical elevation inaccuracies can impact the precision of terrain and flooding simulations. Accurate Digital Elevation Models are essential for precise flood modelling and management [1]. Digital Elevation Models can be developed via contour surveys, cartography, photogrammetry, interferometry, and radar imaging; horizontal resolution and vertical accuracy are critical factors in selecting an appropriate DEM product. However, numerous regions globally continue to depend on coarser-resolution, less precise Digital Elevation Models (DEMs) obtained by the Shuttle Radar Topography Mission (SRTM) and Interferometric Synthetic Aperture Radar (InSAR) for the creation of flood inundation maps. Many studies have highlighted the relevance of DEM resolution in flood inundation mapping, concluding that higher-resolution DEMs yield more precise flood maps [2]. An essential application of coastal DEMs is mapping inundation due to sea level rise. Precise projections of land drowned due to sea level rise are essential for adaptation and risk management strategies. However, despite considerable progress in processing methodologies, errors intrinsic to DEMs persist and may significantly influence the dependability and precision of subsequent studies and decision-making processes. Despite recent improvements to existing global DEMs, high and persistent errors in these DEMs result in significant uncertainty when analyzing coastal processes.

However, it has long been recognized that vertical accuracy is equally important in quality criteria [3]. To accurately identify and delineate lands in a specific region that are vulnerable to eustatic sea-level rise, the underlying coastal processes and their relationships must be well understood. Topography is a key parameter that influences many of the processes involved in coastal change; therefore, up-to-date, high-resolution, high-accuracy elevation data are required to model the coastal environment [4].

[5] uses high-resolution terrain data to evaluate the vertical precision of three digital elevation models (DEMs) -

SRTM, ASTER, and TanDEM-X 90m. ASTER demonstrated superior precision, although overstated elevation values in several areas. Despite its superior resolution, TanDEM-X 90m exhibited diminished positional accuracy due to systematic data collection and processing errors. The SRTM data underestimated elevation values in the study area. The research indicates that GPS-based field terrain models and TanDEM-X 90m are appropriate for localized locations. In contrast, ASTER and SRTM are ideal for global-scale analyses, provided corrections such as smoothing and anomaly identification are applied. Also, [6] compares ASTER GDEM and SRTM 1-arc second DEMs in mountainous terrain, finding that SRTM has better initial accuracy. However, ASTER showed significant improvement, while SRTM showed minimal enhancement. The study recommends elevation-specific modeling approaches and advanced machine learning methods for better accuracy enhancement. It emphasizes the importance of DEM source selection for hydrological studies, terrain analysis, and watershed management.

When examining DEMs, it is crucial to consider the disparities between freely available datasets and those with a higher resolution. By comparing the two types of DEMs, a deeper understanding of the accuracy and details of elevation data could be achieved.

In the realm of free DEMs, the level of detail is often limited due to the data source and processing methods constraints. These datasets are generally produced using lower-quality satellite or aerial imagery, resulting in coarser resolution and potential inaccuracies in elevation measurements. On the other hand, high-resolution DEMs offer a more precise representation of the terrain regarding the utilization of advanced remote sensing technologies such as LiDAR, which can penetrate vegetation canopies to capture the underlying ground and differentiate between various objects, including vegetation, buildings, and terrain [7]. This results in greater accuracy in elevation data, with finer details captured in the topography. So, it depicts the terrain's surface derived from elevation data. The Digital Terrain Model (DTM) represents the ground surface's morphology, whereas the Digital Surface Model (DSM) encompasses the surface's configuration, incorporating vegetation, infrastructure, and buildings, as illustrated in Figure 1. Consequently, DEMs are extensively utilized in geoscience. The quality of a DEM is the primary criterion for each application and can influence many processing stages, like The quality must satisfy the user's specifications [8].

