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COMPARATIVE EVALUATION OF IDW AND SPLINE INTERPOLATION METHODS FOR ANALYZING GROUNDWATER TABLE DEPTH AND ELEVATION

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Abstrak**—** Air tanah merupakan sumber daya vital dan krusial bagi manusia, sehingga pengelolaannya memerlukan data yang akurat mengenai kondisi dan karakteristiknya, yang umumnya diperoleh melalui survei lapangan. Namun, keterbatasan aksesibilitas sering kali menghambat perolehan data secara optimal, sehingga interpolasi diperlukan untuk mengisi kekosongan data tersebut. Penelitian ini mengevaluasi penerapan metode interpolasi Inverse Distance Weighting (IDW) dan spline untuk analisis kedalaman serta elevasi muka air tanah di wilayah perkotaan dan pedesaan. Penelitian dilakukan di empat lokasi: dua mewakili wilayah perkotaan (perbatasan Kota Yogyakarta–Kabupaten Bantul–Kabupaten Sleman, serta Kecamatan Lowokwaru–Blimbing di Kota Malang) dan dua mewakili wilayah pedesaan (Kapanewon Kalibawang–Samigaluh di Kabupaten Kulon Progo, serta Kapanewon Sanden di Kabupaten Bantul). Pada setiap lokasi, dibangun tiga model IDW dan spline dengan kombinasi data pemodelan dan validasi yang berbeda untuk analisis kedalaman dan elevasi muka air tanah, sehingga diperoleh total 96 model (24 model per wilayah). Akurasi model dibandingkan menggunakan Root Mean Square Error (RMSE) dan Mean Absolute Error (MAE). Hasil penelitian menunjukkan bahwa metode interpolasi IDW lebih akurat untuk analisis kedalaman muka air tanah. Untuk analisis elevasi muka air tanah, metode IDW terbukti lebih akurat di wilayah perkotaan, sedangkan metode spline lebih akurat di wilayah pedesaan.

Kata kunci: Air Tanah, IDW, Interpolasi, Lingkungan, Spline

Abstract**—** Groundwater is a vital and critical resource for human life; thus, its management requires accurate data on its conditions and characteristics, which are generally obtained through field surveys. However, limited accessibility often hinders optimal data collection, making interpolation necessary to fill these gaps. This study evaluates the application of the Inverse Distance Weighting (IDW) and spline interpolation methods for analyzing groundwater depth and groundwater table elevation in urban and rural areas. The research was conducted at four locations: two representing urban areas (the border of Yogyakarta City–Bantul Regency–Sleman Regency, and Lowokwaru–Blimbing Districts in Malang City) and two representing rural areas (Kalibawang–Samigaluh Districts in Kulon Progo Regency, and Sanden District in Bantul Regency). At each location, three IDW and spline models were developed with different combinations of modeling and validation data for groundwater depth and elevation analysis, resulting in a total of 96 models (24 models per area). Model accuracy was assessed using the Root Mean Square Error (RMSE) and Mean Absolute Error (MAE). The findings indicate that the IDW interpolation method is more accurate for groundwater depth analysis. For groundwater table elevation analysis, IDW was found to be more accurate in urban areas, while the spline method was more accurate in rural areas.

Keywords: Groundwater, IDW, Interpolation, Environment, Spline

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I. INTRODUCTION

Water is one of the most vital and indispensable resources for human life. Approximately 70% of accessible freshwater originates from groundwater, underscoring its crucial role in meeting human needs and supporting sustainable development [1]. Consequently, groundwater analysis is an essential step toward understanding and managing this resource effectively.

The first stage in groundwater analysis involves mapping the groundwater table depth and elevation, which are typically obtained through field surveys. However, time constraints and limited accessibility often hinder data collection in certain areas, necessitating the adoption of alternative methods to complement existing datasets. One such method for addressing data gaps is interpolation [2].

Interpolation is a technique used to estimate values at unsampled locations based on mathematical calculations derived from surrounding known data points [3]. Several interpolation methods are commonly applied, including Kriging, Inverse Distance Weighting (IDW), and Spline. Kriging is a geostatistical approach that incorporates data distribution, distance, and variation in its analysis. It is widely recognized as one of the most flexible and accurate interpolation techniques [4], [5]. Nevertheless, Kriging presents certain challenges that limit its practical application. First, it requires substantial computational resources, which may be prohibitive for researchers without access to adequate computing infrastructure. Second, its implementation demands an in-depth understanding of spatial structures and variogram modeling [6]. As a result, despite its high accuracy, Kriging is often avoided in practice.

