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Determining the Optimal Sample Density of Measurements for Mapping Stream Geomorphology Using Land Surveying

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Determining the optimal sample density of measurements for mapping stream geomorphology using land surveying

by

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ABSTRACT

Digital elevation models (DEMs) are commonly used to illustrate and model topographic information related to river or stream channels. DEMs are frequently generated using interpolation to approximate elevation values in between points that are directly surveyed. Data collection using surveying is time-consuming; therefore, minimizing the number of surveyed locations while accurately capturing the topographic features is important. Survey data of geomorphological features and five cross sections were collected along a 100m length of the Arikaree River, a short grass prairie stream in eastern Colorado. Inverse distance weighted (IDW) and kriging interpolations were performed with 100 iterations of a random selection of 50, 60, 70, 80, and 90 percent of the points. The cross-section measurements were excluded both as a whole and for selected stream morphology features. For each sample density, the root mean square error (RMSE) of the five cross sections was found by comparing the measured elevation values to the interpolated values. The RMSE values were compared with the cross section of origin and the sample density as predictor variables. Sample density did not have a statistically significant effect on accuracy. The effect of interpolation on sample density varied between cross sections. There was a statistically significant difference in accuracy when the sample density of different morphology types was reduced while the rest of the data was not. Future surveys should focus on topography, the quality of sampling, and should reduce the amount of area where no points are being collected.

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1. Introduction

Actions of humankind are significantly impacting watersheds and river channels all over the world through climate change, land use, and direct channel alterations. Digital Elevation Models (DEMs) are used to examine such changes and model ecological processes requiring geomorphic information. DEMs are useful for modeling geomorphic changes to river channels because they provide high-resolution topographic data that can be used to predict response to environmental impacts. For example, DEMs have been used to investigate channel sediment regime changes following land conversion (Jones et al. 2014), geomorphologic impacts to a stream as a result of habitat restoration (Geerling et al. 2008), and consequences of channel engineering on salmon habitat (Brown and Pasternack 2008). Studies that do not involve DEM creation as a primary methods component often use existing DEMs to visualize data. Most publically available DEMs are created by government organizations, such as the United States Geological Survey, and these may not provide adequate resolution for many applications (Holmes et al. 2000).

Despite the ubiquity of DEMs in scientific research, information pertaining to the relationship between DEM accuracy and sample density is often sparse and contradictory. Intuition suggests that high sample densities produce accurate interpolations because there are more directly measured points in the same area of interest, but this is not necessarily true. While many efforts have found that sample density did positively affect the accuracy of an interpolation (Aguilar et al. 2005), others concluded that the effect of sample density on the accuracy of the data depended on the interpolation method used. The most common types of interpolation used in the creation of elevation maps are inverse distance weighted (IDW) and kriging (Bourennane et al. 2000, Erdogan 2009). A literature review by Li and Heap (2014) found that changing the sample density had no impact on the accuracy of interpolation in 32 of 80 cases. Raber et al. (2007) found that more sampling sometimes increased error.

One potential explanation for such discrepancies is that a change in density is more likely to influence accuracy if the original density is relatively low (Chaplot et al. 2006). Accuracy may vary more between different interpolations when the original density is low, which may explain why some have demonstrated different results for different interpolations while others did not (Li and Heap 2014). Another explanation is that the effect of sample density on DEM accuracy may be confounded by other variables such as the effect of the size of the study area or the quality of the sample (Li and Heap 2011).

The main objective of the current study was to investigate the effect of interpolation method and sample density on accuracy in DEM models intended to serve as geomorphic depictions of river channels. Knowing whether sample density influences accuracy is important because research organizations would like to minimize the amount of time required to perform a geomorphology survey without reducing accuracy. Knowing whether interpolation influences accuracy is important because this will determine when to use different methods of interpolation. Knowing whether the reduction of sample density at different morphologies influences accuracy is important because people surveying stream reaches will then know which morphological features need a larger sample density.

2. Methods

a. Study location and preparation

Field sampling was performed in the NEON Arikaree River aquatic site which is located in Eastern Colorado. The dominant riparian vegetation cover at this site is prairie shortgrass and plains cottonwood, and the terrain is relatively flat. The approximate width of Arikaree River is 10m. Seven benchmarks were deployed to georeference data along a 1km reach using a total station. Each benchmark was on the opposite side of the stream from the previous benchmark and established using a metal marker. Latitude, longitude, and height above ellipsoid were recorded for the benchmarks using a Trimble GEO XH 6000 GPS receiver and post-processed using a base station off of the CORS network.

b. Mapping Procedures

Topographic detail was recorded using a total station and prism pole. A CST/Berger 302R total station was used to record points. To determine the extent that would be measured from each benchmark, halfway points between each benchmark on both sides of the bank were found using the GPS and they were marked with pin flags. The initial backsight was set at magnetic north and at the farthest visible distance from the total station. For subsequent benchmarks, backsights were set as the closest upstream benchmark to the location of the total station. The foresight was the closest downstream benchmark. Due to time constraints, points were only recorded at the first two benchmarks at Arikaree. .

Surveyed morphological stream features that were measured included a lower bankfull edge, an upper bankfull edge, the toe slope and the thalweg following Keim et al. (1999) (Figure 1).

