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Comparative Accuracy Assessment of Shuttle Radar Topography Mission, NASA Digital Elevation Model, and Copernicus Digital Elevation Model in Perlis, Malaysia

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ABSTRACT

Digital Elevation Models (DEMs) are essential tools for applications such as flood risk mapping, geoid modelling, and terrain analysis. The increasing availability of global digital elevation models (GDEMs), including the Shuttle Radar Topography Mission (SRTM), NASA Digital Elevation Model (NASADEM), and Copernicus DEM (CopDEM), has significantly improved access to elevation data worldwide. However, their accuracy varies depending on topography and data acquisition methods. This study evaluates the performance of SRTM, NASADEM, and CopDEM in the Perlis State region of Malaysia. Ground truth data were obtained from 38 Global Navigation Satellite System (GNSS) benchmarks and 1,177 points of Advanced Topographic Laser Altimeter System (ATLAS) onboard the Ice, Cloud, and land Elevation Satellite-2 (ICESat-2). Prior to analysis, ellipsoidal heights were converted to orthometric heights using the Earth Gravitational Model 1996 (EGM96) geoid model. DEM elevation values were interpolated at each validation point, and accuracy was assessed using Mean Error (ME), Standard Deviation (STD), and Root Mean Square Error (RMSE). Results indicate that NASADEM demonstrates the highest accuracy, with RMSE values of ±1.855 m (GNSS) and ±5.814 m (ICESat), followed by CopDEM and the SRTM DEM. All three (3) GDEMs show strong positive correlations with ground truth data (R > 0.98). These findings suggest that NASADEM provides the most reliable elevation data for the Perlis region, particularly in relatively flat areas. This study

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contributes to better decision-making in selecting appropriate DEMs for environmental and geospatial applications in similar terrains.

INTRODUCTION

The A Digital Elevation Model (DEM) is a three-dimensional representation of the Earth's surface constructed from elevation data. DEMs have become indispensable in numerous fields and are widely applied in flood mitigation (Hermas et al., 2021; Avand et al., 2022; Vashist et al.,2023), watershed management (Fathy et al., 2019; Tesema, 2021), geoid modelling (Varga et al., 2021; Pa'suya et al., 2022), and engineering and infrastructure development (Yilmaz, 2017). The accuracy of DEMs depends on their source, generation method, and the specific requirements of the intended application. DEMs can be derived from various sources, including photogrammetry, satellite imagery, field surveys, and Light Detection and Ranging (LiDAR) data (Makineci & Karabörk, 2016; Dakheel et al., 2020). Among these, LiDAR-derived DEMs are often the most accurate (Li et al., 2022). However, LiDAR coverage is limited, primarily to developed countries, covering only about 0.005% of Earth's land area (Hawker et al., 2018), and large-area surveys are costly.

Advances in radar and optical sensor technology on spaceborne platforms have enabled the generation of Global DEMs (GDEMs), providing near-global elevation data. Since 2000, several GDEM products have been freely available, including the Shuttle Radar Topography Mission (SRTM) DEM, the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) DEM, the Advanced Land Observing Satellite World 3D – 30 Meter Resolution (AW3D30) DEM, the Copernicus DEM (CopDEM), and NASADEM. Among these, the SRTM DEM and ASTER DEM are the most widely used. Released in 2003, the SRTM DEM is generally considered accurate, with reported accuracies ranging from 2.18 to 21.70 m (Sampson et al., 2015; Purinton et al., 2017; Pa'suya et al., 2019), whereas ASTER DEM shows lower accuracy (Gesch, 2018). NASADEM, derived from reprocessed SRTM radar measurements, was released by NASA in 2020 (Okolie et al., 2024). Several studies (Buckley et al., 2020; Uuemaa et al., 2020; Li et al., 2022; Aziz et al., 2023) have evaluated NASADEM. For example, Buckley et al. (2020), using ICESat data, reported an accuracy of approximately 5.5 m, while Uuemaa et al. (2020) found that NASADEM outperformed SRTM. The Copernicus DEM, derived from high-resolution commercial radar data collected during the mission of TerraSAR-X Add-on for Digital Elevation Measurement (TanDEM-X), was released in 2020 by the European Space Agency (ESA). Although its performance has been less frequently examined, Guth and Geoffroy (2021) reported that CopDEM outperformed other GDEMs. Li et al. (2022), using ICESat-2 altimetry data across selected terrains in China, found that CopDEM achieved accuracy nearly equivalent to NASADEM and AW3D30 DEM.

