Assessment of LiDAR-based DEMs in Delineating Depressional Wetlands

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INTRODUCTION

Wetlands

Wetlands have been protected in the United States since the 1970's under the Federal Clean Water Act. As part of this protection, wetlands are delineated to separate them from uplands (Environmental Laboratory, 1987). A wetland is a land area where vegetation and soil properties are indicative of water saturation (Cowardin *et al.*, 1979). Therefore, delineation methods are designed to identify plants, soils and other indicators that, under natural conditions, are reliant on the presence of saturation to occur.

In Florida, wetlands connected to navigable waters fall under federal jurisdiction and are delineated using United States Army Corps of Engineers (ACOE) rules (Environmental Laboratory, 1987). Isolated wetlands fall under state jurisdiction and are delineated by the Florida Department of Environmental Protection (FDEP) and Water Management Districts using rules defined by Chapter 62-340 Florida Administrative Code (FAC). Both the federal and state delineation procedures involve on-site investigations of soils, hydrologic indicators, and vegetation to identify the upland extent of a wetland. The state procedure, as defined in Chapter 62-340 FAC, allows for a wetland boundary to be delineated using the definition of a wetland or one of five field tests. To be delineated using the definition, the extent of the wetland must be clearly defined by a vegetative community break with an abrupt boundary separating the wetland from the upland. Alternatively, field tests (A, B, C, D, and Altered Sites) are defined in the FAC. These tests rely on a combination of wetland vegetation, hydric soils, hydrologic indicators, and reasonable scientific judgment to establish a boundary (Gilbert *et al.*, 1995). The on-site process of delineating wetlands is resource intensive, requiring experienced scientists to spend considerable time in the field to make these necessary observations of soil, vegetation, and hydrologic indicators.

Off-Site Tools

With the creation of the National Wetland Inventory (NWI) (Cowardin *et al.*, 1979) and availability of high resolution satellite and aerial imagery, use of Geographic Information Systems (GIS) data offers useful information for off-site analysis of wet landscapes. This approach is useful for identification of wetlands (Klemas, 2011; Adam *et al.*, 2010), however, these data do not currently provide a means to accurately identify a wetland boundary at a scale that is capable of substituting for on-site delineation. Barrette *et al.* (2000) found that comparing on-site delineated wetland boundaries to those using aerial photography and digital orthophotography produced mean errors of 4.53 ± 4.05 m and 3.43 ± 3.45 m respectively with errors as large as 20 m or more.

Light Detection and Ranging (LiDAR) data are acquired by an aircraft equipped with a laser that returns point observations. These data have many elevation-related products, one of which is a set of XYZ points representing the earth's surface and vegetation. In order to isolate the surface points, the raw data are filtered to remove vegetation returns from ground returns (Slatton *et al.*, 2007). The resulting “bare earth” product is used to generate digital elevation models (DEMs) of the surface (Shrestha *et al.*, 1999; Hogg and Holland, 2008). These DEMs are typically created using a triangular irregular network (TIN) or kriging methods for research applications (Lefsky et al, 2002; Guo *et al.*, 2010; Lane and D’Amico, 2010).

LiDAR can provide a dense cloud of elevation observations, with unfiltered data ranging from 1-5 points/m^2 (Leberl *et al.*, 2010). Ellis *et al.* (2012) demonstrated that a DEM derived from these data can provide a useful off-site view of the soil surface in and around depressional wetlands along with accurate (2-3 m) delineation; however this tested only seven observations of a single wetland. Further exploration of this approach is necessary to best recommend its role in the wetland delineation process.

Objectives

The goal of this study is to explore the use of LiDAR in the delineation of depressional wetlands. This will be accomplished with the following objectives: 1) Identify and delineate (on-site) several depressional wetlands in an area with high-resolution (e.g. < 1 m) aerial photography and LiDAR coverage; 2) Using a bare-earth LiDAR data set, create high-resolution DEMs using the traditional TIN and spatial interpolation methods; 3) Use the DEMs to delineate the wetlands from within a GIS environment; and 4) Compare field-based and LiDAR-based delineations.

METHODS

Site Description

The wetlands studied are located in Austin Cary Memorial Forest (ACMF), an approximately 840 ha teaching and research forest owned by the School of Forest Resources and Conservation at the University of Florida. The forest, located approximately 15 km NE of Gainesville, FL is a managed forest that receives frequent prescribed burns. The burns promote well defined vegetation community breaks between the wetlands and uplands. Silviculture is a common practice at ACMF, providing the flatwoods with a canopy of planted *Pinus elliottii* (slash pine) and an understory dominated by *Serenoa repens* (saw palmetto). The landscape is a relatively flat sand hill interspersed with depressional wetlands dominated by *Taxodium ascendens* (pond cypress) and *Woodwardia virginica* (Virginia chain fern). The dominant soils mapped in ACMF are Pomona sand, Pomona sand depressional, Newnan sand, and Wauchula sand (Cummings and Wittstruck, 1985; Soil Survey Staff, NRCS).

The site was selected for its representation of a common landscape found throughout the state of Florida that is frequently chosen for development, expressing the need to conduct on-site wetland delineations. The wetlands studied are located in close proximity to each other in the northeast corner of ACMF, just south of Waldo Road. All four wetlands are isolated depressional wetlands at similar elevations in the landscape. Depressional wetlands are the lone wetland type being studied due to the strong relationship between their boundary and elevation.

Wetland Delineation

Four depressional wetlands located in ACMF were delineated in close coordination with St. Johns River Water Management District staff for this study (Figure 1). To identify the landward extent of the wetlands, the delineation process followed those defined by Chapter 62-340 FAC. At sites that displayed a clear break in the wetland and upland communities, the definition of a wetland was used for delineation (section 62-340.200 FAC). At the remaining locations, the five field tests (section 62-340.300 FAC) were employed (Table 1).

