KATHMANDU UNIVERSITY

DHULIKHEL, KAVRE

PROJECT REPORT ON ACCURACY ASSESSMENT AND COMPARISON OF DEM INTERPOLATION TECHNIQUES IN GIS

A Third Year Project Report submitted in Partial fulfilment of the requirements for the degree of Bachelor of Engineering

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Project Supervisors

Assoc. Prof. Dr. Subash Ghimire

Er. Saurav Raj Khanal

SUBMITTED BY:

Sonik Neupane [029017-21]

Sudhan Oli [029018-21]

Rajan Pandit [029021-21]

Aarya Pant [029022-21]

Lochan Pant [029023-21]

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ABSTRACT

DEM (Digital Elevation Model) interpolation techniques are approaches used to predict elevation values at unsampled points, improving the accuracy and completeness of the terrain representation. The precision of the generated terrain model relies on the chosen interpolation method, so it is essential to evaluate and compare the effectiveness of various interpolation techniques. This report presents an accuracy assessment and comparison of various DEM interpolation techniques within a GIS (Geographic Information System) framework. The study aims to evaluate the performance of six interpolation methods: Natural Neighbor, Inverse Distance Weighting (IDW), Spline, ANUDEM, Triangulated Irregular Network (TIN), and Kriging. The project was conducted using spatial data from Thaha Municipality, with the primary objective of determining the most accurate interpolation technique for this area.

The methodology involved data acquisition, preprocessing, and implementation of the interpolation techniques, followed by error assessment using statistical measures such as Mean Absolute Error (MAE) and Root Mean Square Error (RMSE). The results indicate that TIN was the most accurate method, followed closely by Natural Neighbor and Kriging. ANUDEM and IDW exhibited moderate accuracy, while Spline showed the highest errors and the lowest model fit.

This study provides valuable insights into the selection of appropriate DEM interpolation techniques for different terrains and data characteristics, contributing to improved accuracy in spatial analyses and decision-making processes in geomatics engineering.

ACKNOWLEDGEMENT

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Lastly, we recognize the broader community of researchers and practitioners in the field of geomatics engineering, whose published works and ongoing research have inspired and informed our own study. The collaborative spirit and shared knowledge within this community have been a constant source of motivation and insight.

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LIST OF ABBREVIATION

ALS	Aerial Laser Scanning
CL	Contour Line
DEM	Digital Elevation Model
DGPS	Differential Global Positioning System
GCP	Ground Control Point
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
ID^2	Inverse Distance Squared
IDW	Inverse Distance Weighted
MAE	Mean Absolute Error
MARS	Multivariate Adaptive Regression Splines
NN	Natural Neighbor
RBF	Radial Basis Function
RMSE	Root Mean Square Error
TIN	Triangulated Irregular Network
UTM	Universal Transverse Mercator
WGS	World Geodetic System

1. INTRODUCTION

The Digital Elevation Model (DEM) is a three-dimensional depiction of the ground surface relief to realize topographical features by interpreting the landscape using technology in surveying. It is the primary input data for research in many scientific disciplines that can be produced using remote sensing techniques or by reference elevation data collected from various survey methods (Habib, 2021). DEM is an array representation of squared cells (pixels) with an elevation value associated with each pixel. DEMs can be obtained from contour lines, topographic maps, field surveys, photogrammetry techniques, radar interferometry, and laser altimetry. Different interpolation methods applied over the same data sources may result in different results and hence it is required to evaluate the comparative suitability of these techniques (Arun, 2013). DEMs seem to facilitate the analysis task and produce significant savings in computation time. Another important application is in the area of digital image rectification and orthophoto production. The contribution of DEMs in image matching is significant and has been discussed by several researchers. There is no doubt that the efficiency of image-matching techniques can be increased if an approximate DEM of the area of interest is provided before executing the matching algorithm. The DEM also aids automatic recognition of terrain features in town planning and automatic building extraction, and it offers a potential for quantitative and automated assessment of land resources and attributes. These are only some examples of practical applications of DEMs (Algarni & El Hassan, 2001).

Spatial interpolation is the process of using captured data to estimate the value of properties at certain positions (Algarni & El Hassan, 2001). It is typically a raster procedure, but it can also be conducted in a vector form, viz. triangulated irregular network (TIN). The principle underlying spatial interpolation is Tobler's first law of geography or distance decay, which states: "Everything is related to everything else, but near things are more related than distant things."(Tobler, 1970). Unfortunately, there is no rule of thumb for choosing a specific interpolation technique that will be suitable for a particular surface. The accuracy of DEM is strongly impacted by the degree of terrain complexity and estimation method. Geographic information system presents an efficient analytical tool to generate a DEM with high quality appropriate for the construction sector from the ground control points (GCPs) using interpolators (Habib, 2021).

Among the various studies on comparing interpolation techniques for generating digital terrain models, only a few examined the accuracy of interpolation techniques concerning data sample size, sample spacing and landform types. Especially the effects of terrain morphologies that exist in natural landscapes and over a large range of scales, have seldom been investigated. So, there is still a need to evaluate the performance of these techniques in different landform types. The main objective of this study is to evaluate the effects of different interpolation techniques on the accuracy of DEM generation concerning landform types (Tan & Xu, 2014a).

1.1 Spatial Interpolation Techniques

Spatial interpolation methods can be classified into global interpolators and local interpolators. The global interpolation method uses all the sampling point data in the study area to make features fitting for the region.

The global interpolation method is usually not used directly for spatial interpolation but for detecting the maximum deviation part different from the general trend. For the global interpolation method, which takes short-scale and local changes as random and non-structural noise, the information of this local area is lost. The six commonly used spatial interpolation methods in the experiment belong to local interpolators.

Table 1: Spatial Interpolation Techniques

Interpolation method	Scope	Exactness	Model
Polynomial fitting	Global	Approximate	Deterministic
Basis Splines	Global	Approximate	Deterministic
Inverse Distance Weighting	Local	Exact	Deterministic
Radial Basis Function	Local	Exact	Deterministic
Ordinary Kriging	Local	Exact	Stochastic

Local interpolation methods, in contrast to global interpolation, address localized irregularities by utilizing a limited subset of nearby data points, acknowledging the principle that spatial proximity implies similarity. By employing a sliding "window" of neighbouring data points, these methods generate interpolated surfaces that adapt to local variations while minimizing the influence of outliers. However, determining the appropriate size of this window, whether based on a fixed number of points or a specific radius, remains a challenge in implementing these techniques effectively. Despite potentially resulting in less smooth surfaces compared to global methods, local interpolation offers resilience against outliers and preserves the integrity of nearby data relationships, making it suitable for addressing local anomalies in spatial datasets (Tan & Xu, 2014a).

A. Natural Neighbor

The Natural Neighbor interpolation algorithm finds the closest subset of input samples to a query point and applies weights to them based on proportionate areas to interpolate a value. It is also known as Sibson or "area-stealing" interpolation. Its basic properties are that it's local, using only a subset of samples that surround a query point, and interpolated heights are guaranteed to be within the range of the samples used. It does not infer trends and will not produce peaks, pits, ridges, or valleys that are not already represented by the input samples. The surface passes through the input samples and is smooth everywhere except at the locations of the input samples(Tan & Xu, 2014a).

B. Triangulated Irregular Network

The TIN technique is one of the most simple spatial interpolation techniques. This approach relies on the construction of a triangular network based on the sample's spatial location. Multiple triangulation methods might be used to create the network but that of Delaunay is the most commonly reported. This method aims at creating non-overlapping triangles (as equilateral as possible) whose circumscribed circles contain only the three points that gave birth to the triangle. TIN interpolation is particularly useful when the data points are irregularly spaced or when there are variations in the density of data points across the study area (Rishikeshan et al., 2014).

