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Developing a Local Geoid Model in Egypt using Artificial Neural Networks: A Case Study on the Red Sea coast

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Abstract
The growing usage of the Global Navigation Satellite Systems (GNSS) in many engineering projects along Red Sea coasts in Egypt necessitates the development of a local geoid model in this area. The accuracy of the global geopotential models EGM2008, EIGEN-6C4, and XGM2019e 2159 was evaluated in this study. Then, an attempt was made to create a local geoid model for the study area using a geometric method. The height of the geoid at any point of the geoid model was calculated and predicted using an Artificial Neural Network (ANN). The effect of the number of GNSS/leveling points used on model accuracy was also investigated. The accuracy of geoid heights derived from EGM2008 in the study area has an RMSE of around 0.47m, whereas the accuracy of geoid heights derived from EIGEN-6C4 and XGM2019e 2159 has an RMSE of about 0.25 m and 0.27 m, respectively. The ANN-created local geoid model showed significant improvement in research. The accuracy of the ANN models in determining the local geoid model in the research area ranged from -0.11 m to 0.08 m, with an RMSE of 0.06 m. Furthermore, the results demonstrated that the accuracy of the ANN-created local geoid model improves with increasing number of points.

1 Introduction

The coast of the Red Sea contains a diverse range of natural, ecological, and social characteristics, and are noted for their coral reef communities and abundant marine life. Large tourist cities overlooking the Red Sea, such as Dahab, Hurghada, Nuweiba, and Sharm el-Sheikh, are popular with tourists and contribute significantly to Egypt's GDP. As a result, the government of Egypt has recently been focused on these areas, completing several major engineering projects. Global Navigation Satellite Systems (GNSS) are currently one of the most widely used geodetic technologies [1]. The coordinates produced by GNSS, on the other hand, include information about the height of the ellipsoid [2]. These heights are solely determined by the ellipsoid's geometry. In engineering, the vertical distance above the geoid is known as orthometric height, which is a linear representation of the gravitational potential [3].

With spherical harmonic factors, the Global Geoid Model (GGM) describes the components of the Earth gravitational field's long and medium wavelengths, and hence the geoid [4]. The development of the EGM2008 model by the US National Geospatial Agency (NGA) as well as the rise of additional GGM models, has tremendously aided in the global mapping of GGMs [5]. The successful execution of the CHAMP, GRACE, and GOCE projects has opened up new possibilities for high-precision on-line monitoring of earth mass movements that cause changes in the structure of GGMs [6]. The height of the geoid at control points is usually determined independently using GNSS/leveling data and compared to the derivatives of the geopotential function [7]. There have been a lot of research devoted to the evaluation of GGMs, such as [8–11].

Currently, satellite leveling can be viewed as an alternative to classical leveling [12]. In satellite leveling, geodetic heights (h) can be converted to orthometric heights (H) by applying the fundamental equation, where N is the heights of the geoid, (Fig. 1).

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

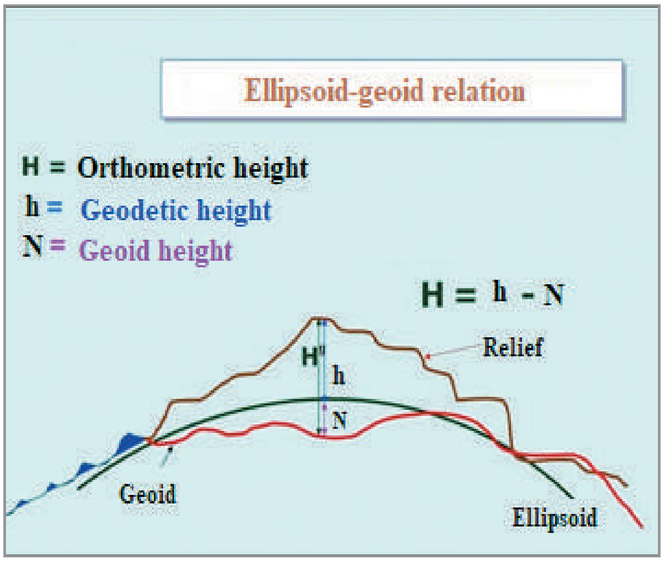

Fig. 1. Ellipsoid-geoid relationship.