In comparison, IDW and Spline are relatively simpler interpolation methods. IDW estimates values using a weighted average of nearby known points, with distance serving as the primary weighting factor (Equation 1) [7]. A key characteristic of IDW is that points closer to the estimation location exert a greater influence on the calculated value [8]. This proximity-based weighting often results in output patterns characterized by isolated circular features.

$$Z_0 = \left. \sum_{i=1}^{s} Z_i \, {}^{1}\!/_{d_i^k} \middle/ \sum_{i=1}^{s} {}^{1}\!/_{d_i^k} \right. \tag{1}$$

Notes:
Z_0 : estimated value for at location 0
Z_i : value at known point
D_i : distance between known point and unknown point
n : Exponent for weighting

Spline, in contrast, is an interpolation method that emphasizes regional trends to generate smooth surfaces with continuous gradients [9]. Unlike IDW, spline interpolation seldom produces isolated circular patterns; instead, it yields a more continuous and seamless spatial distribution. In ArcGIS, spline interpolation refers to the Radial Basis Function (RBF) method [7].

$$S_{(x,y)} = T_{(x,y)} + \sum_{j=1}^{N} \lambda_j R(r_j) \tag{2}$$

Notes:
j : 1, 2, …, n
N : total number of data points
λ_j : coefficients derived from linear equations
r_j : Distance between known point and point j
$T_{(x,y)}$: Tension Spline selection
$R_{(r)}$: Regularized Spline selection

Comparative studies of interpolation methods have been widely conducted in groundwater research. However, most have been limited to evaluating interpolation techniques using a single dataset from a specific area. This study seeks to extend such comparisons by evaluating interpolation methods across multiple areas with distinct characteristics, specifically urban and rural environments. Furthermore, the analysis considers two parameters: groundwater table depth and groundwater table elevation. Groundwater table depth refers to the vertical distance from the ground surface (topographic surface) to the groundwater table, which is the upper surface of an unconfined aquifer. Groundwater table elevation refers to the height of the groundwater table above. Comparative studies of interpolation methods have been widely conducted in groundwater research. However, most have been limited to evaluating interpolation techniques using a single dataset from a specific area. This study seeks to extend such comparisons by evaluating interpolation methods across multiple areas with distinct characteristics, specifically urban and rural environments. Furthermore, the analysis considers two parameters: groundwater table depth and groundwater table elevation. Groundwater table depth refers to the vertical distance from the ground surface (topographic surface) to the groundwater table, which is the upper surface of an unconfined aquifer. Groundwater table elevation refers to the height of the groundwater table above mean sea level (masl), typically represented by contour lines connecting points of equal elevation. mean sea level (masl), typically represented by contour lines connecting points of equal elevation.

II. METHODOLOGY

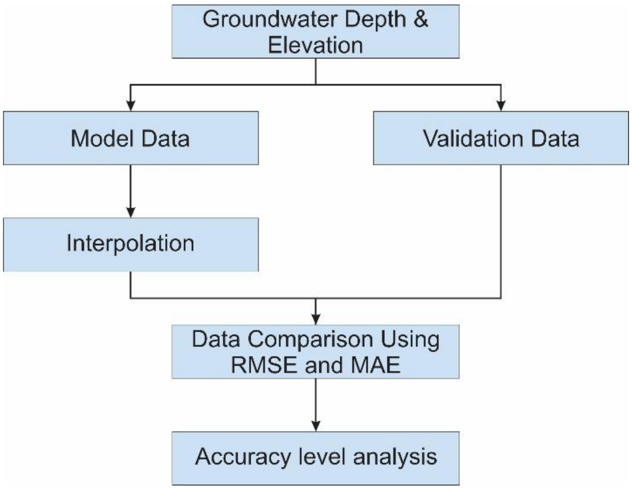
This research was conducted at four locations, comprising two sites with primary data and two with secondary data. Each settlement type—urban and rural—was represented by one primary data site and one secondary data site to ensure a balanced analysis across different settlement characteristics.