In general, GDEM accuracy is strongly influenced by topography, land cover, and slope (Li et al., 2022). Previous studies have evaluated accuracy using LiDAR (Trevisani et al., 2023; Bielski et al., 2024; Okolie et al., 2024), GNSS levelling (Rahman et al., 2022; Santillan, 2023; Zayed et al., 2023), and ICESat altimetry (Nandam & Patel, 2024). This study assesses the performance of three (3) widely available GDEMs—SRTM, NASADEM, and CopDEM - over the Perlis State region, using GNSS levelling stations and ICESat-2 altimetry as reference datasets.

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STUDY AREA AND DATA

Study Area

The study area covers the state of Perlis, as illustrated in the Figure 1 which is located in the northern part of Peninsular Malaysia, bordering Thailand to the north and Kedah to the south. Perlis lies approximately between latitudes 6°15′N to 6°45′N and longitudes 100°05′E to 100°25′E, covering an area of about 821 km². The region is characterised predominantly by flat to gently undulating terrain, with low-lying agricultural areas forming most of the landscape. Elevations across most of Perlis range between 20 m and 100 m above sea level, which provides an ideal setting for DEM accuracy studies in relatively flat conditions. Despite its generally flat topography, Perlis also contains localised hilly areas such as the Nakawan Range along the border with Thailand, which reaches elevations above 500 m. These areas introduce terrain variability that allows for the assessment of DEM performance across both flat and moderately rugged landscapes. The combination of paddy fields, urban settlements, forested hills, and limestone outcrops makes Perlis a suitable test site for evaluating the sensitivity of different DEM products to variations in land cover and slope.

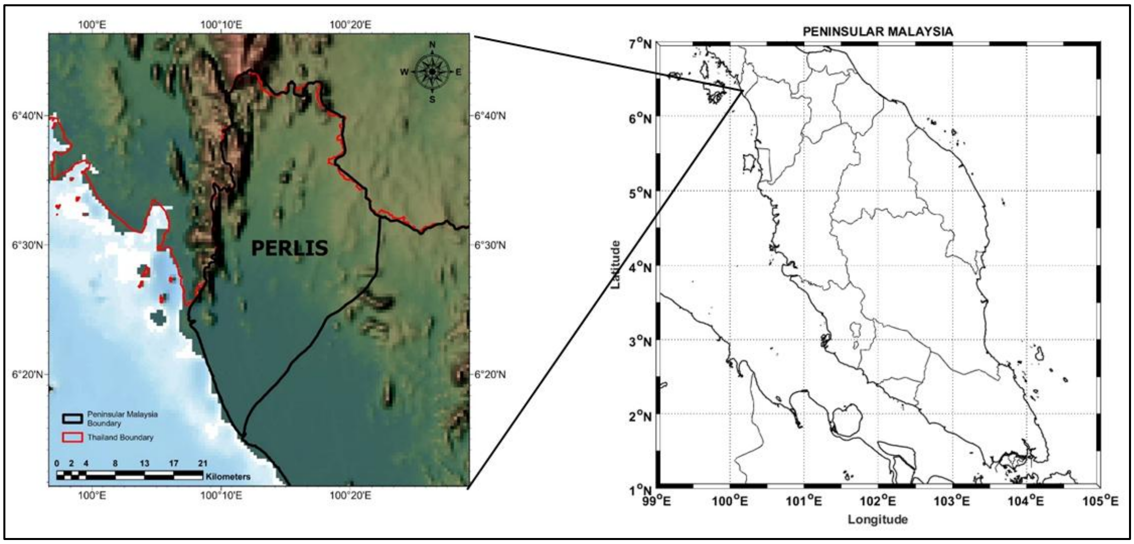

Fig. 1. Study Area in Perlis

Sources: Authors (2025)

Datasets

Global DEMs

This study evaluates three (3) global DEMs: SRTM, NASADEM, and Copernicus DEM (CopDEM). Details of these datasets are summarised in Table 1 and illustrated in Figure 2.

Table 1. Overview of Global DEM Products Evaluated in This Study.

Global DEM	Spatial Coverage	Spatial Resolution	Data Acquisition	Primary Data Source
SRTM DEM	56◦S–60◦N	1 arc-second	2000 (11 days)	C-band radar

NASADEM	56◦S–61◦N	1 arc-second	2000 (11 days)	Reprocessed C-band radar
CopDEM	Global	1 arc-second	2011–2015	Reprocessed X-band radar

Source: Authors (2025)

(i) SRTM DEM

The SRTM DEM is one (1) of the most widely used global elevation models. It was generated using a modified radar system aboard the Space Shuttle Endeavour (Tahir & Din, 2022). The mission was a joint effort by NASA, the National Imagery and Mapping Agency (NIMA), the German Space Agency (DLR), and the Italian Space Agency (ASI), with the aim of producing the most comprehensive high-resolution topographic database in the world. The DEM was released in two (2) spatial resolutions: 1 arc-second (~30 m) and 3 arc-seconds (~90 m).

