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Research Article

Standardization of the elevation in the AW3D30 global digital elevation model to the Vietnamese national vertical datum: An experiment in Ninh Binh province and surrounding areas

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Abstract: This study proposes a method for normalizing the elevation of the global digital elevation model (GDEM) ALOS World 3D - 30 m (AW3D30) to Vietnam's national height system, based on national GNSS/levelling data from Ninh Bình province and surrounding areas. The correction process consists of three main steps: (1) Collecting GNSS/levelling data, global DEM data, and EGM96 geoid model data to ensure accuracy and consistency; (2) Determining correction parameters to transform AW3D30 global elevations to local heights, including analyzing differences between global and local geoid models and assessing tidal influences; (3) Verifying, correcting, and evaluating the accuracy of AW3D30 after correction to align with the national height system. Experimental results show that after correction, the root mean square error of the AW3D30 model in the national vertical datum is ±1.613 m, while the maximum deviation between AW3D30 elevations and GNSS/levelling heights is reduced from 9.014 m to 5.238 m. Approximately 91.7% of GNSS/levelling points have deviations within the acceptable range, demonstrating that the correction method significantly enhances the accuracy and applicability of AW3D30 in the national vertical datum. This method not only facilitates the normalization of AW3D30 in the study area but can also be applied to other regions in Vietnam, as well as to other GDEMs. The research findings contribute to improving the accuracy of topographic data, supporting spatial planning, resource management, disaster forecasting, and related applications.

Keywords: AW3D30; National Vertical Datum; DEM; GNSS/levelling; Ninh Binh.

1. Introduction

The global digital elevation model (GDEM) is a crucial product of Earth sciences, serving as a foundational tool for various research fields and practical applications. The digital elevation model (DEM) provides topographic data at different levels of resolution, enabling a more detailed representation of the Earth's surface than traditional methods. As a result, DEM plays a key role in geological, geomorphological, hydrological, glaciological studies, and natural disaster risk assessments [1]. Due to its ability to depict large-scale terrain structures, DEM is not only an essential tool for terrain visualization and analysis [2–3] but also supports the simulation of natural processes [4–6] and provides critical information for infrastructure planning, climate change studies, disaster monitoring, and natural resource management [7–12]. Recent studies have demonstrated that DEM is essential for surface flow modeling, flood assessment, and identifying landslide-prone areas [13, 14]. Currently, several widely used global DEMs exist, including the shuttle radar topography mission

(SRTM), advanced spaceborne thermal emission and reflection radiometer global digital elevation model (ASTER GDEM), NASADEM, and AW3D30, which are extensively utilized in research and practical applications [15–17]. These GDEMs provide large-scale topographic data with relatively high resolution, contributing to improved accuracy in terrain, hydrology, and environmental change studies. Among them, AW3D30, developed by the Japan Aerospace Exploration Agency (JAXA) using ALOS satellite imagery, is considered one of the most accurate models [18, 19]. With a spatial resolution of 30 m, AW3D30 utilizes stereoscopic data collected by the ALOS PRISM satellite and applies advanced image processing algorithms to generate a high-quality terrain model. Studies have shown that the accuracy of AW3D30 is higher than that of other global DEM models such as SRTM and ASTER GDEM [20–23]. Therefore, AW3D30 is selected for this study to assess the model's suitability under experimental conditions.

Although the global digital elevation model AW3D30 provides topographic data over a wide area, a significant limitation is the discrepancy between the model's vertical reference system and the national height system. Specifically, AW3D30 uses the global geoid EGM96 (tide-free system), whereas Vietnam's official height system (HN-72) is based on the long-term mean sea level at the Hon Dau tide gauge in Hai Phong (tide-mean system).

This discrepancy leads to significant differences between the DEM-derived elevations and actual surveyed heights, as EGM96 does not accurately reflect the regional gravity field of Vietnam and is not consistent with the local height system, which is influenced by oceanographic and regional topographic factors. Moreover, the Hon Dau reference point is determined from long-term sea level observations, while EGM96 is a global model built on satellite gravity and geodetic data. This results in systematic errors that can reach several meters in certain areas. Study [20] also emphasizes that to minimize errors when applying DEMs to local studies, they must be standardized according to the national height system.

