Comparison of IDW and Spline Interpolation for Topographic Accuracy Assessment Using Geomatics Approaches

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ABSTRACT

The advancement of computer and software technologies has facilitated the widespread adoption of spatial analysis, particularly Geographic Information Systems (GIS), representing one of the most transformative developments in modern cartographic applications. GIS capture the geographical and non-geographical data in a way that allows for visual interpretation and analysis. In the present work, the study area of Al-Mada'in is examined along with the topographic surface accuracies obtained by the Inverse Distance Weighted (IDW) and Spline methods, based on the sampling points' number (40) and the grid size of 30 m. This study compares different interpolation algorithms using their respective prediction mean errors, prediction Root Mean Squared Error (RMSE), and Standard Deviation (STD). The IDW method showed a maximum elevation value of 48.332 m and a minimum of 39.028 m with a mean of 44.265 m, an STD of 2.512 m, and an RMSE of 1.585 m. In contrast, the Spline method achieved a higher accuracy, recording a maximum value of 47.934 m and a minimum value of 39.453 m. It also achieved a mean value of 44.339 m, an STD of 2.345 m, and a lower RMSE of 1.531 m. According to the experimental findings on biased and normalized data, Spline outperformed the IDW approach as it demonstrated a more accurate and superior interpolation inside the sample space.

Keywords-inverse distance weighted; spline; topographic surfaces; terrain modeling; interpolation

I. INTRODUCTION

Assessing the ecological vulnerability and monitoring the soil erosion are key applications of the spatial elevation data interpolation in environmental management. Since the collection of continuous spatial-temporal data across an entire region is impractical and unnecessary [1], measurements from representative sample points should be gathered and the values at unsampled locations should be estimated through spatial interpolation [2, 3]. The remote sensing research has increasingly focused on deriving and analyzing topographic surfaces from such data [4]. GIS provide powerful tools for performing spatial interpolation, allowing scientists to generate continuous datasets for diverse earth and environmental applications [5, 6]. The accuracy of these interpolated surfaces is typically evaluated using methods such as cross-validation, comparisons with independent reference points, or detailed topographic surveys [7, 8]. Beyond the physical terrain, maps can also integrate non-material information, such as land assessments, evaluations, or statistical data, creating a framework for multi-dimensional analysis [9]. Reviewing and validating the results from topographic surface modeling studies is, therefore, essential to confirm their reliability and guide future research directions [10, 11]. The present study builds on this foundation by enhancing the accuracy of topographic surface modeling through the application of optimized interpolation strategies, particularly the Spline and IDW methods.

II. MATERIALS AND METHODS

Figure 1 provides a schematic representation of this study's methodology. The steps include geographic interpolation, statistical accuracy testing, and method validation.

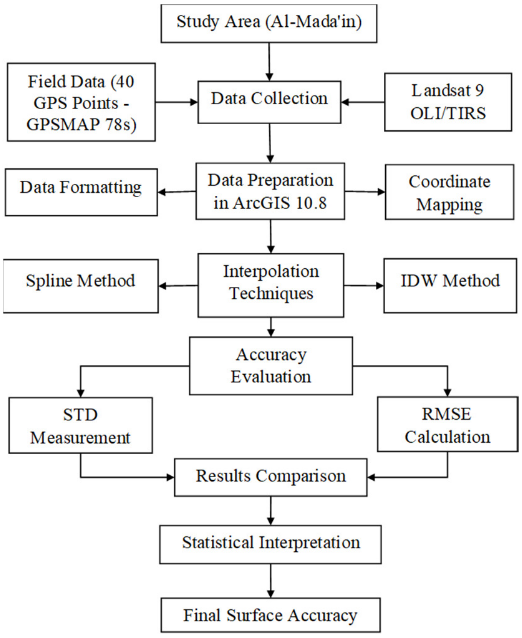

Fig. 1. The research step flowchart.

A. *Study Area*

Al-Mada'in, one of the culturally and geographically significant districts of Baghdad Governorate, is located southeast of Baghdad along the Tigris River. The area is characterized by fertile lands dotted with villages and farms. It borders with Al-Rusafa District to the north, New Baghdad District to the west, and Mahmoudiyah District to the south. Geographically, the district lies between approximately 33°–34° north latitude and 44°–45° east longitude, as shown in Figure 2. Al-Mada'in was selected as the study area due to its diverse terrain and limited elevation data, making it a suitable site for testing the interpolation accuracy under challenging and data-sparse conditions.