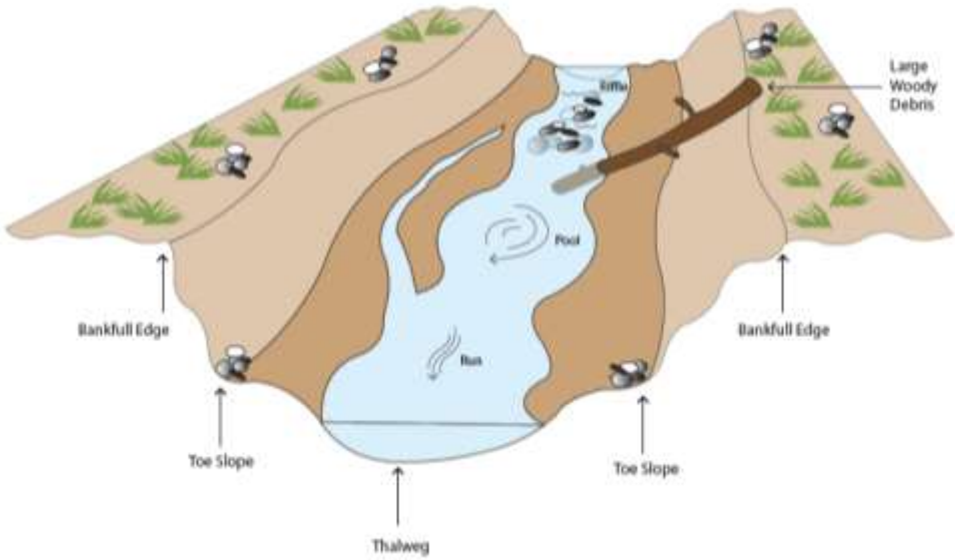

Figure 1: The locations of the bankfull edge, toe slope, and thalweg on an idealized stream. Also depicts different stream environments and large woody debris (LWD). Figure by Jenna Stewart (NEON).

Points were directly measured along longitudinal transects every 1m where there were major directional changes and every 5m otherwise. In addition, other prominent in-stream features, such as large woody debris and snags, and features that may affect the elevation, such as point bars and islands, were also directly measured. The floodplain was the section of the stream from the bankfull edge to about 20m perpendicular to the stream away from it.

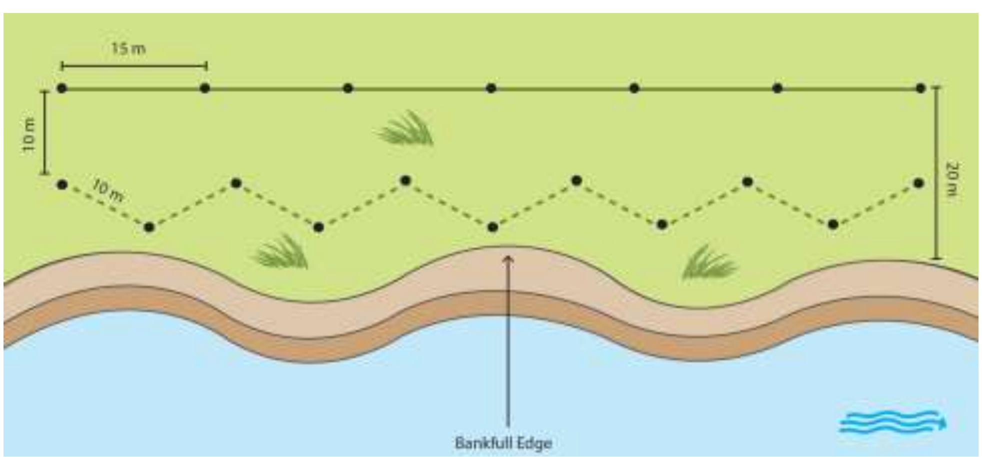

Figure 2: Floodplain point collection procedures employed. Figure by Jenna Stewart (NEON).

Additional points were also made in a zig-zag pattern along the floodplain approximately every 10 m in order to have a better estimate of the floodplain elevation and every 15m in a straight line about 10m away from the edge of the floodplain to estimate the elevation data for the edge of the map (Figure 2). At each point, the horizontal angle relative to the backsight, zenith angle, slope distance, and elevation relative to the total station were recorded.

Five cross sections within the surveyed reach were also measured to provide a means of assessing the accuracy of the interpolations. Each cross section was surveyed in a straight line perpendicular the stream thalweg. Eighteen to thirty-five points were collected in each cross section, including points at all prominent morphological features of the stream.

c. Map Creation

For each benchmark, the grid azimuth from the backsight was calculated using the following formula:

$$Grid\ Azimuth = tan^{-1}\left(\frac{Easting_{BS} - Easting_{FS}}{Northing_{BS} - Northing_{FS}}\right)$$

Equation 1

Locations of points were then found using this grid azimuth and the slope distance to the total station.

d. Interpolation

Both IDW and kriging interpolations were performed first using 100 randomly selected simulations with 50, 60, 70, 80, and 90 percent of the data (excluding the cross sections), then 100 simulations were only the thalweg data was reduced by 50-90 percent, then 100 simulations were only the toe slope and bankfull edge data were reduced by 50-90 percent. These different reductions were done to determine whether collecting fewer points in different areas had more of an effect on interpolation accuracy than in other areas.

. Inverse distance weighted (IDW) interpolation estimates the elevation of an unknown location using the following formula:

$$Z = \frac{\sum_{i=1}^{n} \frac{1}{(Di)^q} Z_i}{\sum_{i=1}^{n} \frac{1}{(Di)^q}}$$

Equation 2

where Z is the interpolated value for a point, Z_i is the i^{th} measured value, D_i is the distance between the interpolated point and the i^{th} sampled values, and q is a constant applied to determine the significance of each known value that is used for the calculation based on their distances (Sun et al. 2009). For the IDW interpolation, the number of points used for each calculation was 12, $q = 2$, and the search radius was variable. This interpolation was used because it is the default IDW interpolation for ArcMap.

For the kriging interpolation, the ordinary method was used with a spherical semivariogram and a variable search radius. These parameters were also used because they are the default parameters for ArcMap. Kriging interpolation estimates the elevation of an unknown location by weighing the measurements of the residuals of each known location. Weights are developed such that:

$$Z(x_0)^* = \sum_{i=1}^{n} \lambda_i Z(x_i)$$

Equation 3

$$\sum_{i=1}^{n} \lambda_i = 1$$

Equation 4

where $Z^*(x_0)$ is the estimated value at x_0, $Z(x_i)$ is the measured value at x_i; λ_i is the weight assigned for the residual of $Z(x_i)$, and their summation is 1 (Sun et al 2009).

Weights are then chosen to produce unbiased estimates where the variance of the estimated elevations is minimized:

$$\hat{\sigma}^2{}_{Z(x_0)} = \sum_{i=1}^{n} \lambda_i \gamma(Z(x_i), Z(x_0))$$

Equation 5

where $\gamma(Z(x_i),Z(x_0))$ is a spherical variogram between the measured and estimated elevation (Sun et al 2009).