Standardizing the global DEM AW3D30 to the local height system not only improves accuracy but also ensures consistency in practical applications. However, this process is not a simple conversion but requires a combination of field measurements, error modeling, and accuracy assessment. One of the biggest challenges is the complexity of terrain, as differences in elevation modeling methods can introduce significant interpolation errors. Mountainous areas with steep elevation changes tend to have greater errors than plains or coastal regions due to abrupt height variations and uneven point density, which can reduce the accuracy of DEM correction. Additionally, tidal effects play an important role in height standardization, especially in coastal and estuarine regions. Sea level fluctuations caused by tidal cycles and oceanographic dynamic factors, such as currents and atmospheric pressure changes, can impact the determination of the reference height system, leading to discrepancies in DEM conversion. Finally, the difference between the global geoid model and the local geoid is a crucial factor that must be carefully considered, as the global geoid EGM96 does not accurately represent Vietnam's regional gravity field, resulting in nonlinear errors in height transformation. This necessitates appropriate geoid correction models to align the DEM's vertical coordinate system with the national height system. Therefore, to optimize the performance of DEMs in geographic and environmental science applications, a suitable correction approach must be applied, integrating local geoid correction models, actual elevation survey data, and accurate interpolation algorithms. This not only minimizes errors but also ensures that DEMs can be effectively used in terrain analysis, hydrology, and climate change studies.

Previous studies have proposed various DEM height correction methods to minimize discrepancies between global DEMs and national vertical reference systems [24]. Some common approaches include:

Ground control point (GCP)-based correction method: Utilizing known elevation points within the local vertical system to adjust the DEM. The elevation values of these points are

compared with the corresponding DEM elevations, and mathematical transformations are applied to correct the model [25–29].

Geoid model-based correction method: Employing geoid models to convert elevations from the global vertical system to the local datum [30–32].

Regression model-based correction method: Applying regression models to predict and remove systematic DEM errors based on terrain and climate factors [33–36].

LIDAR data-based correction method: Utilizing high-accuracy LIDAR data to refine GDEMs [37–39].

Artificial neural network (ANN)-based correction method: Using ANN models to learn and predict DEM errors, then applying trained algorithms to adjust the data [40, 41].

Kriging interpolation-based correction method: Applying kriging interpolation to detect and eliminate systematic DEM errors [42–46].

Additionally, combining multiple correction methods has been used in studies [40, 41], [45] to optimize accuracy.

Although elevation correction methods for DEMs improve accuracy when converting between global DEMs and national height systems, each method has its own limitations. Ground control point-based corrections depend on the distribution of survey points, while geoid model-based methods may introduce errors due to the limited accuracy of global geoid models. Regression models and artificial neural networks require high-quality training data, whereas Kriging interpolation is only effective when the data points are densely distributed. LIDAR data offers high accuracy but is expensive to collect and has limited coverage. Combining multiple methods can optimize correction efficiency, but it also increases computational complexity and challenges in result evaluation. Therefore, selecting an appropriate correction method requires careful consideration of factors such as terrain conditions, available data, and accuracy requirements for specific applications.

In this context, studies in Vietnam have focused on assessing and improving the accuracy of DEMs, particularly the SRTM model, to align with the national height system. These studies have compared SRTM-derived elevations with actual survey data from GNSS/levelling points [47–49] or with elevation data extracted from topographic maps [47, 50]. Additionally, some studies have proposed correction methods to reduce DEM errors for practical applications [48–49].

The results of the aforementioned studies indicate that while SRTM can be applied in Vietnam, it requires standardization to ensure higher accuracy, particularly in areas with complex terrain. Among the methods studied, using GNSS/levelling data is an optimal solution because these points have elevations directly determined in the national height system, eliminating errors caused by differences between height systems. Compared to topographic map data, GNSS/levelling provides higher accuracy and more accurately reflects terrain conditions at the time of measurement, avoiding compounded errors from interpolation or digitization processes. This method not only allows for a direct assessment of DEM deviations relative to the local height system but also provides a reliable dataset for systematically correcting DEMs, forming a foundation for further research and practical applications.

Therefore, this study focuses on using GNSS/levelling data to correct the global digital elevation model AW3D30 according to Vietnam's national height system. Specifically, high-precision and reliable first-order, second-order, and third-order GNSS/levelling data from national networks will be utilized. These points are measured simultaneously using GNSS and levelling techniques, providing both ellipsoidal and orthometric heights, thereby enabling a robust and reliable correlation between the global height system, global geoid models, and Vietnam's national height system.

The primary distinction of this study from previous research [47, 48, 50] is that GNSS/levelling data is not only used for comparing elevations between global models and

actual survey data but also plays a crucial role in the correction process. Influencing factors include tidal effects, discrepancies between global and local geoid models, and the accuracy of AW3D30 when converted to the national height system. While this issue was addressed in [49] for the SRTM model, AW3D30 has the potential to provide more precise terrain data and warrants further investigation [51–53].

To ensure a systematic correction process, this study proposes a three main steps: (1) Collecting GNSS/levelling data, global DEM data, and EGM96 geoid model data to ensure accuracy and consistency; (2) Determining correction parameters to transform AW3D30 global elevations to local heights, including analyzing differences between global and local geoid models and assessing tidal influences; (3) Verifying, correcting, and evaluating the accuracy of AW3D30 after correction to align with the national height system.

