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The Effect of Modernizing the National Datums on Floodplain Mapping

A Cooperative Pilot Project between the National Geodetic Survey, North Carolina Floodplain Mapping Program, North Carolina Geodetic Survey, and the Federal Emergency Management Agency

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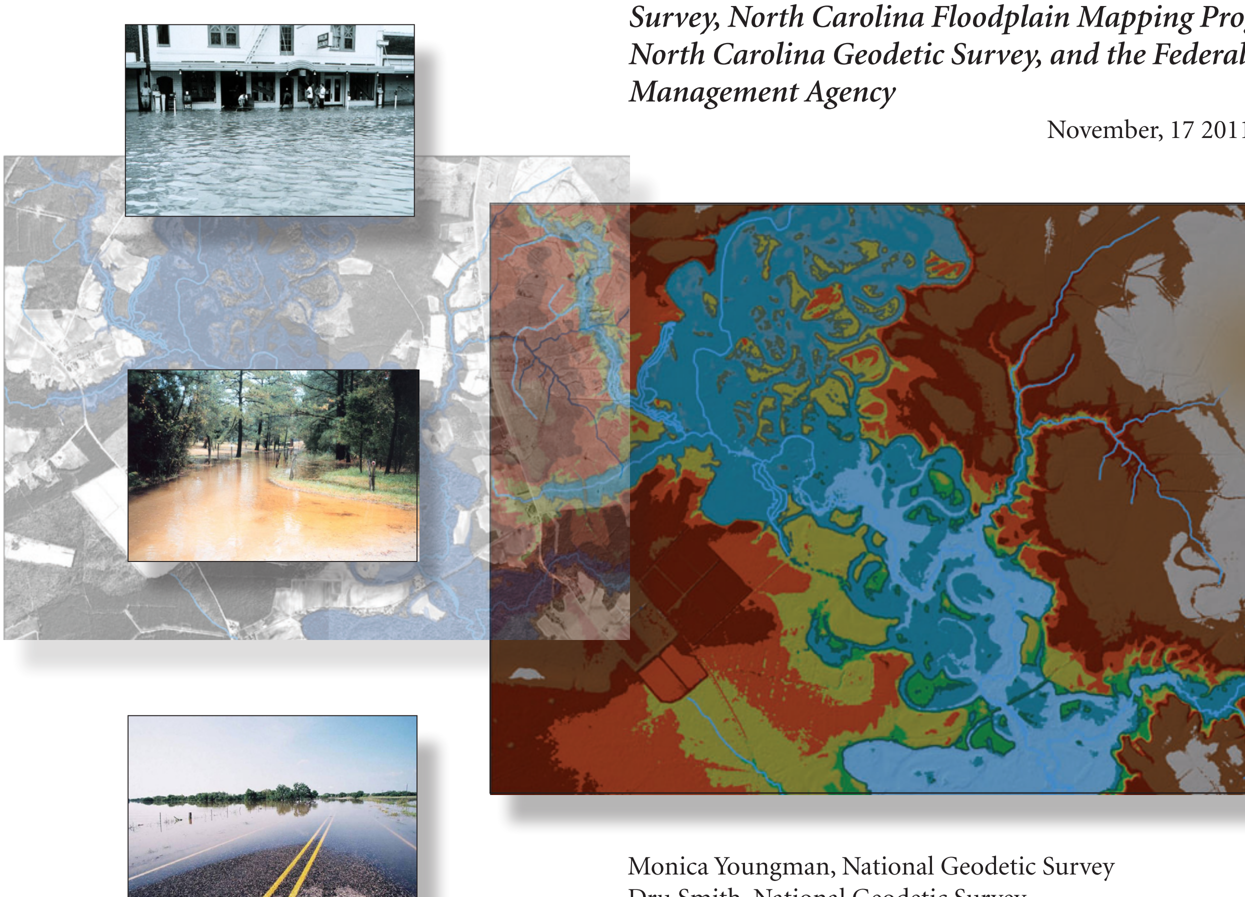

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EXECUTIVE SUMMARY

This study was conducted to examine the effects on floodplain mapping of replacing the national datums of the United States. By approximately 2022, NOAA's National Geodetic Survey (NGS) will modernize (replace) the official datums, currently the North American Datum of 1983 (NAD 83) and the North American Vertical Datum of 1988 (NAVD 88). Based on new technologies and methods, NGS will define new geometric and geopotential datums that will replace NAD 83 and NAVD 88, respectively. Georeferencing spatial data to the correct datum is extremely important to many geospatial applications, including construction, agriculture, resource management, navigation, and emergency management. These updates will provide a critical improvement to orthometric heights, which are offset up to 2 meters (over 6 feet). In addition to the new datums, NGS is also considering promoting appropriate use of the passive control network by publishing estimated orthometric height accuracies for bench marks. In order to investigate the effects of this coming change, a pilot study was conducted in cooperation with the North Carolina Floodplain Mapping Program (NCFMP) and the North Carolina Geodetic Survey (NCGS). This report reflects the outcome of that pilot study.

For this study one stream reach, Tranters' Creek in Pitt County, North Carolina, was chosen for analysis. Tranter's Creek is in the coastal plain of North Carolina and has a recently updated detailed flood study using *Li*ght *D*etection *A*nd *R*anging (LiDAR) data in addition to an *effective*[1] limited detailed study. The coastal plain was selected as a conservative estimate since small changes in water levels have a larger effect on the floodplain than in mountainous areas (National Research Council, 2009).

To understand the effects of the datum modernization, the first step was to model the change for specific coordinates. For the study location all geospatial data were transformed from the existing reference frame to available proxy datums that most closely resemble the future datums. For the geometric (horizontal) datum NAD 83 (HARN[2]) was transformed to the International Terrestrial Reference Frame of 2005 (ITRF2005)/Geodetic Reference System of 1980 (GRS-80). For the geopotential (vertical) datum GEOID99 was replaced with the U.S. Gravimetric Geoid model of 2009 (USGG2009) as the orthometric datum zero height surface.

[1] An effective model is one that has been accepted for use in the official maps.

[2] High Accuracy Reference Network (HARN) is the designation for the statewide geodetic network upgrade. In North Carolina this was done twice, in 1995 and 2001. The data received for this study was referenced to the 2001 adjustment.

The ITRF2005 geodetic coordinates were projected to State Plane Coordinate System of 1983 (SPCS 83) North Carolina zone (Zone 3200) in U.S. survey feet using the existing SPCS 83 projection parameters.