B. *Database*

Since they offer a complete view of the Earth's surface features, satellite images have become valuable tools for a wide range of scientific and practical research projects [12]. Table I demonstrates that the stations surveyed using GPS (type of device: GPSMAP 78s) are spread across different locations with varying coordinates. The elevations range from 35.808 m (station 23) to 48.629 m (station 9). This indicates a range of topographical variations within the study area.

TABLE I. STATIONS MONITORED IN THE FIELD TO CONDUCT THE MATHEMATICAL EXTRAPOLATION PROCESS

Observation station	Easting (m)	Northing (m)	Height (m)
1	434088	3669493	44.126
2	439683	3668138	42.954
3	442792	3668647	45.743
4	447451	3668489	46.958
5	452264	3665562	43.860
6	454683	3660802	43.842
7	453835	3657641	45.664
8	452091	3652967	46.790
9	450677	3648093	48.629
10	447948	3646986	47.857
11	443503	3647539	44.756
12	439503	3647958	42.129
13	437021	3651073	40.278
14	434651	3654123	39.994
15	431961	3658692	47.739
16	431988	3662649	45.443
17	433293	3666729	46.853
18	438114	3665774	40.652
19	441549	3664829	45.839
20	445431	3664345	44.732
21	450696	3662800	38.670
22	450396	3658449	36.973
23	447892	3657539	35.808
24	445231	3658345	44.008
25	441959	3659089	42.837
26	437467	3659974	38.560
27	434347	3658477	36.085
28	434995	3655703	45.809
29	441537	3653552	48.556
30	443534	3653012	44.763
31	445534	3652935	42.983
32	448869	3653181	40.410
33	452605	3655932	42.678
34	447985	3643491	45.867
35	440416	3642742	41.432
36	429846	3665829	40.801
37	439949	3657320	45.780
38	438820	3645522	40.002
39	445880	3645019	38.450
40	456642	3651890	36.094

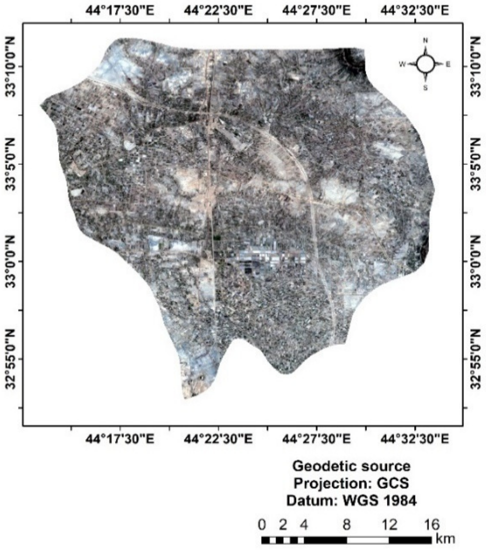

Fig. 2. Location of study area.

Table II exhibits that the stations collected using GPS surveys are well distributed across the study area, indicating a wide geographical coverage. The eastern coordinate range extends from approximately 430.431 m to 456.392 m, while the northern coordinate range extends from 3644461 m to 3670071 m. This distribution demonstrates that the data cover a relatively large area, allowing for a comprehensive terrain analysis. The elevations range from 38.52 m to 48.562 m, indicating a moderate variation in station elevations. This variation can be important for determining the terrain and land surface changes and the impacts of the urban planning, road design, and drainage systems.

TABLE II. VERIFICATION STATIONS MONITORED AT THE STUDY AREA SITE

Test station	Easting (m)	Northing (m)	Height (m)
1	436477	3670071	44.092
2	436179	3666841	43.921
3	436991	3663736	39.954
4	440148	3662595	38.52
5	443421	3662312	42.728
6	447633	3660904	39.995
7	452295	3660550	41.839
8	454638	3662979	46.302
9	449379	3665775	48.005
10	451113	3668602	45.382
11	435311	3661439	45.294
12	433775	3664219	40.432
13	431228	3665094	45.392
14	430431	3662264	46.377
15	432550	3655588	46.22
16	437060	3657141	39.334
17	438653	3654295	45.241
18	440298	3650789	45.339
19	443407	3650177	44.395
20	443494	3655716	45.405
21	447438	3655629	42.376
22	444069	3659143	45.326
23	440187	3659825	43.287
24	445801	3660914	43.275
25	450858	3650862	46.382
26	449943	3645789	48.562
27	446228	3647655	47.825
28	442881	3645696	45.522
29	439815	3644461	46.372
30	441396	3648474	41.854
31	437956	3649485	48.042
32	448241	3649887	46.936
33	452129	3649273	47.773
34	454532	3652098	45.739
35	455545	3654995	44.732
36	456392	3658157	46.977
37	456356	3662378	44.428
38	444941	3666063	45.854
39	441282	3666611	42.643
40	441302	3669843	40.635