The frequency of sites used as delineation locations were approximately 10 m intervals along the wetland edge. Some locations deviated from the 10 m interval to avoid areas that had been disturbed by fire breaks, road fill, or other unnatural features. The delineation boundary was marked with pin flags. The XYZ positional coordinates at each flag was later recorded using a total station with 1 cm horizontal and vertical accuracy.

LiDAR and DEM Creation

The bare earth LiDAR data set used in the study is part of the Alachua County LiDAR survey flown in January 2001. The data were processed by 3001, Inc. and are distributed by the Alachua County Property Appraiser's office. Once imported into ArcGIS 10.0, the data points were clipped to a 50 ha area of interest (AOI) surrounding the wetlands. The data points were then modeled into 1m DEMs using (i) Triangular Irregular Network (TIN) processing, (ii) ordinary kriging (OK), (iii) local polynomial trend surface (1^{st} order, 70% local), and (iv) local polynomial trend surface (1^{st} order, 100% local) (Figure 2). ArcGIS Geostatistical Analyst extension was used to create the ordinary kriging, 1^{st} order polynomial trend surface set to 70% local (LP70), and 1^{st} order polynomial trend surface set to 100% local (LP100) models. For the LP model creation, the extension allows for adjustments to be made to change the amount of influence neighboring data points have on any one cell. With the local influence set to 100%, the resulting surface is more flexible to raise and fall under the influence of nearby points. With the local influence set to 70%, the surface will be slightly less flexible and result in a smoother model. ArcGIS 3D Analyst was used to create the TIN model (Booth, 2000). Default settings were used for the kriging and TIN model creation to show a standard representation of their processing. Hill shades were created using the Spatial Analyst extension for enhanced visualization quality.

Wetland Boundary Extraction and Error

To model the wetland edge, a boundary for each wetland must be derived. Model elevation was extracted for each XY location of the wetland delineation points. For each wetland, the model elevations were averaged. A contour line of the average elevation was created from the model and used to represent the boundary at each wetland (Figure 3). The modeled elevations were used instead of the surveyed elevations to avoid any error of the LiDAR data from surveyed surface (Guo *et al.*, 2010).

Once the average elevation contour had been selected and used as the model boundaries for each wetland, the next step was to determine the horizontal error of the boundary from each delineation point. The Euclidean distance tool in the Spatial Analyst extension was used to determine the errors. When the modeled boundary was inside the wetland compared to the delineation point, underestimating the wetland's landward extent, the error was assigned a negative value. When the modeled boundary was outside of the point, overestimating the wetland's extent, the error was assigned a positive value.

LiDAR Point Density and DEM Slope

The density of LiDAR elevation returns varies due to vegetative cover and many other factors (Lee *et al.*, 2008). This can be a potential source of error during the DEM creation in areas where the vegetation is dense, blocking the laser from accurately measuring the elevation of earth's surface. The vegetative and other erroneous returns are filtered out during processing of the bare earth dataset and therefore the density of elevation data points varies throughout the extent of the data. Density maps with a 1m cell size were created using the point density function in ArcMap Spatial Analyst tools to compare trends between error and density. Various search radius sizes were used to create density maps, selecting the map based from a search radius of 13 m to use for analysis. This was the estimated maximum horizontal distance between any of the LiDAR data points and its nearest neighbor within the AOI. The density values were extracted at each delineation site to compare to error values.

Slope was also compared to error to explore possible trends. Slope maps were generated from each DEM model using the slope tool in ArcMap Spatial Analyst. The slope maps were created with a 2 m cell size to mute sudden, localized shifts in the modeled surface. The values of the slope at each delineation point were extracted for the four models for analysis.

RESULTS AND DISCUSSION

Wetland Delineation

Table 2 provides a summary of surveyed elevations at 48 wetland delineation locations. These elevations provide a context for understanding how the delineated wetland boundary is controlled by elevation. They are not the modeled elevations on which the model wetland boundaries are based. The standard deviation in elevations was minimal for each wetland, ranging from 6.5 to 7.4 cm. The variability of elevations at delineation locations for each wetland is similar when more elevation observations are included (Figure 4). The convergence to 6-8 cm occurs with eight or more observations. This suggests that more than eight observations may not be necessary to achieve the best estimate of average boundary elevation at a given depressional wetland.

Modeled Wetland Boundaries

Reported in Table 3 are the average and standard deviation (STDEV) of model predicted elevations at the 48 delineation locations. The standard deviations ranged from 7 to 30 cm, which is greater than the on-site surveyed elevations. The larger standard deviations suggest the modeled surface is more erratic than the actual ground surface. This is counter to what was expected given the smoothing nature of geostatistical models kriging and polynomial trend surfaces.

The tortuosity of the modeled boundaries is similar to those presented by Ellis *et al.* (2012), with the TIN and LP 100 models as the most erratic (Figure 5). The TIN and LP100 boundaries weave back and forth while the OK and LP70 models follow a straighter path. An example of the different boundary patterns can be seen in the northwest corner of Figure 5.

The lowest overall average error was the LP70 model with a value of 0.296 m (Table 4). LP70 is therefore the least bias model. The LP100 boundary produced the lowest overall root mean squared error (RMSE) with 2.470 m, making it making it the most accurate model. The average error values for the definition and B test points were similar for all the models while the average errors from the D test points were much higher, ranging from 1.619 to 1.914 m. These higher values suggest that the D test delineation may have a tendency to fall lower in the landscape, although this is inconclusive with the data collected for this study. All of the models, with the exception of the LP70 on Wetland 1, have a positive value for their average error. This indicates that the models overestimate the wetland extent.