C. Spline Method

Another commonly used local interpolation method is the bi-cubic splines (often simply known as splines). The spline interpolation estimates the elevation of a specific point using a mathematical function that minimizes the overall surface curvature, resulting in a smooth surface that passes exactly through the input points. Conceptually, the sample points are extruded to the height of their magnitude; spline bends a sheet of rubber that passes through the input points while minimizing the total curvature of the surface. It fits a mathematical function to a specified number of nearest input points while passing through the sample points (Tan & Xu, 2014a).

There are two spline methods: regularized and tension. The regularized method creates a smooth, gradually changing surface with values that may lie outside the sample data range. The tension method controls the stiffness of the surface according to the character of the modelled phenomenon. It creates a less smooth surface with values more closely constrained by the sample data range. The main parameters of the spline interpolation are the number of sampled points used for interpolation and the weight. For the regularized spline, the higher the weight, the smoother the output surface. For the tension spline, the higher the weight, the coarser the output surface.

D. Inverse Distance Weighted (IDW)

IDW is a spatial interpolation approach that is used commonly to estimate an unsampled or unmeasured variable at any location in a study area. IDW is a deterministic interpolation approach which considers the distance of an unsampled point towards a set of surrounding sampling points in the weight determination stage. In contrast with stochastic interpolation approaches like Kriging, which uses inter-point correlation in weight determination, IDW is simpler and faster in computation (Razali & Wandi, 2019). IDW uses:

$$Z_o = \frac{\sum_{i=1}^{s} Z_i \frac{1}{d_i^K}}{\sum_{i=1}^{s} \frac{1}{d_i^K}}$$

where Z_o is the predicted value at the unsampled location, Z_i is the observed value, d_i is the distance between the prediction location and the measured location, and s is the number of measured sample points within the neighbourhood. K is the power parameter that defines the rate of reduction of the weights as distance increases.

E. Kriging

The Kriging interpolation is similar to IDW in that it weights the surrounding measured values to derive a prediction for an unmeasured location. However, in kriging, the weights are based not only on the distance between the measured points and the prediction location but also on the overall spatial arrangement of the measured points (Oliver & Webster, 1990). Kriging assumes that the distance or direction between sample points reflects a spatial correlation that can be used to explain the variation in the surface. To use the spatial arrangement in the weights, the spatial autocorrelation must be quantified through empirical semivariograms.

The models for the semivariogram can be Gaussian, linear, spherical, exponential, or circular. There are two types of kriging techniques: Ordinary and Universal. The universal kriging approach assumes that there is a dominant trend in the data, which is represented by a polynomial, whereas the ordinary kriging approach assumes that the constant mean is unknown. Kriging fits a mathematical function to a given number or all points within a given radius. The procedure consists of several steps, such as surface creation, variogram modelling, exploratory statistical analysis of the data, and (optionally) variance surface exploration. Kriging works best in situations where the data have a directional bias or a spatially correlated distance (Tan & Xu, 2014a).

F. ANUDEM

Based on the geomorphologic principle, (Hutchinson, 1989) put forward an ANUDEM method to produce a hydrologically correct DEM via an iterative drainage enforcement algorithm, which can yield a good shape and drainage structure in the calculated DEM. The method calculates values on a regular grid of a discretized smooth surface fitted to large numbers of irregularly distributed elevation data points, contour lines (CLs), brake lines, sink points, lake boundaries, and cliff lines. The subsequent research (Hutchinson, 2000) has resulted in the ANUDEM method becoming one of the most well-known, reliable, and computationally efficient tools for generating high-quality DEMs (Zheng et al., 2016). The ANUDEM method has been integrated into ArcGIS software in the Topo to Raster interpolation tool.

1.2 Problem Statement

Currently, there is hardly any research conducted to compare the accuracy of interpolation techniques used to interpolate DEM of places with varying terrain like that of Nepal. It is difficult to find an interpolation method that fulfils all the requirements for a wide range of georeferenced data. Different methods produce different spatial representations in different datasets; also, in-depth knowledge of the phenomenon in question is necessary for evaluating which of the interpolation methods produces results closest to reality. The use of an unsuitable method or inappropriate parameters can result in a distorted model of spatial distribution, leading to potentially wrong decisions based on misleading spatial information. A wrong interpolation result becomes very critical when the estimates are inputs for simulations, as small errors or distortions can cause models to produce false spatial patterns (Erdogan, 2009).

This paper examined the accuracy of spatial interpolation methods in modelling topography. The experimental study of this work employed an area comprising a slope and a plain as a landform-adaptability test area and focused on the comparative analysis of commonly used interpolation methods of Natural Neighbor, TIN, Spline, IDW, Kriging and ANUDEM.

1.3 Objectives

The primary objective of this project is to assess the accuracy and compare interpolation techniques used to produce a Digital Elevation Model.

The secondary objectives of this project are as follows:

i. To evaluate the performance of commonly used DEM interpolation methods, in representing terrain surfaces.
ii. To quantify and compare the spatial accuracy of the interpolated DEMs through statistical measures such as root mean square error (RMSE) and mean error.
iii. To understand the algorithm of different interpolation techniques.

1.4 Scope

This study focused on assessing and comparing the accuracy of digital elevation model (DEM) interpolation techniques within the realm of Geographic Information Systems (GIS). The scope encompassed a comprehensive examination of commonly employed interpolation methods, including Natural Neighbor, TIN, Spline, Inverse Distance Weighting (IDW), Kriging and ANUDEM (Topo to Raster). The study involved the analysis of spatial accuracy metrics such as Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) to quantify the performance of each interpolation technique. Additionally, the project explored the applicability of these methods across varying terrain conditions and interpolation algorithm assumptions. The scope was limited to evaluating the accuracy of DEM interpolation techniques and did not encompass other aspects of GIS analysis or spatial modelling.

2. LITERATURE REVIEW

Arun (2013) compared the accuracy of DEM generated from DGPS data through five different interpolation techniques around the MANIT campus and surrounding areas of Bhopal city in India. He compared Inverse Distance Weighted (IDW), Kriging, ANUDEM, Natural Neighbor (NN), and Spline techniques. He calculated the elevation from different interpolation techniques compared with the observed DGPS value and calculated the RMSE values of each interpolation technique. He concluded that the Kriging method performs better when compared to other contemporary methods in most contexts.

Szypuła (2017) created DEM of the south part of Poland in the Katowice Upland mesoregion. In this paper, he decided to use the most popular methods of data interpolation: IDW, NN, Spline, Radial Basis Functions, Local Polynomial and Kriging. He analyzed visual effects (3D view and profiles), summarized the basic geomorphometric statistics (heights, local relief, slopes, aspects, curvatures) and assessed the vertical accuracy of developed models (RMSE and result conformity). He concluded that the best interpolation methods for the analysis of the relief are NN and Kriging.

Erdogan (2009) studied the magnitudes and spatial patterning of elevation errors using different interpolation methods. Measurements were performed with theodolite and levelling around a rocky hill near the campus of Afyon Kocatepe University, Turkey. The purpose of this study was to investigate the size and spatial patterning of errors in digital elevation models obtained with direct survey methods for large-scale areas, comparing IDW, Radial Basis Functions, and Kriging interpolation methods to generate digital elevation models. The study is important because it shows how the accuracy of the digital elevation model is related to data density and the interpolation algorithm used. Cross-validation, split-sample and jack-knifing validation methods were used to evaluate the errors. Global and local spatial auto-correlation indices were then used to examine the error clustering. He concluded the best results were obtained using the thin plate spline algorithm.

Habib et al. (2020) conducted research aimed at investigating the impact of estimation techniques on generating a reliable and accurate DEM suitable for large-scale mapping. The test area was situated in Safita, one of the cities of Tartus governorate in the Syrian Arab Republic. As a part of this study, the deterministic interpolation algorithms such as ANUDEM (Topo to Raster), IDW, and triangulated irregular network (TIN) were tested using the ArcGIS desktop for elevation data obtained from real total station readings, with different landforms to show the effect of terrain roughness, data density, and interpolation process on DEM accuracy. Furthermore, comparison and validation of each interpolator were carried out through the cross-validation method and numerous graphical representations of the DEM. Finally, the results of the investigations showed that ANUDEM and TIN models are similar and significantly better than those attained from IDW.