In recent years, a number of studies have focused on geoid determination for Egypt, including: [13–15], while high-precision geoid modeling remains an unresolved challenge. Other studies have created geoid models for specific areas of interest in Egypt: for example, as part of an ongoing national project to update hydrographic and topographic maps of the Nile, Dawod developed a geoid model for the northern part of the Nile River, and the model's standard deviation was reduced to 0.17 m [16]. For the Rosetta zone in northern Egypt, Al-Krargy built a local geoid model with a standard deviation of 0.05 m [8].

As satellite technologies are increasingly being employed for engineering work, one of the key issues when employing a geoid model is obtaining orthometric heights relative to mean sea level (MSL) using geodetic heights derived via GNSS [15]. Several factors according to geometric methods affect the accuracy of the geoid model [16], including:

- The number and distribution of control points (GNSS/leveling points). These points should be evenly spread across the coverage region of the model, and they should be chosen to accurately depict changes on the geoid surface,
- The accuracy with which GNSS data are used to obtain geodetic heights and the accuracy with which leveling heights are determined,
- The method used to interpolate the geoid heights.

In this regard, a number of mathematical models exist that relate the geoid height (N) to the corresponding location to define the geoid surface. In recent years, artificial neural networks (ANNs) are a widely used technology that provides an alternative modeling method [17]. The ANN is made up of neurons, which are connected blocks or nodes, and links, which are the connections between them. A large number of weighted connections are used to convey information between neurons. The neuron mixes the received input data using complicated nonlinear functions with many parameters to produce outcomes. The ANN recognized the association between the input and output variables by reviewing the data previously recorded. An major advantage of ANN is their capacity to provide a solution to a problem that does not have an algorithmic answer or for which an algorithmic solution is difficult to determine [18].

ANN is now widely employed in mechanical engineering, manufacturing, technology, and other sectors and also considered one of the new approaches for creating a geoid model.

In view of the foregoing, the goals of this research are to evaluate the accuracy of several GGMs, namely EGM2008, EIGEN-6C4, and XGM2019e 2159, as well as to develop a local geoid model with centimeter accuracy using artificial neural networks for the Red Sea coast.

2 Methods and materials

2.1 The study area and the data used

The research region involves Egypt's Red Sea coast from Hurghada to Marsa Alam. From station H1 (27 ° 22'40.53 "N, 33 ° 38'26.85 "E) to station L56 (24 ° 12'25.52 "N, 35 ° 25'51.29 "E), this area runs for nearly 400 kilometers along the Red Sea coast. 70 stations (GNSS/leveling points) were chosen to ensure a consistent distribution while taking into account the geography of the region. The Egyptian State Geodetic Coordinate System was used to conduct the GNSS measurements. Figure 2 illustrates the layout of the study area.

Fig. 2. Location of the study area.

2.2 Method

The following methodology is used to assess the accuracy of the EGM2008, EIGEN-6C4, and XGM2019e 2159 models, as well as to create a local geoid model in the study region:

- All 70 stations' geodetic coordinates (E, N, h) and (H) are determined first.
- The geoid heights ($N_{GNSS/level}$) of 70 points are then determined from the geodetic and orthometric heights using equation (1).
- The $N_{GNSS/level}$ are compared with the corresponding values obtained from the GGM (N_{GGM}), which were obtained using the ICGEM calculation service [19].
- Then, utilizing $N_{GNSS/level}$, the ANN is applied and developed to create a local geoid model for the research area.

Three cases were studied utilizing 40, 50, and 60 points to investigate the influence of point distribution density, and three local models were generated.

ANN models were assessed using 10 control points in all cases. The best model from the ANN was used to calculate the obtained geoid heights. The next subsections go over these steps in further depth. Figure 3 shows a flowchart of the methodology used.