This research aims to assess and evaluate the distinctions between free Digital Elevation Models (DEMs), such as SRTM and ASTER, compared to high-resolution Digital Elevation Models (DEMs) to ascertain their accuracy, usability, and appropriateness for diverse applications. The results will assist in determining the most suitable type of DEM for particular geographic and engineering applications, including coastal flood risk assessment, terrain analysis, hydrological modelling, and infrastructure planning, hence enhancing decision-making on the utilization of elevation data.

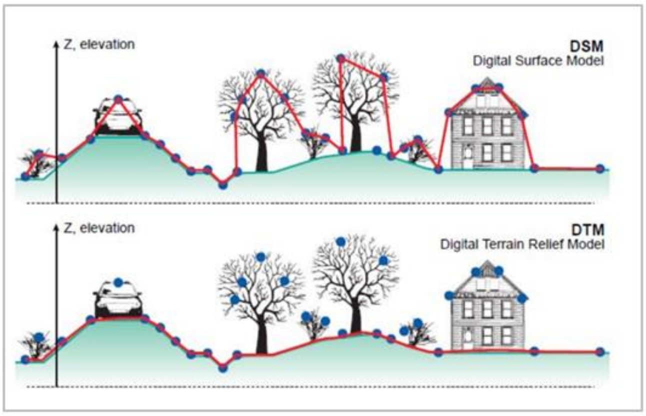

FIGURE 1. The difference between Digital Surface Model and Digital Terrain Model

2. MATERIALS AND METHODS

The evaluation methodology between free DEMs and the reference DEM (HRDEM) begins with DEM differencing, which is utilized to assess accuracy by contrasting the elevations across all DEM sources, yielding insights into model inconsistencies. The accuracy assessment metric is followed by concentrating the statistical variables such as Root Mean Square Error (RMSE), skewness, and kurtosis. Visual analysis and map comparison were performed to facilitate a side-by-side assessment of terrain characteristics, enabling the recognition of qualitative disparities in spatial detail. These integrated methodologies provide a comprehensive framework for assessing the efficacy and applicability of diverse DEMs.

2.1 STUDY AREA DESCRIPTION

The study area, depicted in Figure (2), is extending along the Red Sea coast, the Egyptian Red Sea Governorate, between latitudes 27° 10′ 0″ N and 30° 00′ 0″ N and longitudes 32° 20′ 0″ E and 34° 40′ 00″ E, covering approximately 440 km from Suez to Hurghada. The study region holds considerable economic, industrial, social, and cultural significance. Moreover, a substantial initiative is underway to develop new industrial complexes alongside expanding tourism operations.

2.2 FREE SOURCES OF DEMS

2.2.1 SRTM (SHUTTLE RADAR TOPOGRAPHY MISSION)

Shuttle Radar Topography Mission – SRTM - released in 2003. developed based on radar data (two synthetic aperture radars aboard Space Shuttle Endeavour) The C-band Spaceborne Imaging Radar and the X-Band Synthetic Aperture Radar (X-SAR) hardware were used on board the space shuttle in April and October 1994 to gather data about Earth's environment, the first version covers an area of Earth between 60◦ north and 56◦ south, most of the world was released at a resolution of 3″ except the U. S of resolution 1″ [9]. The second version results from a substantial editing effort. It exhibits well-defined water bodies and coastlines and the absence of spikes and wells 1˚ x 1˚ tiles, although some areas of missing data ('voids') are still present. These voids occur mainly over water bodies (lakes and rivers), snow-cover areas, and mountainous regions. Version three is provided by the Consultative Group on International Agricultural Research–Consortium for Spatial Information (CGIAR–CSI). This dataset has undergone post-processing of the NASA data to fill in the data voids through interpolation techniques. It is provided with a 'voids mask' depicting the areas of Version 2 voids filled in. The fourth version, The SRTM 90m DEM, has a resolution of 90m at the equator and is provided in mosaiced 5˚x 5˚tiles for easy download and use. The data will be utilized to generate a rectified, terrain-corrected mosaic covering about 80% of the Earth's terrestrial topography (from 60 degrees North to 56 degrees South latitude) at a resolution of 30 meters. SRTM has a minimum vertical accuracy of 16 m absolute error at 90% confidence (Root Mean Square Error (RMSE) of 9.73 m worldwide [10].