The experimental area selected for this study is Ninh Bình province and its surrounding regions, which feature diverse topography, including low-lying plains, dense river networks, and low mountainous areas. The selection of this area aims to concretize the proposed correction method while assessing the accuracy of the AW3D30 global DEM. The results obtained will serve as a critical foundation for evaluating the feasibility of applying this model in practical scenarios. The proposed correction method in this study can be extended to other regions across Vietnam. Standardizing and unifying AW3D30 DEM data according to the national height system will enhance the accuracy of topographic data, paving the way for new approaches in utilizing and applying geospatial data in Vietnam.

2. Materials and Methods

2.1. Methods

2.1.1. Adjusting global elevation to local elevation

The AW3D30 global digital elevation model provides elevation referenced to the global geoid based on EGM96, within the tide-free system. In contrast, Vietnam's national vertical datum uses the multi-year mean sea level at Hon Dau Island, Hai Phong, within the mean-tide system. To adjust the elevation of the AW3D30 global digital elevation model to the national vertical datum, GNSS/levelling survey data (height control points) are utilized, specifically as follows:

Adjust the height anomaly of GNSS/levelling points derived from the global gravity field model EGM96 in the tide-free system to the mean-tide system using equation 1 [31, 54]:

$$\zeta_i^{mean} = \zeta_i^{free} + (1+k)\left(0,099 - 0,29\sin^2 B_i\right) \quad (1)$$

In this study, the Earth is considered a rigid body, then k = 0.

The difference in height anomalies of GNSS/levelling points in the mean-tide system, as determined from the global gravity field model EGM96 and measured data, is calculated using equation 2:

$$\Delta\zeta_i = \zeta^{GNSS/levelling} - \zeta_i^{mean} \quad (2)$$

The elevations of GNSS/levelling points, extracted from the AW3D30 global digital elevation model and converted to the national vertical datum, are calculated using Equation 3:

$$H_i^{reg} = H_i^{AW3D30} + \Delta\zeta_i \quad (3)$$

where ζ^{free} is the global height anomaly extracted from the EGM96 model in the free-tide system; ζ^{mean} is the global height anomaly in the mean-tide system; $\zeta^{GNSS/levelling}$ is the height anomaly measured at GNSS/levelling points; $\Delta\zeta$ is the difference between the global height anomaly extracted from the EGM96 model and the measured height anomaly at GNSS/levelling points; H^{AW3D30} is the global elevation extracted from the AW3D30 model;

H^{reg} is the global elevation in the national vertical datum after tidal correction; i is the index of the GNSS/levelling point.

2.1.2. Verification of AW3D30 global elevation data after conversion to the national vertical datum

a) Check for raw bias

The difference between the elevation of the AW3D30 global digital elevation model, after being adjusted to the national vertical datum, and the actual surveyed elevation at GNSS/levelling points is determined using equation 4:

$$\Delta_i = H_i^{reg} - H_i^{GNSS/levelling} \quad (4)$$

where Δ is the difference between the elevation of the AW3D30 global digital elevation model, after being converted to the national vertical datum, and the measured elevation at GNSS/levelling points.

The mean value of the deviation between the elevation of the AW3D30 global digital elevation model, after being converted to the national vertical datum, and the measured elevation at GNSS/levelling points is determined according to equation 5:

$$\Delta_{aver} = \frac{\sum_i^n \Delta_i}{n} \quad (5)$$

where Δ_{aver} is the mean height deviation of n points.

The deviation value between Δ and Δ_{aver} is calculated using equation 6:

$$d_i = \Delta_i - \Delta_{aver} \quad (6)$$

The standard deviation of the height error of the AW3D30 global digital elevation model in the national vertical datum, compared to the measured height at GNSS/levelling points, is calculated using equation 7:

$$\sigma = \sqrt{\frac{[dd]}{n-1}} \quad (7)$$

where σ is the standard deviation of the elevation from the AW3D30 global digital elevation model after being converted to the national vertical datum.

The standard deviation is used to assess the stability of the elevation data from the AW3D30 global digital elevation model in the national vertical datum. The threshold error limit (Δ_{limit}) is chosen to represent the distribution of data around the mean value as 3σ, this means that $\Delta_{limit} = \pm 3\sigma$, corresponding to approximately 99.7% of the data falling within this range [55].

b) Check for systematic bias

The deviation between the elevation from the AW3D30 global digital elevation model, after being adjusted to the national vertical datum, and the actual surveyed elevation at GNSS/levelling points must satisfy inequality 8:

$$\left|[\Delta]\right| \le 0,25\left[|\Delta|\right] \quad (8)$$

If inequality (8) is not satisfied, it indicates the presence of a systematic bias in the series of height deviations between the AW3D30 global digital elevation model in the national vertical datum and the measured heights. Therefore, correction is required.

The correction value is determined based on the deviation between the elevation from the AW3D30 global digital elevation model in the national vertical datum and the actual surveyed elevation at GNSS/levelling points, calculated using equation 9:

$$\theta = \frac{[\Delta]}{k} \quad (9)$$

where θ is the correction value, and k is the total number of GNSS/levelling points used in the calculation.