To determine what group of percentages was the most accurate, the root mean squared error (RMSE) for each cross-section was calculated using the following equation:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Z(x_i) - Z(x_0)^*)^2}$$

Equation 6

(Sun et al. 2009).

The relationship between sample density and accuracy was assessed in a two-way ANOVA model. Independent variables that were used for the ANOVA included the cross section where the points were measured and the sample density. The relationship between what morphology was reduced and accuracy was also assessed using a two-way-ANOVA model. The independent variable assessed was morphology and each cross section was assessed individually. The relationship between interpolation method and accuracy was assessed using a paired t-test with each morphology reduction assessed individually. The relationship between what morphology was reduced and the relationship between what interpolation method was used were analyzed with RMSE values derived from a sample density of 50 percent.

All mapping operations were performed in Esri ArcMap (Esri 2013, Version 10.2). Monte Carlo simulations were conducted using Python (Python 2010, Python Version 2.7, Python Software Foundation) and statistical analyses using R (R 2014, Version 3.1.1, R Foundation for Statistical Computing).

3. Results

a. Overview

The cross-sections collected were labeled from west to east with numbers 1-5 (Figure 3).

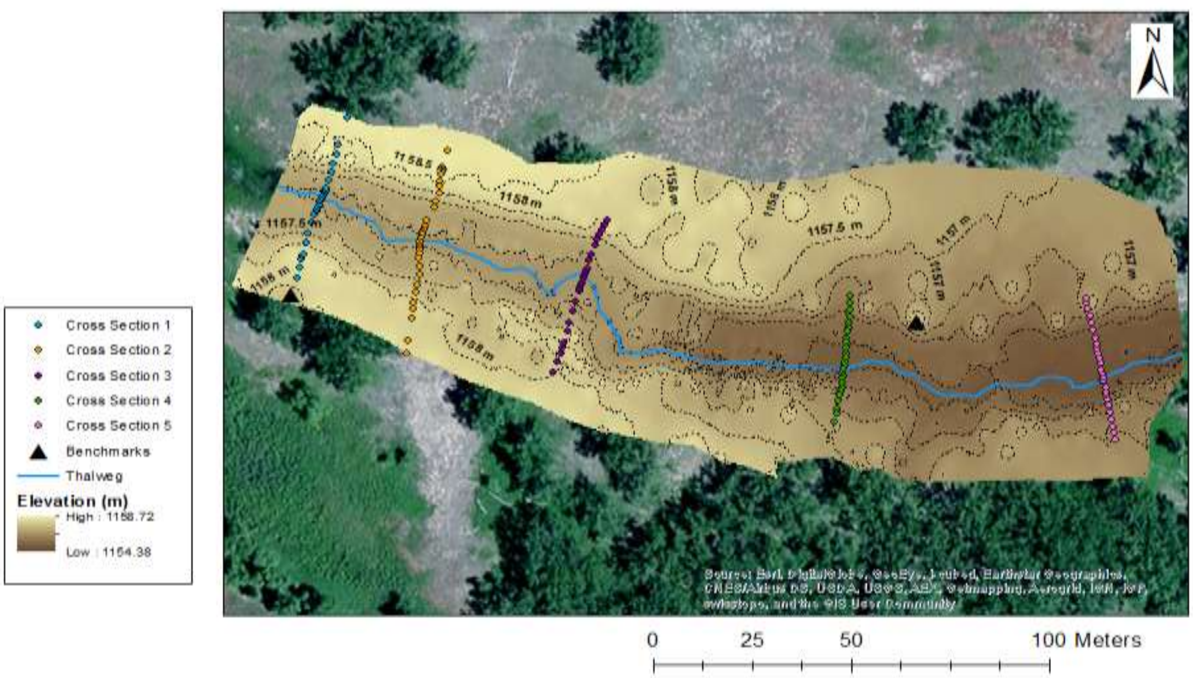

Figure 3: Map of the thalweg, cross sections, and elevation of the Arikaree site, CO. Elevation gradient and contours created using an inverse distance weighted (IDW) interpolation.