Tan & Xu (2014b), in their research, applied six spatial interpolation algorithms, including an internationally popular ANUDEM method and five other commonly used interpolation methods in three different landform regions, that is, hills, mountains, and alpine areas of the Longjing county, Yanbian Korean Autonomous region in northern China. Quality analysis and accuracy comparison were carried out using random point check, overlay comparison between derived contours with original ones, 3D visualization analysis etc. Experimental results show that the accuracies of DEMs generated by ANUDEM are the highest. IDW method ranks second. TIN, Kriging and natural neighbourhood methods have similar accuracy, and the spline-function method is the last. For a specific interpolation method, the greater the terrain undulated, the lower the accuracy of the generated DEM was.

Salekin et al. (2018) conducted a study to show that, in a time where Aerial Laser Scanning (ALS) is commonly used to generate DEMs, Global Navigation Satellite Systems (GNSS) surveyed data can be used to create accurate DEMs. The data interpolation method and spatial resolution from this method need to be optimized to create accurate DEMs. Moreover, the density of GNSS data is likely to affect DEM accuracy. This study investigates three different deterministic approaches, in combination with spatial resolution and data thinning, to determine their combined effects on DEM accuracy. DEMs were interpolated, with resolutions ranging from 0.5 m to 10 m using NN, topo to raster (ANUDEM), and IDW methods. DEM accuracy was measured by RMSE and MAE. The ANUDEM method yielded the greatest DEM accuracy from a quantitative however, NN produced a more visually appealing surface. In all the assessments, IDW showed the lowest accuracy. It was found that the highest resolution produced the lowest errors in resulting DEMs. Thinning the input data by 25% and even 50% had relatively little impact on DEM quality; however, accuracy decreased markedly at 75% thinning.

Ajvazi & Czimber (2019) researched the difference in accuracy in DEM interpolation of Rahovec, Kosovo area. Their paper compared different spatial interpolation methods such as IDW, Kriging, NN and Spline. The DEM data set used was from aerial photogrammetric surveying. They interpolated the DEM values using 10%, 20% and 30% of randomly selected control points. MAE and RMSE for these three scenarios were calculated. They concluded that the most accurate results are derived from the Spline and Kriging interpolation methods.

3. METHODOLOGY

3.1 Study Area

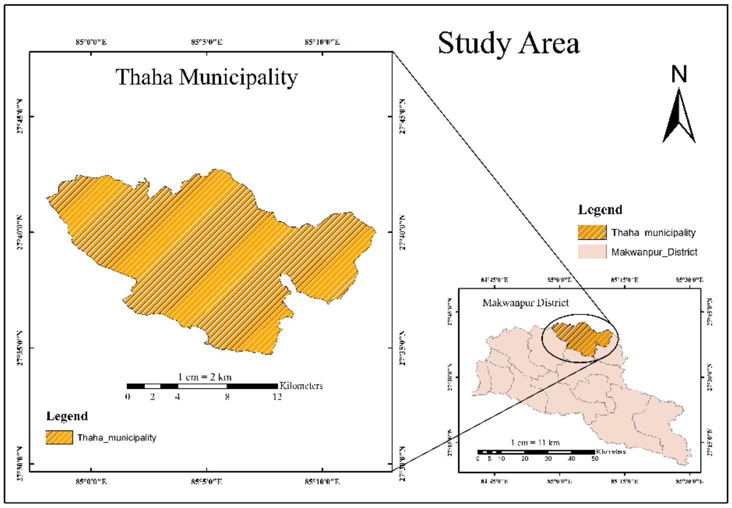

Figure 1: Thaha Municipality

For study relevance, a site (Bajrabarahi) was selected in the Makwanpur District. Bajrabarahi is a prominent locality situated within Thaha Municipality, Makwanpur district, Bagmati Province, Nepal. It is located approximately at 27.5167° N, 85.0167° E, with altitudes ranging from 400 to 1800 meters above sea level.

Being part of Thaha Municipality, Bajrabarahi benefits from the centralized facilities and services provided by the municipality, including education, healthcare, governance, and economic activities. This centralization has contributed to the development and growth of the area. Based on the most recent census data available (2021), the population of Bajrabarahi is estimated to be around 30,000, with an annual population growth rate of approximately 2.5%. This growth indicates a steady increase in the population over time.