The elevation value from the AW3D30 global digital elevation model, after being converted to the national vertical datum, is further corrected according to equation 10:

$$H_i^{local} = H_i^{reg} + \theta \quad (10)$$

where H^{local} is the elevation from the AW3D30 global digital elevation model after being converted to the national vertical datum and adjusted to eliminate systematic bias.

The deviation value between the elevation from the AW3D30 global digital elevation model, after verification, and the actual surveyed elevation at GNSS/levelling points in the national vertical datum is calculated using equation 11:

$$\varepsilon_i = H_i^{local} - H_i^{GSNN/levelling} \quad (11)$$

where ε represents the deviation between the elevation from the AW3D30 global digital elevation model, after adjustment, and the actual surveyed elevation at GNSS/levelling points in the national vertical datum.

The accuracy of the elevation from the AW3D30 global digital elevation model in the national vertical datum is assessed through the root mean square error (RMSE), calculated using equation 12:

$$m = \sqrt{\frac{[\varepsilon\varepsilon]}{2k}} \quad (12)$$

The standardization of the elevation of the global digital elevation model AW3D30 to Vietnam's national height system is summarized in the following diagram:

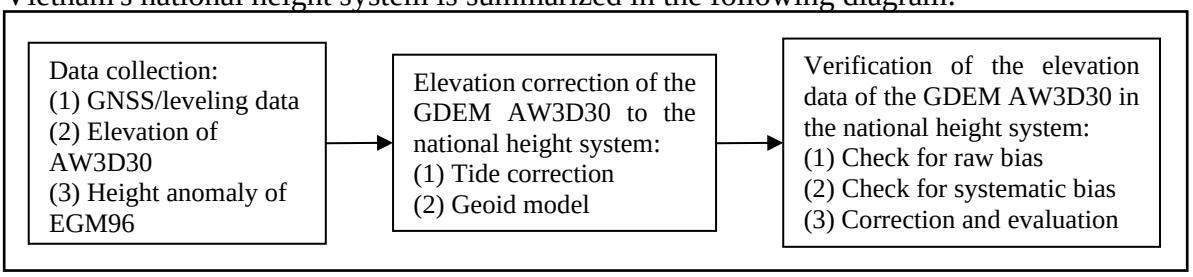

Figure 1. The standardization process of the AW3D30 GDEM in the national height system.

2.2. Data

The study area of this paper includes Ninh Binh province and adjacent regions in northern Vietnam. This area exhibits diverse topography, transitioning from low-lying plains to low hills. The average elevation ranges from 10 to 150 meters above sea level. Most of the region belongs to the Red River Delta, with elevations between 5 and 20 meters, while areas with elevations exceeding 100 meters are primarily concentrated in the west, along the edges of low mountain ranges.

For this study, 36 national GNSS/levelling of class I, II, and III (managed by the Department of Survey, Mapping, and Geographic Information Vietnam) within the region were used as reference points to transform the elevation of the AW3D30 global digital elevation model into the national vertical datum of Vietnam [31]. These points were also employed to assess the model's accuracy after correction (Figure 2).

Detailed information on the GNSS/levelling points is presented in Table 1. The parameters include geographic coordinates (B, L), elevation in the national vertical datum (h), geoid undulation (ζ), elevation from the AW3D30 global digital elevation model (H^{AW3D30}), which was obtained from JAXA's website, and geoid undulation from the EGM96 model (ζ^{EGM96}), retrieved from NGA's website. The specific values are listed in Table 1.