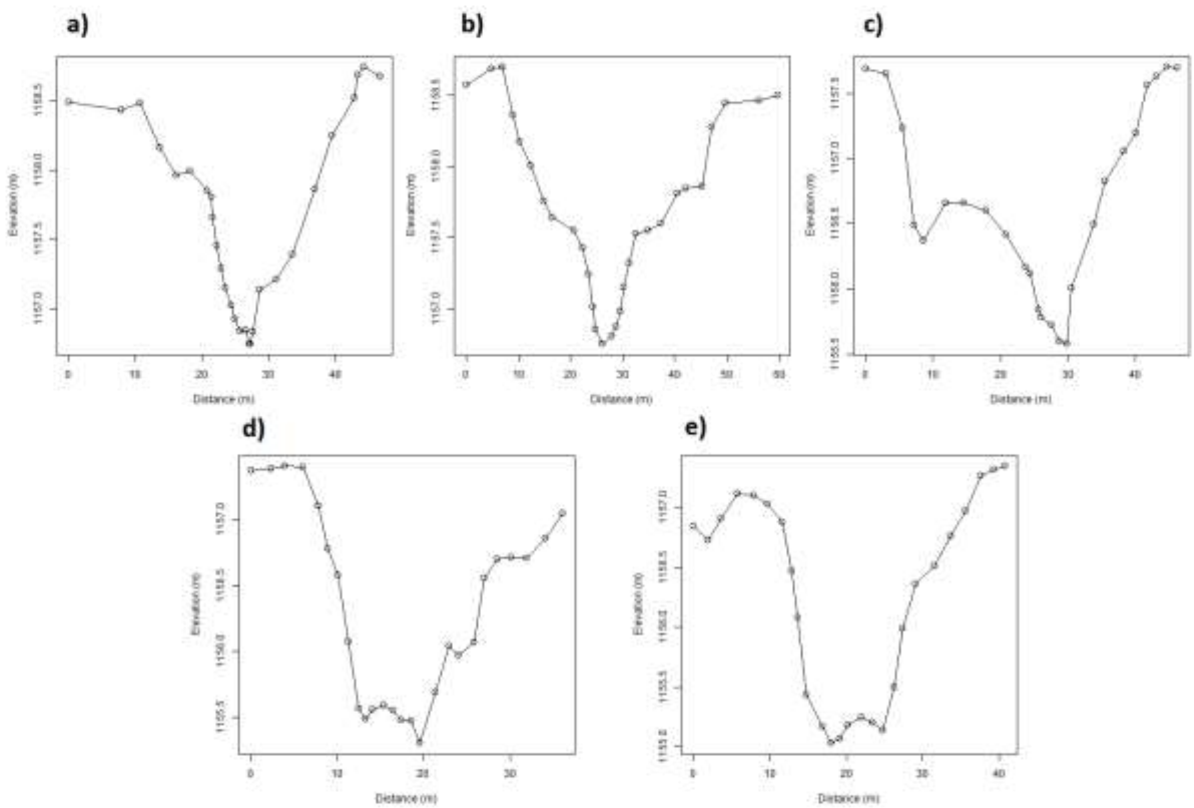

Figure 4: Cross Sections used in the analysis. a) Cross Section 1 b) Cross Section 2 c) Cross Section 3 d) Cross Section 4 e) Cross Section 5. "Distance" is the horizontal distance and "Elevation" is the height above mean sea level (MSL) using NAD1983.

b. Inverse Distance Weighted Interpolations

When all morphological features were reduced, RMSE values ranged from a maximum of 0.99 to a minimum of 0.21 with Cross Section 2 having the lowest RMSE value and Cross Section 3 having the highest (Figure 5). When only the thalweg was reduced, RMSE values ranged from a maximum of 0.92 to a minimum of 0.22 with Cross Section 2 having the lowest RMSE value and Cross Section 5 having the highest (Figure 5). When only the bankfull edge and toe slope values were reduced, RMSE values ranged from a maximum of 0.92 to a minimum of 0.21 with Cross Section 2 having the lowest RMSE value and Cross Section 5 having the highest (Figure 5). Precision increased as the sample density increased, which can be shown in how the error bars decreased (Figure 6). For all reductions in morphology, the interpolated model produced a better fit in the thalweg for the interpolated cross sections than the slopes, where elevations were underestimated for all cross sections except for Cross Section 3 (Figure 7).

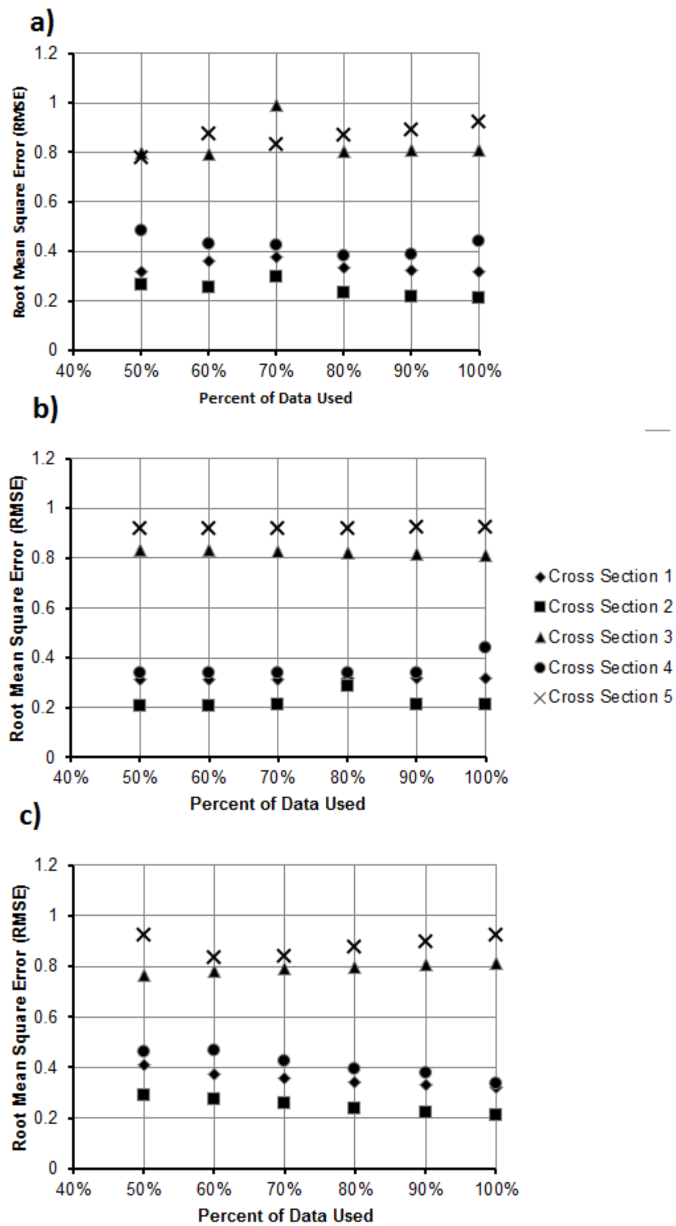

Figure 5: Comparison of Root Mean Square Error (RMSE) values between inverse distance weighted (IDW) interpolations where a) All morphological features are reduced , b) Only the thalweg was reduced and c) Only the toe slope and bankfull edge were reduced