3.2 Study Workflow

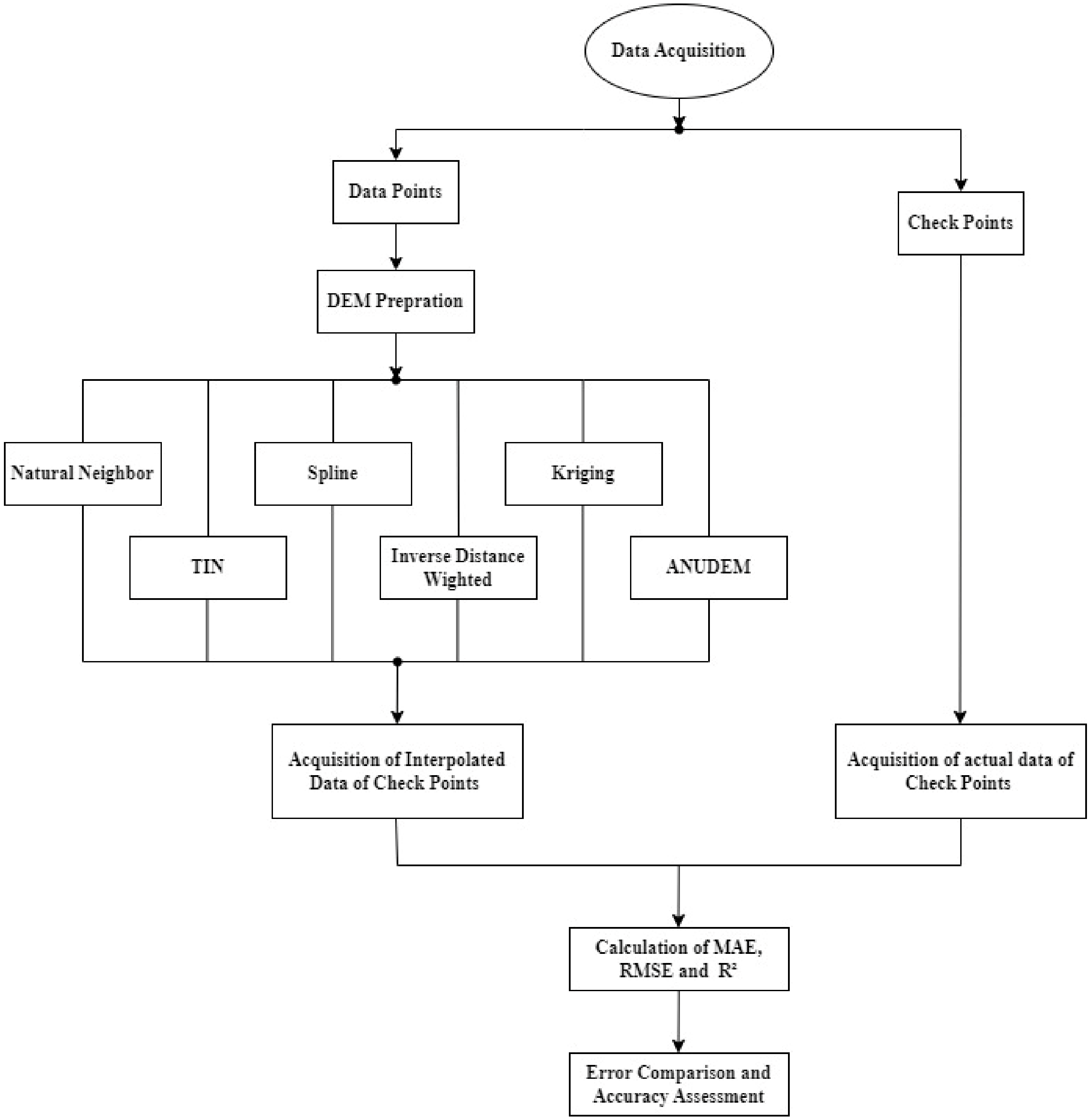

Figure 2: Project Workflow

→ **Data Acquisition**

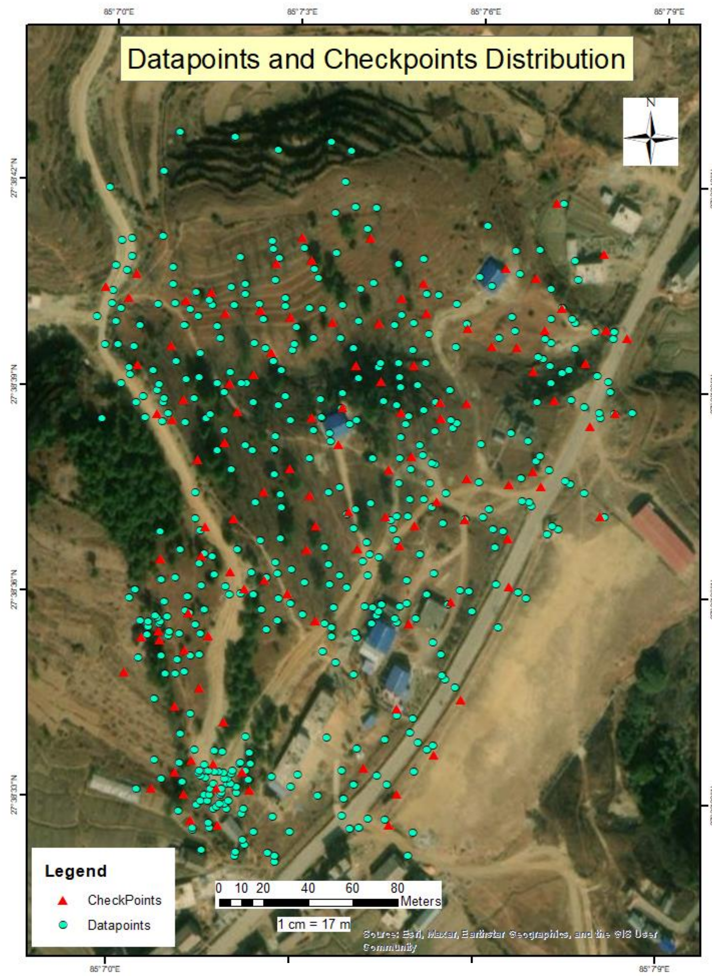

Figure 3: Data Distribution

The data used are the recent data collected in the last topographic survey in Thaha municipality via Theodolite. We collected about 564 data points in the 250 x 250 meters area in the locality. About 80% of data points were used to create DEM and the remaining 20% data points were used as checkpoints.

→ **DEM Preparation**

Using 452 data points Digital Elevation Models were produced following different interpolation techniques such as Natural Neighbor, TIN, Spline, IDW, Kriging and ANUDEM.

→ **Acquisition of Interpolated Data**

Through the data models prepared following the different interpolation techniques, the elevations of the interpolated checkpoint values was obtained. Therefore, we obtained two values for the same location (ie one value was obtained by the field survey and another value was obtained from interpolated models).

→ **Error Comparision and Accuracy Assessment**

In this study, the estimated height (Z) from the collected interpolation technique was compared at each point to the checkpoint using the mean absolute error (MAE), the root mean square error (RMSE) and R-squared (R^2).

- **Mean Absolute Error (MAE)**

  Mean Absolute Error (MAE) is a measure of the average magnitude of errors between actual values and predicted values generated by an interpolation technique. In the context of DEM accuracy assessment, MAE provides insight into how closely the interpolated surface matches the true terrain. It is calculated as the mean of the absolute differences between observed and predicted elevations at various points. The formula for MAE is:

  $$MAE = \frac{1}{n}\sum_{k=1}^{n} |Z_k - z_k|$$

  where n is the number of data points, Z_k is the interpolated elevation value and z_k is the actual elevation of that point. A lower MAE value indicates that the interpolation method produces predictions that are, on average, very close to the actual elevations, implying high accuracy. In DEM creation, achieving a low MAE means that the generated model accurately represents the real-world terrain with minimal average error.

- **Root Mean Square Error (RMSE)**

  Root Mean Square Error (RMSE) is another metric used to evaluate the accuracy of interpolation techniques, specifically measuring the standard deviation of the prediction errors. In the context of DEM accuracy assessment, RMSE provides a comprehensive measure of the differences between observed and predicted elevations, giving more weight to larger errors due to the squaring of residuals. It is computed as follows:

  $$RMSE = \sqrt{\frac{1}{n}\sum_{k=1}^{n}(Z_k - z_k)^2}$$

  where n is the number of data points, Z_k is the interpolated elevation value and z_k is the actual elevation of that point.

  A lower RMSE value indicates that the interpolated elevations are generally close to the actual values, with fewer significant errors. RMSE is particularly useful in DEM accuracy assessment because it highlights the interpolation method's ability to minimize large deviations, thus ensuring that the terrain model is both precise and reliable.

- **R-Squared (R^2)**

  R-squared (R^2) is a statistical measure that represents the proportion of the variance in the observed data that is predictable from the interpolation model. In the context of DEM accuracy assessment, R^2 indicates how well the interpolation technique captures the overall variability in the actual terrain data. The formula for R^2 is:

$$R^2 = 1 - \frac{\sum_{k=1}^{n}(Z_k - z_k)^2}{\sum_{k=1}^{n}(Z_k - \bar{z})^2}$$

  where n is the number of data points, Z_k is the interpolated elevation value and z_k is the actual elevation of that point, $\bar{z}$ is the mean of the actual elevation of checkpoints.

  R^2 values range from 0 to 1, with higher values indicating a better fit of the model to the data. An R^2 value close to 1 suggests that the interpolation method accurately explains most of the variance in the elevation data, thus providing a high level of confidence in the DEM's representation of the actual terrain. High R^2 values in DEM accuracy assessment signify that the model is effective in capturing the underlying patterns of the terrain, leading to a more reliable and accurate elevation model.

3.2.1 Data Sources Used

We used the data obtained from a tacheometric survey done by us in a recent field survey. The data contains a total of 564 data points and 10 control points within them. 452 data were used as data points to create DEM and 112 data were used as checkpoints. All the data was converted to the same projection system (WGS 1984 UTM zone 45N).

3.2.2 Software used

For the preparation of DEM, mostly Esri ArcGIS 10.8 was used since most of the interpolation techniques are easily usable there. However, we also used QGIS 3.36.0 for some other interpolation techniques not included in ArcGIS software. MS Excel was also used to calculate RMSE, MAE and R^2.