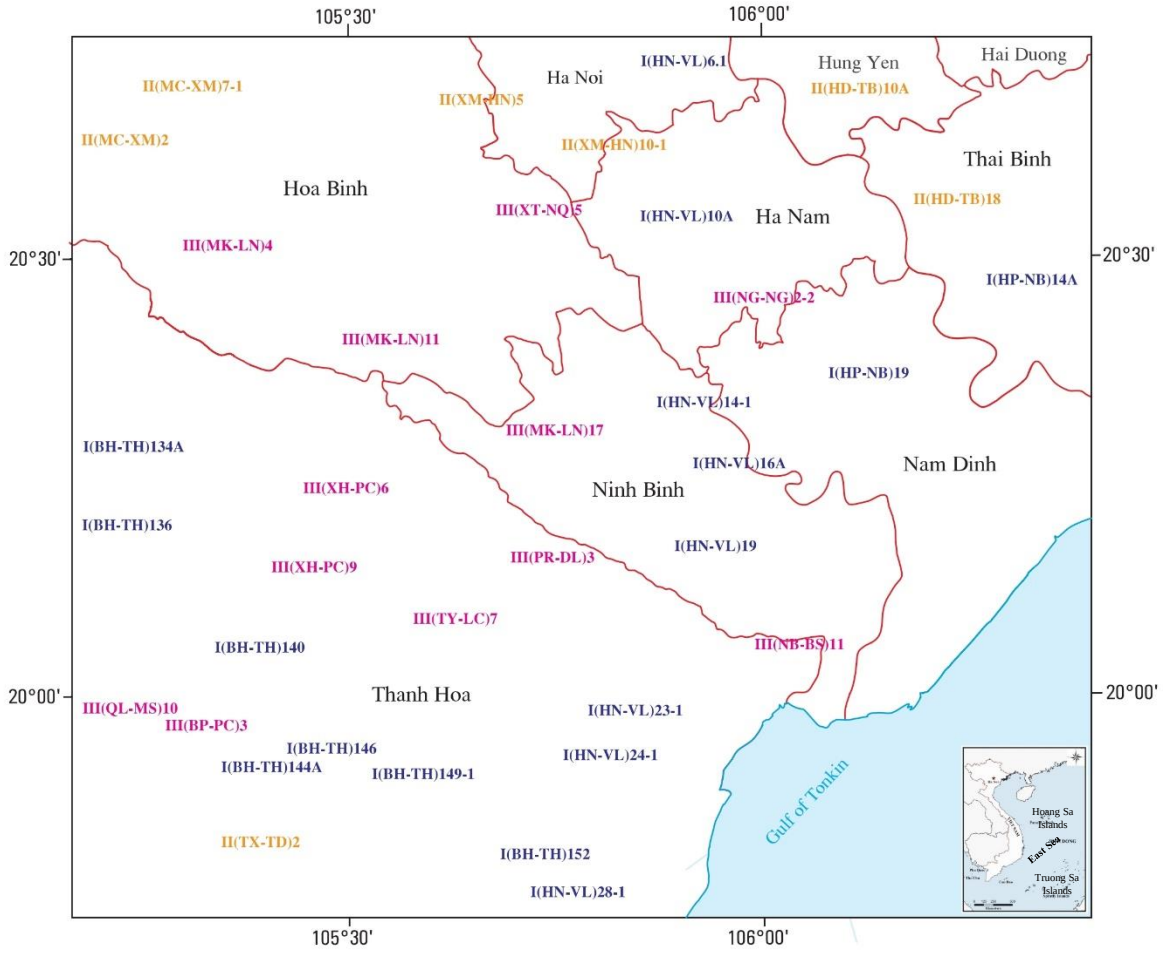

Figure 2. The experimental area includes Ninh Binh province and its surrounding areas.

Table 1. Data of GNSS/Levelling.

N^0	Point name	B (°)	L (°)	h (m)	ζ (m)	H^{AW3D30} (m)	ζ^{EGM96} (m)
1	I(BH-TH)140	20.05652	105.39390	33.286	-25.576	38.491	-26.836
2	I(BH-TH)144A	19.91975	105.40804	17.292	-25.495	22.241	-26.531
3	I(BH-TH)146	19.94081	105.48019	13.075	-25.275	17.445	-26.383
4	I(HN-VL)10A	20.54737	105.91174	4.701	-25.726	7.388	-25.917
5	I(HN-VL)14-1	20.33468	105.93127	1.579	-25.240	3.371	-25.445
6	I(HN-VL)16A	20.26464	105.97354	1.621	-25.112	7.829	-25.130
7	I(HN-VL)19	20.17042	105.94407	1.017	-24.897	4.004	-25.116
8	I(HN-VL)23-1	19.98303	105.84626	6.273	-24.633	9.387	-25.191
9	I(HN-VL)24-1	19.93214	105.81605	3.262	-24.598	5.186	-25.211
10	I(HN-VL)6-1	20.72451	105.90901	3.004	-26.0805	5.878	-26.341
11	I(HP-NB)14A	20.47301	106.35673	0.805	-25.0529	1.234	-23.886
12	I(HP-NB)19	20.36705	106.13044	2.820	-24.9932	7.986	-24.548
13	II(HD-TB)10A	20.70225	106.12370	2.633	-25.7538	4.374	-25.283
14	II(HD-TB)18	20.56484	106.23877	1.127	-25.4052	2.815	-24.418
15	II(MC-XM)7-1	20.69792	105.31415	191.545	-26.7516	198.777	-27.879
16	II(XM-HN)10-1	20.63084	105.81869	4.251	-25.939	7.861	-26.518
17	II(XM-HN)5	20.68137	105.66371	9.087	-26.220	13.732	-27.176
18	III(BP-PC)3	19.96750	105.32913	49.300	-25.667	52.902	-26.803
19	III(MK-LN)11	20.40808	105.55323	35.336	-25.799	41.181	-27.117
20	III(MK-LN)17	20.30344	105.75076	2.521	-25.463	8.446	-26.234