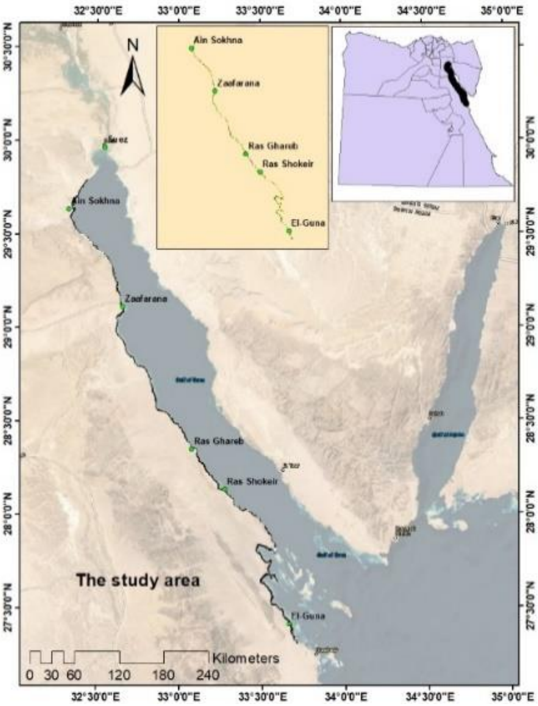

FIGURE 2. The study area

2.2.2 ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer)

ASTER version 1 was released in 2009, it was generated using 1,264,000 Level-1A scenes acquired between March 1, 2000 and November 30, 2007. also, it was created by stacking all individual cloud-masked scene DEMs and non-cloud-masked scene DEMs and then applying various algorithms to remove abnormal data, While Version 2 was released in 2011. employs data collected between 2000 and 2010, covering the earth's surface between 83◦ north and 83◦ south while its horizontal resolution is around 30 m at the equator [9]. The ASTER GDEM2 showed improvements compared with the first version, such as better georeferencing, the inclusion of more scenes acquired between 2008 and 2011, and a smaller correlation kernel (5×5 versus 9×9 for GDEM1) and higher spatial resolution with vertical accuracy of approximately 10 m [11]. On August 5, 2019, Japan's Ministry of Economy, Trade, and Industry (METI) and the United States National Aeronautics and Space Administration (NASA) jointly announced the release of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model Version 3 (GDEM 003) and the ASTER Water Body Dataset (ASTWBD). The ASTER V3 and SRTM V4.1 data for this study were downloaded from the United States Geological Survey's website (www.usgs.gov). The data available on this site has been updated to the most recent version, utilizing advanced interpolation algorithms and enhanced auxiliary DEMs. Consequently, this version represents a substantial improvement over previous iterations.

3. HRDEM CONSTRUCTION (REFERENCE DEM)

This research highlights the process of developing a detailed **High-Resolution** **D**igital **E**levation **M**odel (**HRDEM**) along the study area as it is highly required for accurate flood inundation maps; it is the preferable dataset in hydrodynamic modelling and simulations while improving flood simulation accuracy is crucial to implement cost-effective strategies for mitigating and preventing damages and economic losses resulting from flood threats. The topographic survey and creating contour maps were conducted across two stages, the first stage was setting up the Reference Stations Network, including the GPS control point and Levelling step. The second stage was obtaining the topographic contour maps [**Error! Reference source not found.**].

3.1 GPS CONTROL POINT

71 control points were installed along the study area from Suez to Hurghada as shown in Figure.3, Table.1 and Figure 4. The Global Navigation Satellite Systems (GNSS) were utilized to establish the geodetic network. Six GNSS receivers were used in the field. The six receivers simultaneously received the available satellites signals from all available GNSS systems (GPS, GLONASS, Galileo, and Be Diou). The international standards and specifications have been applied for such a high-precision geodetic network.