4. RESULTS

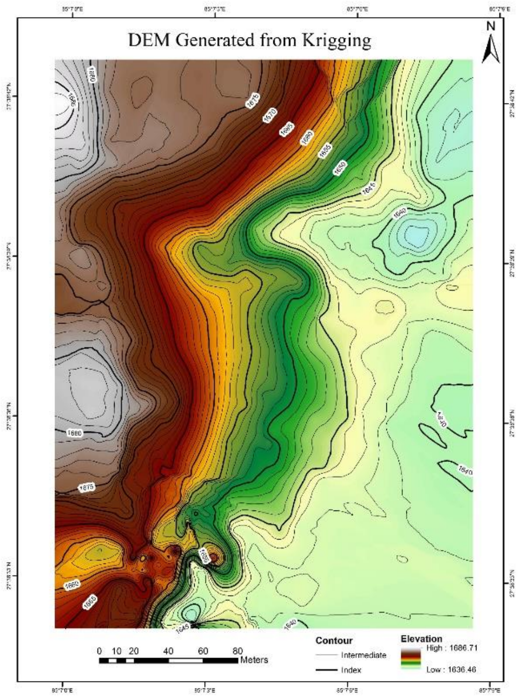

Figure 4: Interpolation using Kriging

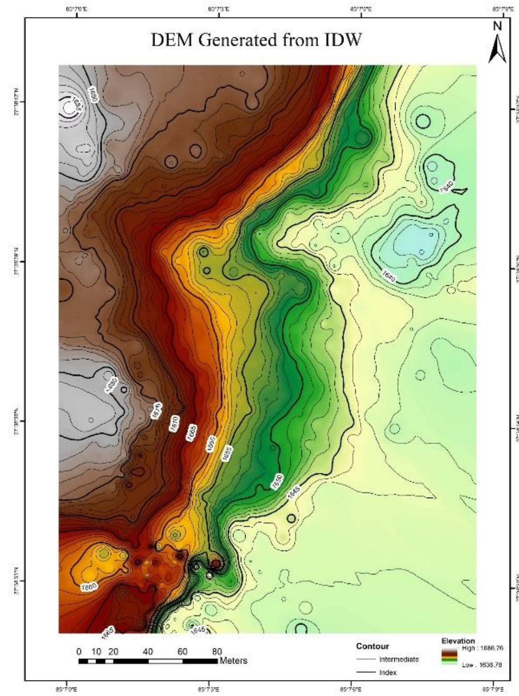

Figure 5: Interpolation using IDW

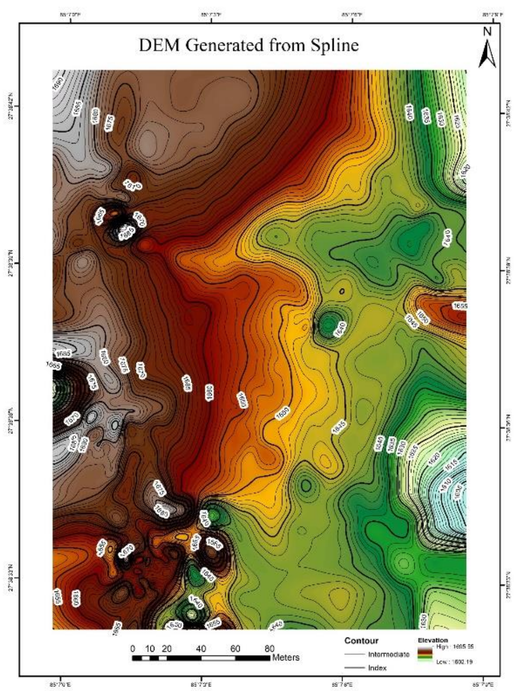

Figure 6: Interpolation using Spline

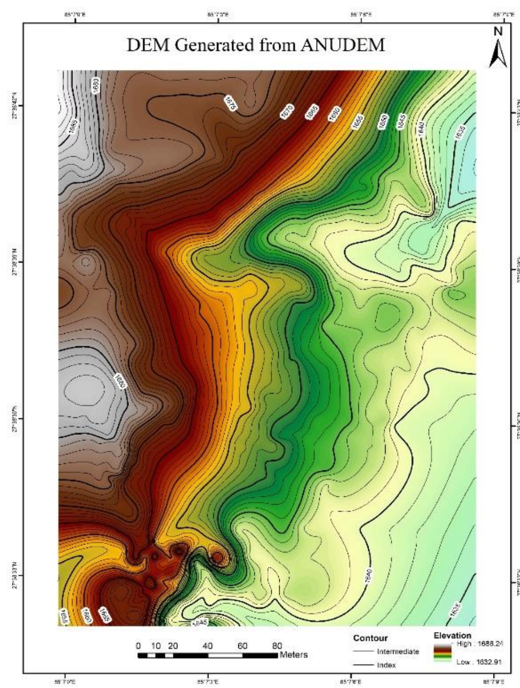

Figure 7: Interpolation using ANUDEM

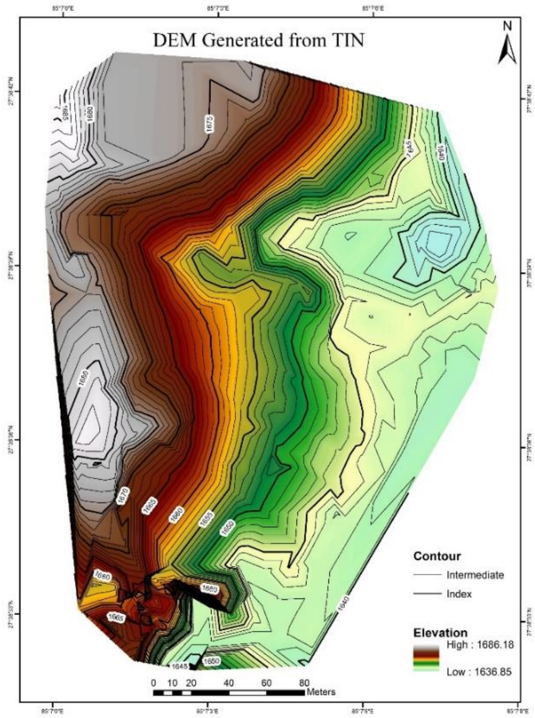

Figure 8: Interpolation using TIN

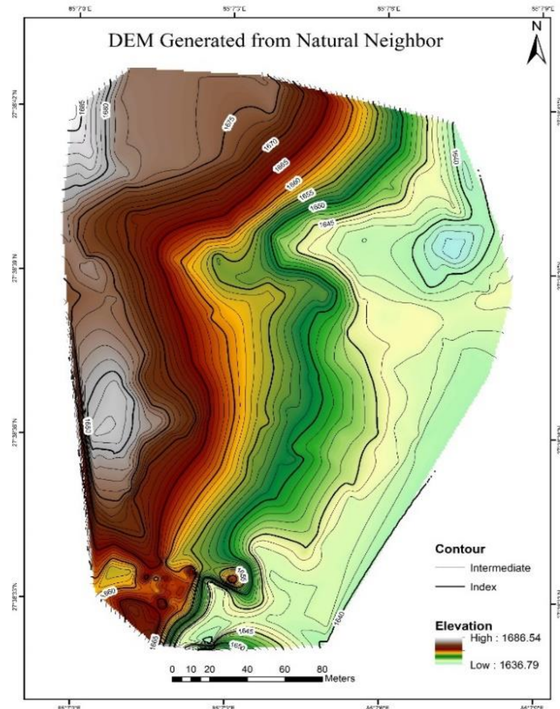

Figure 9: Interpolation using Natural Neighbor

4.1 Error Calculation

The errors calculated for the elevation values obtained from different interpolation algorithms are tabulated below:

Table 2: Error Assessment

Interpolation Techniques	MAE (m)	RMSE (m)	R^2
Natural Neighbor	0.847	1.504	0.986
IDW	1.141	1.688	0.983
Spline	1.367	2.386	0.967
ANUDEM	0.926	1.683	0.983
TIN	0.854	1.455	0.987
Krigging	0.852	1.506	0.986

4.1.1 Natural Neighbor

Natural Neighbor interpolation achieves high accuracy with the lowest MAE (0.847) among the methods compared, indicating it closely interpolates actual values. Its RMSE is also low (1.504), suggesting a small spread of errors, and it has a high R^2 (0.986), demonstrating a good fit for the data. This makes it one of the best techniques for creating accurate DEMs.

4.1.2 IDW

IDW shows moderate performance with an MAE of 1.141 and an RMSE of 1.688, which are higher than those of the best-performing methods. Its R^2 value (0.983) is slightly lower but still indicates a reasonable fit. While it provides decent accuracy, it is not as effective as Natural Neighbor, TIN, or Kriging.