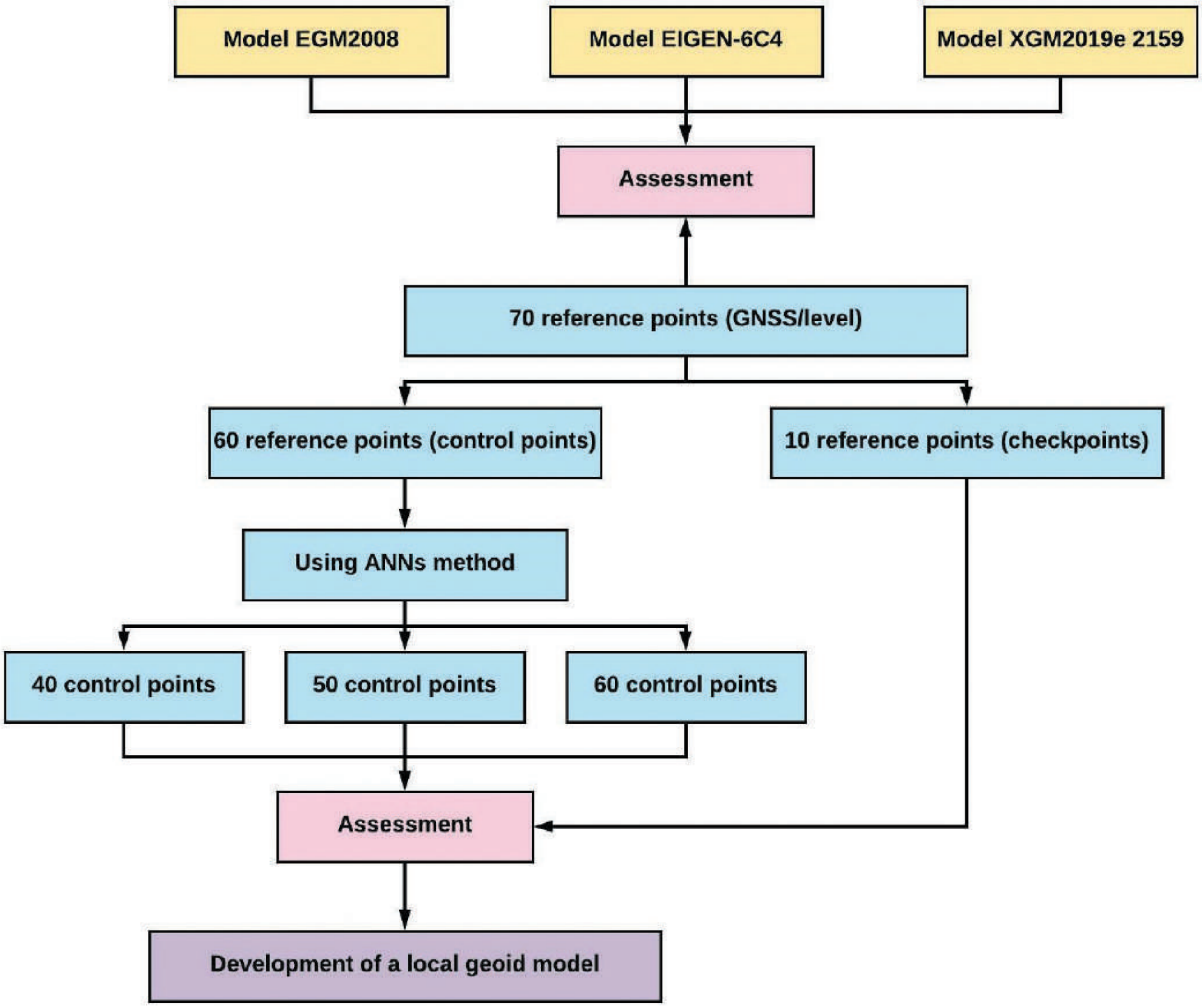

Fig. 3. Flow chart of the used methodology.

