What if the Earth is Not Flat?
Cross-Scale Analysis of Sub-Pixel Variations in Digital Elevation Models

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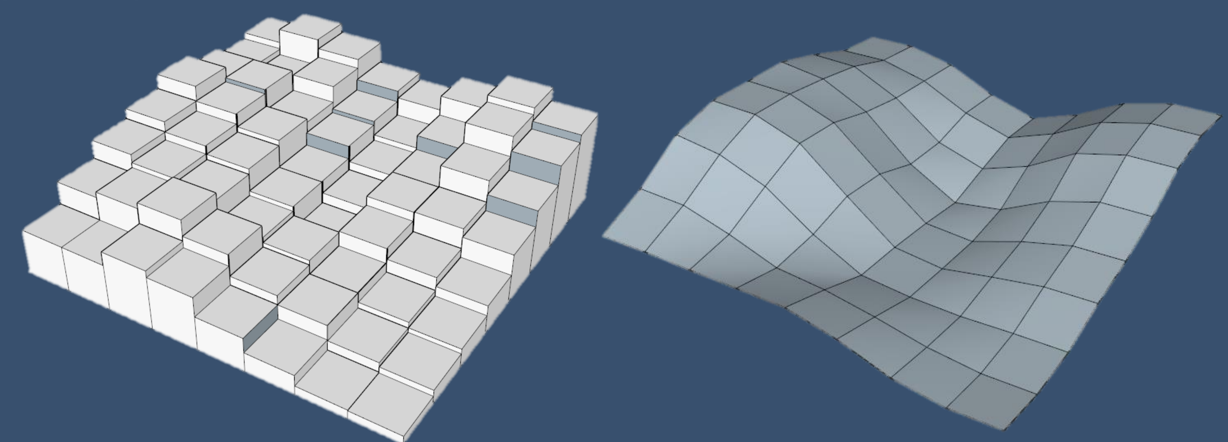
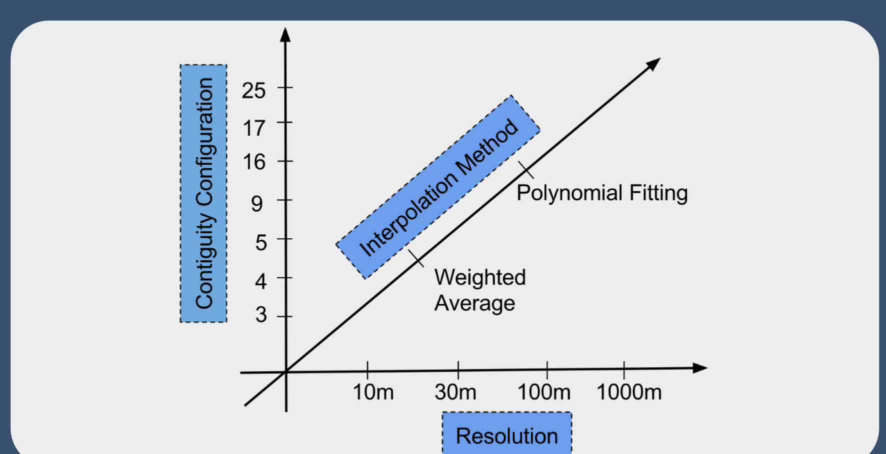
Problem