The average horizontal shift in this location was 2.72 feet (0.829 m) in the horizontal (in the west-northwest direction) and -0.98 feet (-0.298 m) in the vertical (i.e., lower than NAVD 88). The results show these horizontal and vertical shifts are spatially dependent. This means that the shift from the current datums to the future datums will be a tilted surface rather than a constant horizontal or vertical shift. While this provides a first look at the order of magnitude of the coordinate shifts, actual changes will vary across the U.S.

Four issues were investigated related to floodplain mapping and data management: (1) Determining whether derived Digital Elevation Models (DEMs) would need to be recreated from transformed Light Detection and Ranging (LiDAR) data; (2) Testing whether the assumption that the hydrologic models could remain the same, by comparing the drainage area of the original and transformed watersheds; (3) Examining the effect on the floodplain boundary and base flood elevations (BFEs); and (4) Evaluating when an error bar on a bench mark would be too large for use in a floodplain mapping survey by measuring the effect of vertical uncertainty on an obstruction.

The method of mapping the floodplain for this project was based on the usual process employed by the Federal Emergency Management Agency (FEMA), but it was automated and simplified to focus on the effect from the datum change. The floodplain boundary was determined by subtracting the ground surface TIN (Triangulated Irregular Network) based on LiDAR from the water surface TIN for the base flood (100-year or 1% chance). All areas greater than zero were considered in the floodplain.

Four floodplain boundaries were created from high and low accuracy base data: original high accuracy, transformed high accuracy, original low accuracy, and transformed low accuracy. The four ground surface TINs were created from the original and transformed LiDAR[3] and the USGS National Elevation Dataset (NED)[4] elevation data, which were used as examples of high and low accuracy elevation data, respectively. Four corresponding water surface TINs were created using stream cross sections and water levels from the U.S. Army Corps of Engineers Hydrologic Engineering Centers River Analysis System (HEC-RAS) tool. To test the sensitivity of this floodplain to the potential uncertainty in bench mark heights, one bridge was reinserted into the HEC-RAS model and examined at various heights.

The results of the DEM analysis (1) showed that 96.1% of the points fell within a 2 foot tolerance between the transformed DEM and DEM derived from transformed LiDAR. This falls within the accepted 95% confidence interval. In addition, the hydrologic analysis (2) indicated that 99.92% of the watershed area remained the same between the original and transformed watershed. This is not a significant change for the published North Carolina rural regression equations.

[3] Collected in 2001 with a final nominal post spacing of 3 meters

[4] Since the current NED incorporates the LiDAR information, 7.5-minute NED data from 1999 with a spatial resolution of 30 meters was used to simulate areas of the country where high accuracy elevation data is not available. The center of the cell was used to create mass points from the DEM.

The results of the floodplain boundary analysis (3) showed that changes caused by the datum modernization cannot be ignored in future floodplain mapping. From the floodplain area based on the LiDAR data, the floodplain area decreased by 1.16% while the floodplain based on the NED increased by 0.35%. The vertical shift in the BFEs at the cross sections is similar to the overall vertical shift at an average of -0.966 feet (LiDAR) and -0.947 feet (NED). Although this indicates coordinates and BFEs will change significantly, for this location and study area the floodplain itself will not because there is little relative change. However, each location will have unique characteristics and the small changes at Tranter's Creek suggest that there should be further investigation into where significant change might occur (e.g., subsidence areas).

Some changes in the floodplain boundary may be an artifact of the mapping process. As part of the procedure for generation of the automated floodplain boundary, the cross sections used to produce the water surface elevation TIN were extended across the entire mapping area, resulting in interpolations across large distances further away from the stream center. Because an automated mapping process was used to eliminate individual judgment, it is difficult to say whether these boundary changes would appear with the full FEMA mapping process. Additionally, many of the observed differences occurred in backwater fingers of the main stem of the stream, which are typically manually edited as part of the FEMA process for producing the final floodplain boundary. It is also interesting that there was minimal change with the lower accuracy elevation data (NED) and the change was not concentrated in a few areas as was seen with the high accuracy data.

The results from the bridge analysis (4) examined when height uncertainties in survey data would cause significant changes in the floodplain boundary or BFEs. This analysis showed that a -0.5 ft shift in the bridge height caused a significant horizontal difference in the floodplain width (over 11 ft). However, his was very dependent on the shape of the cross section in the hydraulic model and the hydraulic characteristics of the bridge. It is expected that this would vary across streams and types of obstructions. Additional analysis in a variety of locations is recommended to identify a lower bound on what height shift in obstructions would cause a significant change in the floodplain.

While the effective floodplain models and boundaries are not significantly affected by the datum shift, it is extremely important for floodplain mapping to understand and address height uncertainties, particularly as new technologies increase the accuracy of geospatial measurements and products. Depending on the location, type of previous elevation data, and engineering variables, the shift in heights by approximately 1 foot may make some existing floodplains fail the Floodplain Boundary Standard (FEMA, 2007). However, in most locations with current updated elevations the relative shift in coordinates is likely to be minimal. The main conclusions from this study are:

- Coordinates will shift significantly horizontally and vertically with the datum modernization
- The datum shift will have a larger impact on higher accuracy elevation data
- The size and shape of the watershed does not change significantly and thus the hydrology calculations do not need to be estimated based on transformed data

- DEMs can be transformed directly and do not need to be regenerated from transformed data
- In some areas there will be minimal relative changes and thus minimal changes in the floodplain boundaries or BFEs, but this will depend on the location-specific characteristics, the mapping method used, and engineering judgment
- Even in locations where there is no change in the floodplain boundary, existing floodplain models and BFEs that were generated in the current datums will be significantly different from ground data measured in the new datums
- While this study provides the first look at the expected effects, additional studies are warranted prior to the 2022 modernization
- Because of the significant coordinate shift and potential impact, the development of an implementation plan is extremely important for FEMA and other federal agencies who are required to adopt the official U.S. datums
- Successful implementation of the new datums will depend on a clear message and open communication to all constituents to explain why changes are occurring

While the release of the new datums is years away, adequately preparing for this change well in advance will assist in a timely and smooth transition. The next steps should include testing other locations, a more in-depth analysis of how FEMA will implement the new datums, and developing specifications for the use of bench marks. An implementation plan should include, but not be limited to, identifying all specifications, guidelines, and policies that need to be revised, preparing a data management plan that includes the databases that would need to be updated, and organizing an outreach and education plan. Successful cooperation and communication on the appropriate and timely implementation of the datum modernization will improve the accuracy of floodplain maps that are vital to saving lives and property.