FIGURE 3. The location of the established 71 control points for the study area [12]

TABLE 1. Description of a sample of the reference card [12]

Point Name	Latitude	Longitude	Northing (m)	Easting (m)	Height (MSL)
P1	N29°57'49.439089"	E32°32'11.110662"	3314857.070	455272.251	4.219

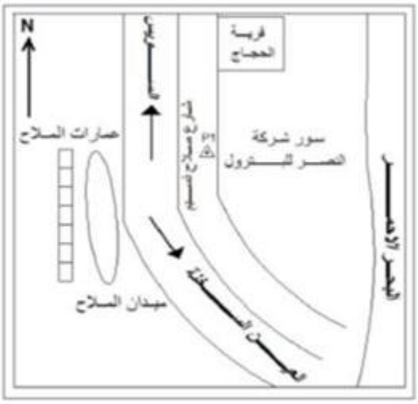

FIGURE 4. Sample of the reference card [12] (The point is located in front of Nasr Petroleum Company, to the right of the navigator on the road leading to Suez)

3.2 LEVELLING SURVEY

The obtained GNSS-based heights are referenced to the WGS84 ellipsoid or geodetic datum. In civil engineering applications, orthometric height is utilized relative to the Mean Sea Level (MSL) datum. Therefore, the GNSS heights are not referenced to Egypt's surveying and mapping applications. Consequently, the precise levelling technique is applied to obtain the required orthometric heights for all control stations. The Leica NA2 precise level instrument is used. The established GNSS control points had to be referenced to the existing Bench Mark/s (BM) established by the Egyptian Survey Authority (ESA) to obtain the orthometric heights of the stations.

3.3 OBTAINING THE TOPOGRAPHIC CONTOUR MAPS

The survey was done from the shoreline landward direction through sections almost perpendicular to the shoreline. The length of each section is about 500 to 900m with an interval of about 2km between each two consecutive cross sections. Moreover, an additional survey was conducted between the measuring sections to increase the accuracy of the obtained topographic contour line. This innovative approach revolutionizes cartography, providing unparalleled detail and accuracy in mapping the terrain.

The survey measurements were referenced to the mean sea level and UTM WGS84. Utilizing GNSS instruments in topographic mapping is faster than any other terrestrial technique. The kinematic survey utilized one fixed receiver and three moving (kinematic) rovers. The raw data of all receivers were revised for quality control assurance. Figure (5) shows an example of the obtained data. The final coordinates were obtained with the precise satellites' orbits available, and the contour maps were developed.

After determining the levels of grid points along the study area, a High-Resolution Digital Elevation Model (HRDEM) was created using about 438,000 survey points, with an accuracy of 10×10 m and a sub-meter (<10 cm) vertical resolution; the model covers an inland distance ranging between 500 to 900 meters and is spanning approximately 440 kilometers, stretches from Suez to Hurghada. The HRDEM, as shown in Figure (6), is an essential factor in accurately assessing the effects of sea level rise, as vertical precision plays a vital role in maintaining high-quality data standards [13].

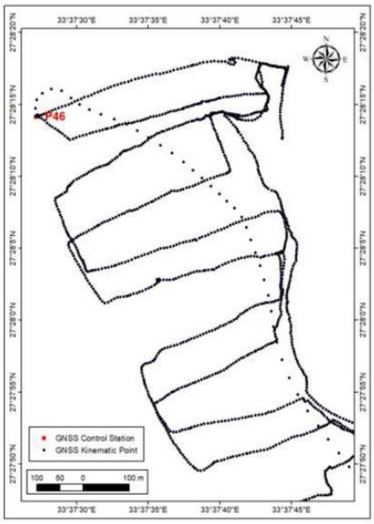

FIGURE 5. GPS Topographic Mapping Session [12]