2.3 Evaluation of GGMs for the study area

To evaluate the accuracy of the global models EGM2008, EIGEN-6C4 and XGM2019e_2159 models, the following steps are performed:

- The $N_{GNSS/level}$ of all reference points are calculated using equation (1),
- The N_{GGM} of the same points are obtained;
- Finally, the results are compared to determine the GGMs' accuracy in the study region. The following formula is used to compute the differences between $N_{GNSS/level}$ and N_{GGM}

$$dN = N_{GGM} - N_{GNSS/level} \quad (2)$$

2.4 Development of a local geoid model using ANN

A multilayer feedforward network, radial basic network, extended regression network, and probabilistic networks are only a few examples of ANNs. The option of a multilayer feedforward network was used in this study to develop a local geoid model since it has strong representational capabilities. Two hidden layers with 20 neurons were employed in an ANN model that was constructed and assessed over 10,000 iterations. These numbers were utilized in this study because they offered the best results based on experience with numerous models, algorithms, and functions. As a training function, we used the TRAINLM function built into MATLAB, which trains the ANN using the well-known Levenberg-Marquardt algorithm (Fig. 4). To minimize the error, the Levenberg-Marquardt algorithm was used, which adaptively changes unknown parameters (weights and biases) between gradient descent update and Gauss-Newton update according to equation (3) until the algorithm reaches a stable state.

$$\Delta R_k = -\left[J^T J + \mu_k I\right]^{-1} J^T \left(\mathrm{N} - \hat{\mathrm{N}}\right) \qquad (3)$$

Where ΔR_k - is the theoretical difference between successive estimates of the same unknown parameter; it is also called the performance index. J^T - is the transpose of the Jacobi matrix with respect to the unknown parameters $[\partial R_k / (\partial w_i)$ and $(\partial b_0)]^T$. μ_k – is a scalar value used to make the Hessian matrix ($J^T J$) invertible. I - is the identity matrix, the dimension of which is equal to the number of unknown parameters. N is the target response signals (in our case, these are the measured common point heights as in equation 1, and $\hat{\mathrm{N}}$ is the predicted common point heights calculated from equation (4).

$$\hat{\mathrm{N}} = \sum_{i=1}^{n} a_k^l W_i^1 + b_0^1 \qquad (4)$$

$$\text{Where:} \quad a_k^l = F\left(n_k^l\right) = \frac{e^{n_k^l} - e^{-n_k^l}}{e^{n_k^l} + e^{-n_k^l}} \qquad (5)$$

MATLAB R2016a software was used to create the ANN model. Training, validation, and testing were the three steps of the model's development.

1. 70 % of the initial and needed data were used in the model's training. This set allowed for the establishment of a connection between the original and required data, as well as the evaluation of the generated model's accuracy.

2. During the validation process, 15 % of the original and target data were used to refine the computed model. The training of the model stops when the test result stops improving.

3. During testing, 15 % of the original and target data was used to assess the accuracy of the final model independently.

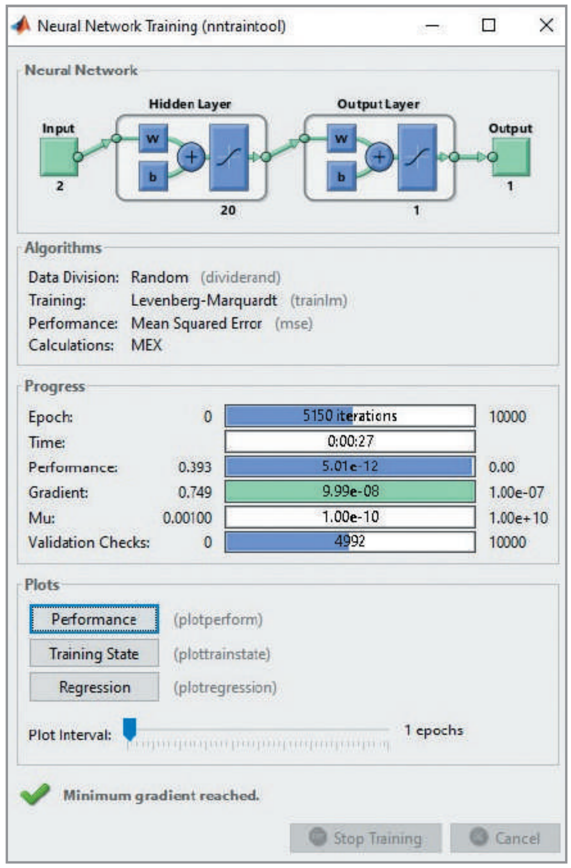

Fig. 4. The characteristics of utilized ANN.