1. INTRODUCTION

The official national datums of the United States are the foundation for all geospatial activity and their accuracy is extremely important to many applications, including construction, agriculture, resource management, navigation, and emergency management (Office of Managmenet and Budget, 2002). The National Geodetic Survey (NGS), following its mission to "define, maintain and provide access to the National Spatial Reference System (NSRS) to meet our nation's economic, social, and environmental needs," plans to modernize the official datums by approximately 2022. This modernization will mean the replacement of the current official horizontal and vertical datums, the North American Datum of 1983 (NAD 83) and the North American Vertical Datum of 1988 (NAVD 88), with new geometric and geopotential datums, respectively (National Geodetic Survey, 2008). For federal agencies, for which the NSRS is the fundamental geodetic control (Office of Managmenet and Budget, 2002), this shift will require resources to manage changes to data collection methods and maintenance of existing data holdings.

In order to prepare for this transition, NGS initiated a pilot project with the Federal Emergency Management Agency (FEMA), the North Carolina Floodplain Mapping Program (NCFMP) and the North Carolina Geodetic Survey (NCGS) to examine how the shift will affect a specific application – floodplain mapping – and what preparations would assist the process. North Carolina was chosen as the study location because they are a Cooperating Technical State with FEMA and have extensive mapping data. The goals of this project were to:

1) Quantify (magnitude, direction, and spatial distribution) the expected coordinate shifts and determine what data and/or products need to be converted (effect on data)
2) Determine the impact on floodplain mapping analysis (effect on analysis)
3) Investigate the tolerance for survey uncertainty to guide future data collection (effect on collection)
4) Provide recommendations for tools or actions that would assist with the above

Details on the two main components of this project, the national datums and floodplain mapping, are provided below. Section 2 describes the methods used in this study and the results are provided in Section 3. Section 4 and 5 provide the conclusions and recommendations respectively. Because of the technical nature of this study, Appendix A lists a glossary of common terms and Appendix B provides a list of acronyms and abbreviations.

1.1. MODERNIZING THE NATIONAL DATUMS

Over the last two decades, the technologies of geodesy and surveying have changed radically. In order to provide the most accurate reference system to the nation, NGS is planning on releasing a new geopotential (vertical) datum by 2022 to replace the North American Vertical Datum of 1988 (NAVD 88), the current official vertical datum of the Unites States. At the same time the North American Datum of 1983 (NAD 83), the current official horizontal datum, will be replaced with a new geometric reference frame. These replacements are planned in order to remove systematic deficiencies in the current datums and provide reference frames more compatible with modern positioning technologies, especially space-based systems. Of particular importance to floodplain maps, these updates will provide a critical adjustment to orthometric heights that are offset up to 2 meters (over 6 feet) and have significant impact on many federal agencies. While the actual impact to the floodplain is the question of this study, the new geopotential datum will also impact national floodplain standards. As The National Research Council stated in *Mapping the Zone*, "…uniform national standards for FEMA flood maps cannot be met until an improved orthometric height datum and geoid model exist" (National Research Council, 2009, p. 27). Although both datums will be replaced, it is the change to orthometric heights in the new geopotential datum that are expected to have the most significant effect on floodplain maps.

1.1.1. Bench marks: Current and Future Access to the Vertical Datum

The current vertical datum, NAVD 88, is primarily accessed through passive marks in the ground (bench marks) of "known" heights published in the NGS database. These bench marks are the foundation for access to orthometric heights. The problem with this method is as NGS states in the Gravity for the Redefinition of the American Vertical Datum (GRAV-D) plan:

> Because the heights on these marks are not regularly checked, and because they are destroyed by construction, the maintenance of a vertical datum by this method cannot be perpetuated. Only a new method—through [the Global Positioning System (GPS)] and gravity—can allow NOAA to maintain a quality level of service to the nation in the definition of the vertical datum (The GRAV-D Project: Gravity for the Redefinition of the American Vertical Datum, 2007, p. 3).

The ideal future method would be a combination of Global Navigation Satellite System (GNSS, of which GPS is a part) and gravity to allow real-time access to the new geopotential datum. Instead of the current *modus operandi* of starting on and tying to bench marks, which may be miles away from the target location and have moved (vertically) since last measured, a project could use GNSS to define a starting point accurate on that day and wherever is most convenient. This vision removes the uncertainty caused by the time difference of the survey and the epoch on the database height as well as bench mark maintenance problems.

However, moving away from the use of unchecked bench marks to GNSS-only access is not simple. Although there are accepted scientific reasons to discontinue the use of bench marks, practical and legal hurtles will likely prevent a complete shift. While the trend will likely be towards GNSS methods, certain sectors will continue to rely on bench marks. NGS is considering a number of options to increase awareness and promote the appropriate use of bench marks, such as publishing error bars on bench marks that change over time, placing prominent warnings on suspect datasheets, or simply not publishing uncertain values.

While a decision has not been made by NGS, this study will address the case that error bars are published for orthometric heights. This option provides the user with the most information, but also the responsibility to use the information appropriately. One aspect of this study is to determine how floodplain mapping should handle these error bars. In other words, how much uncertainty in a bench mark height is acceptable? Answering this question for multiple applications will assist in future decisions on how organizations will access the NSRS.

1.1.2. Gravity for the Redefinition of the American Vertical Datum (GRAV-D)

NGS' goal for the new geopotential datum is to provide fast and accurate orthometric heights with an accuracy of 2 centimeters at 95% confidence where possible. Orthometric heights are calculated by subtracting geoid undulations from ellipsoid heights (obtained from GNSS). While ellipsoid heights from GNSS may have an accuracy of 1 centimeter (depending on equipment, time span of data collection, etc), the current geoid model does not match that. The calculation of an accurate national geoid model (i.e., the equipotential gravity surface best approximating mean seal level), requires spatially and temporally consistent measurements of gravity. Initiated in 2007, GRAV-D aims to fulfill this need by 2022.

GRAV-D is an initiative to implement airborne gravity collection techniques on a national scale. Airborne gravity was chosen to connect available local ground and global satellite measurements. Over roughly twelve years, a gravimeter will be flown over the United States and its territories in a grid pattern with about 10 km spacing. By combining ground, aerial, and satellite measurements, a highly accurate geoid model can be produced and monitored for changes. This will ultimately provide nationally consistent, highly accurate, and easily accessible heights for many applications, particularly those concerned with the flow of water.