4.1.3 Spline

Spline interpolation performs the worst among the evaluated methods. It has the highest MAE (1.367) and RMSE (2.386), indicating significant interpolation errors and the largest spread of residuals. Its R^2 (0.967) is the lowest, showing the poorest fit to the data. Consequently, Spline is less suitable for precise DEM interpolation.

4.1.4 ANUDEM

ANUDEM provides relatively good accuracy with an MAE of 0.926 and an RMSE of 1.683. Its R^2 value (0.983) indicates a good model fit. Although it performs well, it is slightly outperformed by Natural Neighbor, TIN, and Kriging, making it a moderately effective method for DEM interpolation.

4.1.5 TIN

TIN interpolation stands out as the best-performing technique. It has a very low MAE (0.854) and the lowest RMSE (1.455), indicating minimal interpolation errors and the least spread of residuals. Its R^2 (0.987) is the highest, showing an excellent fit to the data. TIN is highly recommended for creating accurate DEMs, particularly in terrains with significant elevation changes.

4.1.6 Krigging

Kriging is also highly effective, with an MAE (0.852) close to the lowest and an RMSE (1.506) similar to Natural Neighbor. Its high R^2 value (0.986) indicates a strong model fit. Kriging is a robust choice for DEM interpolation, offering high accuracy and reliability.

The best techniques for DEM interpolation are TIN, Natural Neighbor, and Kriging, which provide high accuracy and excellent model fit, with TIN being the top performer. ANUDEM and IDW offer moderate accuracy but are less effective than the top methods. Spline is the least effective, showing the highest errors and the lowest model fit, making it unsuitable for this context.

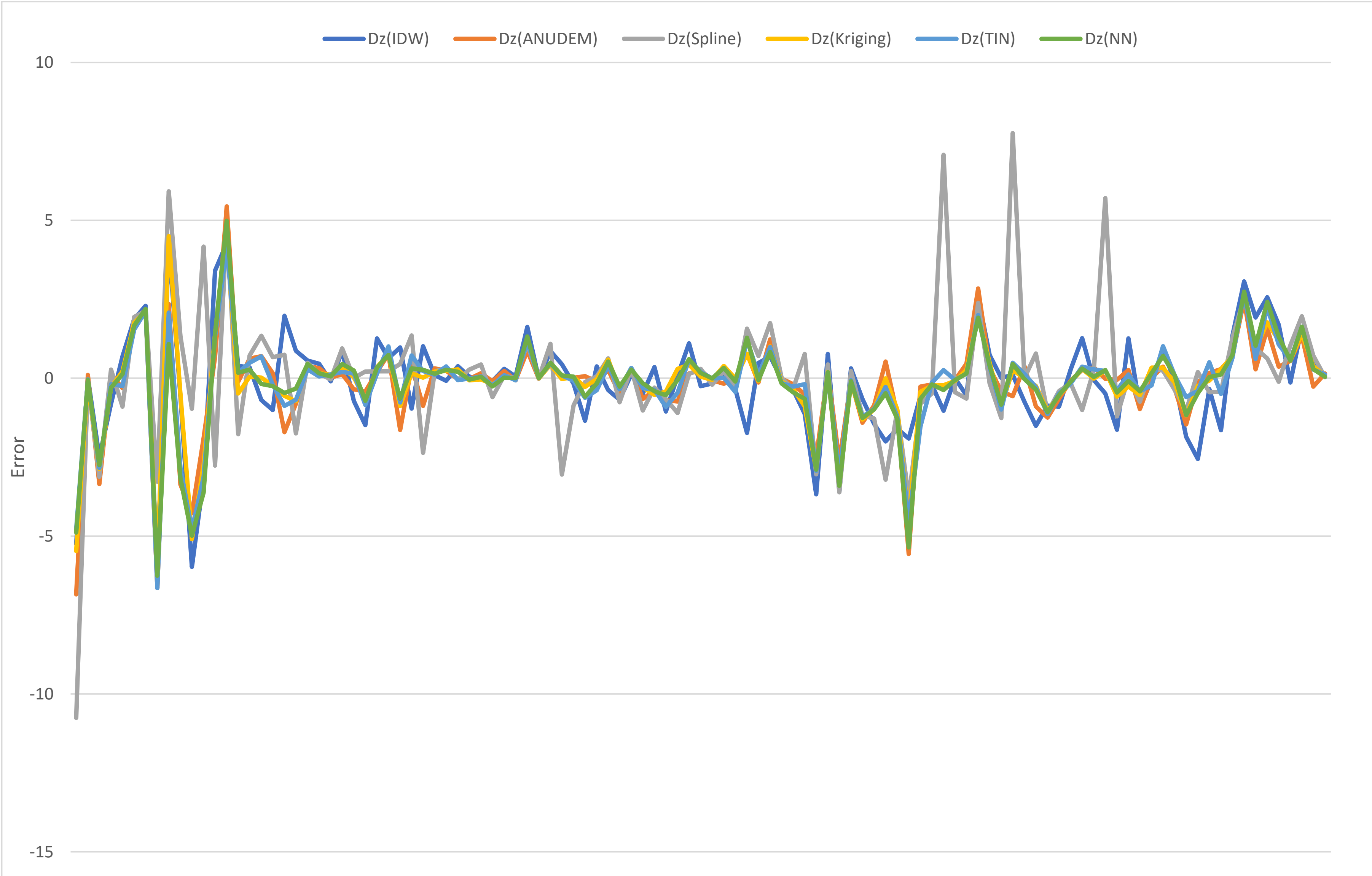

Figure 10: Error Curves for Different Interpolation Methods

5. DISCUSSION

Our study found that TIN, Natural Neighbor, and Kriging were the most accurate DEM interpolation techniques, with TIN slightly outperforming the others. ANUDEM and IDW showed moderate accuracy, while Spline was the least effective, exhibiting the highest errors and lowest model fit. The high accuracy of TIN, Natural Neighbor, and Kriging can be attributed to their ability to effectively capture local variations in terrain. TIN's performance is likely due to its use of triangles to model the surface, which adapts well to varying terrain features. The moderate accuracy of ANUDEM and IDW might be due to their reliance on specific assumptions about the spatial distribution of data, which may not always hold. Spline's poor performance could be because it tends to oversmooth the data, leading to less accurate representations of abrupt terrain changes.

The accuracy of interpolation techniques also depend on the distribution and density of used data points and terrain type. The spline may be most accurate for uniformly varying terrain. One limitation of this study is the geographic scope, which was restricted to a specific region. The accuracy assessment was based on a limited dataset, which may not capture all possible terrain variations.

6. CONCLUSION AND RECOMMENDATION

In conclusion, this project evaluated the accuracy of various interpolation techniques for Digital Elevation Model (DEM) generation by using key metrics such as MAE, RMSE, and R^2. It was found that TIN, Natural Neighbor, and Kriging are the most effective methods due to their high accuracy and excellent model fit, with TIN slightly outperforming the others. ANUDEM and IDW showed moderate accuracy, while Spline was the least effective, exhibiting the highest errors and lowest model fit. These findings highlight the importance of selecting the appropriate interpolation method to ensure accurate DEMs, which are critical for applications such as hydrological modelling, landscape analysis, and urban planning.

Future research should focus on expanding the geographic scope of the study, incorporating larger and more diverse datasets, and exploring advanced machine learning techniques to further enhance DEM interpolation accuracy. Other interpolation techniques which are not studied in this project such as Bilinear Interpolation, Bicubic Interpolation, Nearest Neighbor, Polynomial Interpolation, Radial Basis Function(RBF), Inverse Distance Squared(ID^2), Co-krigging, Multivariate Adaptive Regression Splines (MARS), etc can be used to determine the most accurate interpolation technique. By continuing to refine these methods, we can improve the quality and reliability of DEMs, thereby supporting more informed decision-making in environmental and spatial planning.