LiDAR Density and DEM Slope

In the bare earth data utilized in this study, the LiDAR returns were separated by as much as 13 m from their nearest neighbor. The LP70 modeled boundary lines in Figure 6 tend to occur in areas of low point density. When horizontal error between model boundary and delineation location is plotted against point density (Figure 7) it appears that large errors occur in areas where fewer bare-earth LiDAR data are available. In general, the density of bare earth LiDAR points along the wetland edge is low compared to open areas such as the road in the upper left hand corner of the map, having a negative effect on error magnitude. The average density at the delineation points is 0.028 points/m^2, while the maximum is an estimated 0.775 points/m^2.

Values extracted from DEM slope maps were compared to reveal the TIN and LP100 models had a much higher average slope than the OK and LP70 (Table 5). The more flexible nature of the TIN and LP100 models resulted in slopes that reached a max of 19% and 14% respectively, while the smoother OK and LP70 models had much lower maximum slopes, 7% and 6%. The graphs in Figure 8 show that all models had lower horizontal error in areas of higher slope.

CONCLUSIONS

LiDAR-based DEMs have the capability of identifying a depressional wetland boundary within 2-3 m. In this study, the local polynomial models outperformed the TIN and kriging models in their ability to accurately model the wetland boundaries. While this LiDAR-based approach does not currently provide the accuracy that on-site field delineations do, the ability to estimate these delineations within a few meters using an off-site tool shows much promise. Informal determinations or instances where a few meters are not a cause for concern, the local polynomial models provide a modeled wetland boundary requiring less on-site field work. As newer LiDAR data sets become available, the potential exists for these DEMs to improve with a reduction horizontal error.

Further research investigating the source of errors and ways to minimize them would be the next step in improving the accuracy of these models. Also, exploring ways of eliminating the need for on-site investigations to create the modeled boundaries would offer this process as a completely off-site tool. Slope inflection was lightly explored as a possible avenue of this during the course of the research but no conclusions could be made.

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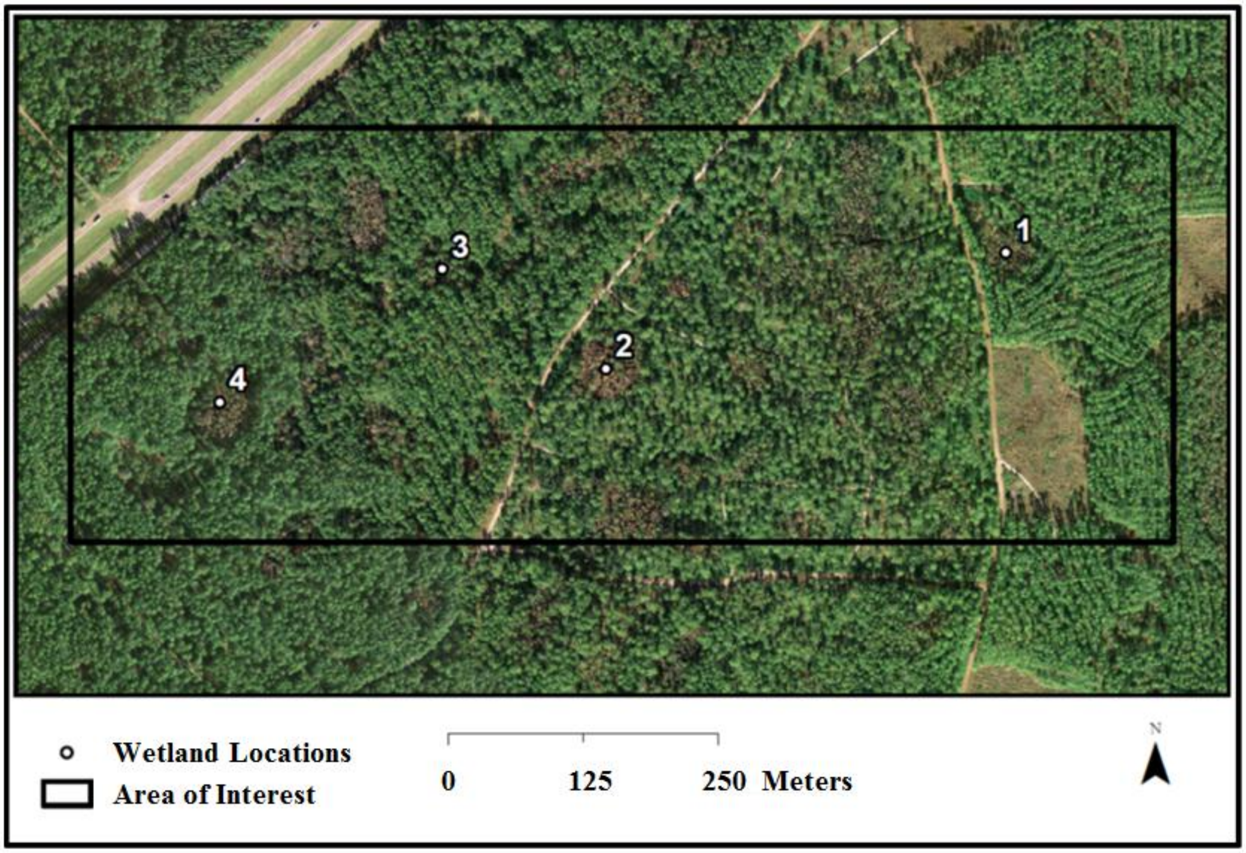