1.2. FLOODPLAIN MAPPING PROCESS

FEMA is responsible for managing the National Flood Insurance Program (NFIP) that relies on maps of flood risk. Floodplain mapping relies heavily on vertical measurements and some areas may see significant changes to floodplains when using the new geopotential datum. Ensuring that FEMA is prepared to successfully incorporate the new datums is critical to efficiently realizing billions of dollars of potential benefits to life and property (Leveson, 2009).

1.2.1. Overview of Floodplain Mapping Process

Floodplain mapping combines three sets of data – imagery, elevation, and flood data – to create a Digital Flood Insurance Rate Map (DFIRM). Aerial imagery data are used as a base layer for reference. While the imagery is not involved in determining the floodplain boundary or flood elevations, it is included in the final product to assist in the identification of buildings, roads and other infrastructure.

Depending on availability, elevation data comes from a variety of different sources, including photogrammetry, light detection and ranging (LiDAR), and radar. While LiDAR has been found to be the most cost-effective within FEMA accuracy standards (National Research

Council, 2007), many localities do not have this data or the funds to acquire it. Instead, the United States Geologic Survey (USGS) National Elevation Dataset (NED) is often used even though “elevation uncertainties of the NED are about 10 times greater than those defined by FEMA as acceptable for floodplain mapping” (National Research Council, 2009, p. 3).

Finally, flood data consists of hydrologic and hydraulic models that produce water level heights for a statistical flood. Hydrologic models, such as Hydrologic Engineering Center—Hydrologic Modeling System (HEC-HMS), use topography and statistical rainfall data to convert rainfall into stream flow. This information is used in the hydraulic models, such as the Hydrologic Engineering Center-River Analysis System (HEC-RAS), with ground cross-section survey data, topography, and a stream centerline to determine the water surface elevation at various stream cross-sections. Specialized models are created for coastal areas to deal with tidal affects and storm surge. HEC is part of the U.S. Army Corps of Engineers (USACE) and is the principal author of hydraulic models utilized for flood delineation in FEMA studies.

To create the floodplain boundary, the cross-section water heights, or base flood elevations (BFEs), are overlaid with the elevation data and a boundary is drawn based on the contours of the land. For a detailed study the 100-year and 500-year boundaries are combined with the imagery and supporting information, such as BFE values and locations, bench marks, and the floodway (area of highest flow that is required to discharge floodwater), to produce the FIRM or DFIRM. The amount and type of data used in the study and the information displayed on the map are determined by the type of study conducted.

FEMA allows four types of flood studies: detailed, limited detailed, approximate, and redelineation. Detailed studies require the most data collection, review of all models, and provide the most information on maps about flood hazards, including BFEs, floodway, and moderate flood hazard areas. Limited detailed studies are similar, but do not require survey information on bridges or culverts and do not include a mapped floodway. Approximate studies provide only an estimate of the flood boundary with no BFEs, floodway, or other details. Finally, redelineation is used when new topographic data are available. A redelineation analysis is rerun using the new data, but flow and field survey data are used as published with the previously created engineering models (National Research Council, 2009).

The analysis for this study focused on key pieces of the above process. A stream with a detailed and limited detail riverine study was chosen for simplicity. Only the elevation and flood data components were analyzed. While imagery is an important aspect of the DIFRM and does need to be geospatially consistent, it does not affect the location or depth of the floodplain. Finally, this study does not discuss all geospatial aspects, but focuses on the effect of positioning, specifically the role of bench marks and the future datums, on floodplain mapping.

1.2.2. North Carolina Floodplain Mapping Program

To do a detailed data analysis, a specific site needed to be chosen for the case study. North Carolina (NC) was chosen as the site for this study based on the NC Floodplain Mapping Program’s (NCFMP) close involvement with FEMA and leadership in floodplain mapping. As the first Cooperating Technical State (CTS) within FEMA’s CTS partnership initiative, NCFMP takes ownership and responsibility for the Flood insurance Rate Maps (FIRMs), which includes the analysis and updates of that state's digital FIRMs (DFIRMs). Through this partnership the NCFMP has taken the lead on collecting and maintaining accurate flood information. This wealth of information allowed the study to compare and evaluate various mapping methods. In addition, the willingness of NCFMP to contribute personnel and financial resources to the project was a significant asset, particularly in contributing the floodplain mapping perspective and building the support to promote and hopefully implement the recommendations.

1.2.3. FEMA Accuracy Requirements

Current FEMA accuracy requirements, described in the Methods Section 2.1.3, are used as the measure for significant change in the floodplain boundary or BFEs. The results of the analysis are based on these requirements. However, FEMA requirements may not remain constant in the future, as described in the subsequent section. While the conclusions use the current standards, the results presented may be evaluated against any standard of interest.

1.2.4. Future of Floodplain Mapping

While data collection technology is not expected to change significantly, the method of producing floodplain maps and delivering the accompanying data is changing. Rather than producing printed hard copy Flood Insurance Rate Maps (FIRMs), there is movement toward digital-only maps. Although Digital Flood Insurance Rate Maps (DFIRMs) are available today, digital data is not a deliverable and it is still a requirement that maps are physically printed. Printed maps are the main driver in the current accuracy requirements because a printed line takes up physical "space" on a map. This inherent inaccuracy on a printed map would be removed in a fully digital environment. With the move to digital-only maps it is uncertain if FEMA will update accuracy requirements and how they will change. As a result, any shifts in the floodplain or BFEs in this study need to be considered not only with respect to current accuracy requirements, but also with regard to the potential for tighter future accuracy requirements.

2. STUDY METHOD

The methodology was split into two parts: A) data transformation into proxy datums to approximate the future datums and B) data analysis of the shift and impact to floodplain mapping. Part A was developed specifically for this project in order to evaluate Part B. The actual method of transforming data in the future will likely be streamlined with the release of the official datums. Part B was then designed to answer specific question to address the first three goals identified above. It is divided into the following sections:

1) Quantify (magnitude, direction, and spatial distribution) the expected coordinate shifts and determine what data and/or products need to be converted (effect on data)
    a. What is the average coordinate shift and range? Is this spatially consistent?
    b. Can derived products be transformed or do they need to be recalculated from transformed base data or original observations?
2) Determine the impact on floodplain mapping analysis (effect on analysis)
    a. Does hydrology need to be recalculated for existing studies? In other words, does the area or slope of the watershed change significantly?
    b. How much does the floodplain boundary change? BFEs? Is this different for LiDAR and the NED?
3) Investigate the tolerance for survey uncertainty to guide future data collection (effect on collection)
    a. Under the current FEMA guidance, when is error on a bench mark too large for the published height to be used without resurveying the mark?