N⁰	Point name	B (°)	L (°)	h (m)	ζ (m)	H^{AW3D30} (m)	ζ^{EGM96} (m)
21	III(MK-LN)4	20.51584	105.35620	58.724	-26.364	63.531	-27.661
22	III(NB-BS)11	20.05737	106.04462	1.175	-24.471	4.972	-24.511
23	III(NG-NG)2-2	20.45389	106.00441	1.553	-25.389	3.686	-25.275
24	III(PR-DL)3	20.16046	105.75938	86.750	-25.012	88.596	-25.916
25	III(TY-LC)7	20.08866	105.62975	10.772	-24.995	16.318	-26.252
26	III(XH-PC)6	20.23835	105.49836	27.506	-25.544	32.447	-26.967
27	III(XH-PC)9	20.14820	105.43782	77.032	-25.535	83.006	-26.929
28	II(MC-XM)2	20.63549	105.18108	259.537	-26.767	266.563	-28.018
29	III(QL-MS)10	19.97696	105.21077	100.006	-25.701	104.443	-27.064
30	I(BH-TH)152	19.81928	105.73691	10.247	-24.694	10.472	-25.300
31	I(HN-VL)28-1	19.77585	105.77616	2.225	-24.624	4.363	-25.073
32	I(BH-TH)136	20.19649	105.22886	94.821	-26.030	101.591	-27.420
33	II(TX-TD)2	19.83409	105.39434	55.899	-25.458	63.920	-26.419
34	I(BH-TH)134A	20.28721	105.19301	59.512	-26.190	67.154	-27.626
35	I(BH-TH)149-1	19.91137	105.59042	8.669	-24.883	16.540	-25.995
36	III(XT-NQ)5	20.55524	105.73283	11.681	-25.915	15.868	-26.736

3. Results and discussions

3.1. Results

The analysis results of the national height control points in the study area (Table 1) were used to compute the global height anomaly in the mean tide system and to adjust the global elevation to the local height. These results are presented in Table 2.

Table 2. Adjustment of global elevation to local height.

N⁰	Point name	ζ^{mean} (m)	H^{reg} (m)	N⁰	Point name	ζ^{mean} (m)	H^{reg} (m)
1	I(BH-TH)140	-26.772	39.687	19	III(MK-LN)11	-27.054	42.435
2	I(BH-TH)144A	-26.466	23.212	20	III(MK-LN)17	-26.170	9.153
3	I(BH-TH)146	-26.319	18.489	21	III(MK-LN)4	-27.598	64.765
4	I(HN-VL)10A	-25.854	7.516	22	III(NB-BS)11	-24.447	4.947
5	I(HN-VL)14-1	-25.382	3.512	23	III(NG-NG)2-2	-25.212	3.510
6	I(HN-VL)16A	-25.066	7.783	24	III(PR-DL)3	-25.852	89.437
7	I(HN-VL)19	-25.053	4.159	25	III(TY-LC)7	-26.187	17.510
8	I(HN-VL)23-1	-25.126	9.881	26	III(XH-PC)6	-26.903	33.806
9	I(HN-VL)24-1	-25.147	5.735	27	III(XH-PC)9	-26.865	84.337
10	I(HN-VL)6-1	-26.279	6.077	28	II(MC-XM)2	-27.956	267.052
11	I(HP-NB)14A	-23.823	0.004	29	III(QL-MS)10	-26.999	105.741
12	I(HP-NB)19	-24.485	7.478	30	I(BH-TH)152	-25.235	11.013
13	II(HD-TB)10A	-25.221	3.842	31	I(HN-VL)28-1	-25.008	4.747
14	II(HD-TB)18	-24.355	1.765	32	I(BH-TH)136	-27.357	102.518
15	II(MC-XM)7-1	-27.817	199.242	33	II(TX-TD)2	-26.354	64.816
16	II(XM-HN)10-1	-26.456	8.378	34	I(BH-TH)134A	-27.562	68.526
17	II(XM-HN)5	-27.114	14.626	35	I(BH-TH)149-1	-25.930	17.587
18	III(BP-PC)3	-26.739	53.974	36	III(XT-NQ)5	-26.674	16.626

The deviation between the global elevation after conversion to local height and the elevation of the GNSS/levelling points is presented in Table 3 and Figure 3.

Table 3. Check the global elevation data AW3D30 after conversion to the national height.