Figure 1: Aerial photo showing the area of interest (AOI) and wetland locations

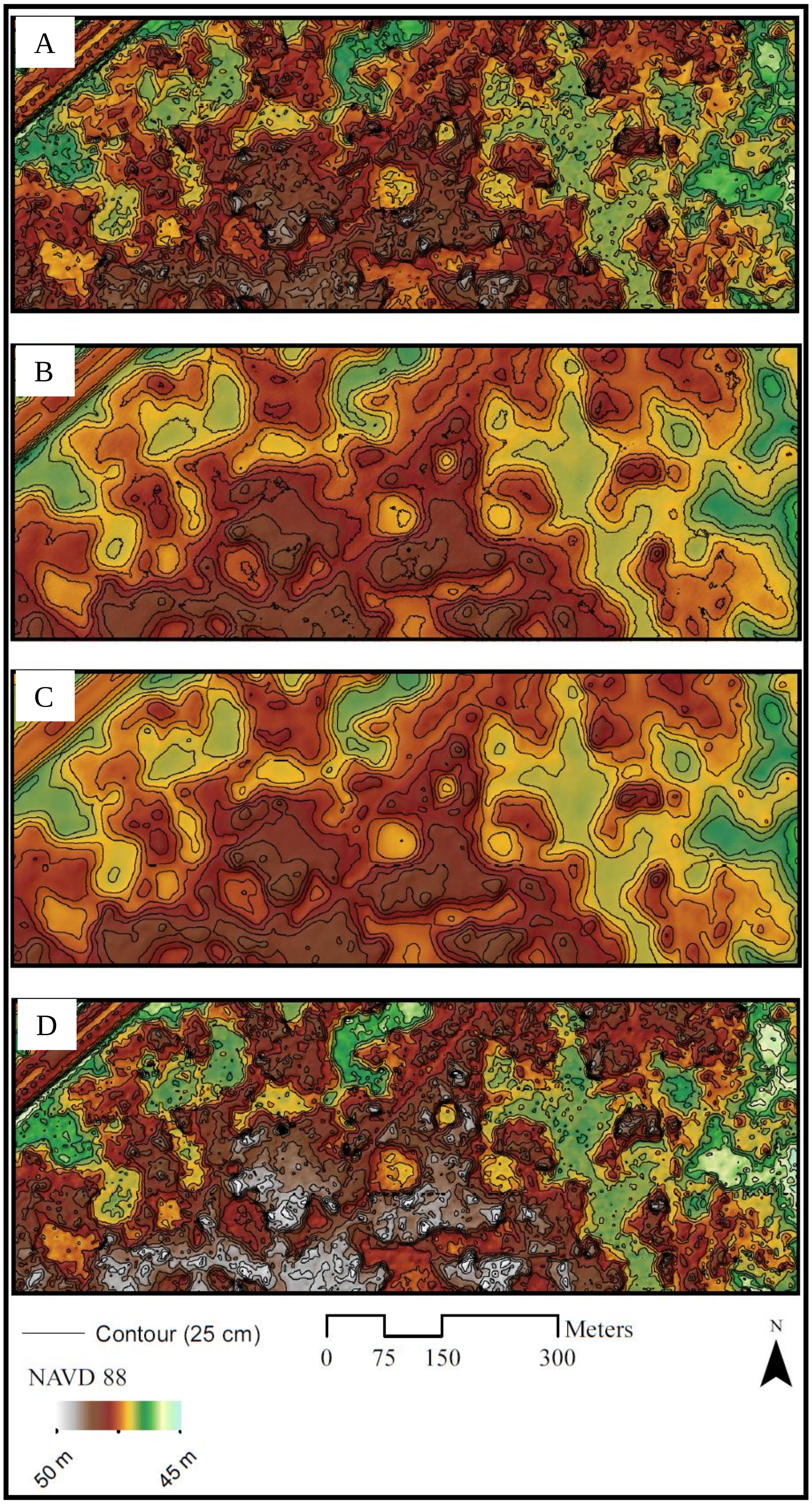

Figure 2: Surface modeled LiDAR using TIN (A), OK (B), LP70 (C), and LP100 (D); all to the same extent