Figure 3 illustrates the spatial distribution of the stations, where the monitoring stations are shown as red dots and the test stations as blue dots. The monitoring stations, which are evenly spread across the study area, are used to collect essential environmental, meteorological, and related data. Similarly, the test stations, also evenly distributed and in some cases overlapping with the monitoring stations, are employed to gather verification and supplementary field measurements. The map is presented using the World Geodetic System 1984 (WGS 1984) as a Geographical Coordinate System (GCS).

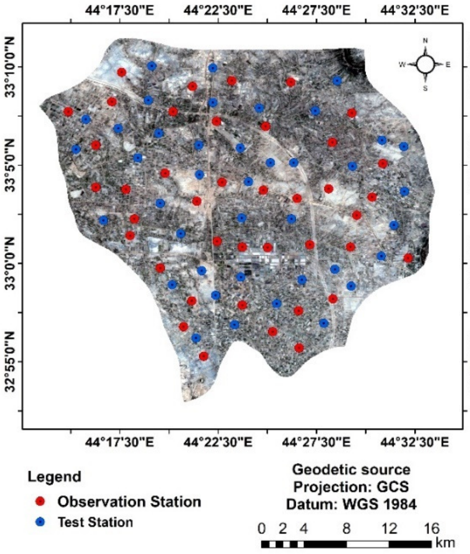

Fig. 3. Observation stations and test stations.

C. Methods

1) Inverse Distance Weighted Method

The unknown variable Z(So) at location So is calculated using [13]:

$$Z(sS_0) = \sum_{i=1}^{n} W_I Z(S_i) \quad (1)$$

where n is the number of the monitoring stations, and $Z(S_i)$ is the value at each sampled place. Wi represents the weight of S_i, which can be described as [14]:

$$W_i = \frac{\frac{1}{d_i^k}}{(\sum_{i=1}^{n}\frac{1}{d_i^k})} \quad i=1, 2, …., n, \quad (2)$$

where d_i represents the horizontal distance that separates the interpolation points from those observed, and k is the power of the space. ArcGIS 10.8 was used during each of the IDW method's computations.

2) Spline Method

This method generates a smooth surface that passes through all known points. The specific surface is created using mathematical functions that minimize the curvatures between the points, resulting in a continuous surface. Spline has a better adaptability to the changes in data than IDW and is especially useful in terrains with sharp changes. In spline interpolation, a surface interpolation formula is utilized, as shown in [15]:

$$S_{(x,y)} = T_{(x,y)} + \sum_{j=1}^{N} \lambda_j \, R(r_j) \quad (3)$$

where j = 1,2,3, ….., n, N is the number of points, λ_j are the coefficients obtained from the linear equation system, r_j is the distance between the point i and point j, and $T(x,y)$ and $R(r)$ are defined differently based on the selection method (Regularized

Spline and Tension Spline). The elevation accuracy for each method is essential in interpreting the data obtained from topographic surfaces and remote sensing [16, 17]. The difference between the fused and original images is determined by RMSE [18, 19]:

$$\mathrm{RMSE} = \sqrt{\frac{\Sigma_x \Sigma_i \left(A_i(x) - F_i(x)\right)^2}{n * m * d}} \tag{4}$$

where x is the pixel, i is the band number, (n, m) are the image coordinates, and d is the band number. In this study, IDW interpolation was implemented using ArcGIS 10.8 through the IDW and Spline tools available in the Spatial Analyst toolbox.

III. RESULTS AND DISCUSSION

Accurate geodetic data are essential for any project that relies on terrain. Minor errors in determining the coordinates or elevations in engineering projects can lead to issues, such as unstable foundations or water drainage problems. Table III presents the data of different test stations' locations, including the coordinates and predicted elevations for each station deploying the IDW and Spline methods. The predicted elevation values differ between the two methods (IDW and Spline) for each station.