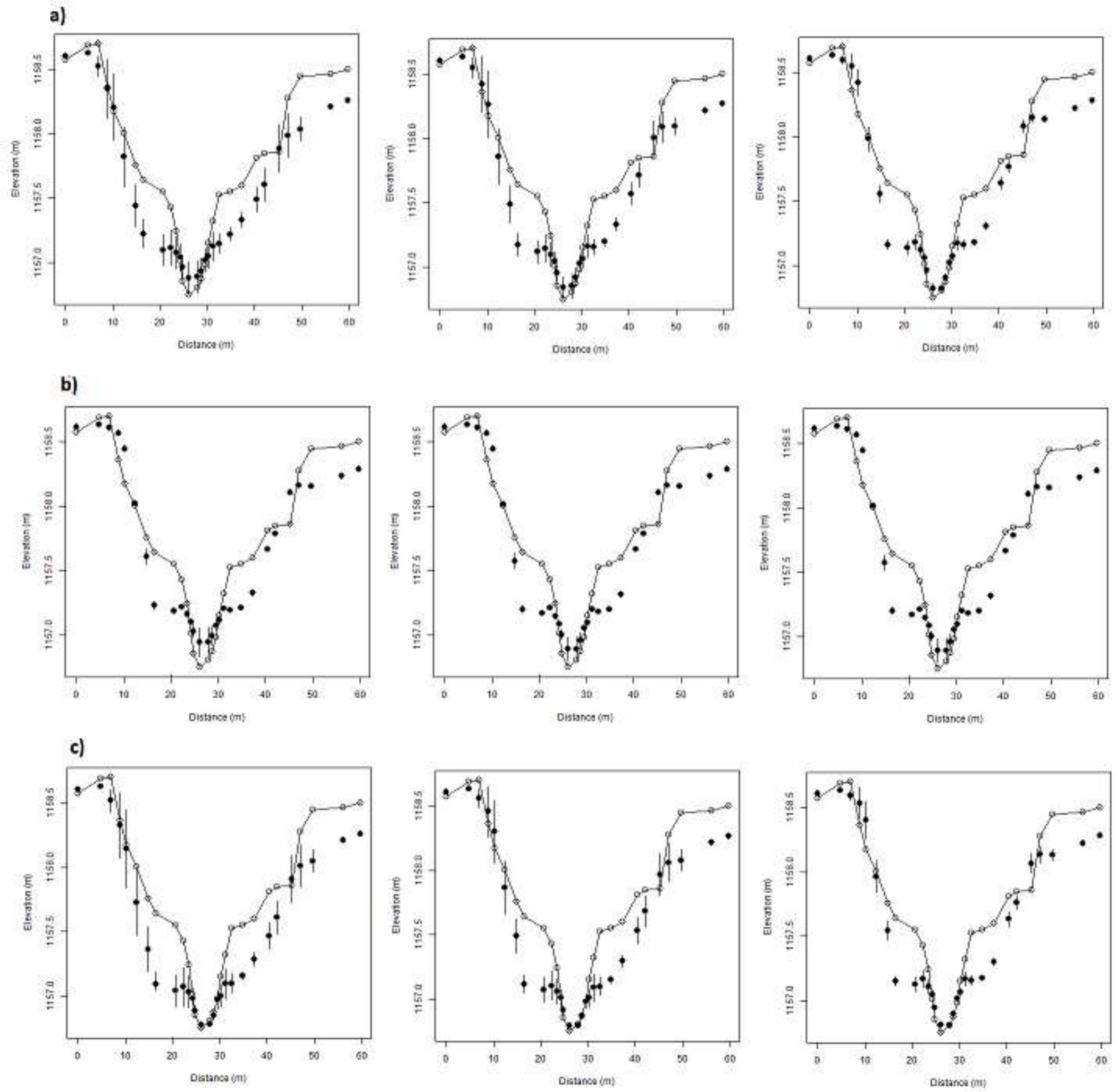

Figure 6: Measured (white dots) and interpolated (black dots) values with an inverse distance weighted (IDW) interpolation for Cross Section 2 using 50 percent (left), 70 percent (center) and 90 percent (right) of the data where a) All geomorphology was reduced b) thalweg was reduced, and c) Only the toe slope and bankfull edges were reduced. "Distance" is the horizontal distance and "Elevation" is the height above mean sea level (MSL) using NAD1983.

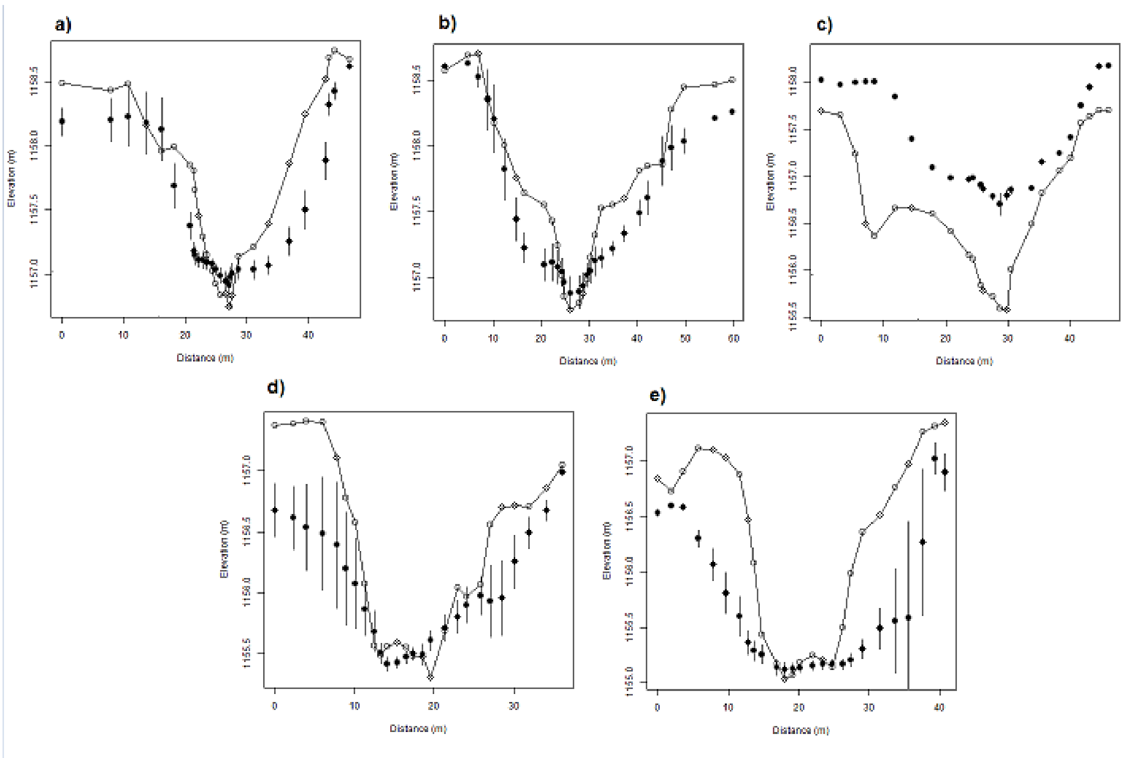

Figure 7:Measured (white dots) and interpolated (black dots) values with an inverse distance weighted (IDW) interpolation for a) Cross Section 1, b) Cross Section 2, c) Cross Section 3, d) Cross Section 4, and e) Cross Section 5 for a sample reduction of 50 percent applied to all morphological features. "Distance" is the horizontal distance and "Elevation" is the height above mean sea level (MSL) using NAD1983.