To answer these questions three locations were initially chosen to compare results from different geographic areas. However, because of limited time and resources this study presents only one of the three. The chosen site is in the coastal plain with the least change in elevation. It is expected with coordinate shift that this location would be most sensitive to small elevation changes and would therefore be a conservative location to judge how floodplain mapping results may be affected.

Section 1 studied coordinate shift and was conducted through statistical and spatial methods. Because of their high accuracy and density, the LiDAR points were used to quantify the shift and determine the distribution. A random sampling of LiDAR points was also used to study spatial patterns of the horizontal and vertical shift. The derived product analyzed for the purposes of floodplain mapping was the 50 foot DEM derived from LiDAR, which is typically used for hydrology. The difference between the transformed 50 foot DEM (D5) and a 50 foot DEM created from the transformed LiDAR was analyzed with regards to FEMA accuracy standards of 2 foot contours for flat areas. If 95% of the points in the D5 DEM fell within 2 feet of the DEM from transformed LiDAR then the 50 foot DEM would not need to be recreated and could instead be transformed directly.

Section 2 examined the impact on the engineering models and floodplain mapping result to inform what processes would be influenced by the coordinate shift. The first engineering step, hydrology modeling, is most sensitive to catchment area, or the watershed for a section of stream (National Research Council, 2009). Using a standard watershed delineation process in ArcMap, watersheds based on the original and transformed 50 foot DEM were compared. The watershed areas were used in USGS regression models to determine the expected change in discharge for a base flood (100-year storm or storm with a 1% probability).

The second engineering step, hydraulic modeling, uses a standard step backwater solution at cross-sections extracted from LiDAR to determine the water level for a given storm discharge from the hydrology modeling. In order to remove all aspects of engineering judgment that could skew the results, the effective model and associated model parameters were not used and new engineering model cross-sections were extracted for the original and transformed LiDAR and NED data. These cross-section elevations where sent through the same, repeatable model in an automated process to determine changes in the floodplain boundary and BFEs. The other engineering parameters required for the model were set to be constant along the stream and set to be equal to the average of the parameters in the effective model. The resultant water surface elevation changes were also compared between the LiDAR and NED to determine if spatial resolution makes a difference in the impact of the shift.

Section 3 looked at how error bars on bench marks would be treated in floodplain mapping. Since there is existing guidance on the accuracy of survey data, a literature review of the FEMA and surveying standards was conducted to determine when a bench mark with an error bar could be used for floodplain mapping. This was supplemented by a quantitative analysis that added in transformed survey data for a structure to the simple hydraulic model used above. This structure was then adjusted up and down to figure out the limits to the height error.

The following sections provide details about the method outline above, including 1) Initial assumptions and parameters, 2) selection of study locations, 3) data transformation, and 4) data analysis.

2.1. METHOD PARAMETERS

2.1.1. Proxy for New Datums

Since the new datums are not available, proxy datums were used. Where access to NAD 83 or NAVD 88 is required in the existing floodplain mapping process ITRF2005 (referenced to the GRS-80 ellipsoid) was used in place of NAD 83, while the USGG2009 gravimetric geoid served as a proxy for the zero elevation surface of the new geopotential datum. While they are not equivalent, the new geometric reference frame will be similar to ITRF2005/GRS-80 except for the rotation of the North American tectonic plate with respect to ITRF. Similarly, the new geopotential datum will use a gravimetric geoid as its zero elevation surface, but the final surface will differ from USGG2009. Despite these differences, ITRF2005 and USGG2009 were the best estimates of the new datums at the time of this study. Although USGG2009 is tied to

ITRF2000, ITRF2005 was used for both the geometric and in the calculation of heights to be consistent and the difference between the two is minimal, about 7 mm in North Carolina.

2.1.2. Accuracy Requirements for Evaluation of Results

The significance of floodplain or BFE changes is determined by FEMA accuracy requirements. According to Appendix A: Aerial Mapping and Surveying, digital topographic data must have a vertical accuracy of:

- Two-foot equivalent contour intervals for flat terrain ($Accuracy_z$ = 1.2 feet at the 95-percent confidence level)
- Four-foot equivalent contour interval for rolling to hilly terrain ($Accuracy_z$ = 2.4 feet at the 95-percent confidence level) (FEMA, 2003, pp. A-5)

In other words, for flat terrain 95% of the heights used to test the surface must be within 1.2 feet of the surface elevation. The corresponding root mean square errors are 0.61 feet (18.5 centimeters) and 1.22 feet (37 centimeters) (National Research Council, 2009, pp. 115-116). The transformation of existing flood data into a new datum will maintain the *relative* accuracy of the data and is unlikely to cause a violation of these standards.

Of greater interest is when errors on bench marks introduce significant uncertainty. Based on FEMA accuracy requirements, the National Research Council determined that "… a variation that produces a change in BFE of more than 1 foot may be significant" (Mapping the Zone: Improving Flood Map Accuracy, 2009, p. 46). Therefore, the maximum acceptable error on bench marks is when the maximum and minimum heights on bench marks produce a shift in the BFE of more than 1 foot.

The change to BFE was primarily used for evaluation since in the floodplain mapping process this value, combined with an elevation model, determines the boundary. The BFE and horizontal boundary are directly related. One study from the coastal plain showed that a 1-foot change in BFE causes a horizontal change of 42 feet (National Research Council, 2009). The horizontal change is evaluated and reported, but the standard of a 1-foot change is used as the metric for significant change.

2.2. SELECTION OF STUDY LOCATION

Initially, three study locations were selected and compared to determine if geography made a difference in how the methods affected the floodplain. However, after scoping the resources and time required for the analysis, only one of the three was chosen for this study. Although the selected location is expected to be the most conservative of the sites, should additional resources be found it is hoped that the other two locations will be analyzed to determine if the results differ in various geographies.

Possible study locations were streams that were previously studied in detail and had effective engineering models.[5] A number of additional criteria were used to narrow down the sites, including:

[5] An effective model is one that has been accepted for use in the official maps.