(ii) CopDEM

The Copernicus DEM (CopDEM) is a 1-arcsecond Digital Surface Model (DSM) generated from the TanDEM-X mission using Synthetic Aperture Radar (SAR) interferometry. Data were acquired between December 2010 and January 2015, and the model was released in three (3) resolutions: 0.4″, 1″, and 3″ (Li et al., 2022).

(iii) NASADEM

NASADEM is an updated DEM created by reprocessing SRTM data (Buckley et al., 2020). Its primary goal is to improve SRTM quality, particularly by eliminating voids, and to provide higher accuracy compared to the original dataset. The reprocessing incorporated an enhanced algorithm and additional data from ASTER and the ICESat Geoscience Laser Altimeter System (GLAS). ASTER data were used to fill voids, while ICESat data served as a reference for height error correction (Buckley et al.,2020).

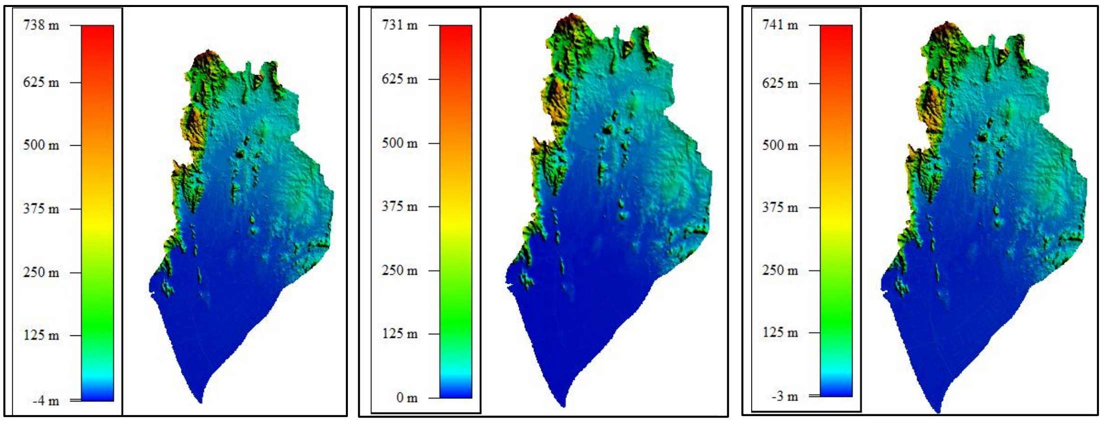

Fig. 2. GDEMs from (left) NASA DEM; (centre) CopDEM; and (right) SRTM DEM over Perlis Region.

Source: Authors (2025)

Reference Height

Two (2) reference datasets were used for validation: (i) GNSS observations and (ii) ICESat-2 ATLAS08 altimetry. GNSS observations were collected at 38 benchmarks across Perlis, using a TOPCON GR5 receiver with a two (2) hour observation period and a one (1) second sampling rate. The GNSS data were processed in Trimble Business Center (TBC) using two (2) Malaysian Real Time Kinematic GNSS Network (MyRTKnet) reference stations, namely Arau and Universiti Utara Malaysia, which served as the control stations. The distribution of GNSS points is shown in the left panel of Figure 3, while the right panel illustrates the second dataset consisting of ICESat-2 ATLAS08 points. Launched in 2018, ICESat-2, with its ATLAS provides denser and more accurate global elevation measurements than its predecessor (Neuenschwander & Magruder, 2019). Since high-accuracy LiDAR DEMs are limited to small regions (Hawker et al., 2018), ICESat-2 data are valuable as a globally distributed reference for DEM validation (Yue et al., 2017; Zhao et al., 2015; Li et al., 2023). In this study, a total of 1,177 ICESat-2 ATLAS08 points was obtained from the OpenAltimetry website.