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ANNEX I

Data used

FID	x	y	z	z_IDW	z_ANUDEM	z_Spline	z_Krigging	z_TIN	z_NN
0	314239.064	3059019.471	1667.946	1662.700	1661.100	1657.190	1662.470	1663.160	1663.060
1	314334.8762	3059019.281	1642.059	1642.080	1642.160	1641.960	1641.920	1642.020	1642.010
2	314319.9762	3059030.824	1644.884	1642.380	1641.530	1641.760	1642.010	1642.040	1642.130
3	314334.6777	3059057.401	1645.850	1645.040	1645.970	1646.120	1645.560	1645.660	1645.550
4	314363.8397	3059061.447	1641.851	1642.540	1641.540	1640.950	1642.070	1641.610	1641.980
5	314331.124	3059005.191	1640.082	1641.950	1641.980	1642.020	1641.840	1641.620	1641.750
6	314351.4949	3059036.945	1639.835	1642.130	1641.980	1641.970	1641.950	1641.960	1642.030
7	314257.1786	3059051.679	1668.233	1662.180	1661.590	1664.960	1662.170	1661.590	1661.980
8	314268.6509	3059021.018	1658.140	1662.400	1660.490	1664.060	1662.640	1660.220	1659.220
9	314254.2674	3059005.25	1666.284	1665.690	1662.920	1667.610	1665.770	1663.430	1663.110
10	314242.0201	3059007.732	1672.585	1666.610	1668.310	1671.620	1667.490	1667.780	1667.600
11	314242.7578	3059034.781	1666.354	1663.170	1664.450	1670.520	1663.600	1663.220	1662.730
12	314235.2364	3059029.408	1656.107	1659.510	1656.780	1653.340	1657.510	1657.420	1657.510
13	314252.7283	3059032.958	1658.365	1662.640	1663.810	1663.290	1662.750	1662.530	1663.350
14	314265.6277	3059028.997	1660.139	1660.530	1660.030	1658.370	1659.660	1660.320	1660.310
15	314224.711	3059022.11	1658.957	1659.300	1659.580	1659.680	1659.010	1659.450	1659.230
16	314260.1033	3059118.952	1674.344	1673.650	1675.040	1675.690	1674.360	1675.030	1674.160
17	314266.505	3059111.676	1671.135	1670.130	1671.290	1671.800	1670.900	1670.930	1670.880
18	314250.533	3059090.244	1669.219	1671.200	1667.510	1669.960	1668.660	1668.340	1668.750
19	314249.098	3059139.376	1672.326	1673.190	1671.520	1670.580	1671.600	1671.640	1672.000
20	314234.2011	3059187.709	1673.652	1674.210	1674.030	1674.140	1674.080	1673.930	1674.100
21	314239.0831	3059196.757	1671.431	1671.890	1671.750	1671.570	1671.590	1671.490	1671.590
22	314257.5901	3059177.316	1666.519	1666.420	1666.540	1666.480	1666.630	1666.640	1666.580
23	314259.9754	3059203.533	1661.917	1662.780	1662.040	1662.860	1662.250	1662.110	1662.370
24	314396.0367	3059209.077	1638.509	1637.790	1638.160	1638.520	1638.540	1638.660	1638.750
25	314405.6747	3059195.918	1641.022	1639.540	1640.600	1641.230	1640.310	1640.180	1640.310
26	314354.4004	3059195.306	1644.578	1645.840	1644.780	1644.800	1644.930	1644.730	1644.920
27	314354.7409	3059187.827	1644.972	1645.610	1645.730	1645.190	1645.730	1645.980	1645.710
28	314366.3284	3059194.7	1643.117	1644.090	1641.480	1643.570	1642.230	1642.350	1642.470
29	314327.4858	3059204.67	1648.210	1647.250	1648.590	1649.560	1648.370	1648.930	1648.520
30	314270.6268	3059207.553	1658.034	1659.050	1657.160	1655.670	1658.050	1658.260	1658.300

FID	x	y	z	z_IDW	z_ANUDEM	z_Spline	z_Krigging	z_TIN	z_NN
30	314270.6268	3059207.553	1658.034	1659.050	1657.160	1655.670	1658.050	1658.260	1658.300
31	314396.1258	3059164.358	1643.156	1643.250	1643.470	1643.370	1643.370	1643.270	1643.300
32	314385.3696	3059158.488	1643.363	1643.280	1643.600	1643.700	1643.590	1643.740	1643.630
33	314399.5136	3059157.47	1642.108	1642.490	1642.080	1642.060	1642.390	1642.050	1642.310
34	314384.5806	3059134.074	1642.960	1643.010	1642.940	1643.230	1642.890	1642.950	1642.920
35	314385.0712	3059112.33	1642.655	1642.630	1642.810	1643.090	1642.620	1642.710	1642.700
36	314343.0372	3059140.031	1649.049	1648.960	1648.950	1648.450	1648.860	1648.830	1648.790
37	314336.3511	3059130.763	1650.431	1650.730	1650.660	1650.510	1650.460	1650.530	1650.450
38	314359.2617	3059105.544	1645.786	1645.840	1645.720	1645.790	1645.790	1645.720	1645.790
39	314340.0472	3059095.794	1646.444	1648.070	1647.310	1647.530	1647.620	1647.600	1647.770
40	314365.5601	3059142.557	1644.896	1644.880	1644.880	1644.890	1644.890	1644.900	1644.900
41	314352.7109	3059150.577	1645.603	1646.460	1646.060	1646.690	1646.030	1646.070	1646.090
42	314366.1461	3059160.955	1644.250	1644.690	1644.270	1641.200	1644.220	1644.340	1644.340
43	314341.4295	3059170.95	1648.592	1648.420	1648.600	1647.730	1648.630	1648.510	1648.640
44	314336.5706	3059190.529	1653.464	1652.120	1653.530	1653.340	1653.190	1652.840	1652.880
45	314308.9692	3059176.363	1655.719	1656.090	1655.610	1655.780	1655.690	1655.340	1655.550
46	314331.1805	3059165.007	1649.631	1649.260	1649.900	1650.260	1650.220	1650.020	1650.160
47	314329.9177	3059143.964	1651.610	1650.930	1651.110	1650.850	1651.260	1651.260	1651.340
48	314313.3662	3059145.943	1654.604	1654.730	1654.910	1654.910	1654.910	1654.930	1654.880
49	314298.4436	3059097.284	1655.701	1655.210	1655.040	1654.680	1655.410	1655.390	1655.540
50	314285.706	3059109.477	1662.020	1662.370	1661.640	1661.720	1661.490	1661.650	1661.610
51	314275.5085	3059115.484	1666.910	1665.860	1666.210	1666.250	1666.490	1666.000	1666.370
52	314261.3591	3059143.068	1668.741	1668.810	1668.000	1667.640	1669.040	1668.280	1668.680
53	314294.5179	3059129.04	1658.594	1659.700	1658.740	1658.730	1659.020	1659.180	1659.200
54	314275.1221	3059155.299	1663.121	1662.870	1663.370	1663.420	1663.170	1663.320	1663.290
55	314295.5581	3059153.501	1658.608	1658.440	1658.540	1658.400	1658.560	1658.600	1658.600
56	314298.3176	3059139.809	1657.661	1657.770	1657.490	1657.890	1658.050	1657.670	1657.990
57	314317.3304	3059129.586	1653.373	1653.030	1653.380	1653.010	1653.360	1652.940	1653.270
58	314245.4194	3059169.56	1671.039	1669.310	1671.810	1672.610	1671.810	1672.260	1672.320
59	314286.6814	3059165.662	1660.208	1660.690	1660.070	1660.910	1660.120	1660.310	1660.140
60	314263.266	3059191.359	1662.043	1662.730	1663.270	1663.790	1663.050	1663.030	1662.870