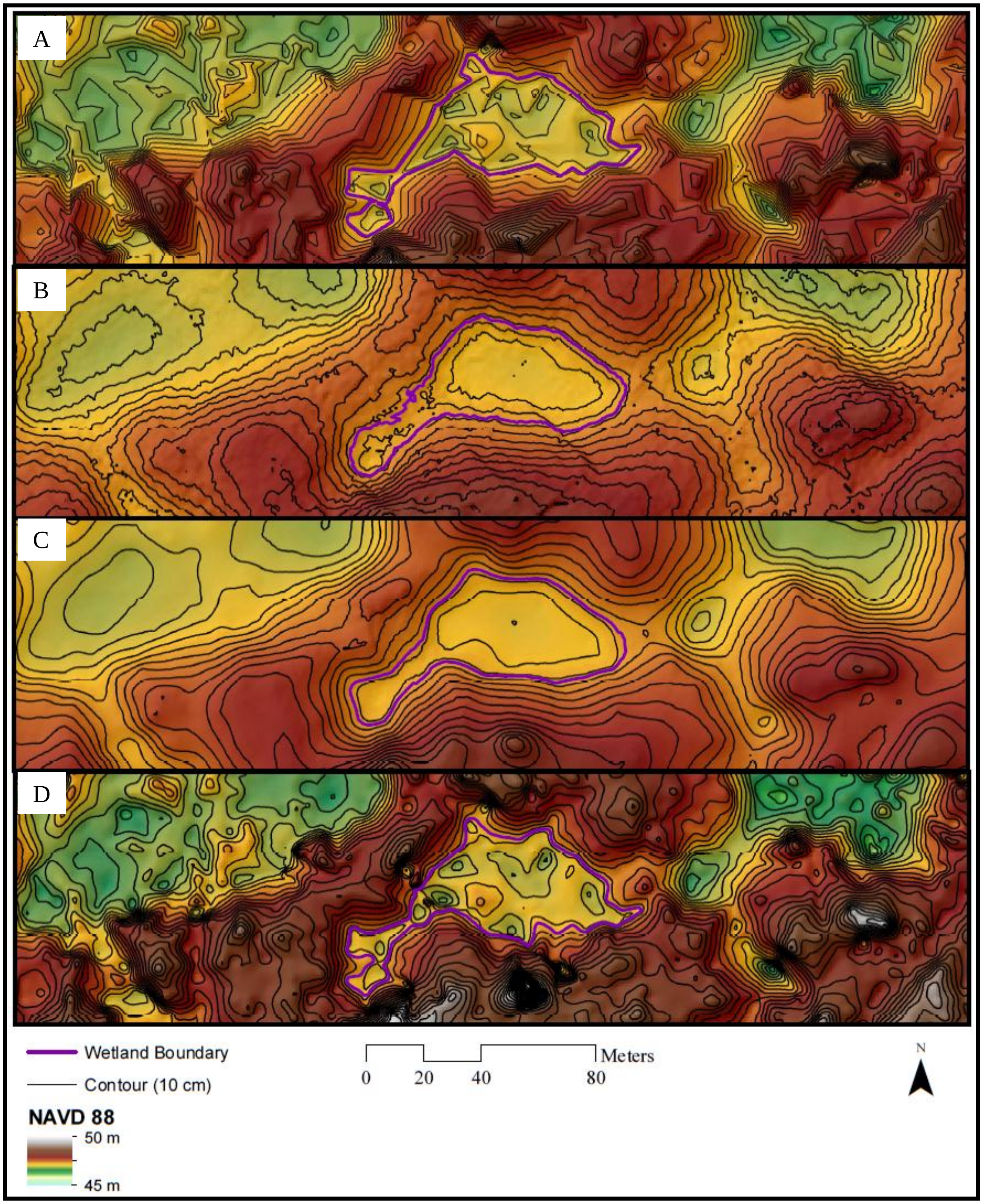

Figure 3: Wetland 3 DEM modeled boundaries for TIN (A), OK (B), LP70 (C), and LP100 (D); all to the same extent.