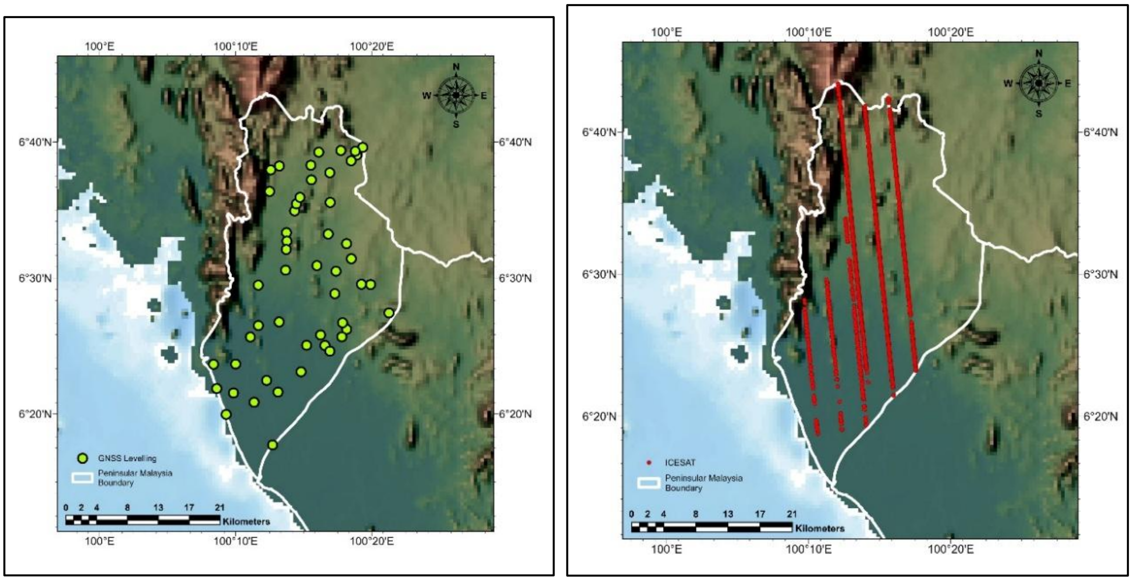

Fig. 3. Distribution of (left) GNSS levelling; and (right) ICESAT-02 ATLAS08 over the Perlis Region.

Source: Authors (2025)

METHODOLOGY

Generation of Reference Dataset

In this study, the accuracy of each GDEM was evaluated using GNSS and ICESat-2-derived topographic heights. GDEMs are typically referenced to the geoid surface, most commonly the EGM96 model (Table 1), while GNSS observations and ICESat-2 altimetry data provide ellipsoidal heights. To ensure consistency, ellipsoidal heights (h) were converted to orthometric heights (H) by subtracting the EGM96 geoid height (N):

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$$H = h - N_{EGM96} \quad (1)$$

It is important to note that the reference ellipsoids for GNSS coordinates and GDEMs are different. The reference ellipsoid is a mathematical model that represents the Earth's shape. It provides a simplified model for determining GNSS positions on the Earth's surface, which is more efficient in calculations. In the local context, we used the Geocentric Datum of Malaysia (GDM) 2000. It aligned with the International Terrestrial Reference Frame (ITRF) 2000, in which GRS80 is the reference ellipsoid. In comparison, the GDEMs are mostly referenced to the WGS84 ellipsoid, which is similar to GRS80 but with different inverse flattening values. Such differences are minimal, with an overall RMS difference of 1 cm (NGA, 2014; Malys, 2016), which is generally considered negligible in vertical datum transformations. This is further supported by Din et al. (2022), who reported a vertical discrepancy of approximately 3.88 cm between ITRF2014 and WGS84 over Peninsular Malaysia.

The relationship between GNSS ellipsoidal height, geoid height, and orthometric height is illustrated in Figure 4.

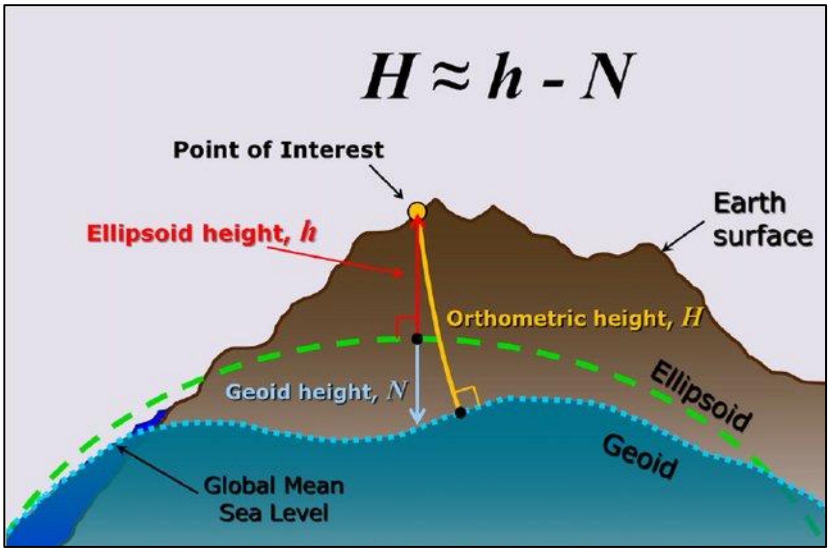

Fig. 4. Relationship Between Ellipsoidal Height, Orthometric Height and Geoid Height.