Research Area 1 is located in Kapanewon Umbulharjo, Banguntapan, Kotagede, and surrounding areas, representing an urban setting characterized by rapid development and substantial industrial activity. Primary data were collected for this site. Research Area 2, situated in the Lowokwaru and Blimbing Districts of Malang City, also represents an urban area, with data obtained secondarily from the study conducted by Irvandi [10].

In contrast, Research Area 3 is located in Kapanewon Kalibawang and Samigaluh, Kulon Progo Regency, representing a rural area dominated by agricultural land use and sparse settlements. Primary data were collected for this location. Research Area 4, located in the Sanden District of Bantul Regency, also represents a rural area, with secondary data sourced from the research conducted by Susatio [11].

Following data acquisition, the research workflow, illustrated in Figure 1, was implemented. The datasets for each location were randomly divided into two portions: 70% for model construction and 30% for validation, ensuring objectivity in data partitioning. The model datasets were processed using interpolation methods to estimate two parameters: groundwater table depth and groundwater table elevation. The validation datasets were used to evaluate model performance.

Data interpolation was performed using the IDW and spline tension methods, with each method executed three times per parameter. As a result, six models were generated for each location—three IDW models and three spline models. For the analysis of a single parameter, a total of 48 models were produced. Since the study examined two parameters, the overall number of models generated was 96.



Figure— 1. Research Flowchart

Interpolation modeling was conducted using ArcGIS 10.7.1 software, applying its default interpolation parameter settings to maintain methodological consistency across all models. Model accuracy was evaluated by comparing the interpolated results with actual measurements using two standard statistical metrics: Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) [12], [13]. RMSE calculates the square root of the mean squared difference between the interpolated and observed values, while MAE computes the mean of the absolute differences between these values. Higher RMSE or MAE values indicate lower model accuracy, whereas lower values indicate higher accuracy.

The RMSE was calculated using Equation (1), and the MAE was calculated using Equation (2).

$$RMSE = \sqrt{\frac{\Sigma(Z_i - Z)}{n}} \qquad (1)$$

$$MAE = \frac{\sum_{i=0}^{n} Z - Z_i}{n} \qquad (2)$$

Notes:
Zi : Interpolation value
Z : Actual value
n : Number of data points

The spatial distribution of data points for each research area is presented in Figure 2.

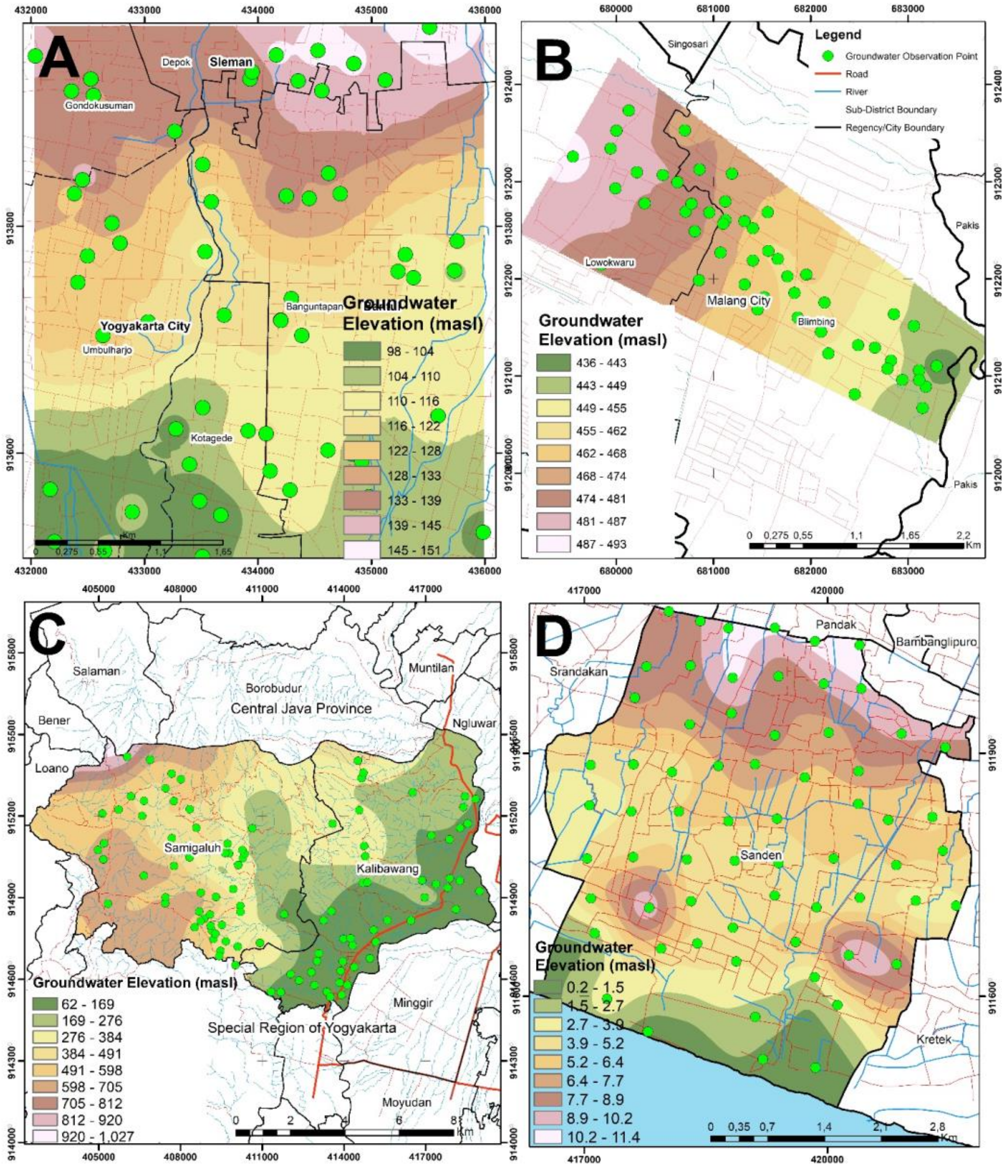
Research Area 1 contains 59 data points, comprising 47 points used as model data and 11 points as validation data. All data for this area are primary data. The spatial distribution for Research Area 1 is shown in Figure 2A.