3 Results and Discussion

3.1 Evaluation of EGM2008, EIGEN-6C4 and XGM2019e_2159

The $N_{GNSS/level}$ and N_{GGM} of the 70 points were determined. Figure 5 depicts the geoid heights for the study region obtained from the EGM2008, EIGEN-6C4, and XGM2019e_2159 models, respectively, calculated by ICGEM. To assess the accuracy of EGM2008, EIGEN-6C4, and XGM2019e_2159, the difference between $N_{GNSS/level}$ and N_{GGM} was calculated using equation (2). Table 1 provides a comparison between $N_{GNSS/level}$ and N_{GGM} at the 70 points.

It can be seen from Table 1 that the EIGEN-6C4 model gives the smallest standard deviation for differences with a value of 0.25 m. While the XGM2019e_2159 model takes second place inaccuracy with a standard deviation of 0.27 m. The last place was taken by the EGM2008 model with a standard deviation of 0.47 m. For the study area, the EIGEN-6C4 and XGM2019e_2159 models give a noticeably better result than the EGM2008 model.

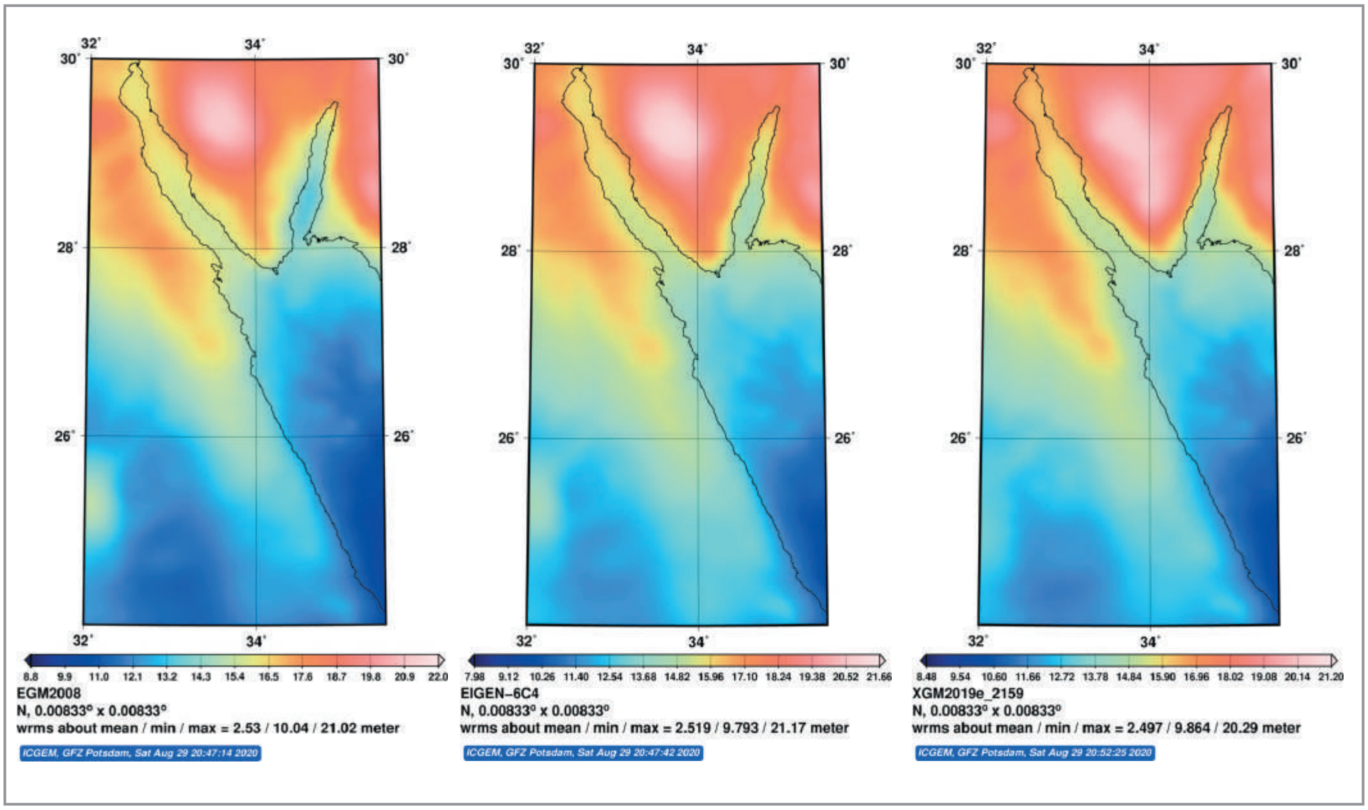

Fig. 5. Geoid heights maps of the study area from global models EGM2008, EIGEN-6C4, and XGM2019e_2159 respectively.

deviation	EGM2008	EIGEN-6C4	XGM2019e_2159
mean (m)	0.34	0.05	0.01
standard deviation (m)	0.47	0.25	0.27
range (m)	1.82	1.33	1.31
minimum (m)	-0.28	-0.56	-0.60
maximum (m)	1.55	0.78	0.72

Table 1. Comparison between N_{GGM} and $N_{GNSS/level}$ for the 70 points.

These results are consistent with the fact that Kanushin mentioned that the EIGEN-6C4 model showed an improvement in the spatial resolution and accuracy of the heights of the geoid in the studied regions compared to the data of the EGM2008 model by 5% [10]. Based on these findings, it can be concluded that the accuracy acquired using GGMs in the research area is insufficient for many engineering projects, necessitating the creation of a more accurate local geoid model.

3.2 Evaluation of creating a local geoid model using the ANN

ANNs were generated by the MATLAB program using the "nntool" neural network toolbox. Using 40, 50, and 60 points, three different local models were created (denote the geoid heights obtained from the created geoid model (N_{ANN}). In addition, to evaluate the effect of geodetic height (H) on the results, in each case N_{ANN} was calculated using only East and North coordinates (E and N) or using E, N, and H. Figure 6 shows the evaluation of the ANN using the correlation function (R) between the output network and the target network. It can be noted that the training, validation and testing processes indicate the presence of a dependence when the value of R is closer to 1. These results confirm the reliability of the ANN structure and its potential, which will be used to model new values.