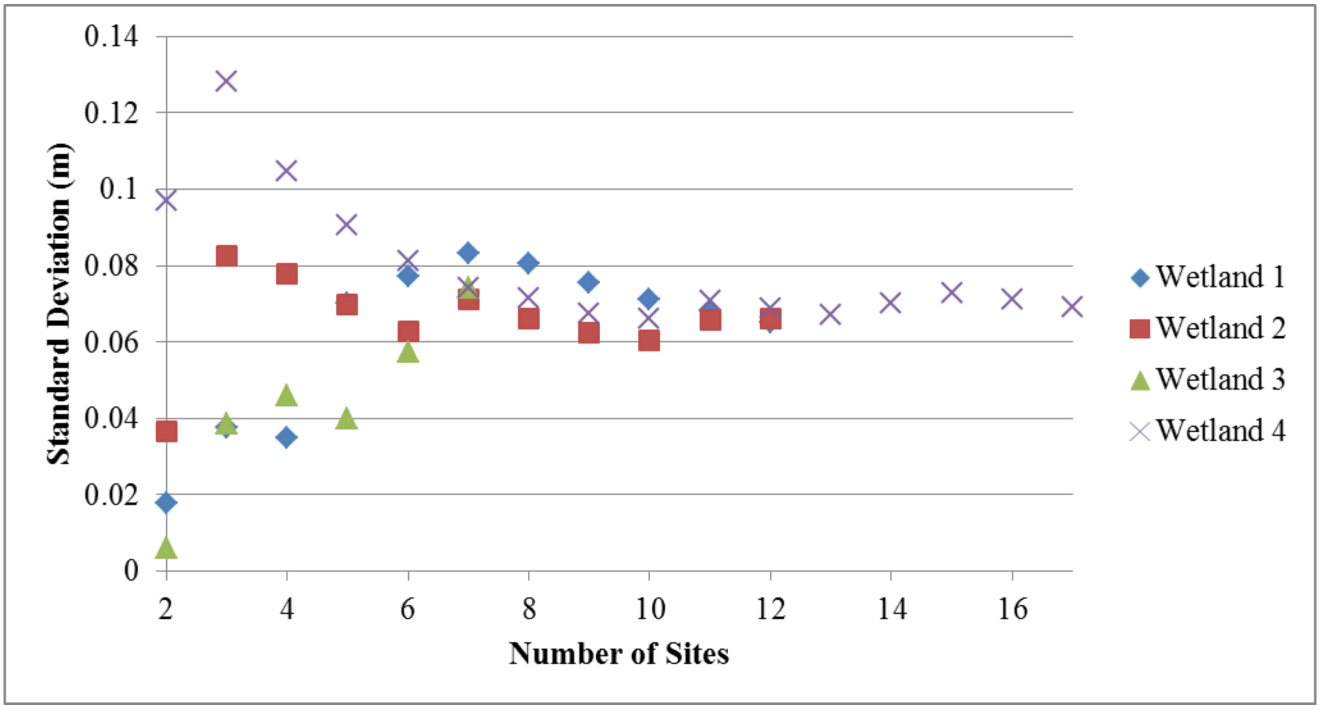

Figure 4: Variability of ground elevation measurements

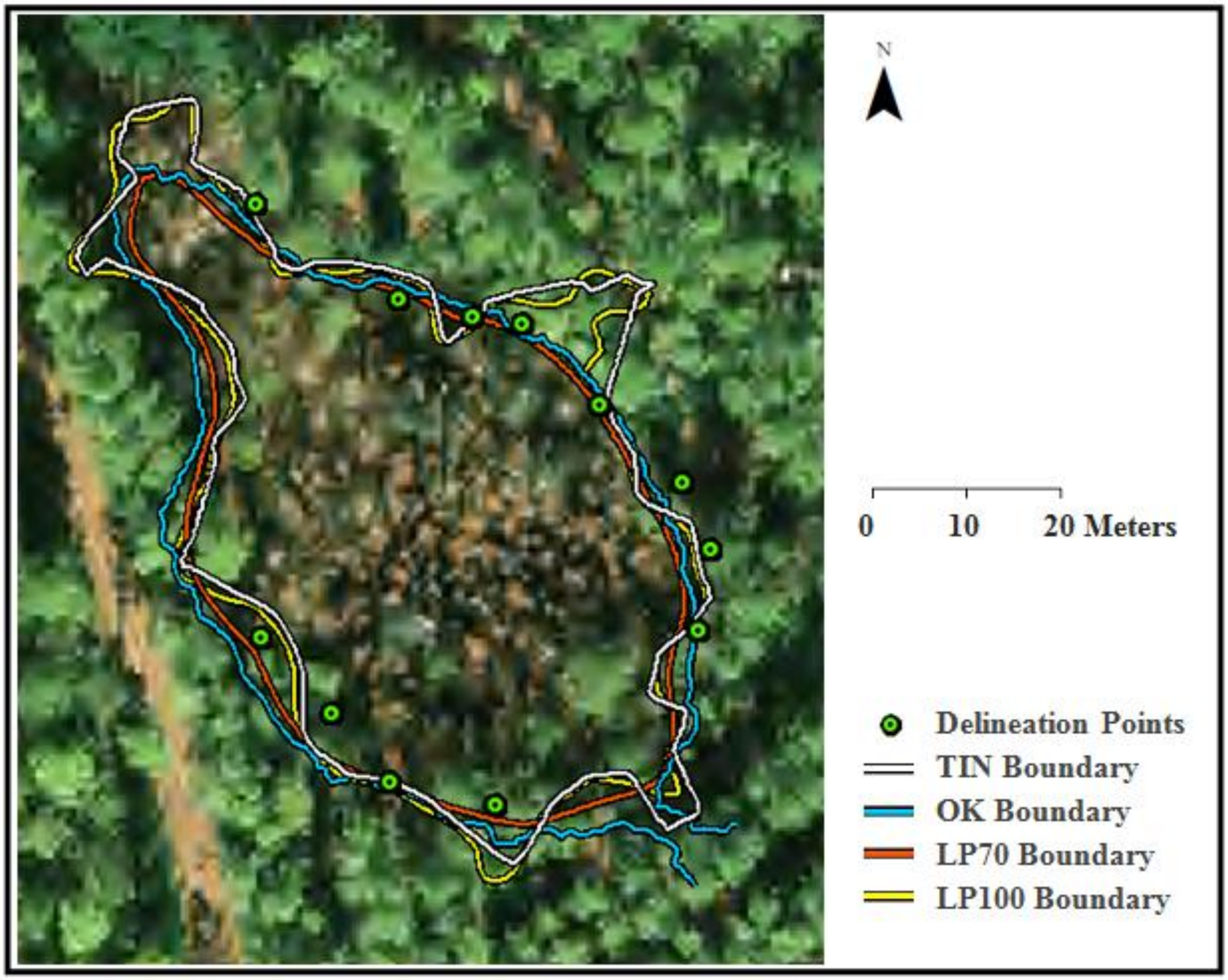

Figure 5: Modeled Boundaries of Wetland 1

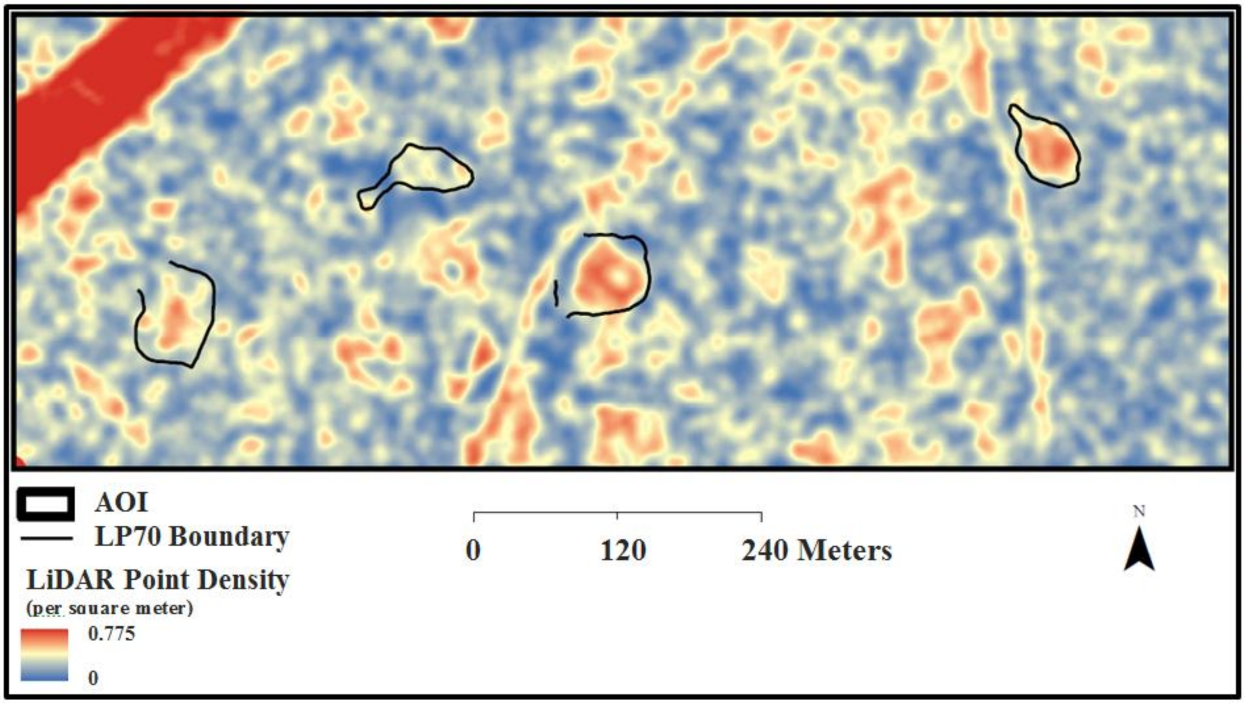

Figure 6: Density of bare earth LiDAR returns

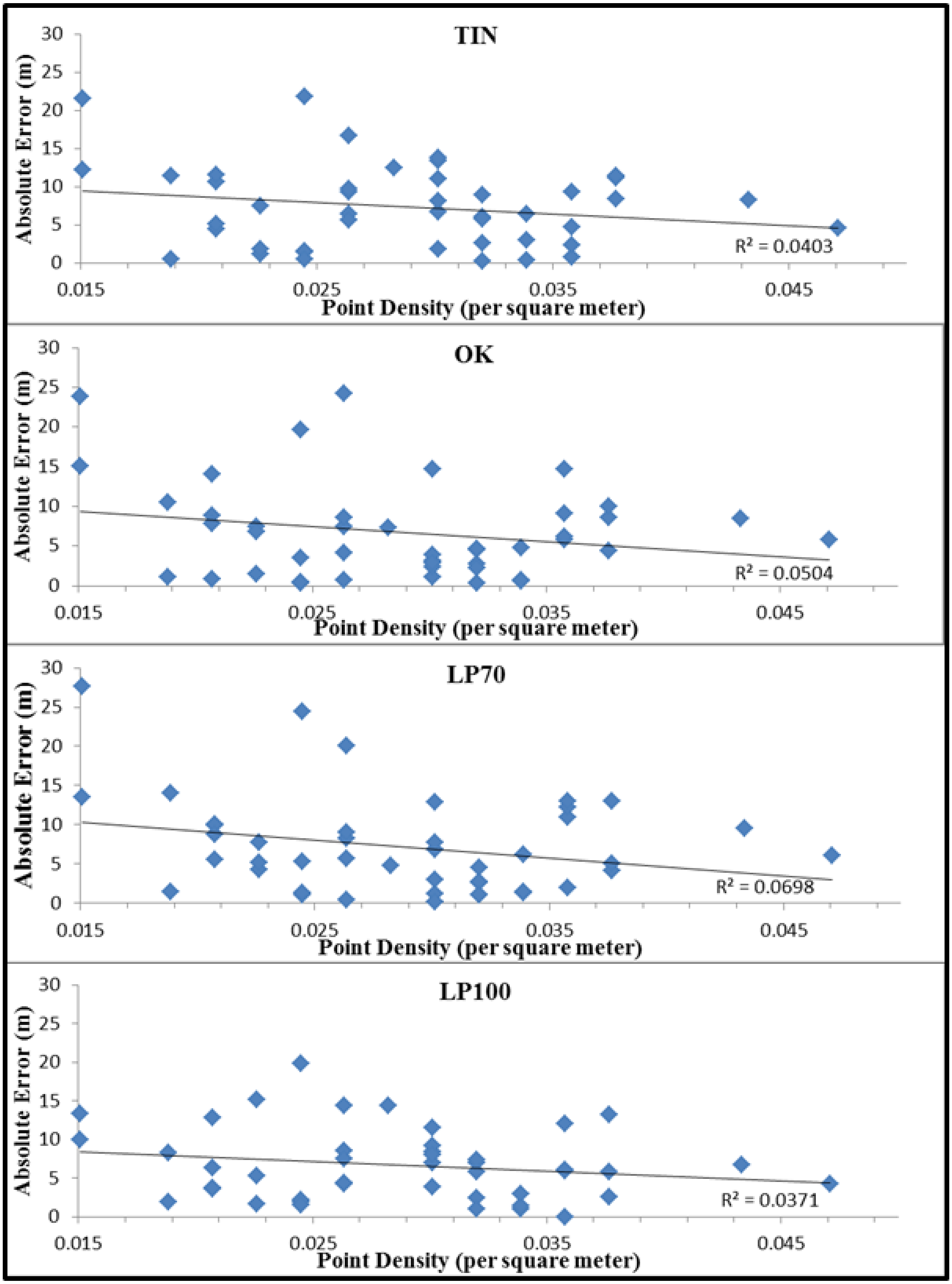

Figure 7: Absolute error as LiDAR point density increases

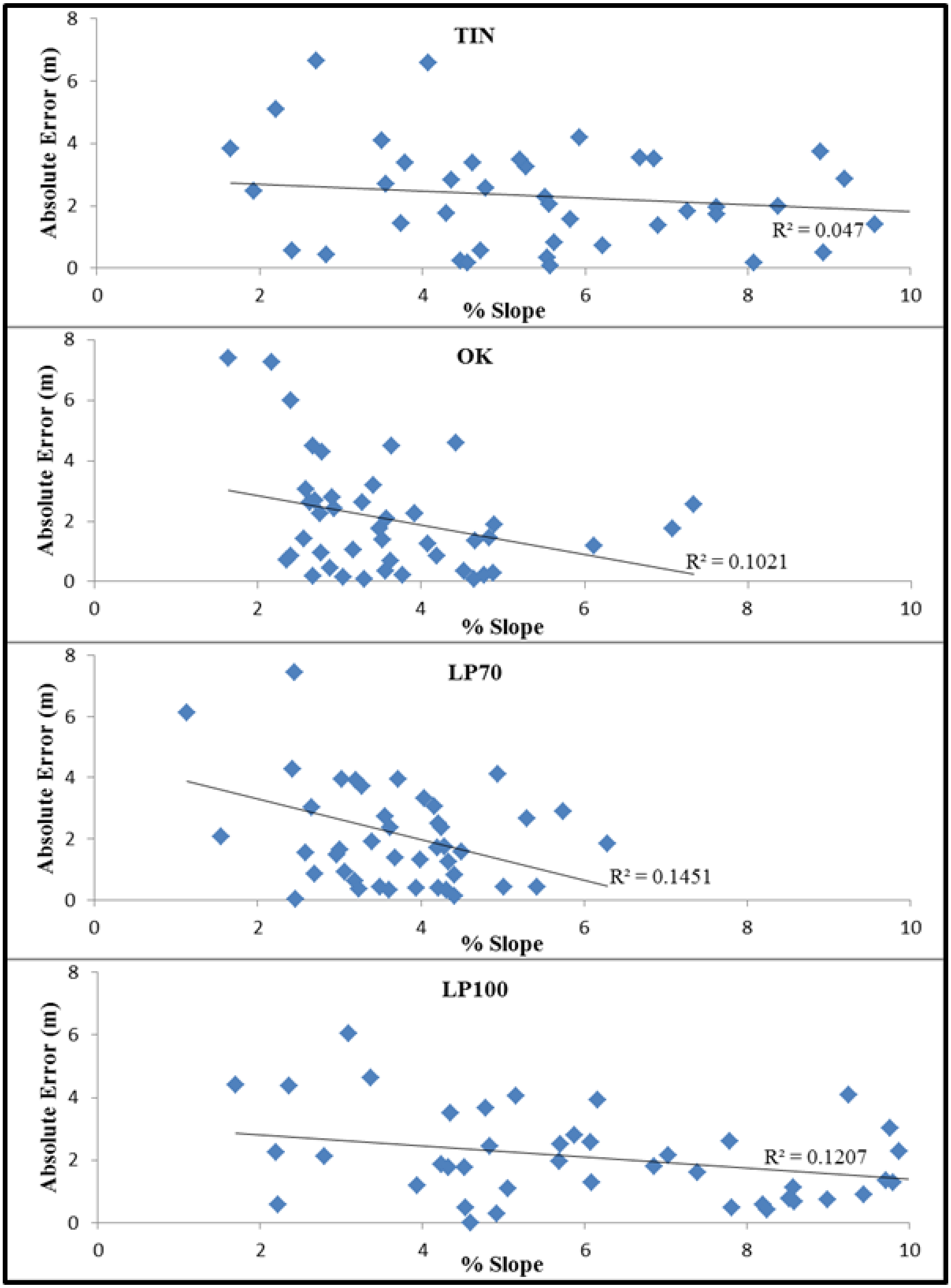

Figure 8: Absolute error as modeled slope increases

Table 1: Field tests used for wetland delineation in accordance with Chapter 62-340.300 FAC

Test Type	Definition of Test
"A" Test	Obligate Vegetation > Upland Vegetation AND Hydric Soils or Riverwash OR Hydrologic Indicators
"B" Test	Obligate + Facultative Wet Vegetation ≥ 80% AND Hydric Soils or Riverwash OR Hydrologic Indicators
"C" Test	An undrained hydric soil that meets at least one of the following criteria: 1. Soils classified as Umbraqualfs, Sulfaqualfs, Hydraquents, Humaquepts, Histosols (except Folists), Argiaquaolls, or Umbraquults 2. Saline Sands 3. Frequently Flooded or Depressional map units as designated by the USDA.