Research Area 2 contains 51 data points, consisting of 40 points used as model data and 12 points as validation data. All data for this area are secondary data obtained from the study by Irvandi [10]. The spatial distribution for Research Area 2 is shown in Figure 2B.

Research Area 3 contains 131 data points, consisting of 104 points used as model data and 27 points as validation data. All data for this area are primary data. The spatial distribution for Research Area 3 is shown in Figure 2C.

Research Area 4 contains 65 data points, comprising 52 points used as model data and 13 points as validation data. All data for this area are secondary data obtained from the study by Susatio [11]. The spatial distribution for Research Area 4 is shown in Figure 2D.

The use of both primary and secondary datasets in this research was intended to enhance the reliability and objectivity of the analysis, ensuring that the results reflect a broader range of conditions while reducing the limitations inherent in relying on a single data source.



Figure— 1. A (Groundwater Observation Data Distribution in Research area 1 Yogyakarta City), **B** (Lowokwaru and Blimbing Districts, Malang City), **C** (Research area 3 Kalibawang–Samigaluh Kulon Progo Regency), and **D** (Sanden District in Bantul Regency)

III. RESULTS AND DISCUSSION

A. *Results*

A total of 96 models were developed in this study, consisting of 48 models for groundwater table depth and 48 models for groundwater table elevation. A summary of the RMSE and MAE values for the groundwater table depth interpolation results is presented in Table 1, while Table 2 provides a summary of the RMSE and MAE values for the groundwater table elevation interpolation results.

For groundwater table depth, the IDW interpolation method consistently produced lower RMSE and MAE values than the spline method across all research areas, encompassing both urban (Research Areas 1 and 2) and rural (Research Areas 3 and 4) settings. The lowest RMSE and MAE values were obtained in Model 2 at Research Area 3 using the IDW method, with an RMSE of 0.002 and an MAE of 0.001. This indicates that the IDW method achieved an average estimation error of less than 0.002 meters—approximately 2 millimeters—for this model.

Conversely, despite using the same dataset as IDW Model 2, spline Model 2 at Research Area 3 produced the highest RMSE and MAE values among all models analyzed. Such a marked discrepancy between the two methods was not observed in the model comparisons for the other research areas.

Overall, the RMSE and MAE comparisons confirm that the IDW interpolation method provides more accurate estimates of groundwater table depth than the spline method. This finding aligns with previous studies [14], [15], which have identified IDW as the most reliable interpolation technique for groundwater table depth analysis.