TABLE III. TEST STATIONS AND ELEVATIONS

Test stations	Easting (m)	Northing (m)	Height (m)	IDW (m)	Spline (m)
1	436477	3670071	44.092	43.863	43.246
2	436179	3666841	43.921	42.532	43.118
3	436991	3663736	39.954	40.431	40.296
4	440148	3662595	38.52	39.028	39.981
5	443421	3662312	42.728	43.107	43.884
6	447633	3660904	39.995	40.274	39.453
7	452295	3660550	41.839	42.167	40.351
8	454638	3662979	46.302	45.126	45.038
9	449379	3665775	48.005	48.332	47.934
10	451113	3668602	45.382	44.116	44.3
11	435311	3661439	45.294	46.265	46.116
12	433775	3664219	40.432	39.228	40.092
13	431228	3665094	45.392	46.31	44.738
14	430431	3662264	46.377	45.551	45.344
15	432550	3655588	46.22	46.086	45.873
16	437060	3657141	39.334	40.018	40.638
17	438653	3654295	45.241	44.295	45.663
18	440298	3650789	45.339	45.243	44.968
19	443407	3650177	44.395	44.103	45.35
20	443494	3655716	45.405	44.291	46.438
21	447438	3655629	42.376	41.365	41.773
22	444069	3659143	45.326	45.773	46.325
23	440187	3659825	43.287	44.285	44.331
24	445801	3660914	43.275	44.231	44.008
25	450858	3650862	46.382	45.361	47.249
26	449943	3645789	48.562	48.005	47.293
27	446228	3647655	47.825	46.916	47.662
28	442881	3645696	45.522	44.992	44.127
29	439815	3644461	46.372	47.343	46.046
30	441396	3648474	41.854	42.008	43.575
31	437956	3649485	48.042	47.772	47.384
32	448241	3649887	46.936	45.967	45.307
33	452129	3649273	47.773	47.873	46.552
34	454532	3652098	45.739	44.43	43.845
35	455545	3654995	44.732	45.262	45.33
36	456392	3658157	46.977	46.437	46.164
37	456356	3662378	44.428	44.866	45.302
38	444941	3666063	45.854	44.947	45.21
39	441282	3666611	42.643	43.328	43.038
40	441302	3669843	40.635	39.077	40.208

A. *Results of the IDW Method*

The IDW interpolation method is widely used in geoinformatics and GIS to estimate unknown values based on measures taken at known locations. The method is founded on the principle of spatial proximity, assuming that the points which are closer to each other resemble more than those which are farther apart. In practice, IDW assigns greater weight to the nearby data points and lower weight to those farther away, producing representative surfaces from the existing observations, as illustrated in Figure 4. This means that the predicted value at a given location is influenced primarily by its proximity to the surrounding sample points. IDW is commonly applied in geography, environmental modeling, and statistical analysis to visualize the spatial value distributions. In the resulting maps, the color gradients indicate variability, where the areas with similar colors reflect relatively homogeneous values, while the sharp transitions in color suggest abrupt spatial changes, such as geological or topographic boundaries. By visualizing these gradients, IDW helps reveal the relationship between the geographic locations and provides accurate estimates for regions lacking direct data.

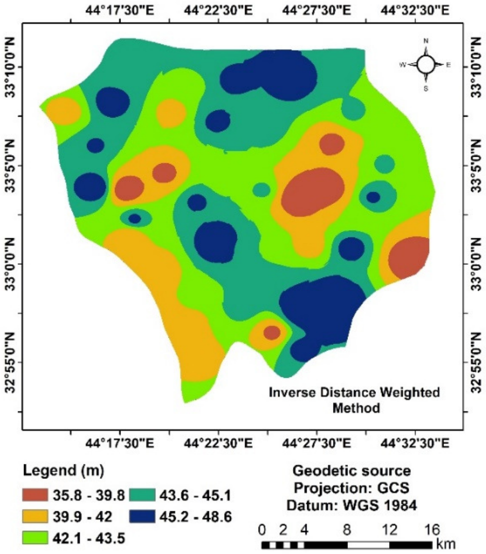

Fig. 4. Interpolation by the IDW method.