c. Kriging Interpolations

When all morphological features were reduced, RMSE values ranged from a maximum of 1.02 to a minimum of 0.24 with Cross Section 2 having the lowest RMSE value and Cross Section 5 having the highest (Figure 8). When only the thalweg was reduced, RMSE values ranged from a maximum of 0.81 to a minimum of 0.21 with Cross Section 2 having the lowest RMSE value and Cross Section 3 having the highest (Figure 8). When only the bankfull edge and toe slope values were reduced, RMSE values ranged from a maximum of 0.81 to a minimum of 0.22 with Cross Section 2 having the lowest RMSE value and Cross Section 3 having the highest (Figure 8). Like the with the IDW interpolating method, precision increased as the sample density increased (Figure 9). For all cross sections but Cross Section 3, this interpolation underestimated elevation in the slopes (Figure 10) and for all cross sections it overestimated elevation in the thalweg (Figure 10).

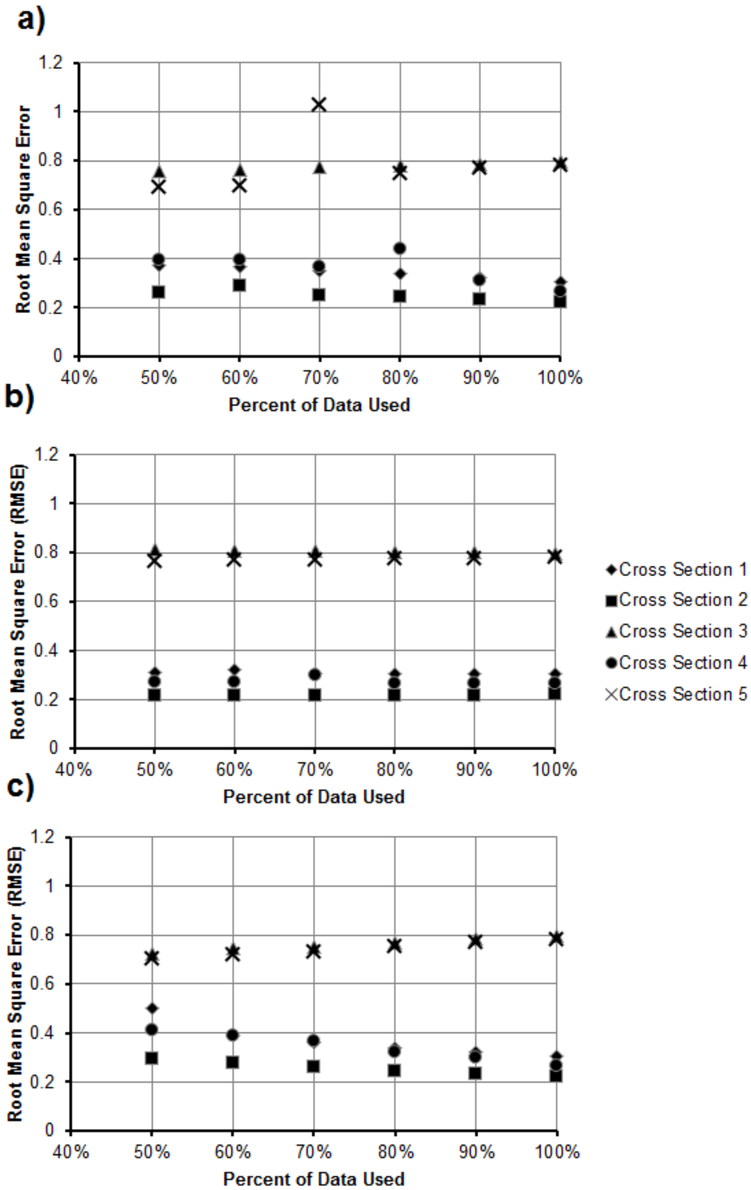

Figure 8: Comparison of Root Mean Square Error (RMSE) values between kriging interpolations where a) All morphological features are reduced , b) Only the thalweg was reduced and c) Only the toe slope and bankfull edge were reduced.