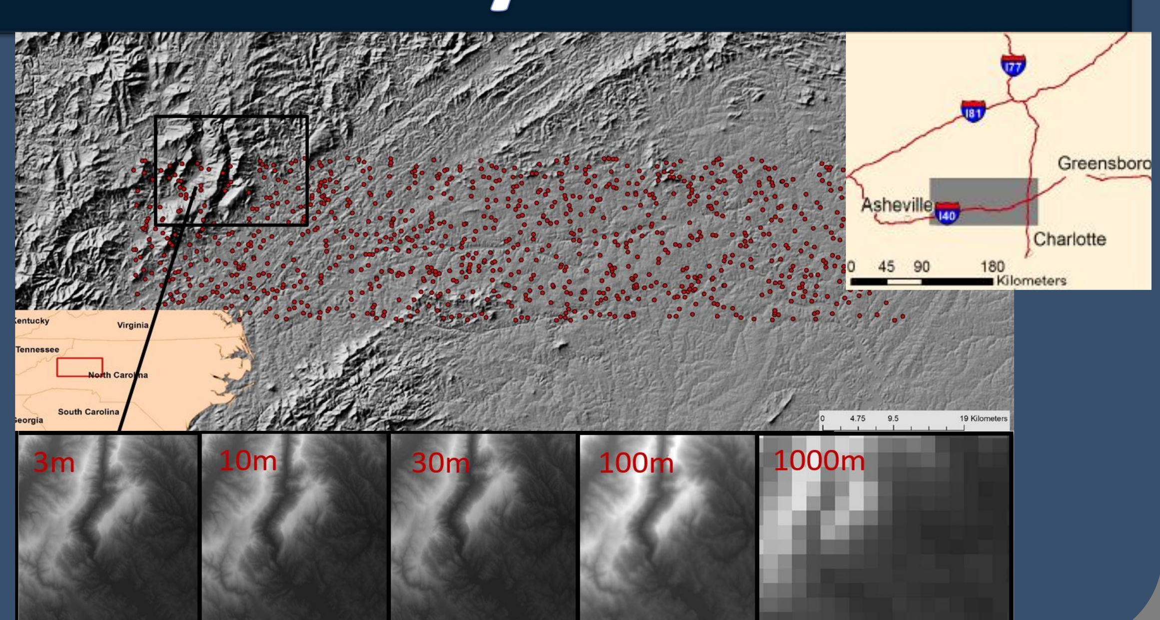
Terrain modeled on a DEM assumes that elevation values are constant within any single pixel ('rigid pixel' paradigm). This paradigm does not account for the slope and curvature of the terrain, leading to information loss. To improve precision of interpolated points, we relax the rigid pixel assumption, allowing possible sub-pixel variations ('surface-adjusted' paradigm) to inform estimates of elevation.



Tests based on interpolating elevation values for 5,000 georeferenced random points from a DEM using the rigid pixel paradigm and different interpolation methods (e.g., weighted average, linear, bi-linear, bi-quadratic, bi-cubic, and best fitting polynomials) and different contiguity configurations (i.e., incorporating first and second order neighbors) are presented. Based on these tests, this paper examines the sensitivity of surface adjustment to a progression of spatial resolutions (i.e., 10, 30, 100, and 1000m DEMs), using sub-pixel variations that can be directly measured from 3m resolution LiDAR data.



Study Area



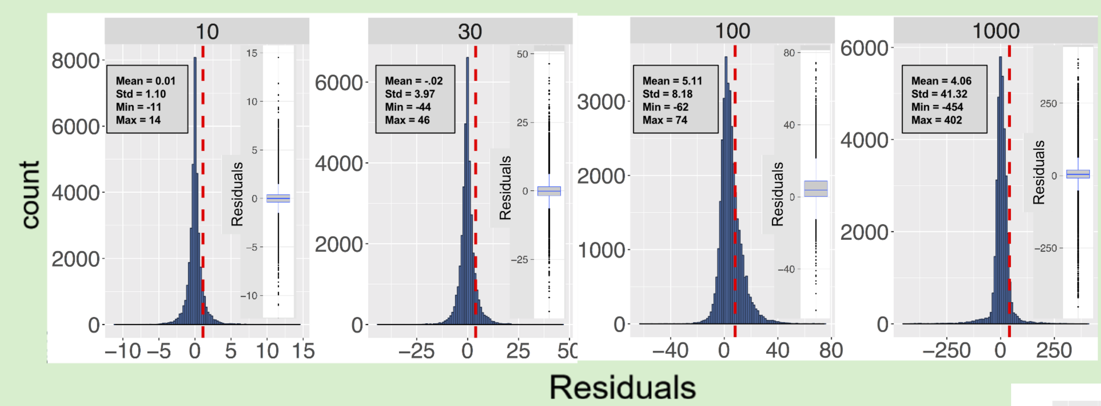
Contiguity Configurations for Elevation Estimation