B. *Results of the Spline Method*

The Spline interpolation is a technique used in geography and GIS to estimate the values at distant locations based on the values at nearby places that are known. The Spline interpolation is a convenient method for producing smooth surfaces that show spatial gradients, making it useful when representing continuous data, such as elevation, pollution, or environmental variables. Figure 5 displays a specific study area in a geographic format with a GCS projection and a WGS 1984 geodetic coordinate system. The map portrays color gradients representing elevations (or a specific value) in m, within the specified ranges of 29417 m-57872 m. Regarding the spatial distribution, the map illustrates a variable distribution of values within the study area. The areas with higher values are concentrated in specific locations, while the areas in blue and green exhibit lower values. The method reveals the fine details of the study areas using the Spline interpolation, which smooths out the changes and represents the data with the highest possible accuracy. Maps constitute a visual tool for understanding the spatial variations of the natural or human phenomena. The grid size of 30 m was selected to align with the standard spatial resolution.

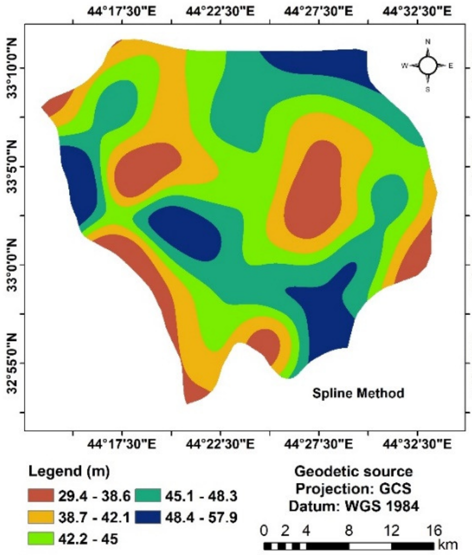

Fig. 5. Interpolation by the Spline method.

Table IV provides a statistical summary for three models or cases (test station, IDW, and Spline). The maximum value of the test station (48.562 m) is the highest among all cases, indicating that some measurements or observations exceed the expected values of the other two models. On the other hand, the maximum value of Spline (47.934 m) is the lowest. The minimum value of the test station (38.52 m) is lower than the minimum values of the other two models (IDW: 39.028 m, Spline: 39.453 m). The test station has a higher mean value (44.468 m) than the IDW (44.265 m) and Spline (44.339 m). These small differences may not be statistically significant, but they indicate that the test station values tend to be slightly higher than the corresponding means. The results show that the IDW method achieved a maximum elevation value of 48.332 m and a minimum elevation value of 39.028 m, with a mean elevation value of 44.265 m. This method had an STD of 2.512 m and an RMSE of 1.585 m, indicating moderate variability in the resulting elevation values. In contrast, the Spline method showed improved accuracy compared to IDW, recording a slight decrease in the maximum elevation value at 47.934 m and a slight increase in the minimum value at 39.453 m, with a mean elevation value of 44.339 m. The STD of this method was lower, at 2.345 m, indicating a greater consistency in the data. The RMSE also decreased to 1.531 m, the lowest level ever recorded, reflecting the superiority of the Spline method in improving the accuracy of the topographic surfaces. These results confirm the effectiveness of the Spline method in providing a more accurate representation of the surfaces compared to IDW.

TABLE IV. SUMMARY OF STATISTICS

Case	Max (m)	Min (m)	Average (m)	STD (m)	RMSE (m)
IDW method	48.332	39.028	44.265	2.512	1.585
Spline method	47.934	39.453	44.339	2.345	1.531

IV. CONCLUSIONS

This study responds to the growing demand for accurate topographic modeling by comparing two widely used spatial interpolation methods: Inverse Distance Weighted (IDW) and Spline. Although both techniques have been examined in previous research, few studies have applied them to sparsely sampled terrains, such as urban environments, using field-collected GPS data. The methodology followed a structured workflow consisting of GPS data acquisition, spatial interpolation with ArcGIS 10.8, and accuracy evaluation through Root Mean Squared Error (RMSE) and Standard Deviation (STD). The results demonstrated that the Spline method consistently outperformed IDW, yielding a lower RMSE (1.531 m) and STD (2.345 m), which indicates a superior interpolation accuracy and smoother surface representation. The novelty of this work lies in combining optimized interpolation models with a realistic dataset under challenging topographic conditions. Compared with previous studies, the findings highlight improved accuracy and adaptability, confirming the suitability of the Spline method for applications that require high-resolution surface modeling.

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