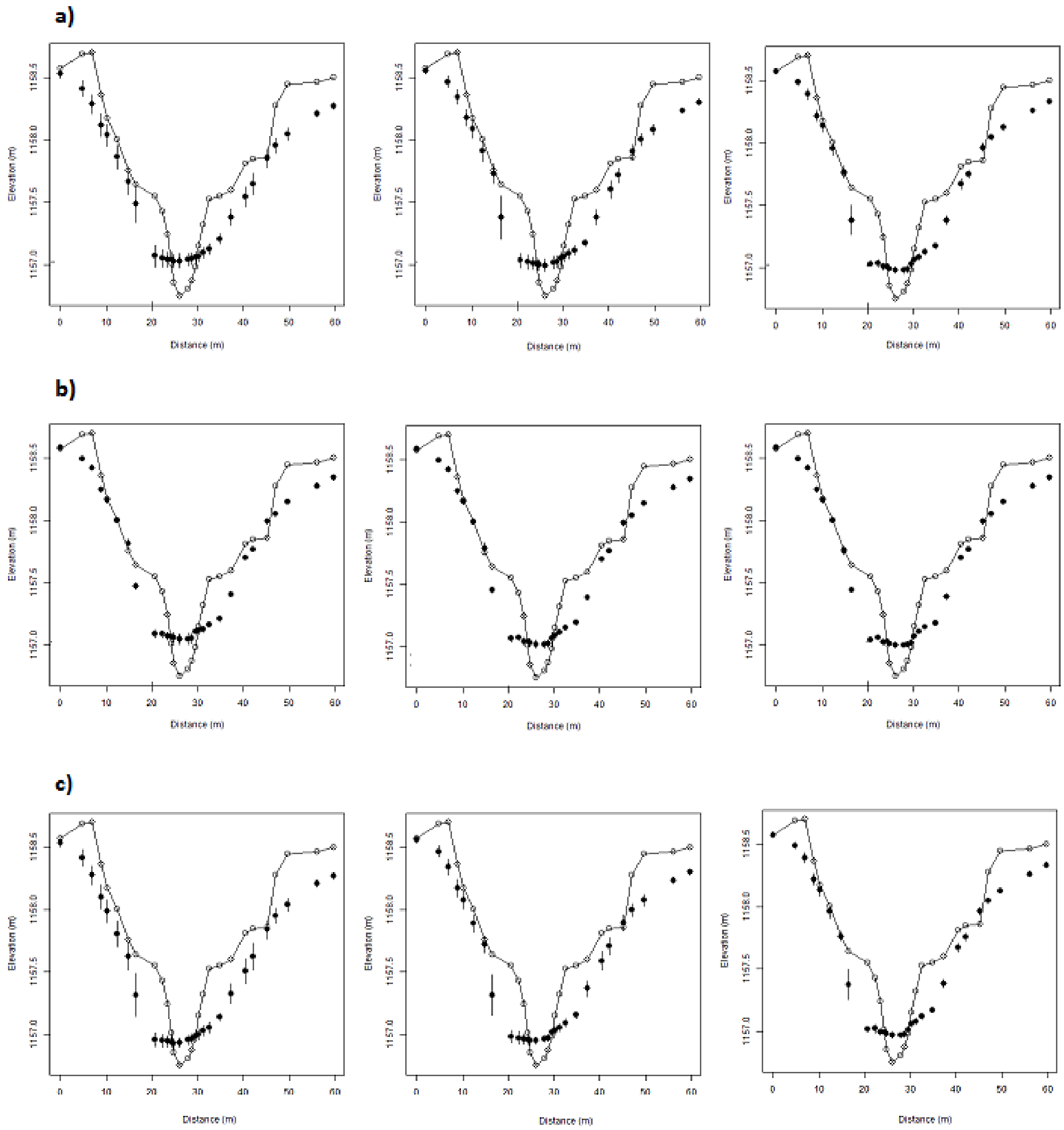

Figure 9: Measured (white dots) and interpolated (black dots) values for Cross Section 2 using 50 percent (left), 70 percent (center) and 90 percent (right) of the data where a) All geomorphology was reduced b) Only the thalweg was reduced, and c) Only the toe slope and bankfull edges were reduced. "Distance" is the horizontal distance and "Elevation" is the height above mean sea level (MSL) using NAD1983.

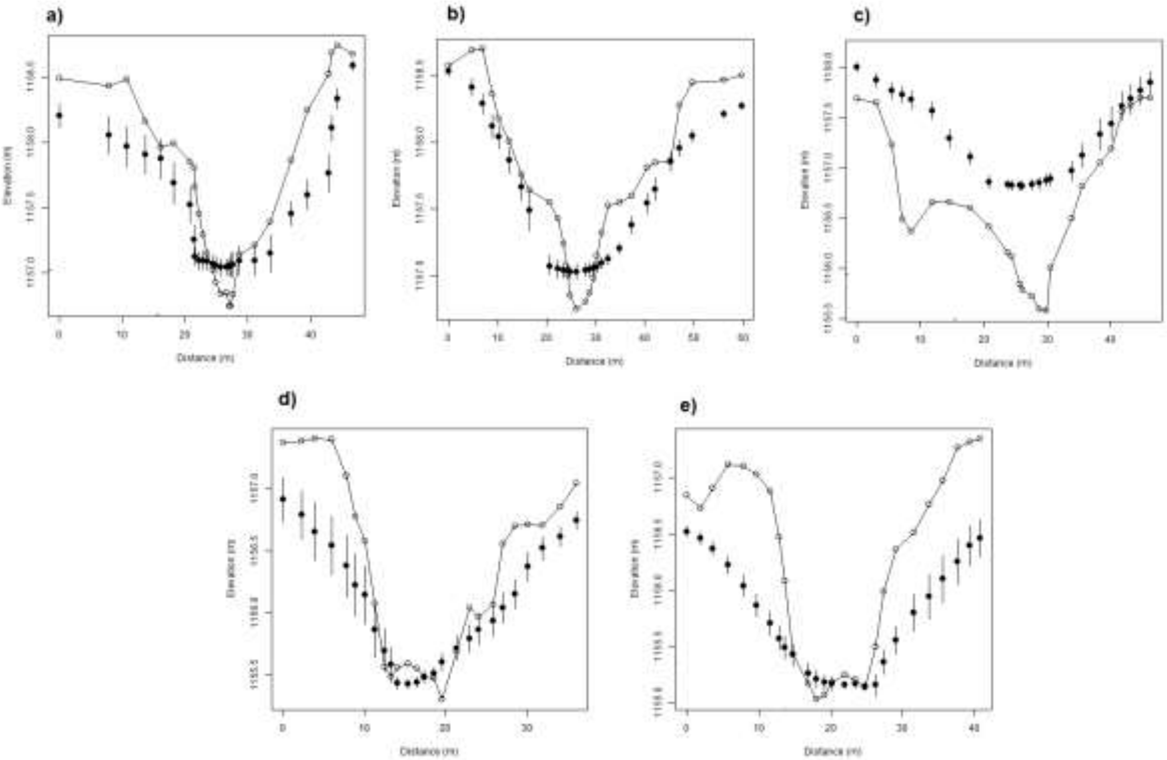

Figure 10:Measured (white dots) and interpolated (black dots) values with a kriging interpolation for a) Cross Section 1, b) Cross Section 2, c) Cross Section 3, d) Cross Section 4, and e) Cross Section 5 for a sample reduction of 50 percent applied to all morphological features. "Distance" is the horizontal distance and "Elevation" is the height above mean sea level (MSL) using NAD1983.

d. Statistical Analysis

The sample density did not affect the accuracy of the inverse distance weighted interpolations when it was reduced for all morphological features (Two-way ANOVA, F = 1.3532, $p = 0.2833$), when only the thalweg was reduced (Two-way ANOVA, F = 0.789, $p = 0.5699$), or when only the toe slopes and bankfull edges were reduced (Two-way ANOVA, F = 0.3098, $p = 0.9012$). There was a statistically significant difference in accuracy between cross sections for reduction of all morphological features (Two-way ANOVA, F = 23.5307, $p < 0.001$), when only the thalweg was reduced, (Two-way ANOVA, F = 2307.121, $p < 0.001$), and when only the toe slope and bankfull edges were reduced (Two-way ANOVA, F = 282.7043, p < 0.001).