Table—1. RMSE and MAE Evaluation of Groundwater Table Depth Interpolation (IDW and Spline) at Research Area

Research area and Data Source	Area Type	Evaluation Metric	Model 1		Model 2		Model 3	
			IDW	Spline	IDW	Spline	IDW	Spline
Research area 1 (Primary Data)	Urban Area	RMSE	1,138	1,412	0,770	1,014	1,300	1,790
		MAE	0,906	1,007	0,587	0,845	0,893	1,280
Research area 2 (Arvandi 2021)	Urban Area	RMSE	1,994	2,268	2,904	3,004	1,301	2,399
		MAE	1,370	2,031	1,656	2,084	1,178	1,836
Research area 3 (Primary Data)	Rural Area	RMSE	5,149	6,035	0,002	6,723	4,979	5,517
		MAE	3,809	4,161	0,001	5,092	3,227	3,507
Research area 4 (Susatio, 2018)	Rural Area	RMSE	0,521	0,570	0,792	1,042	0,744	0,968
		MAE	0,407	0,411	0,590	0,788	0,541	0,754

Table—2. RMSE and MAE Evaluation of Groundwater Table Elevation Interpolation (IDW and Spline) at Research Area

Research area and Data Source	Area Type	Evaluation Metric	Model 1		Model 2		Model 3	
			IDW	Spline	IDW	Spline	IDW	Spline
Research area 1 (Primary Data)	Urban Area	RMSE	5,826	6,210	5,614	19,612	7,305	20,367
		MAE	4,635	5,069	4,503	10,055	4,299	9,737
Research area 2 (Arvandi 2021)	Urban Area	RMSE	3,939	4,631	4,443	5,032	4,066	4,666
		MAE	3,507	3,659	3,413	3,574	2,716	3,358
Research area 3	Rural Area	RMSE	37,093	36,721	35,646	28,802	80,696	77,890

Research area and Data Source	Area Type	Evaluation Metric	Model 1		Model 2		Model 3	
			IDW	Spline	IDW	Spline	IDW	Spline
(Primary Data)		MAE	28,301	23,726	25,319	21,968	42,071	37,932
Research area 4 (Susatio, 2018)	Rural Area	RMSE	1,425	1,392	1,921	1,773	1,065	0,916
		MAE	1,033	0,993	1,431	1,290	0,880	0,616

In contrast, the groundwater table elevation models did not reveal a single interpolation method that consistently outperformed the other across all study areas. Nonetheless, a distinct pattern emerged: RMSE and MAE values for the IDW method tended to be lower in urban areas (Research Areas 1 and 2) but higher in rural areas (Research Areas 3 and 4). Conversely, the spline method yielded lower RMSE and MAE values in rural areas compared to urban areas.

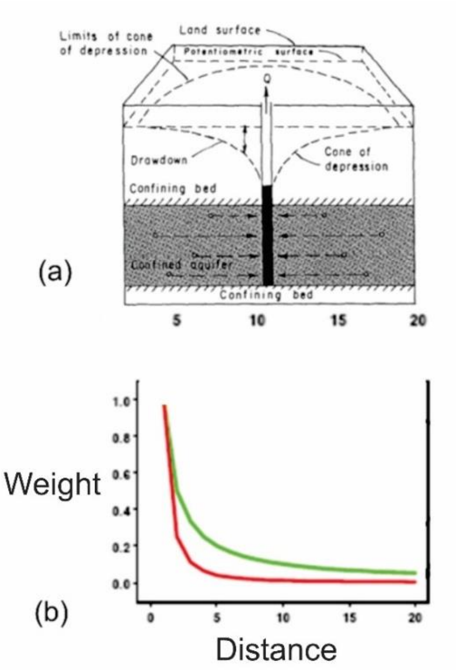
The highest RMSE and MAE values for groundwater table elevation were observed in Research Area 3, which may be attributed to the significant elevation variations in this location relative to the other study areas. It should be noted that the dataset producing the highest RMSE and MAE values for groundwater table elevation differed from that for groundwater table depth: for elevation, Model 3 yielded the highest values, whereas for depth, Model 2 had the highest values (in the spline method).

These results indicate that, for groundwater table elevation analysis, the IDW method performs better in urban environments, whereas the spline method is more suitable for rural settings.