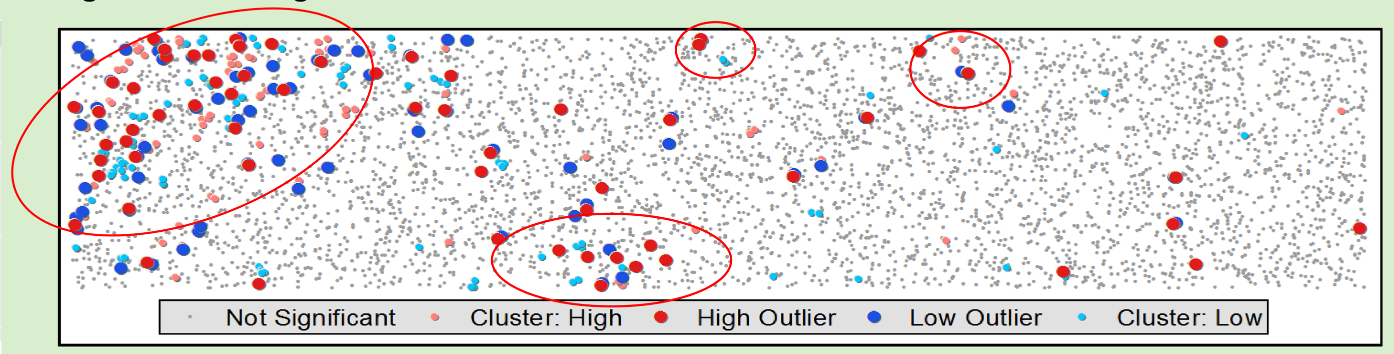
Contiguity configurations are based upon the number of neighbors (here 3, 4, 5, 9, 16, 17, 25). A 1-pixel contiguity configuration will be used as a control to compare the various surface-adjusted methods with a planar "within-pixel" method. In 3, 4, and 16 contiguity configurations, 3, 4, and 16 pixel centroids that are closest to the sample points are selected, respectively.

Results

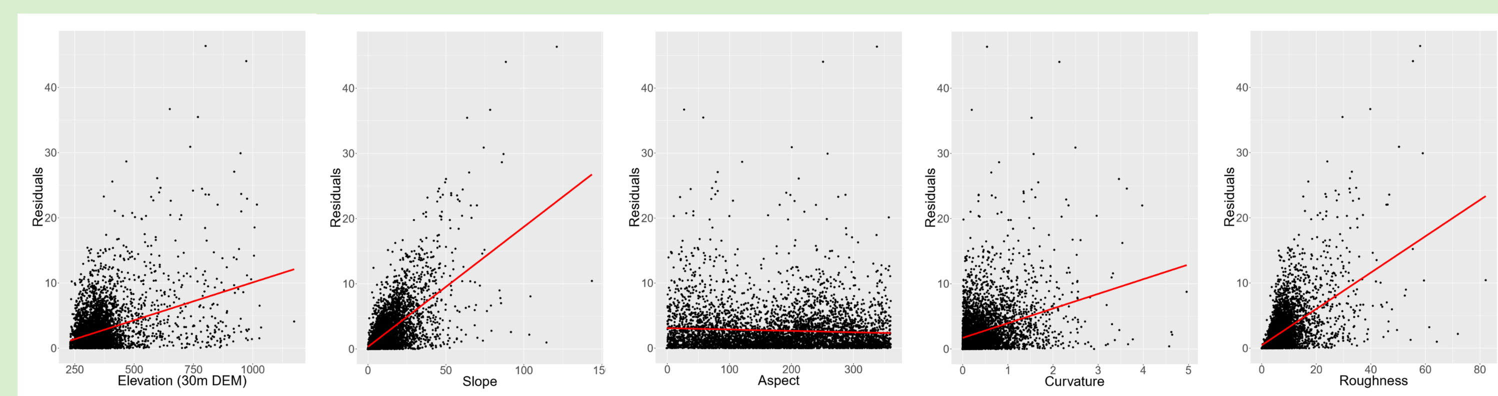
Analysis of Residuals

Results of the Kolmogorov–Smirnov test and the Anderson–Darling test verify that residuals are not normally distributed. Local Moran's I was calculated to visualize clusters and outliers. Residuals display spatial heterogeneity due to the varied character of terrain. The red ovals show the most extreme residuals in the northwest study area, which contains rough terrain. These findings imply that terrain roughness is an important factor needing further testing.