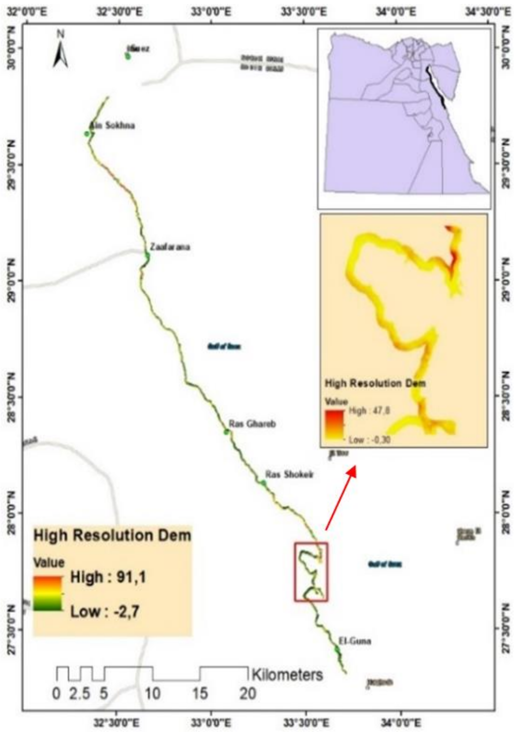

FIGURE 6. High-resolution DEM along the study region

4. EVALUATION METHODOLOGY

The C-band SRTM and ASTER-derived Digital Elevation Models (DEMs) are assessed and validated using a reference DEM. (HRDEM) along the study area from Suez to Hurghada in this research. Several standard methodologies and statistical measures are employed to evaluate each model's accuracy and performance, such as Dem differencing (Error calculation), accuracy assessment metrics (root mean square and skewness and kurtosis), vertical accuracy evaluation, visual analysis and map comparison. The evaluation methods ensure that both quantitative and qualitative aspects of terrain representation are considered. DEMs of the study region were converted to the Universal Transverse Mercator (UTM) zone 36 North projection system. WGS 1984 was selected as the datum and spheroid. A mask was created to cover the area on all Digital Elevation Models (ASTER, SRTM, and Reference). The initial 10m accuracy of the Reference DEM was resampled to 30m to facilitate the evaluation with the other DEMs. Subsequent to resampling, a low-pass filter was applied to all DEMs to eliminate potential outliers in the data. Smooth topographic models and minimal DEM smoothing before geomorphometric analysis have gained more popularity among geomorphometricians [14]. No misalignment between the DEMs was detected; therefore, co-registration was unnecessary. Summary statistics, including skewness and kurtosis [15], were computed for each error map of the three DEMs. Skewness is a dimensionless measure of asymmetry in distribution [16]; negative skewness indicates an extended tail on the left, whereas positive skewness indicates an extended tail on the right. Excess kurtosis is a dimensionless measure that assesses the peakedness of the data distribution. A value over zero (0) indicates a peaked distribution, while a value below zero (0) represents a flat distribution.

$$\text{Kurtosis} = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - x^-)^4}{\left(\frac{1}{n}\sum_{i=1}^{n}(x_i - x^-)^2\right)^2} \tag{1}$$

$$\text{Skewness} = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - x^-)^3}{\left(\frac{1}{n}\sum_{i=1}^{n}(x_i - x^-)^2\right)^{3/2}} \tag{2}$$

$$\text{Standard Deviation} = \sqrt{\frac{\sum(x_i - x^-)^2}{n}} \tag{3}$$

Where:

$x_i = Data\ points$

$x^- = Mean\ of\ the\ dataset$

$n = Number\ of\ data\ points$

Dem differencing was performed to derive elevation error maps by calculating Root mean square error (RMSE) for each error map, a standard measure of quantifying vertical accuracy in DEMs.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - y^{\wedge}{}_i)^2} \tag{4}$$

Where:

$y_i = the\ observed\ value$

$y^{\wedge}{}_i = the\ predicted\ value$

$n = Number\ of\ data\ points$

5. RESULTS AND DISCUSSIONS

The elevation and slope characteristics of the three DEMs—Reference (HRDEM), ASTER, and SRTM—were evaluated using various statistical performance metrics. Additionally, error map statistics were computed across the study area. Sectional profiles were extracted from the target area based on the SPOT 6 map and analyzed to compare all DEMs.