- Riverine models only to simplify the analysis (excludes coastal models)
- One in each of the three North Carolina regions: mountains, piedmont, and coastal
- Two or more bench marks within a ¼ mile to assist ground surveying
- Width of floodplain >10 m to allow for automatic processing of the floodplain boundary and remove processor judgment

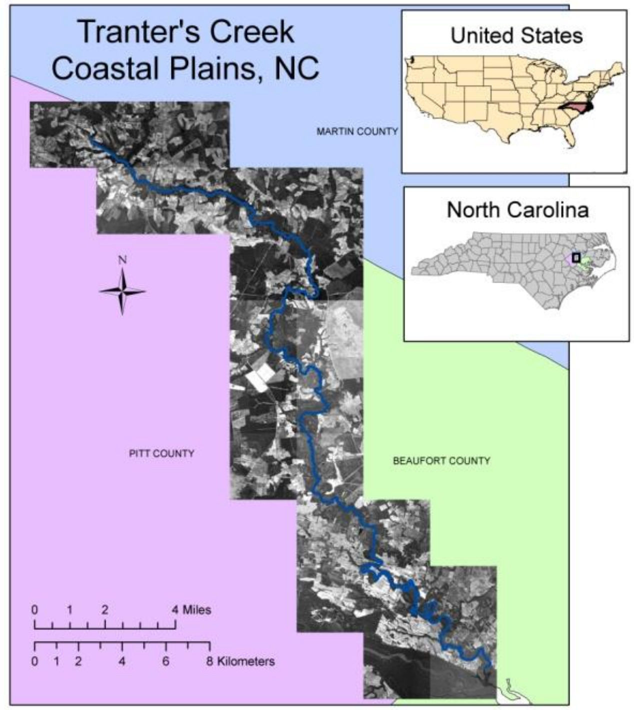


Figure 1: Study Location, Tranter's Creek

A short list from these criteria was reviewed based on the number of obstructions and cross sections in the model. To minimize processing time the three locations with the fewest obstructions and cross sections were chosen. The coastal location (Figure 1) was selected as the study site because small changes in heights in a flat landscape have a greater effect on the floodplain. In addition, watersheds in flat areas are more sensitive to changes in heights. Thus, if expected discharge does not change in the coastal area then it is unlikely to change in the piedmont or mountains.

2.3. PART A: DATA TRANSFORMATION

The transformation involved nine steps (Figure 2). Five types of data were transformed as point files, bare earth LiDAR, stream centerline, 50 foot DEM, engineering cross sections, and survey cross sections. GIS files were first converted into lists of points in ASCII. At the end all files were converted back into ArcGIS (version 9.3) for floodplain analysis. All data was received referenced to NAD 83 (2001), which is the second HARN adjustment for North Carolina.

The following intermediate steps were used to transformation the data. In general terms, the process involves the following steps and NGS software listed in parentheses:

1. Transforming positions from a coordinate system to a geographic system by removing the state plane coordinates and converting feet to meters (SPCS83)
2. Transforming the heights from orthometric (NAVD 88) to ellipsoidal (NAD 83(2001)) by removing the hybrid geoid model GEOID99 (VDatum)
3. Transforming latitude, longitude and ellipsoid height from NAD 83(2001) to NAD 83(NSRS2007) (custom transformation for NC)
4. Transforming horizontal positions (latitude and longitude) from NAD 83(NSRS2007) to ITRF2005 using the same epoch date (HTDP)
5. Calculating the gravimetric geoid undulation values (USGG2009) for the ITRF2005 coordinates (INTG)
6. Converting ITRF2005/GRS-80 ellipsoid heights to proxy "true" orthometric heights using USGG2009 by subtracting gravimetric geoid values

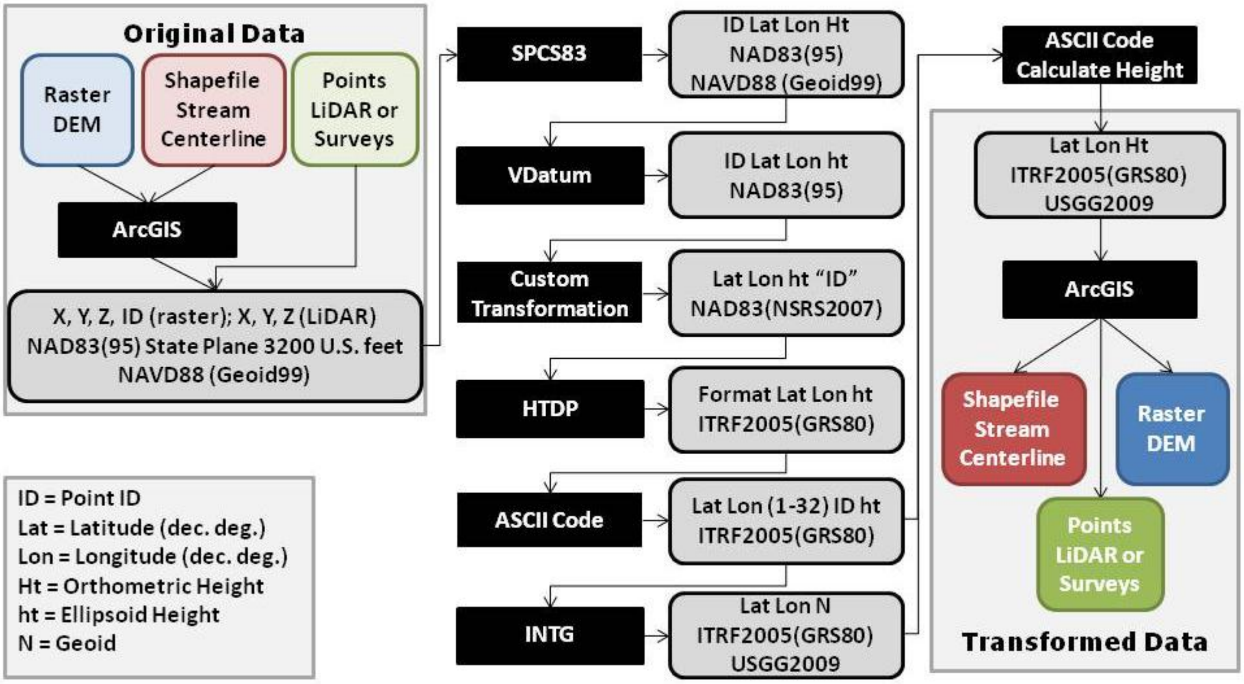


Figure 2: Method of converting coordinates into proxy datums

Except for Step 2 (VDatum), this process was conducted in UNIX using FORTRAN and UNIX batch scripts to quickly process multiple, large text files and address differences in input and output formats between programs. In Step 1 FORTRAN code was used to create an input and output file to and from SPCS83 and included a conversion from U.S. survey feet to meters.