Source: Snay (2012)

Accuracy Assessment

Since DEM values represent elevations at the pixel centre, which may not coincide exactly with the validation point locations, bilinear interpolation was applied to estimate elevations at the precise reference positions. Bilinear interpolation able to provides a balanced approach between accuracy and computational efficiency when estimating DEM elevations at non-grid locations. DEM values represent elevations at the centre of each raster cell, whereas reference GNSS and ICESat-2 points rarely coincide with these exact centres. Bilinear interpolation uses the four (4) nearest pixel values to calculate the elevation at a given point, producing a smoother and more realistic surface than nearest-neighbour interpolation, which may introduce abrupt changes or step-like artefacts. Compared to higher-order methods such as cubic convolution, bilinear interpolation reduces the risk of introducing artificial oscillations or overshoots, which can distort elevation estimates in relatively flat terrains such as Perlis. The error for each point was then calculated as the difference between DEM elevation and reference elevation. Based on these errors, three (3) statistical measures were computed: mean error (ME), standard deviation (STD), and root mean square error (RMSE), defined as:

$$ME = \frac{\sum_{i=1}^{n}(Z_{DEM} - Z_{REF})}{n} \quad (2)$$

$$STD = \sqrt{\frac{\sum_{i=1}^{n}[(Z_{DEM} - Z_{REF}) - ME]^2}{n-1}} \quad (3)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Z_{DEM} - Z_{REF})^2}{n}} \quad (4)$$

where Z_{DEM} represents the DEM elevation, Z_{REF} the reference elevation from GNSS or ICESat-2 ATL08, and n the number of points.

RESULTS

The statistical results for each GDEM are presented in Table 2, while Figure 5 illustrates the errors relative to GNSS observations. Overall, the comparison indicates that NASADEM outperforms both CopDEM and SRTM DEM, with an RMSE of ±1.855 m. CopDEM follows with an RMSE of ±2.450 m, while SRTM shows the lowest accuracy with an RMSE of ±3.131 m. The Mean Error (ME) values of 0.345 m, 1.324 m, and 2.381 m further indicate that all three (3) GDEMs tend to overestimate elevations relative to GNSS benchmarks.

Table 2. Statistical analysis of CopDEM, NASADEM, and SRTM DEM based on GNSS-derived heights.

Model	Min Difference (metres)	Max Difference (metres)	ME (metres)	STD (metres)	RMSE (metres)
NASA DEM	-3.325	4.759	0.345	1.839	±1.855
CopDEM	-2.681	8.515	1.324	2.080	±2.450
SRTM DEM	-2.393	7.758	2.381	2.053	±3.131

Source: Authors (2025)

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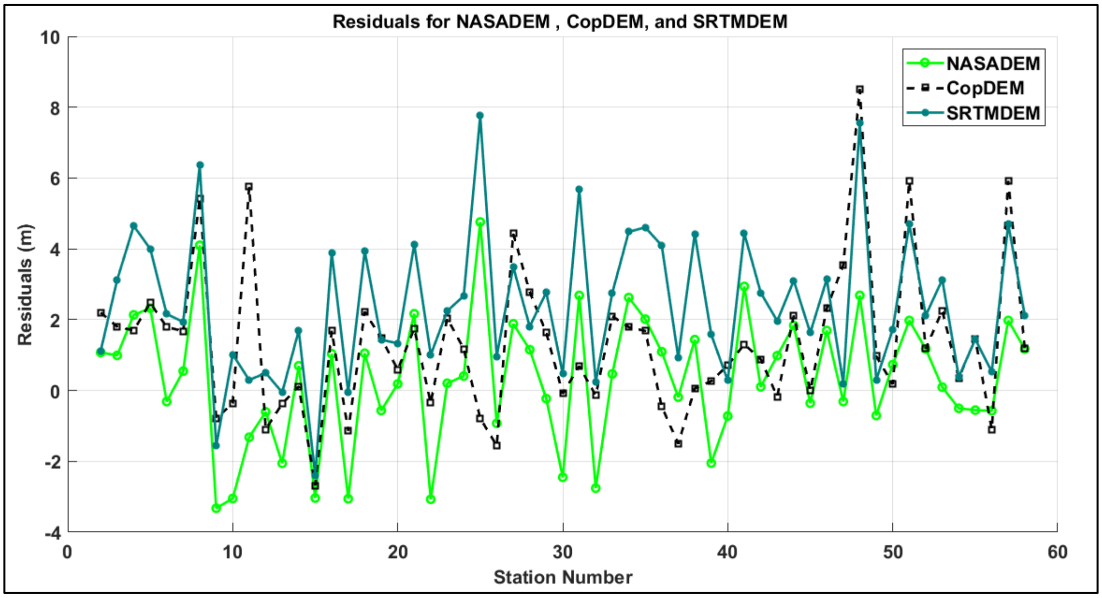