The sample density did not affect the accuracy of the kriging interpolations when it was reduced for all morphological features (Two-way ANOVA, F = 1.1574, p = 0.364), when the thalweg was reduced (Two-way ANOVA, F = 0.685, p = 0.6402), or when the toe slopes and bankfull edges were reduced (Two-way ANOVA, F = 0.3646, p = 0.8667). There was a statistically significant difference in accuracy between cross sections for reduction of all morphological features (Two-way ANOVA, F = 124.4067, p < 0.001), when only the thalweg was reduced, (Two-way ANOVA, F = 13219.963, p < 0.001), and when only the toe slope and bankfull edges were reduced (Two-way ANOVA, F = 260.7232, p < 0.001).

Whether there was a statistically significant difference in accuracy for different interpolations depended on the cross section and geomorphology reduced. When the sample density of all morphological features was reduced, there was no significant difference between accuracy for IDW and kriging for Cross Section 2 (Paired t test, t = 0.9645, p = 0.3372) and Cross Section 4 (Paired t test, t = 0.8609, p = 0.3914). There was a significant difference for Cross Section 1 (Paired t test, t = -4.7129, p < 0.001), Cross Section 3 (Paired t test, t = 9.9702, p < 0.001) and Cross Section 5 (Paired t test, t = 2.4439, p = 0.0163). When only the thalweg was reduced, there was no significant difference in accuracy between IDW and kriging for Cross Section 1 (Paired t test, t = 1.6568, p = 0.1007) only. For Cross Section 2 (Paired t test, t = -8.5462, p < 0.001), Cross Section 3 (t = -8.5462, p < 0.001), Cross Section 4 (Paired t test, t = 96.7327, p < 0.001), and Cross Section 5 (Paired t test, t = 173.2703, p < 0.001). When the sample density of the toe slopes and bankfull edges were reduced, there was no significant difference in accuracy for IDW and kriging for Cross Section 1 (Paired t test, t = -1.4811, df =

94, $p = 0.1419$) and Cross Section 2 (Paired t test, t = -0.9208, $p = 0.3594$). There was a significant difference in accuracy for IDW and kriging for Cross Section 3 (Paired t test, t = 10.0889, p < 0.001), Cross Section 4 (Paired t-test, t = 2.975, $p = 0.003682$), and Cross Section 5 (Paired t-test, t = 6.1607, $p <0.001$).

There was a significant difference in accuracy when the sample density of different morphologies was reduced. This was true for both IDW (Two Way ANOVA, $p > 0.001$) and kriging interpolations (Two Way ANOVA, $p > 0.001$).

4. Discussion

Sample density did not have a significant effect on the accuracy of the interpolation as assessed by total RMSE. Thus, up to half the data that was collected for an Arikaree River reach digital elevation model (DEM) can potentially generate an inverse distance weighted (IDW) or a kriging interpolation with an accuracy that has not been significantly reduced. However, there was a significant difference in accuracy when the sample density of only one morphological feature was reduced at a time. It's very important to logically select sample density based on topographic features.

Although a significant relationship between sample density and accuracy was not found using these particular interpolations and sampling schemes, different parameters may yield a different result. More research is needed as to whether the accuracy of the interpolation varies based on different IDW and kriging parameters. For IDW this means starting with a different number of points or a *q* value. For kriging, this means another semivariogram model besides spherical. It’s also possible that different parameters could change whether interpolation method affected accuracy as well.

This study did find that the topography of the original cross section affected the accuracy of the interpolation, as there were differences between the accuracy of cross sections even at the same sample density. Additionally, whether there was a significant relationship between accuracy and interpolation method varied by cross section.

The two dimensional and perpendicular nature of cross sections contrasts with the three-dimensional nature of a stream survey, and this has led to criticism of cross sections as a tool of measuring the accuracy of interpolation (Geach et al. 2014). Nevertheless, producing accurate cross sectional data is still important because cross sections play a significant role in measuring stream features. In the case of this paper, they showed that there was a consistent low bias in the slopes for all cross sections but Cross Section 3. It is possible that this bias appeared because of how we collected data. Data was collected parallel to the stream, while cross sections are perpendicular to the stream, which means that direct measurements are missing for most cross section topography. This means that no data is being collected between these transects, which may explain the large negative bias when estimating the slope elevations. A large negative bias in estimating slope is problematic because it means the channel appears wider than it is. This will lead to sediment transport capacity being overestimated and the likelihood of flooding underestimated. A better sampling technique may be to collect data along cross sections instead of longitudinal transects. That would capture the variation in elevation between morphological features.

Specific topographic nuances related to channel morphology, such as terraces, affected the accuracy of the interpolation. This issue was exacerbated by how IDW and kriging tend to produce very different interpolated values depending on where data was measured. Flat areas with large concentrations of points will show a similar range of interpolated elevations throughout the area, while flat areas with fewer points will show a lower range of elevations everywhere besides the exact point locations. Combating this problem will require measuring with more locations.

Further research needs to be conducted to determine whether the lack of a relationship between sample density and the accuracy of the interpolation, the mixed results obtained with differences in interpolation method, and the significant relationship between accuracy and altering sample density based on morphology type can be applied more broadly than just to this specific stream site and interpolation. The research should explore other biomes besides the shortgrass prairie, and other types of topography.

5. Conclusions:

Increasing the sample density did not increase the accuracy of an inverse distance weighted (IDW) or kriging interpolation as measured using root mean square error. Previous research into the effect of sample density on accuracy has yielded mixed results. Some papers have found results that are concurrent with the results of this paper, while others did find a significant relationship between sample density and accuracy. Other literature also found different results when comparing the accuracy of different interpolation methods.

The significant relationship between the cross section where data was obtained and the accuracy suggests that topography plays a role on the effectiveness of the interpolation regardless of interpolation type. Additionally, accuracy was significantly affected when some topographic features were reduced and not others. Therefore, future surveys should take topography into account if the goal is to make an interpolated digital elevation model more accurate.

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