Step 2 used VDatum to remove the hybrid geoid (GEOID99) to transform heights from orthometric (NAVD 88) to ellipsoidal (NAD 83(2001)). The input and output horizontal datum was NAD 83 (NSRS2007) with the input vertical datum as NAVD 88 and the output vertical datum set to NAD 83 (NSRS2007).

Step 3 used a custom transformation between NAD 83(2001) and NAD 83(NSRS2007) since there is no official transformation available. NGS has not published an official transformation because the shifts to NSRS2007 are quite small and disparate, making a simple “regional shift model” (like NGS’s NADCON software) inappropriate, as shown in Figure 3. While this was required to input the data into the HTDP software (Step 4), the accuracy of this transformation is uncertain.

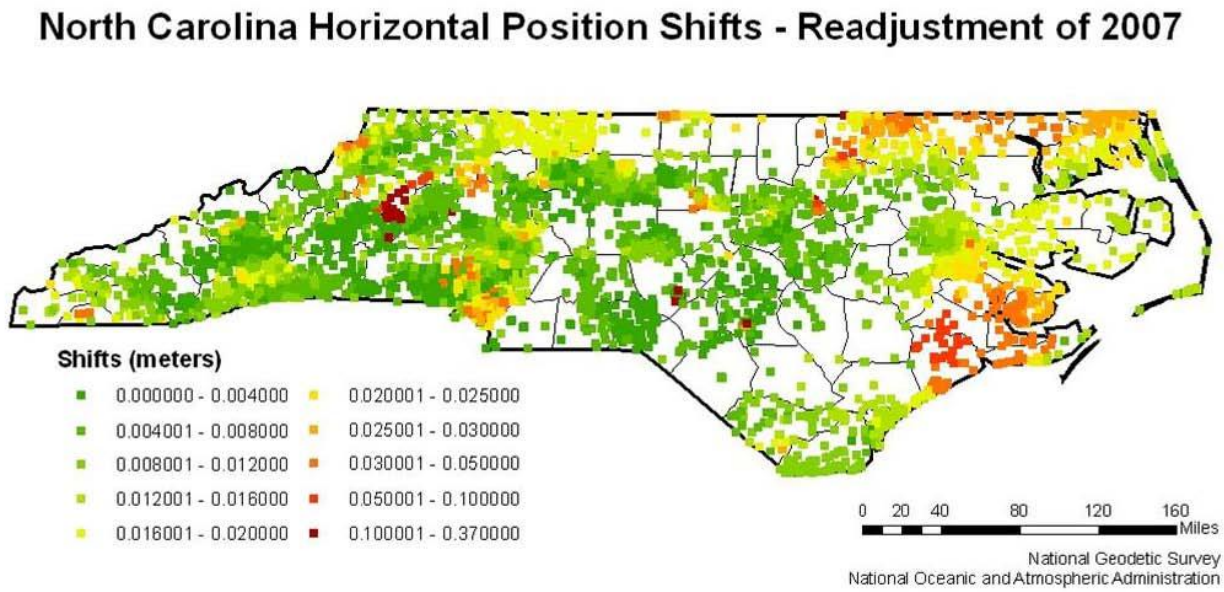


Figure 3: Map of Horizontal Shifts from 2007 Readjustment

The transformation for North Carolina was developed by compiling all bench marks in North Carolina that had measurements in NAD 83 (2001) and NAD 83 (NSRS2007). A 2-D grid of the change between these two values was developed separately for the northing, easting, and height. Values were then interpolated for the entire state and applied to the data points.

The isolated pockets of drastically different shift than the surrounding area (see red/orange pockets in areas of green in Figure 3) makes it difficult to develop an appropriate model. The anomalies are difficult to predict in a general surface, but without a transformation it is difficult to compare positions from different realizations. NGS is evaluating the accuracy of this transformation separately.

Step 4 used HTDP to convert the horizontal datum from NAD 83 (NSRS2007) to ITRF2005 (GRS-80). Although ITRF2008 was available, 2005 was chosen because this was the frame on which the USGG2009 gravimetric geoid was based. Step 5 used INTG to determine the USGG2009 values at each position. The geoid heights were then subtracted from the ellipsoid heights in Step 6 to produce the final transformed points with proxy "true" orthometric heights. The final step was to transform these geographic positions into State Plane northing and easting coordinates through CORPSCON.

2.4. PART B: DATA ANALYSIS

The data analysis was divided up into the following questions to address the three primary goals of this project:

1a. What is the average coordinate shift and range? Is this spatially consistent?
1b. Can derived products be transformed or do they need to be recalculated from transformed base data?
2a. How much does the floodplain boundary change? BFEs?

2b. Does the transformation have a different effect on the floodplain analysis with the use of LiDAR versus the NED as the elevation data layer?
2c. Do hydrology models need to be recalculated for existing studies? In other words, does the area of the watershed change significantly?
3a. Under the current FEMA guidance, when is error on a bench mark too large for the published height to be used without resurveying the mark?

2.4.1. Effect on Coordinates

The first question focuses on the data and providing information on the magnitude, direction, and spatial distribution of the coordinate shift between the two datums. This was analyzed by comparing the original LiDAR points to the transformed LiDAR points as demonstrated in Figure 4.

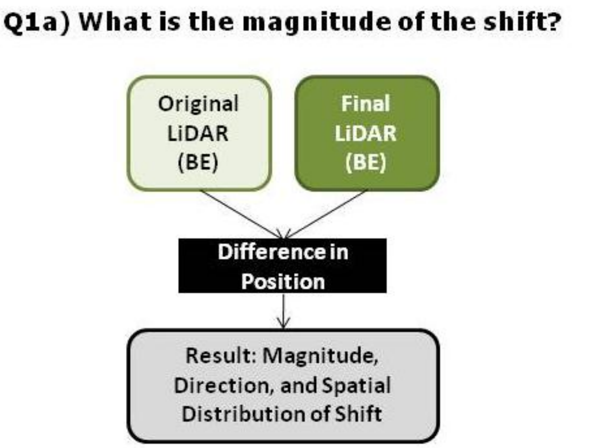


Figure 4: Method flowchart for Question 1a) What is the magnitude of the shift?