Fig. 5. The distribution of residuals for NASADEM (in green solid line), CopDEM (in black dotted line), and SRTM DEM (in dark green solid line).

Source: Authors (2025)

Regression analysis results (Figure 6) reveal strong positive correlations between all three (3) GDEMs and GNSS heights, with correlation coefficients of 0.992, 0.991, and 0.990 for NASADEM, CopDEM, and SRTM DEM, respectively.

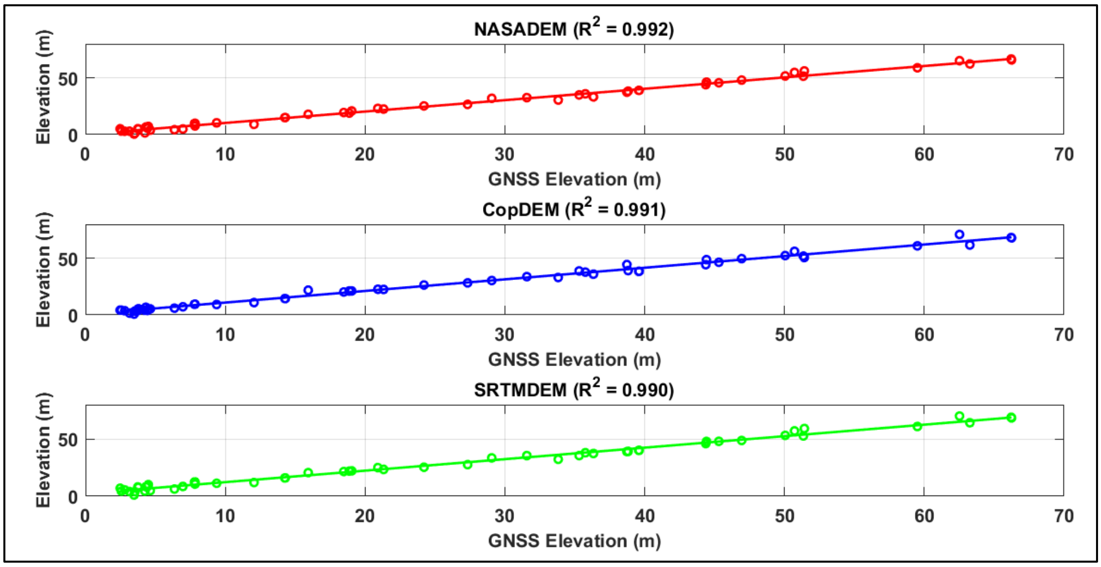

Fig. 6. The R^2 Correlation Coefficient for All GDEMs Against GNSS-Derived Height Elevation.

Source: Authors (2025)

A second evaluation was conducted using elevations derived from 1,177 ICESat-2 ATLAS08 points. The statistical results are summarised in Table 3, and the pointwise differences are illustrated in Figure 7. As expected, RMSE values for all GDEMs are higher than those from the GNSS comparison. This is largely due to the GNSS benchmarks being located in relatively flat areas, while the ICESat-2 ATLAS08 data cover a wider range of topographic conditions. Based on this analysis, NASADEM again provides the highest accuracy, with an RMSE of ±5.814 m, followed by CopDEM (±6.415 m) and SRTM (±7.079 m). These findings are consistent with the results of Li et al. (2022). Among the three (3) GDEMs, NASADEM records the lowest ME (2.771 m) and STD (5.113 m). CopDEM follows with ME and STD values of 3.477 m and 5.393 m, respectively, while SRTM has ME and STD values of 4.602 m and 5.382 m. The correlation analysis (Figure 8) shows high positive correlations for all three (3) DEMs against the ICESat-2 dataset, with coefficients of 0.984 (NASADEM), 0.983 (CopDEM), and 0.982 (SRTM).

Table 3. Statistical Analysis of CopDEM, NASA DEM, and SRTM DEM Based on the Comparison with the ICESat-2 ATLAS08 Dataset.