5.1 ELEVATION AND SLOPE CHARACTERISTICS

Table 2. compares elevation and slope characteristics across Reference, ASTER, and SRTM datasets. ASTER and SRTM provide broader elevation ranges and more rugged terrain than the reference dataset, with significant outliers indicating potential data artifacts or sharp terrain features. While ASTER and SRTM exhibit comparable elevation distributions, both display anomalously high slope values, which require further investigation to ensure accurate terrain modelling and data quality. The skewness and kurtosis metrics suggest that the data is skewed toward lower elevations and slopes, with notable outliers that may influence terrain analysis. The reference DEM captures more extreme slopes with higher variability (as indicated by higher skewness and kurtosis), making it more suitable for detailed and accurate terrain studies.

5.2 DEMS ELEVATION ERROR MAPS

Figure 7. presents the statistics of the error maps along the study area; the **ASTER-Reference** and **SRTM-Reference** datasets show the same minimum and maximum differences, indicating extreme deviations from the reference (HRDEM) dataset in terms of the lowest and highest elevation points. ASTER-Reference has a more negligible overall bias than the reference dataset, with a mean difference 9.64. In contrast, SRTM-Reference has a higher mean difference of 11.3, indicating a more considerable bias in the SRTM dataset. Both datasets have high standard deviations, with ASTER having 26.9 and SRTM having 28.2. The Root Mean Square Error (RMSE) for ASTER-Reference is the same as SRTM-Reference, indicating significant deviations from the reference. ASTER-Reference has a high skewness value of 6.25, indicating a distribution of differences heavily skewed towards higher deviations. SRTM-Reference has a slightly lower skewness of 5.80, indicating a lower distribution. The kurtosis for ASTER-Reference and SRTM-Reference is high at 47.29 and 41.32, indicating sharp or sudden changes in elevation compared to the reference dataset.

5.3 PROFILING

Four horizontal profiles (sections) were generated along the study area using different Digital Elevation Models (DEMs) and subsequently compared to assess their elevation characteristics. A graph plotting elevation against distance was produced for each profile, providing a visual representation of terrain variations. According to Figure (8), the elevation profiles of HRDEM, ASTER, and SRTM across different sections (SEC 1 to SEC 4) varied between flat, rugged, and urban areas. In Section 1, HRDEM demonstrates a smooth and linear elevation profile that corresponds well to the flat topography observed in the spot map, as depicted in Figure (9). Conversely, SRTM and ASTER capture some terrain variations with sharper fluctuations, potentially overestimating actual elevations. For Section 2, SRTM exhibits a steeper elevation increase, while ASTER shows a decline in elevation; the gradual rise in terrain depicted in the spot map aligns closely with the HRDEM profile, as shown in Figure (9). In Section 3, ASTER and SRTM reflect sharper and more pronounced terrain changes compared to the more gradual elevation increase in HRDEM, which is more consistent with the terrain features visible in the spot image. In Section 4, SRTM and ASTER display variable and fluctuating elevation profiles, while HRDEM maintains a relatively stable terrain representation.

TABLE 2. Summary statistics of the three DEMs

Dataset	Description	Min	Max	Mean	Standard Deviation	Skewness	Kurtosis
Reference	Elevation	-2	91.0	5.9	8.5	3.90	23.20
	Slope	0	32.8	1.5	2.13	4.48	32.95
ASTER	Elevation	0	391.0	15.9	29.7	5.70	38.70
	Slope	0	154.6	5.5	9.9	4.3	23.7
SRTM	Elevation	-9	378.0	17.6	31.8	5.10	31.30
	Slope	0	190.8	5.9	9.7	4.2	24.06