B. Discussion

The RMSE and MAE results in this study demonstrate that the IDW method provided higher accuracy for groundwater table depth analysis in both urban and rural areas. This outcome suggests that the spatial distribution of groundwater table depth aligns closely with the fundamental principle of the IDW method, which is based on spatial proximity among data points.

From a hydrogeological perspective, the primary factors influencing groundwater table depth in unconfined aquifers are groundwater pumping activities and the surrounding land cover conditions at the measurement points. Intensive pumping induces the formation of a cone of depression—a zone of declining groundwater levels forming an inverted cone-shaped surface around a well [16]. This surface is not a straight line but rather exhibits gentle curves, indicating that a drop in groundwater level at one point does not directly or uniformly affect adjacent points. This curved configuration reflects the mechanism of the IDW interpolation method, which assigns the highest weight to the nearest data points and progressively less weight to those farther away. Such conceptual similarity is believed to underpin the suitability of IDW for groundwater table depth analysis, particularly in urban regions with extensive pumping activities. Figure 3 illustrates this conceptual analogy between a cone of depression and the IDW interpolation process.



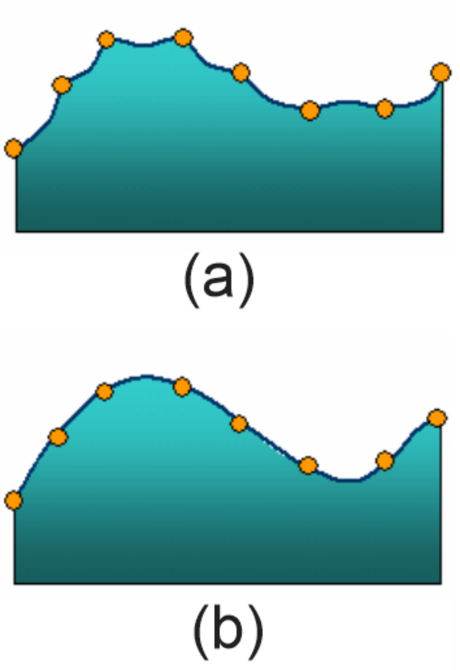
Figure—3. (a) Illustration of a Cone of Depression in an Unconfined Aquifer [17]; (b) Illustration of the IDW Interpolation Method [18]

In addition to pumping, land cover significantly influences groundwater table depth in unconfined aquifers, as different land cover types affect the infiltration capacity of rainwater into the soil. Areas with open vegetative cover, such as plantations or parks, tend to have higher infiltration rates, resulting in shallower groundwater levels compared to built-up areas such as dense residential or industrial zones [19]. These variations in land cover and their effects on infiltration are likely reasons why IDW consistently outperformed spline interpolation in groundwater table depth analysis in this study.

While groundwater table depth analysis clearly favored IDW, the groundwater table elevation results did not reveal a single universally superior interpolation method across all study areas. Instead, the findings indicate that the performance of each method depends on the population density, hydrogeological conditions, and land use characteristics of the area. The RMSE and MAE values showed that IDW achieved greater accuracy in urban areas, whereas the spline method performed better in rural areas. These contrasting outcomes emphasize the importance of interpreting interpolation performance in the context of local environmental and hydrogeological conditions.

In urban environments, groundwater use is typically higher due to dense populations and industrial demand, leading to substantial fluctuations in groundwater levels [20]. Urban land use is dominated by impervious surfaces such as residential, commercial, and industrial buildings, which reduce local infiltration rates. This condition amplifies groundwater level fluctuations and produces a more pronounced and sharply curved cone of depression. Consequently, groundwater elevation patterns in urban areas tend to be more fragmented and localized, often displaying isolated circular features. Such spatial characteristics align with the strengths of the IDW method, which emphasizes local variability by assigning greater weight to nearby data points. Therefore, IDW is considered more suitable for urban settings, as it effectively captures the sharp, localized variations resulting from intensive pumping and low-infiltration land cover.