"D" Test	Hydric Soil + Hydrologic Indicator OR One of the following hydric soil indicators: A4, A7, A8, A9, F2, S4, A5 OR Any NRCS hydric soil indicator in which all the requirements are met starting at the soil surface.

Table 2: Summary of delineation points for the wetlands studied. Elevations are surveyed elevations (NAVD88)

	Average Elevation (m)	**STDEV (m)**	**Max (m)**	**Min (m)**	**Delineation Method (# Sites)***					
					Total Sites	**Definition**	**"A" Test**	**"B" Test**	**"C" Test**	**"D" Test**
Wetland 1	48.257	0.065	48.366	48.161	12	1	0	10	0	2
Wetland 2	48.953	0.066	49.056	48.850	12	2	0	8	0	3
Wetland 3	48.614	0.074	48.733	48.503	7	6	0	4	0	1
Wetland 4	48.590	0.069	48.743	48.486	17	16	0	5	0	3

*Sites may be counted more than once if multiple delineation methods were met at the same location

Table 3: Average model-derived elevations (NAVD88) and standard deviations of the on-site delineation points

	TIN Average (m)	TIN STDEV (m)	OK Average (m)	OK STDEV (m)	LP70 Average (m)	LP70 STDEV (m)	LP100 Average (m)	LP100 STDEV (m)
Wetland 1	47.004	0.125	47.049	0.064	47.044	0.069	46.988	0.125