MODEL	Min Difference (m)	Max Difference (m)	ME (m)	STD (m)	RMSE (m)
NASA DEM	-7.525	50.651	2.771	5.113	±5.814
CopDEM	-6.465	51.969	3.477	5.393	±6.415
SRTM DEM	-4.741	57.833	4.602	5.382	±7.079

Source: Authors (2025)

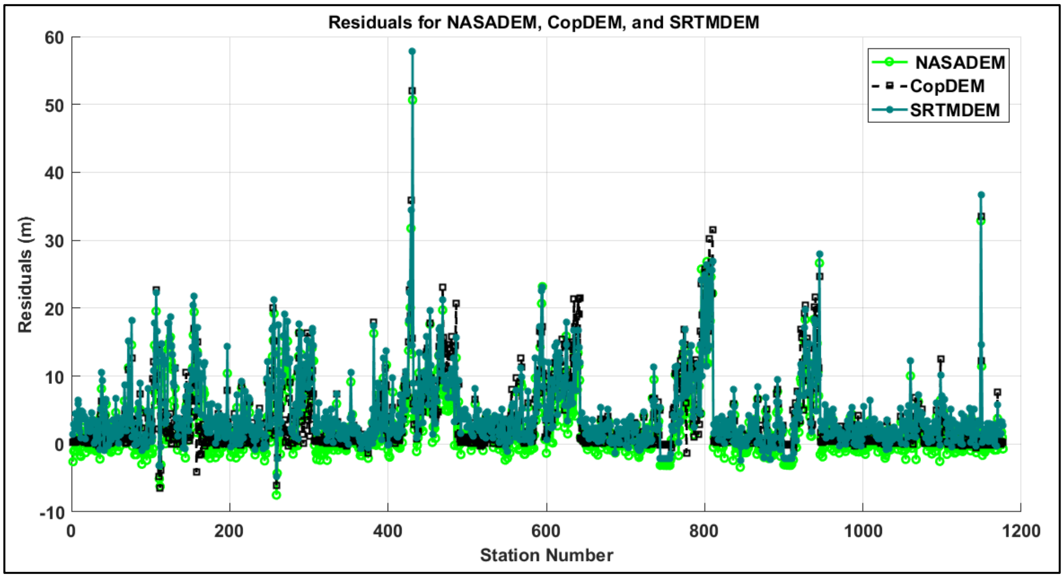

Fig. 7. The Error Between 1177 Points of the ATLAS08 Datasets and Three (3) GDEMs.

Source: Authors (2025)

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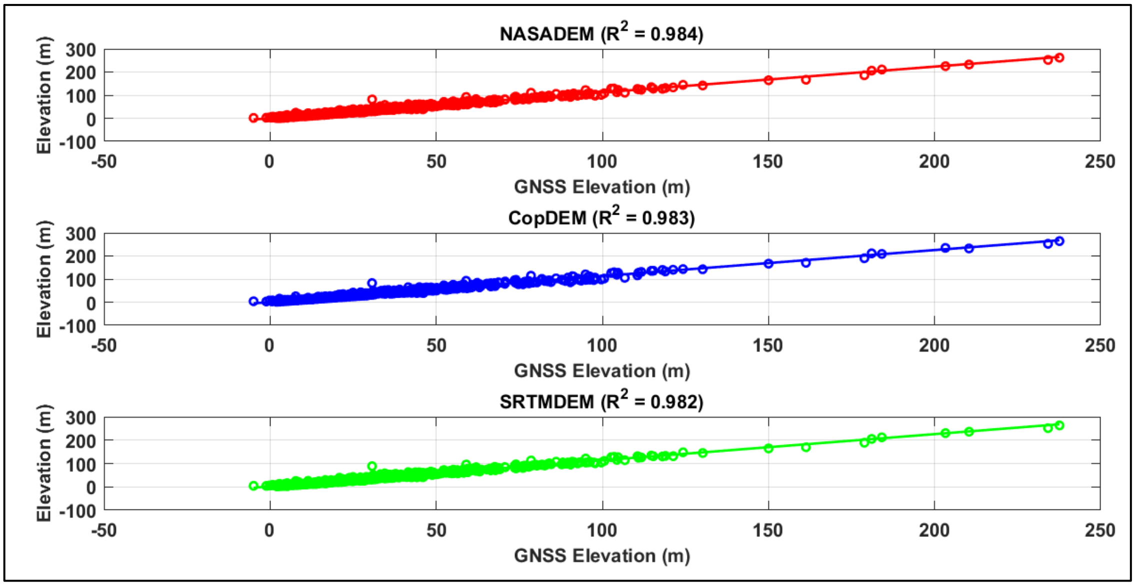

Fig. 8. Correlation coefficient, R of each GDEMs and ICESat-2 ATLAS08.