In contrast, rural areas generally have lower groundwater extraction rates compared to urban areas [21]. These regions are dominated by open land uses such as rice fields, plantations, and community forests, which promote high, stable, and evenly distributed infiltration rates. Under these conditions, groundwater level fluctuations are minimal, leading to smoother and more continuous groundwater elevation patterns. The spline interpolation method, which emphasizes broader regional variation and produces smooth, continuous surfaces, is therefore more appropriate in rural contexts [22]. This distinction in performance can be observed in Figure 4, which illustrates the comparative effectiveness of IDW and spline methods for groundwater table elevation analysis.



Figure—4. (a) Illustration of IDW Interpolation Method for Groundwater Table Elevation; (b) Illustration of Spline Interpolation Method for Groundwater Table Elevation [23]

IV. CONCLUSION & RECOMMENDATION

A. *Conclusion*

This study demonstrates that the IDW interpolation method offers higher accuracy for groundwater depth analysis in both urban and rural settings. This accuracy is attributed to the method's compatibility with local cones of depression formed by groundwater pumping and variations in infiltration.

For groundwater table elevation analysis, IDW produced more accurate results in urban areas, while the spline method was better suited for rural areas. This difference reflects variations in groundwater use intensity and land-use characteristics. The sharp, discontinuous fluctuations typical of urban environments are better captured by IDW, whereas the smoother, continuous patterns in rural areas are more effectively modeled using spline interpolation.

These findings highlight the importance of selecting interpolation methods based on the characteristics of the study area and the parameters under analysis. Choosing the most appropriate approach ensures that groundwater mapping more accurately reflects actual hydrogeological conditions, thereby supporting effective planning and sustainable groundwater resource management.

B. Recommendation

The number and spatial distribution of well data for model calculation and validation should be determined using appropriate sampling techniques to ensure uniformity. The study area should include transition zones between urban and rural regions to identify emerging patterns in groundwater depth and table elevation modeling. The interpolation method with the highest demonstrated accuracy should be prioritized. Additionally, the relationship between model accuracy and influencing factors should be statistically tested to produce quantitative results. Future research should also integrate the morphological characteristics of the study area, as these may provide valuable context for interpreting variations in groundwater depth and elevation.

REFERENCES

[1] S. A. Khan, S. R. Paul, and T. G. Puthucherril, “Introduction: The Changing Waterscape of Groundwater Law in India,” in *Groundwater Law and Management in India: From an Elitist to an Egalitarian Paradigm*, 2021, pp. 1–18. doi: 10.1007/978-981-16-2617-3_1.

[2] H. S. Njeban, “Comparison and Evaluation of GIS-Based Spatial Interpolation Methods for Estimation Groundwater Level in AL-Salman District—Southwest Iraq,” *J. Geogr. Inf. Syst.*, vol. 10, no. 04, pp. 362–380, 2018, doi: 10.4236/jgis.2018.104019.

[3] J. Sreevalsan-Nair, “Interpolation,” in *Encyclopedia of Earth Sciences Series*, vol. 2020, 2020. doi: 10.1007/978-3-030-26050-7_164-1.

[4] D. Spridon, A. M. Deaconu, and L. Ciupala, “Fast CUDA Geomagnetic Map Builder,” in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 2023, pp. 126–138. doi: 10.1007/978-3-031-36805-9_9.

[5] D. Zhan and H. Xing, “A Fast Kriging-Assisted Evolutionary Algorithm Based on Incremental Learning,” *IEEE Trans. Evol. Comput.*, vol. 25, no. 5, pp. 941–955, 2021, doi: 10.1109/TEVC.2021.3067015.

[6] X. Yan, H.-L. Gong, W.-J. Zhao, X.-L. Ma, and Z.-N. Gong, “Research on the PM10 pollutant concentration based on different interpolation method,” in *European Space Agency, (Special Publication) ESA SP*, 2010.

[7] H. Kurniadi, E. Aprilia, J. B. Utomo, A. Kurniawan, and A. Safril, “Perbandingan Metode IDW Dan Spline dalam Interpolasi Data Curah Hujan,” in *Pros. Semin. Nasiional GEOTIK*, 2018, pp. 213–220.

[8] J. Yan, B. Wu, and Q. He, “An anisotropic IDW interpolation method with multiple parameters cooperative optimization,” *Cehui Xuebao/Acta Geod. Cartogr. Sin.*, vol. 50, no. 5, pp. 675–684, 2021, doi: 10.11947/j.AGCS.2021.20200148.