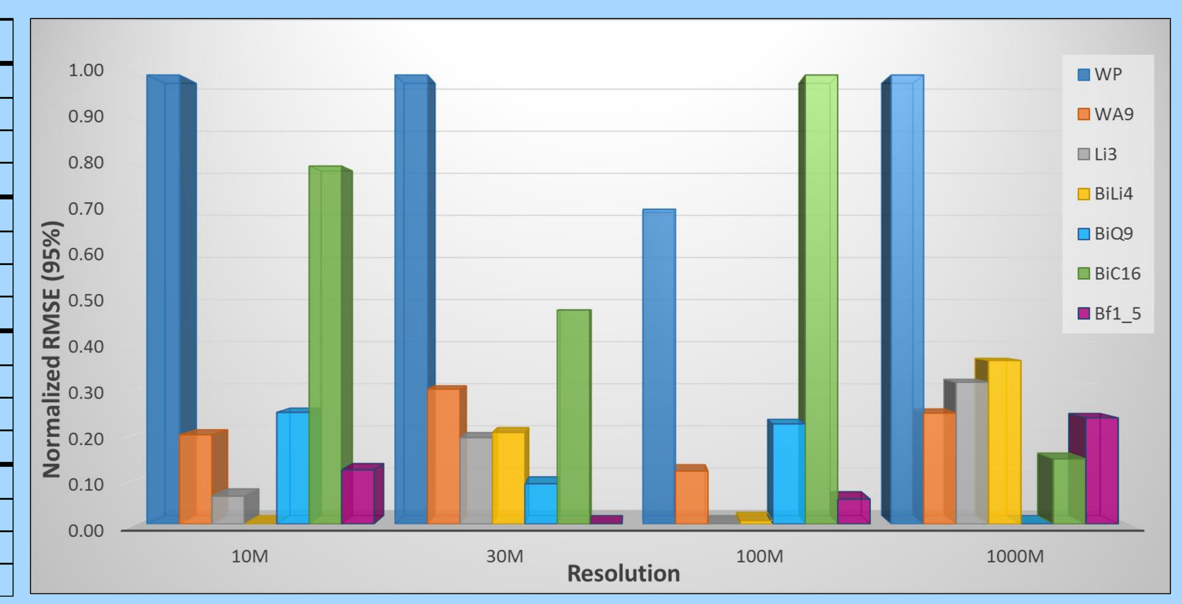
This figure represents the correlation between the residuals and elevation, slope, aspect, curvature, and roughness (the standard deviation of elevation in a 5 by 5 window) based on 30 m DEM. All of the correlation coefficients are significant at 95 percent confidence level, though the relationship with aspect is very weak.



Surface-Adjusted Elevations

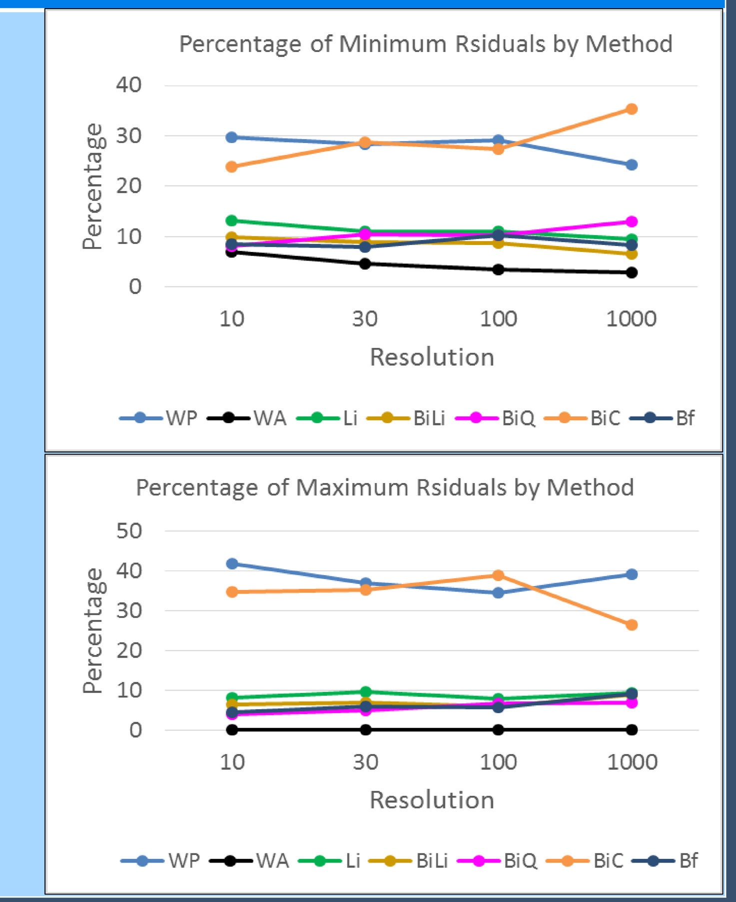
The table represents the accuracy assessment parameters for different interpolation methods in different resolutions; Columns show interpolation methods (left to right): within a pixel, weighted average using 9 neighbors, linear using 3 neighbors, bi-linear using 4 neighbors, bi-quadratic using 9 neighbors, bi-cubic using 16 neighbors, best fitting polynomial of order 1 using 5 neighbors. Red indicates the lowest RMSE in each resolution. Accuracy assessment parameters show a general trend of increase in the residuals at coarser resolutions. The Within-pixel method shows highest magnitude of errors for all resolutions, except the 100m in which the bi-cubic method has the highest amount of error. Bilinear has the least RMSE in the 10 and 100m resolution. Also the best fitting method has the least RMSE in the 30m resolution. Bi-quadratic and bi-cubic methods work better in 1000m resolutions.