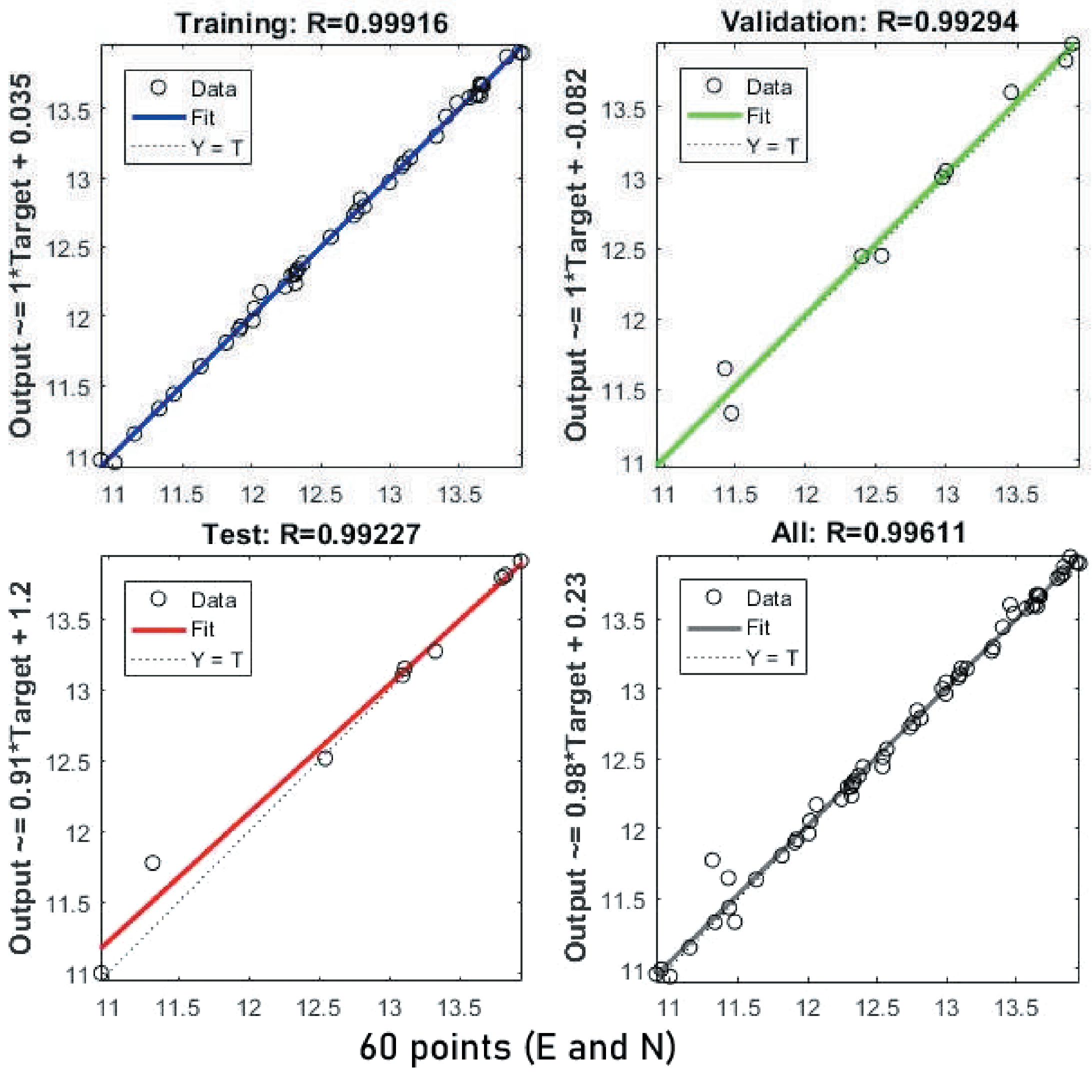

Fig. 6. The regression plot of the training, validation, and testing data from the ANN model when using 60 points.

After that, at the10 control points, the values of the geoid heights from the created model (N_{ANN}) were compared to the $N_{GNSS/level}$. The results are shown in Table 2.

deviation	40 points		50 points		60 points	
	E, N	E, N, h	E, N	E, N, h	E, N	E, N, h
mean (m)	-0.05	0.01	0.03	-0.02	-0.02	-0.03
standard deviation (m)	0.16	0.18	0.11	0.11	0.06	0.09
range (m)	0.58	0.59	0.38	0.35	0.20	0.33
minimum (m)	-0.38	-0.27	-0.14	-0.22	-0.11	-0.19
maximum (m)	0.21	0.32	0.24	0.13	0.08	0.15

Table 2. Comparison between N_{ANN} and $N_{GNSS/level}$ for the 10 checkpoints.