Source: Authors (2025)

DISCUSSION

Although CopDEM is derived from newer and higher-resolution X-band radar data, its RMSE values in this study were slightly higher than those of NASADEM. This outcome may be attributed to several factors. First, NASADEM benefits from extensive reprocessing of the original SRTM data, including the integration of auxiliary datasets such as ICESat/GLAS and ASTER, which enhance vertical accuracy and fill data voids. Second, X-band radar, used in CopDEM, is more sensitive to vegetation canopy and built-up surfaces compared to the C-band radar used in SRTM/NASADEM, potentially introducing larger elevation biases in areas with dense vegetation or complex land cover. In addition, CopDEM has been more extensively validated in Europe, and its regional calibration over Southeast Asia may be less robust, leading to slightly higher residual errors. The results also highlight the influence of terrain type on DEM accuracy. In flat terrain, such as most areas of Perlis, DEM errors are generally lower because radar signals are less affected by slope distortions, and reference GNSS benchmarks provide stable elevation values. By contrast, in hilly or mountainous terrain, errors tend to increase due to radar layover, shadowing effects, and the amplification of vertical discrepancies caused by horizontal misalignments on steep slopes. These factors explain why the GNSS-based comparison yielded lower RMSE values than the ICESat-based comparison, which covered more varied topographic profiles.

The RMSE values obtained in this study are broadly consistent with those reported in earlier evaluations of global DEMs. For instance, Buckley et al. (2020), using ICESat data, reported that NASADEM achieved an accuracy of approximately 5.5 m, which is comparable to the RMSE of ±5.814 m obtained in this study using ICESat-2 data. Similarly, Uuemaa et al. (2020) found that NASADEM generally outperformed SRTM in various regions, a trend also observed in the Perlis case study. Li et al. (2022) evaluated CopDEM, NASADEM, and AW3D30 over selected terrains in China using ICESat-2 altimetry. Their findings showed that CopDEM and NASADEM had nearly identical accuracies, with RMSE values ranging between four (4) and six (6) meters depending on terrain complexity. In the present study, NASADEM again demonstrated slightly better accuracy than CopDEM, although both exhibited strong correlations with the reference data. This suggests that regional factors such as land cover, vegetation density, and slope variability may influence the relative performance of the two (2) DEMs. Comparisons with regional studies also highlight the role of terrain type. For example, Pa’suya et al. (2019) reported SRTM errors in Perlis ranging between 2 and 20 m, depending on land cover and slope. The lower RMSE values obtained in the current study (±3.131 m against GNSS, ±7.079 m against ICESat-2) indicate that recent reprocessed versions of DEMs, particularly NASADEM, have reduced systematic errors and improved reliability, even in relatively flat Southeast Asian environments.

CONCLUSION

This study evaluated and compared the performance of three (3) global digital elevation models (GDEMs): SRTM DEM, NASADEM, and Copernicus DEM (CopDEM) over the Perlis region in Malaysia using GNSS and ICESat-2 altimetry data. The results show that NASADEM provides the highest accuracy, with the lowest RMSE values in both datasets. These findings consistently identify NASADEM as the most reliable source of elevation data, particularly in relatively flat areas. Although CopDEM and SRTM also demonstrated strong correlations with the reference data, they yielded higher RMSE values and lower precision. The outcomes of this study have important implications for selecting suitable DEMs in geospatial applications such as flood risk mapping, geoid modelling, and terrain analysis. Future research should extend these evaluations to more diverse terrain types, considering the effects of land cover and slope variability. Overall, this work provides valuable guidance for informed decision-making in environmental management and geospatial applications across regions with similar characteristics.

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CONFLICT OF INTEREST STATEMENT

The authors affirm that this research was conducted without any personal, commercial, or financial benefits, and they declare that no conflicts of interest exist with the funders

AUTHORS’ CONTRIBUTIONS

Hairie Ilkham Sibaruddin conducted the research activities, while Muhammad Faiz Pa’suya prepared and revised the manuscript. Noorfatekah Talib and Afreena Nisha Mohd Zamri participated in the data acquisition used in this study. Ami Hassan Md Din designed the research framework and supervised its overall progress. Muhammad Faiz Pa’suya led the manuscript review, coordinated the revisions, and approved the final submission. Chien Zheng Yong contributed to data processing and assisted in the refinement of the manuscript.

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