N⁰	Point name	Δ (m)	d (m)	N⁰	Point name	Δ (m)	d (m)
1	I(BH-TH)140	6.402	1.589	19	III(MK-LN)11	7.100	2.287
2	I(BH-TH)144A	5.920	1.108	20	III(MK-LN)17	6.633	1.820
3	I(BH-TH)146	5.414	0.601	21	III(MK-LN)4	6.041	1.229
4	I(HN-VL)10A	2.815	-1.997	22	III(NB-BS)11	3.772	-1.040
5	I(HN-VL)14-1	1.933	-2.880	23	III(NG-NG)2-2	1.957	-2.855
6	I(HN-VL)16A	6.163	1.350	24	III(PR-DL)3	2.687	-2.125
7	I(HN-VL)19	3.143	-1.670	25	III(TY-LC)7	6.738	1.926
8	I(HN-VL)23-1	3.608	-1.205	26	III(XH-PC)6	6.301	1.488
9	I(HN-VL)24-1	2.473	-2.340	27	III(XH-PC)9	7.305	2.492
10	I(HN-VL)6-1	3.073	-1.739	28	II(MC-XM)2	7.515	2.703
11	I(HP-NB)14A	-0.801	-5.614	29	III(QL-MS)10	5.735	0.923
12	I(HP-NB)19	4.659	-0.154	30	I(BH-TH)152	0.766	-4.046
13	II(HD-TB)10A	1.209	-3.604	31	I(HN-VL)28-1	2.522	-2.290
14	II(HD-TB)18	0.638	-4.174	32	I(BH-TH)136	7.697	2.885
15	II(MC-XM)7-1	7.697	2.885	33	II(TX-TD)2	8.917	4.105
16	II(XM-HN)10-1	4.127	-0.686	34	I(BH-TH)134A	9.014	4.202
17	II(XM-HN)5	5.539	0.727	35	I(BH-TH)149-1	8.917	4.105
18	III(BP-PC)3	4.674	-0.138	36	III(XT-NQ)5	4.945	0.133

The average value of the height deviation between the global elevation AW3D30 in the national vertical datum and the surveyed elevation of the GNSS/levelling points is:

$$\Delta_{\text{aver}} = \frac{173.248}{36} \approx 4.812(\text{m})$$

The standard deviation of the global elevation AW3D30 in the national vertical datum is:

$$\delta = \sqrt{\frac{227.647}{35}} \approx \pm 2.550(\text{m})$$

Thus, the limiting error is determined as $\Delta_{\text{limit}} = \pm 3\sigma = \pm 7.650(\text{m})$.

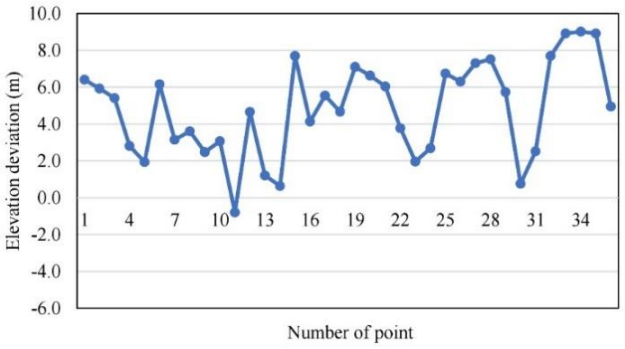

Figure 3. The deviation between the AW3D30 elevation in the national vertical datum and the elevation of the GNSS/levelling points.

In the study area, the points II(TX-TD)2, I(BH-TH)134A, and I(BH-TH)149-1 have deviations between the global elevation AW3D30 in the national vertical datum and the actual surveyed elevation that exceed the allowable error limits, falling outside the range [–7.650, +7.650], and were therefore excluded. As a result, 33 points remain, with deviations within the allowable error limits, accounting for approximately 91.7% of the total number of points. This shows that most of the study points have deviations within the permissible range, indicating that the AW3D30 global elevation model is highly compatible with the national vertical datum in the study area. Next, the systematic deviation is checked within the range of elevation values of the AW3D30 global elevation model in the national vertical datum.

From the data in Table 3, we calculate |[Δ]| = 146.400 (m), 0.25[|Δ|] = 36.600 (m). Therefore, inequality (8) is not satisfied, indicating the existence of a systematic deviation in the range of AW3D30 global elevation values compared to the national vertical datum. This systematic deviation is determined according to formula (9) as follows:

$$\theta = \frac{[\Delta]}{m} = \frac{146.400}{33} \approx 4.436(\mathrm{m})$$

After the adjustment, the deviation between the AW3D30 global elevation and the elevation of the GNSS/levelling is shown in Figure 4.

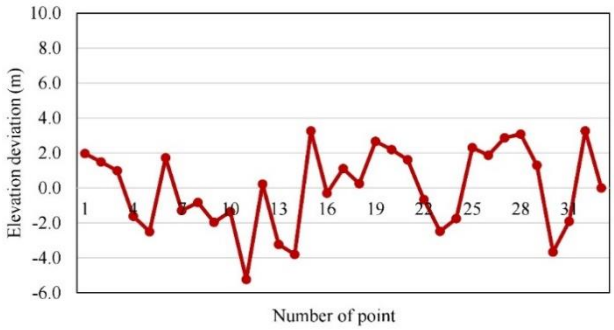

Figure 4. The deviation between the AW3D30 global elevation after adjustment and the elevation of the GNSS/levelling points.