FID	x	y	z	z_IDW	z_ANUDEM	z_Spline	z_Krigging	z_TIN	z_NN
61	314310.4242	3059192.834	1656.019	1655.980	1656.010	1656.030	1655.920	1655.870	1655.850
62	314296.748	3059188.405	1656.456	1656.100	1656.270	1656.110	1656.120	1656.190	1656.010
63	314234.9921	3059058.683	1672.160	1671.030	1671.650	1672.930	1671.270	1671.970	1671.510
64	314239.693	3059084.25	1675.885	1672.210	1673.350	1672.840	1672.970	1672.950	1672.990
65	314212.6969	3059074.254	1672.868	1676.360	1674.930	1676.540	1675.490	-9999.000	-9999.000
66	314220.1816	3059089.725	1677.465	1678.230	1677.710	1677.900	1677.660	1677.630	1677.650
67	314241.1547	3059100.882	1678.704	1675.120	1676.060	1675.090	1675.330	1675.670	1675.300
68	314227.9884	3059092.702	1678.346	1678.660	1678.270	1678.570	1678.230	1678.280	1678.250
69	314228.2918	3059088.805	1679.008	1678.350	1677.600	1677.820	1677.700	1677.790	1677.750
70	314247.2563	3059126.186	1676.467	1675.020	1675.610	1675.190	1675.480	1675.500	1675.480
71	314228.603	3059124.916	1682.202	1680.200	1682.730	1678.990	1682.200	1681.930	1681.730
72	314227.3299	3059190.226	1676.735	1675.130	1675.580	1675.710	1675.740	1675.530	1675.450
73	314246.2345	3059067.024	1673.348	1671.440	1667.780	1669.550	1668.820	1668.800	1667.990
74	314253.8509	3059022.083	1663.249	1662.680	1662.980	1662.440	1662.820	1661.720	1662.600
75	314432.8809	3059190.309	1643.595	1643.390	1643.400	1643.110	1643.360	1643.450	1643.400
76	314421.8288	3059184.176	1643.534	1642.500	1643.240	1650.610	1643.310	1643.790	1643.160
77	314426.2774	3059143.88	1640.368	1640.360	1640.310	1639.920	1640.280	1640.310	1640.310
78	314204.3618	3059247.467	1679.642	1679.100	1680.100	1679.000	1679.910	1679.790	1679.790
79	314218.3213	3059253.353	1677.922	1680.490	1680.760	1680.310	1679.910	1679.920	1679.840
80	314214.635	3059242.359	1676.502	1677.240	1676.830	1676.340	1676.990	1676.870	1676.910
81	314218.5529	3059212.409	1674.761	1674.770	1674.340	1673.500	1673.880	1673.770	1673.920
82	314233.5044	3059220.699	1669.870	1669.970	1669.300	1677.630	1670.130	1670.360	1670.320
83	314296.4227	3059259.247	1670.515	1669.770	1670.900	1670.520	1670.510	1670.650	1670.490
84	314292.471	3059269.548	1674.381	1672.870	1673.490	1675.160	1674.140	1674.100	1674.020
85	314280.9288	3059257.746	1674.195	1673.330	1672.950	1673.100	1673.150	1673.060	1673.120
86	314287.2608	3059233.403	1665.506	1664.610	1664.850	1665.100	1664.960	1665.020	1664.970
87	314273.6114	3059236.748	1667.237	1667.520	1667.160	1667.070	1667.100	1667.070	1667.130
88	314258.1555	3059235.013	1667.995	1669.260	1668.260	1666.990	1668.290	1668.360	1668.300
89	314278.5988	3059217.896	1658.806	1658.750	1659.150	1659.070	1658.790	1659.090	1658.850
90	314240.6321	3059241.262	1671.950	1671.470	1671.930	1677.650	1672.190	1672.180	1672.210
FID	x	y	z	z_IDW	z_ANUDEM	z_Spline	z_Krigging	z_TIN	z_NN
91	314251.8625	3059244.577	1672.834	1671.200	1672.780	1671.630	1672.250	1672.450	1672.380
92	314322.9951	3059268.896	1665.691	1666.950	1665.950	1665.710	1665.430	1665.810	1665.600
93	314401.5779	3059227.44	1639.634	1638.720	1638.660	1638.890	1639.100	1639.220	1639.220
94	314389.0045	3059219.789	1639.902	1639.840	1639.910	1640.210	1640.240	1639.670	1640.060
95	314377.6406	3059220.474	1640.474	1641.350	1640.840	1640.720	1640.810	1641.490	1641.180
96	314397.3848	3059251.083	1643.414	1643.330	1643.080	1643.040	1643.270	1643.500	1643.500
97	314383.7845	3059255.587	1647.129	1645.270	1645.670	1646.100	1645.950	1646.530	1645.960
98	314346.8394	3059248.823	1654.086	1651.530	1653.960	1654.280	1653.840	1653.690	1653.610
99	314348.4499	3059235.293	1646.944	1646.600	1647.110	1646.500	1646.870	1647.450	1646.980
100	314336.9559	3059242.023	1651.599	1649.950	1651.890	1651.170	1651.890	1651.100	1651.720
101	314306.1009	3059231.048	1656.656	1658.000	1657.350	1657.930	1657.340	1657.300	1657.390
102	314366.9346	3059228.661	1639.488	1642.550	1641.970	1642.050	1642.190	1642.170	1642.230
103	314342.5028	3059211.796	1642.209	1644.130	1642.490	1643.150	1643.130	1642.820	1643.240
104	314316.3353	3059211.686	1645.713	1648.280	1647.280	1646.340	1647.480	1647.960	1648.130
105	314326.9528	3059230.829	1646.945	1648.640	1647.310	1646.830	1648.140	1648.010	1648.260
106	314407.0371	3059284.746	1639.938	1639.800	1640.490	1640.980	1640.510	1640.520	1640.500
107	314419.3574	3059212.817	1636.836	1638.470	1638.180	1638.800	1638.240	1638.470	1638.470
108	314438.1386	3059224.193	1640.396	1640.180	1640.700	1640.090	1640.950	-9999.000	-9999.000
109	314428.7822	3059227.492	1639.508	1639.960	1639.240	1640.220	1639.890	1639.780	1639.800
110	314428.0659	3059261.923	1641.276	1640.010	1634.780	1630.130	1638.060	-9999.000	-9999.000
111	314409.2191	3059237.314	1643.278	1643.340	1643.430	1643.310	1643.350	1643.400	1643.320

ANNEX II

Logical Framework

Objective	Sub-Objectives	Activities	Who	How	Expected Outcome	Possible Impact
Accuracy assessment and comparison of dem interpolation techniques.	To analyze spatial patterns in DEM accuracy across the study area to understand the suitability of each technique for different terrain types.	Conduct a literature review on DEM interpolation techniques.	Sonik Neupane	Group Research	• Improved understanding of the accuracy and reliability of DEM interpolation techniques. • Guidance for GIS practitioners and researchers on selecting suitable interpolation methods for specific applications. • Contribution to the advancement of knowledge in spatial analysis and terrain modelling within the GIS domain.	• Enhanced accuracy and reliability of terrain representation in GIS applications. • Optimization of decision-making processes reliant on accurate elevation data. • Facilitation of more informed land use planning, environmental management, and infrastructure development initiatives
		Select and acquire DEM datasets representing diverse terrain types	Aarya Pant	Secondary DEM dataset		
	Compare the accuracy of DEMs generated using statistical metrics such as RMSE and MAE.	Preprocess DEM data to address outliers, voids, and artefacts.	Lochan Pant	GIS Software		
		Implement selected interpolation techniques using GIS software.	Rajan Pandit			
	Evaluate the performance of different interpolation techniques in generating DEMs.	Calculate spatial accuracy metrics (eg RMSE, MAE) for each interpolated DEM.	Sonik Neupane	Manually		
		Conduct statistical analysis to compare techniques	Sudhan Oli			
	Provide recommendations for selecting the most suitable interpolation technique based on the study's findings.	Interpret accuracy assessment results and identify strengths and weaknesses of each interpolation method.	Lochan Pant	Research and validation		