Wetland 2	48.071	0.305	47.959	0.108	47.959	0.112	48.011	0.220
Wetland 3	47.268	0.158	47.366	0.095	47.322	0.124	47.237	0.225
Wetland 4	47.489	0.196	47.478	0.102	47.476	0.105	47.476	0.169

Table 4: Summary of the average errors (m) of the model-derived wetland boundaries for each wetland and for each method of delineation

	TIN Error	TIN RMSE	OK Error	OK RMSE	LP70 Error	LP70 RMSE	LP100 Error	LP100 RMSE
Wetland 1	0.312	2.317	0.396	2.185	-0.465	2.347	0.205	2.442
Wetland 2	1.340	3.188	0.318	2.778	0.365	3.218	0.450	1.972
Wetland 3	0.132	2.493	0.667	3.531	0.949	3.119	0.469	2.929
Wetland 4	0.340	2.921	0.444	2.685	0.434	2.524	0.120	2.632
All Points	0.504	2.763	0.441	2.735	0.296	2.880	0.381	2.470
Definition	0.322	2.664	0.302	2.955	0.343	2.992	0.464	2.509
"B" Test	0.365	2.785	0.341	2.936	-0.023	2.940	0.066	2.406
"D" Test	1.914	3.044	1.839	3.222	1.711	2.876	1.619	2.614

Table 5: Summary of modeled slopes at the delineation points (percent slope)

	TIN	OK	LP70	LP100	Averaged Models
Average	6.123	3.627	3.680	6.364	4.948
Maximum	19.087	7.342	6.285	14.088	11.564
Minimum	1.647	1.635	1.139	1.695	1.834
STDEV	3.215	1.213	1.076	2.773	1.851