Table 2 demonstrates that the accuracy of the local geoid model derived with the ANN improves as the number of points increases, which is to be anticipated. Using 60 points, the best local geoid model in the research region is created (E and N). The absolute error ranges from -0.11 m to +0.08 m, with a mean of 0.02 m and a standard deviation of 0.06 m when using this model. To compare the global geoid models EGM2008, EIGEN-6C4 and XGM2019e_2159 with the local geoid model developed by the ANN method, dN-EGM2008, dN-EIGEN-6C4, dN-XGM2019e_2159, dN-ANN were calculated for 70 control points (Fig. 7), where:

$$dN - EGM08 = N_{EGM2008} - N_{ГНСС/нив} \quad (6)$$

$$dN - EIGEN - 6C4 = N_{EIGEN\text{-}6C4} - N_{ГНСС/нив} \quad (7)$$

$$dN - XGM2019e\_2159 = N_{XGM2019e\_2159} - N_{ГНСС/нив} \quad (8)$$

$$dN - ИНС = N_{ИНС} - N_{ГНСС/нив} \quad (9)$$

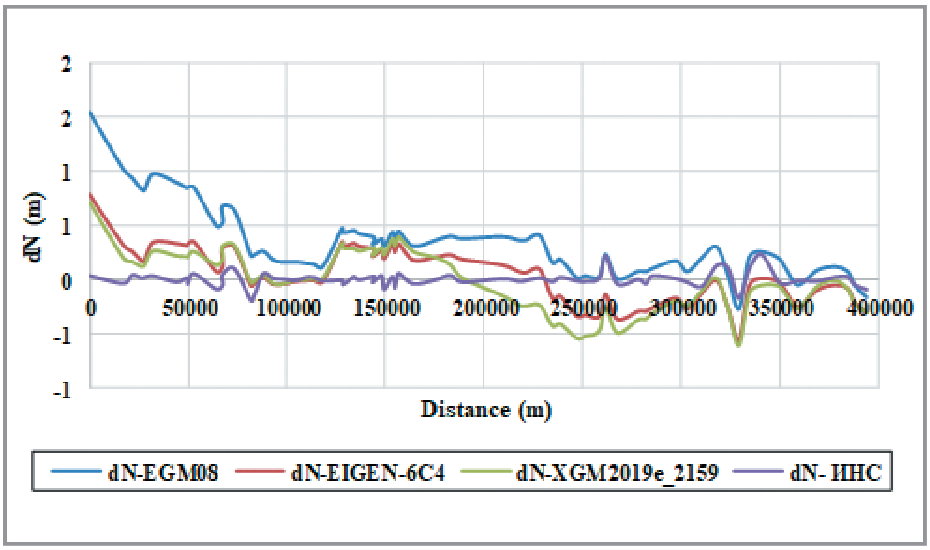

Fig. 7. The relation between dN-EGM08, dN-EIGEN-6C4, dN-XGM2019e_2159, dN-ANN and the distance (start from point H1).

Figure 7 indicates that the generated local geoid model outperformed the EGM2008, EIGEN-6C4, and XGM2019e 2159 models in terms of overall performance. The accuracy of the geoid model created with the ANN was improved by 86 %, 73 %, and 76 % respectively, when compared to the three GGMs.

4 Conclusion

Despite the extensive use of the GNSS system in engineering projects, the challenge in the construction of engineering works is that the geodetic height is obtained from GNSS measurements, whereas orthometric heights are employed.

In this case, obtaining an accurate model of the geoid and, as a result, improving the methodologies and procedures for determining the geoid's heights becomes important. The purpose of this paper is to assess the accuracy of the global models EGM2008, EIGEN-6C4, and XGM2019e 2159 for the region of the Red Sea coast, as well as to create a local geoid model that will allow for more accurate calculation of orthometric heights from observed geodetic heights. The EGM2008 model provides geoid heights for the study area with an accuracy of about 0.47 m, while the EIGEN-6C4 and XGM2019e_2159 provide an accuracy of about 0.25 m and 0.27 m, respectively. The GNSS/leveling method was used in conjunction with ANN to create a local geoid model. The accuracy with which the local geoid model in the study area may be determined using ANN models with an error of less than 0.06 m. The study's findings revealed that as the number of points in the local geoid model created using the ANN increase, the accuracy of the model improves. When creating a geoid model for the entire Egyptian land, it is advised that advanced soft computing techniques such as ANN be utilized.

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