From Figures 3 and 4, a significant improvement in the elevation deviation of the global digital elevation model AW3D30 can be observed after applying the correction. Before correcting raw errors and systematic errors, the absolute deviation between the AW3D30 model elevation and GNSS/levelling elevation reached up to 9.014 m, indicating a substantial discrepancy between the model data and actual measurements. However, after applying the correction method, the maximum absolute deviation was significantly reduced to 5.238 m.

Figure 4 shows that the elevation deviation values are randomly distributed around a mean value of zero, with no systematic trend. This indicates that systematic errors have been eliminated, and no residual errors remain after the correction. The root mean square error, representing the accuracy of the AW3D30 global digital elevation model in the national vertical reference system, is determined according to equation (12) and has a value of: $m \approx \pm 1.613(\mathrm{m})$.

The root mean square error of ±1.613 m reflects the average accuracy of the AW3D30 global digital elevation model across the entire study area. This indicates that AW3D30 is capable of providing reliable elevation data after being adjusted to the national elevation system.

3.2. Discussions

The AW3D30 GDEM has been assessed for accuracy within the national height system in Ninh Bình and its surrounding areas, with a determined root mean square error (RMSE) of ±1.613 m. This value reflects the average error level when compared to reference elevation data in the study area. Compared to previous studies summarized in Table 4, the RMSE of AW3D30 in Ninh Bình and its vicinity is significantly lower than in many other regions. This can be attributed to the topographical characteristics of Ninh Bình, which mainly consists of karst terrain with limestone hills interspersed with plains but without excessively steep slopes, along with an appropriate DEM correction method that helps reduce model errors. Therefore, AW3D30 can be considered a reliable DEM for applications in terrain studies, planning, and environmental management in this region.

Table 4. Accuracy of the AW3D30 GDEM in some areas.

No	References	Regions/countries	Accuracy (m)	Topographic characteristics
1	[20]	Near Istanbul, Turkey	2.49	Terrain with a slope < 10%
2	[21]	Nigeria, West Africa	5.67	Predominantly flat or slightly sloping terrain, with an average elevation < 200 m
3	[23]	Peru	2.172	Tropical forest terrain with many rivers and wide basins
4	[51]	Southwest Australia and northern Bangkok, Thailand	4.4	Mountainous and lowland terrain

No	References	Regions/countries	Accuracy (m)	Topographic characteristics
5	[52]	Eurasia, North America, South America, Australia, Africa	2.49	Lowland terrain
			2.64	Terrain with a slope of 10° - 20°
6	[53]	North America, Europe, Asia, Africa, South America	2–4	Flat terrain
	This study	Ninh Binh and surrounding areas	1.613	Low hills with an average elevation of approximately 150 m

4. Conclusion

This study has converted the global elevation of the AW3D30 global digital elevation model to the national vertical datum of Vietnam through a calibration process. The experiment was conducted in Ninh Bình Province and surrounding areas. The calibration method consists of three main steps: (1) converting the elevation of the AW3D30 model from the global vertical datum to the national vertical datum based on GNSS/levellings; (2) removing points with significant discrepancies exceeding the permissible threshold to ensure the model's stability; (3) performing system error correction to minimize the overall discrepancy between the AW3D30 model data and the GNSS/levelling data.

The experimental results show that after applying the correction method, the root mean square error of the AW3D30 model in the national vertical datum is ±1.613 m. At the same time, the maximum discrepancy between the height of the AW3D30 model and the height of GNSS/levelling points decreased from 9.014 m to 5.238 m. Statistical analysis also shows that 91.7% of the control points have discrepancies within the allowable limits, indicating that the correction method has significantly improved the accuracy and compatibility of the AW3D30 model with Vietnam's national vertical datum in the study area.

With an accuracy of ±1.613 m in the study area, the global digital elevation model AW3D30 demonstrates high reliability in representing terrain. Standardizing the elevation of this model within the national vertical datum not only ensures consistency with domestic survey data but also facilitates practical applications. As a result, AW3D30 can be effectively utilized in various fields such as topographic mapping, urban planning, natural resource management, and terrain change monitoring.

In this study, the conversion of elevations from the global digital elevation model to the national vertical datum was conducted rigorously. The results obtained in the study area indicate that this method not only harmonizes elevation data with the national reference system but also enhances the model’s accuracy. With its flexibility and broad applicability, this method can be effectively implemented in other regions, particularly in topographic studies and territorial spatial management.

This research focuses on lowland and low-hill areas, using data from the nation’s first-order, second-order, and third-order GNSS/levelling points-high-precision control points as the basis for converting and assessing the accuracy of the AW3D30 global digital elevation model within the national vertical datum. To gain a more comprehensive understanding of AW3D30’s performance across Vietnam, further studies should extend to regions with more complex and diverse terrain, such as high mountainous areas, transitional zones between plains and hills, or coastal regions. Additionally, experimenting with other correction methods during evaluation would provide more detailed insights into the model’s errors under different terrain conditions. This would help determine the suitability and practical applicability of AW3D30, particularly in surveying, planning, and resource management.

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