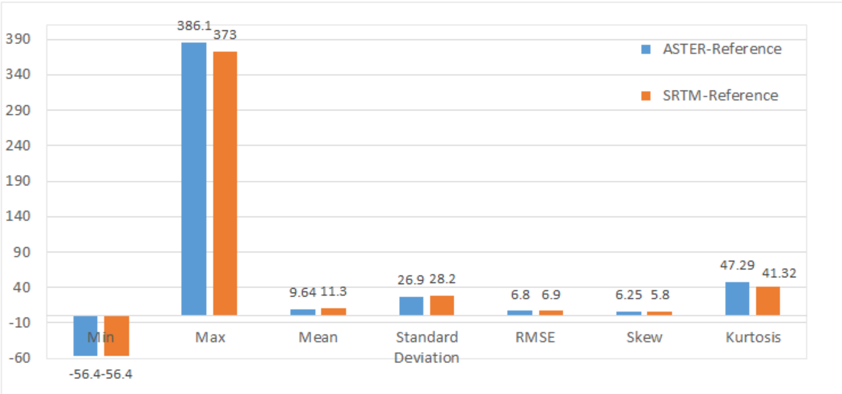

FIGURE 7. The differences in statistics along the study area

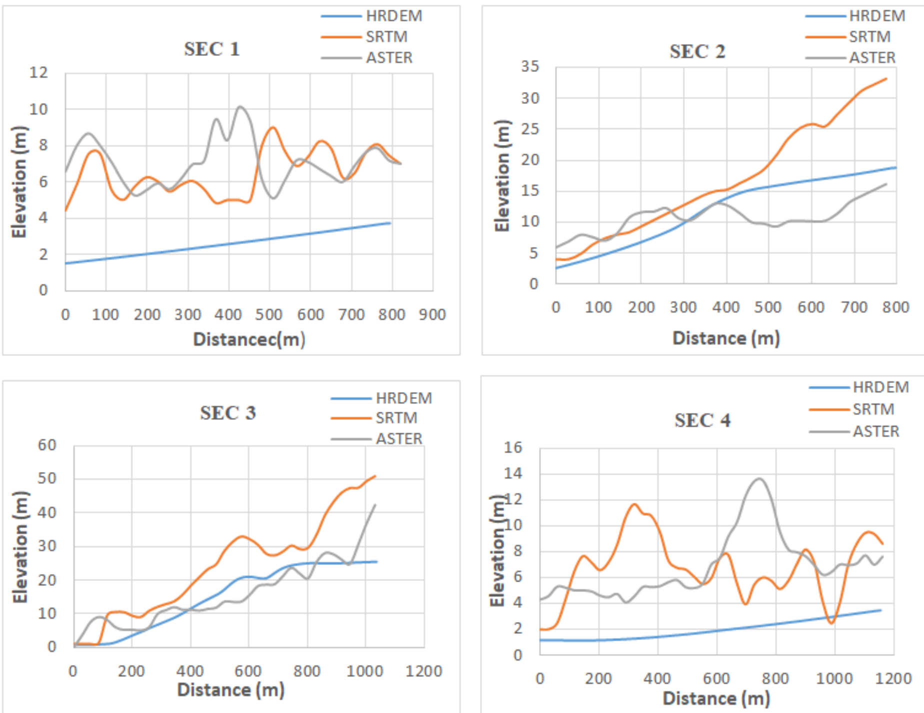

FIGURE 8. Profile Comparison derived from all the DEMs

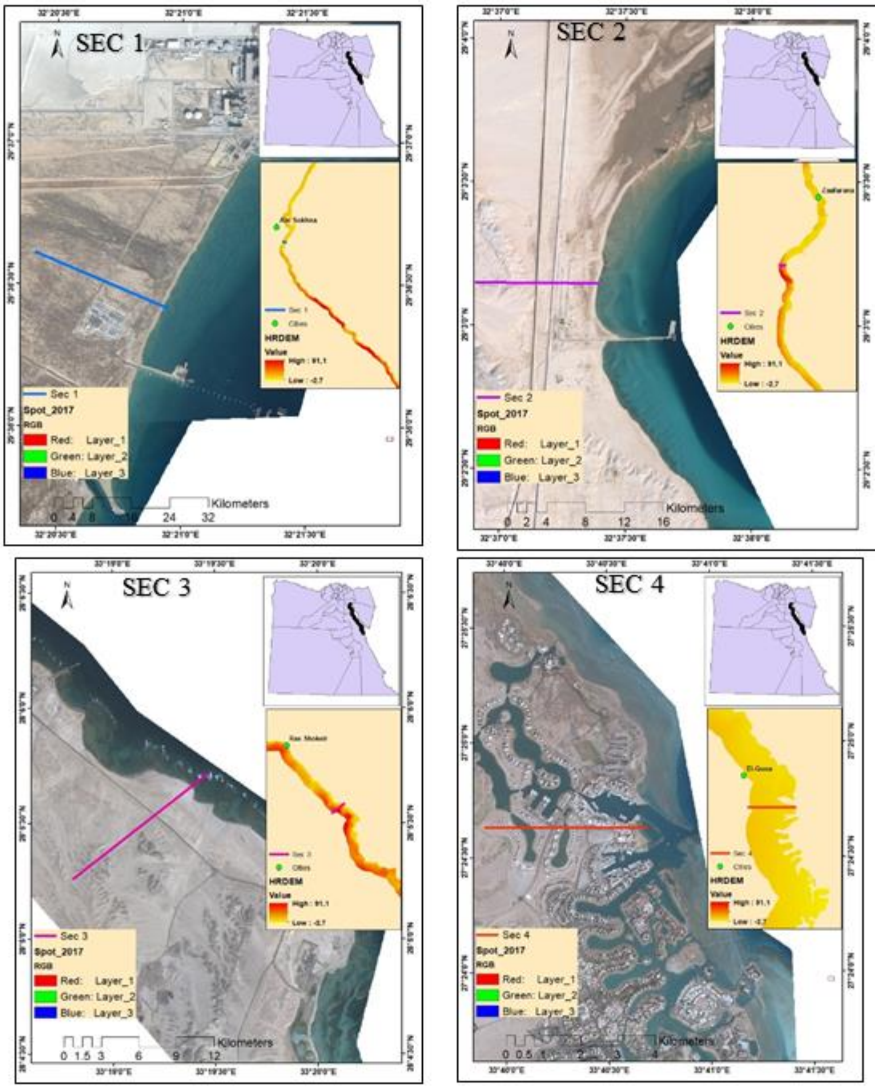

FIGURE 9. Sections profile with Spot Maps

CONCLUSION

The developed High-Resolution Digital Elevation Model (HRDEM), was utilized as a reference for the comparison between SRTM and ASTER, boasts an accuracy of 10 ×10 m and a sub-meter (<10 cm) vertical resolution. It covers an inland distance of 900 meters over 440 kilometers from Suez to Hurghada.

The analysis of elevation and slope data from the Reference, ASTER, and SRTM datasets indicates that ASTER and SRTM encompass a notably wider range of elevation values, implying that these datasets may represent more complex terrain characteristics or include data anomalies resulting in extreme values.

The distribution characteristics of both ASTER and SRTM reveal significant skewness and kurtosis; the elevated skewness and kurtosis values suggest a distribution characterized by frequent sharp or sudden changes in elevation, potentially indicating either genuine topographical features or inconsistencies within the data itself.

Compared to the Reference dataset, ASTER exhibits a marginally lower mean elevation difference than SRTM. However, both datasets present high standard deviations and Root Mean Square Error (RMSE) values, suggesting significant variability and analogous deviations from the Reference model.

The findings highlight the importance of meticulously interpreting ASTER and SRTM data, which could affect applications that demand high precision in elevation measurements. Additional exploration or modifications, including techniques like smoothing or anomaly detection, may be required to improve the dependability of these datasets for comprehensive terrain analysis. At the same time, the reference DEM provides a more precise depiction of elevation and slope, exhibiting reduced variability and a diminished presence of extreme outliers compared to ASTER and SRTM. It also reduces the likelihood of data artifacts or overstated terrain features that may result in erroneous predictions of coastal inundation as sea levels rise.

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