		WP	WA9	Li3	BiLi4	BiQ9	BiC16	Bf1_5
10m	*RMSE*	1.19	1.08	1.08	1.07	1.08	1.13	1.07
	RMSE (95%)	0.75	0.67	0.66	0.65	0.68	0.73	0.67
	MAE	0.72	0.66	0.65	0.65	0.66	0.71	0.65
	STD	1.19	1.09	1.08	1.07	1.08	1.13	1.07
30m	*RMSE*	4.34	3.95	3.96	3.94	3.82	3.90	3.87
	RMSE (95%)	2.75	2.60	2.57	2.58	2.55	2.64	2.53
	MAE	2.70	2.53	2.53	2.53	2.50	2.61	2.50
	STD	4.34	3.95	3.96	3.95	3.82	3.90	3.87
100m	*RMSE*	9.85	9.50	9.47	9.45	9.65	10.12	9.47
	RMSE (95%)	8.25	8.01	7.97	7.97	8.06	8.37	7.99
	MAE	6.87	6.66	6.62	6.61	6.75	7.08	6.63
	STD	8.42	8.01	7.97	7.95	8.19	8.72	7.99
1000 m	*RMSE*	45.08	41.56	42.04	42.09	39.26	39.50	40.85
	RMSE (95%)	23.77	22.07	22.22	22.33	21.51	21.84	22.04
	MAE	24.69	23.20	23.47	23.50	22.36	22.42	22.97
	STD	44.92	41.36	41.85	41.90	39.05	39.28	40.65



Surface-Adjusted Elevations

In another analysis, for each sample point, two methods that result in minimum and maximum absolute value of residual were identified. Surprisingly, first, within a pixel and second, bi-cubic show the minimum and maximum number of absolute high and low residuals.



Summary & Future Work

The current paradigm assumes that the terrain surface is uniform, ignoring slope and curvature of the pixels in DEM. This research employed realistic surface geometries of terrain using different interpolation methods and the information from adjacent pixels for a more accurate and precise interpolation of points.

In the next stage of this project, we are going to investigate how the results of this research do vary with geographic conditions. The next step of this research also addresses the balance between the increased computations needed to measure surface-adjusted elevation against the improvement in precision. In this research sub-pixel variation of elevation was investigated. Sub-pixel variation of slope and curvature also would be examined in the future.

Related Work

- Buttenfield, B. P., Ghandehari, M., Leyk, S., Stanislawski, L. V., Brantley, M., & Qiang, Y. (2016). Measuring Distance "As the Horse Runs": Cross-Scale Comparison of Terrain-Based Metrics. Proceedings of the 9th International Conference on Geographic Information Science, GIScience 2016, montreal, canada.

Acknowledgments

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