[9] Y. Darmawan, D. A. Atmojo, H. Wahyujati, and L. Nainggolan, “Accuracy assessment of spatial interpolations methods using ArcGIS,” in *E3S Web of Conferences*, 2023. doi: 10.1051/e3sconf/202346409005.

[10] M. A. Irvandi, H. Siswoyo, and D. E. Irawan, “Pemetaan Pola Aliran Air Tanah di Sekitar Kali Sumpil Kota Malang sama lain . Interaksi yang mungkin terjadi ialah losing stream atau gaining memberi asupan air ke air tanah , sedangkan gaining stream merupakan,” *Tecnoscienza*, vol. 6, no. 2, pp. 389–403, 2022.

[11] R. Susatio, L. A. T. Buana, and W. Wilopo, “Groundwater Vulnerability on Sanden Sub district , Bantul Regency,” in *Pros. Pertem. Ilm. Tah. Perhimpun. Ahli Airtanah Indones.*, 2018, pp. 343–351.

[12] O. Arkoc, “Modeling of spatiotemporal variations of groundwater levels using different interpolation methods with the aid of GIS, case study from Ergene Basin, Turkey,” *Model. Earth Syst. Environ.*,

vol. 8, no. 1, pp. 967–976, 2022, doi: 10.1007/s40808-021-01083-x.

[13] T. O. Hodson, “Root-mean-square error (RMSE) or mean absolute error (MAE): when to use them or not,” *Geosci. Model Dev.*, vol. 15, no. 14, pp. 5481–5487, 2022, doi: 10.5194/gmd-15-5481-2022.

[14] S. Shahmohammadi-Kalalagh and F. Taran, “Evaluation of the classical statistical, deterministic and geostatistical interpolation methods for estimating the groundwater level,” *Int. J. Energy Water Resour.*, vol. 5, no. 1, pp. 33–42, 2021, doi: 10.1007/s42108-020-00094-1.

[15] N. Rahmawati, K. Rahayu, D. Arisanty, T. N. Adji, and C. Di Salvo, “Variation of groundwater level due to land use, precipitation, and earthquake in Yogyakarta City from 2005 to 2020,” *Groundw. Sustain. Dev.*, vol. 26, p. 101195, 2024, doi: 10.1016/j.gsd.2024.101195.

[16] C. W. Fetter and D. K. Kreamer, *Applied Hydrogeology*. Long Grove, IL: Waveland Press, 2021.

[17] Eckstein Gabriel and Eckstein Yoram, *A Hydrogeological Approach to Transboundary Ground Water Resources and International Law*, vol. 19, no. 2. 2003.

[18] Esri, “How inverse distance weighted interpolation works.” Accessed: Apr. 19, 2025. [Online]. Available: https://desktop.arcgis.com/en/arcmap/latest/extensions/geostatistical-analyst/how-inverse-distance-weighted-interpolation-works.htm

[19] J. Becher, C. Griebler, K. Zosseder, and P. Bayer, “Integrative assessment of urban groundwater quality in the city of Munich, Germany: Spatio-temporal patterns of hydrochemical and selected microbial indicators,” *J. Hydrol.*, vol. 658, 2025, doi: 10.1016/j.jhydrol.2025.133096.

[20] H. Rafiemehr and L. Kozegar Kaleji, “Analyzing spatiotemporal relationship between land use changes and groundwater quantity in Hamedan north plains (Iran),” *J. Water L. Dev.*, vol. 46, pp. 179–189, 2020, doi: 10.24425/jwld.2020.134211.

[21] A. Kumar, D. Kumar, and S. M. Veerabhadrappa, “Analysing Effects on Ground Water Levels Due to Conversion of Rural to Urban Landscapes,” *J. Landsc. Ecol.*, vol. 15, 2022, doi: 10.2478/jlecol-2022-0009.

[22] H. Arslan, “Estimation of spatial distrubition of groundwater level and risky areas of seawater intrusion on the coastal region in Çarşamba Plain, Turkey, using different interpolation methods,” *Environ. Monit. Assess.*, vol. 186, no. 8, pp. 5123–5134, 2014, doi: 10.1007/s10661-014-3764-z.

[23] Esri, “How radial basis functions work.” Accessed: Apr. 20, 2025. [Online]. Available: https://desktop.arcgis.com/en/arcmap/latest/extensions/geostatistical-analyst/how-radial-basis-functions-work.htm