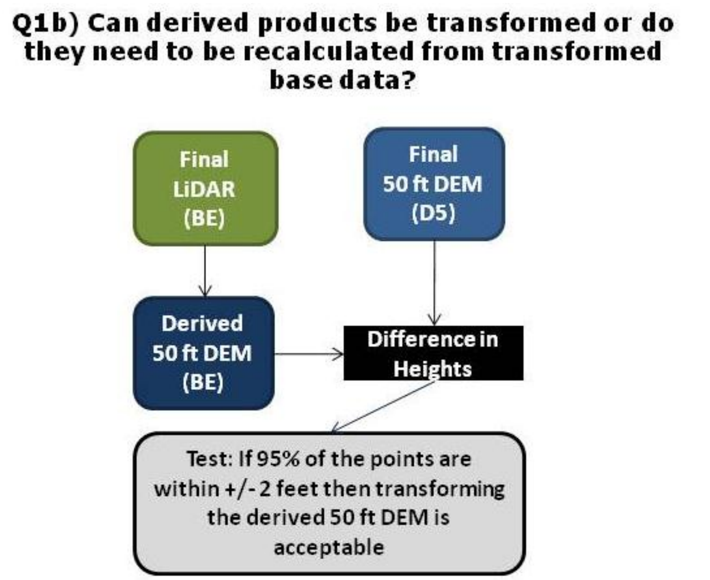


Figure 5: Method flowchart for Question 1b) Can derived products be transformed or do they need to be recalculated from transformed base data?

The second question examines data for floodplain mapping that is derived from other geospatial data. The primary example in floodplain mapping is the 50 foot DEM that is calculated from the LiDAR. The transformed 50 foot DEM was compared to a 50 foot DEM derived from the transformed LiDAR to understand whether a derived LiDAR product would need to be recreated or if the transformation process was acceptable. The significance of the difference was based on the accuracy of the LiDAR-derived surface, which is accurate to 2 feet based on the method of collection. If 95% of the heights in the transformed 50 foot DEM were within 2 feet of the DEM from transformed LiDAR then there was no significant difference (Figure 5).

2.4.2. Effect on Floodplain Mapping

There were two main questions associated with the two engineering steps: hydrology and hydraulic modeling. Since the output from the hydrology, discharge, is an input into the hydraulic model, hydrology was analyzed first to see if that model would need to change with the new datums (Figure 6). This was tested using the hydro-corrected 50 foot DEM. The primary factor in hydrology, which determines the peak flow for a stream, is the size of the watershed. If the watershed size remains the same with the transformation, then the previous runoff model could be used and the hydrology analysis would not need to be repeated. Size of the watershed was compared between the baseline and transformed DEMs for both the NED and 50 foot LiDAR derived DEM. The change in watershed area was imported into the USGS regression equations for hydrology to get a percent change in discharge.

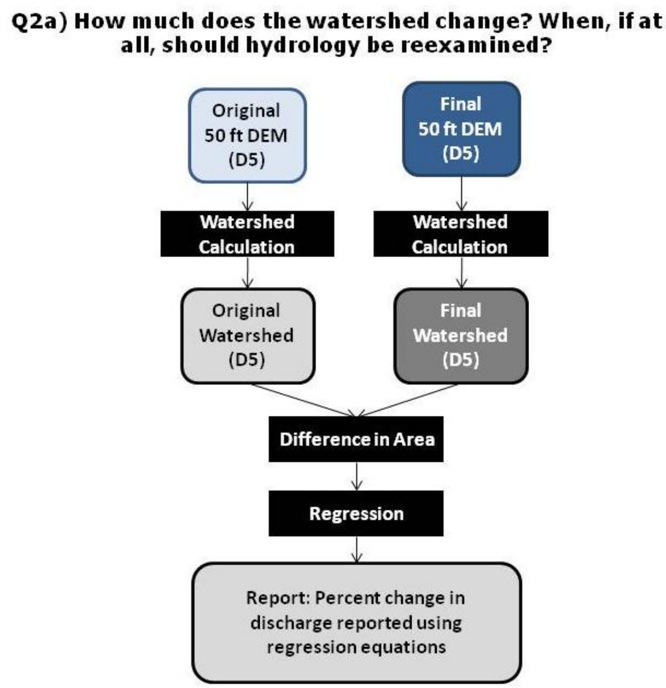


Figure 6: Method flowchart for Questions 2c) How much does the watershed change? When, if at all, should hydrology be reexamined?

The second analysis focused on hydraulic modeling and the creation of a floodplain boundary (Figure 7). The method was designed to be repeatable, absent of engineering judgment and simple in order to isolate the effect of shifting coordinates. The floodplain boundary was created from the difference between a water surface Triangulated Irregular Network (TIN) model and a ground surface TIN (Figure 8). Ground surface TINs were created from the elevation data (LiDAR or NED) as mass points and the centerline as a breakline. To prevent surface anomalies in the stream channel all elevation points within 15 feet of the centerline were removed. All obstructions, including bridges and culverts, were ignored because of the engineering judgment and time that is involved in adding these features. However, one obstruction was added and tested, as described in the following section.

The water surface TINs were created using the HEC-RAS hydraulic model and ArcGIS. Cross sections along the stream were used to extract profiles from the ground surface for the model. Using these profiles, HEC-RAS was used to determine the water level at each cross section based on the discharge from a 100-year storm. To further simplify and limit the impacts of engineering judgment on the analysis, no blocked obstructions or ineffective flow areas were included in the hydraulic model and a single average Manning's n value was used for both the stream channel and overbanks. Manning's n values were estimated from the effective flood studies on the stream. Finally, bank stations, which identify the location of the top of stream bank in the HEC-RAS model and represent where the channel Manning's n value is applied for conveyance calculations, were automatically generated using a uniform distance from the stream centerline.

Water and ground surface TINs were created with both original and transformed data. Transformed cross-sections were used with the transformed ground surfaces. To map the floodplain, each cross section was assigned the water level elevation based on the HEC-RAS output. The cross sections were extended in order to guarantee the entire floodplain area of the main channel would be captured. The cross sections were then used as breaklines for the water surface TIN. The ground surface was then subtracted from the water surface. All areas with a positive difference were considered in the floodplain.

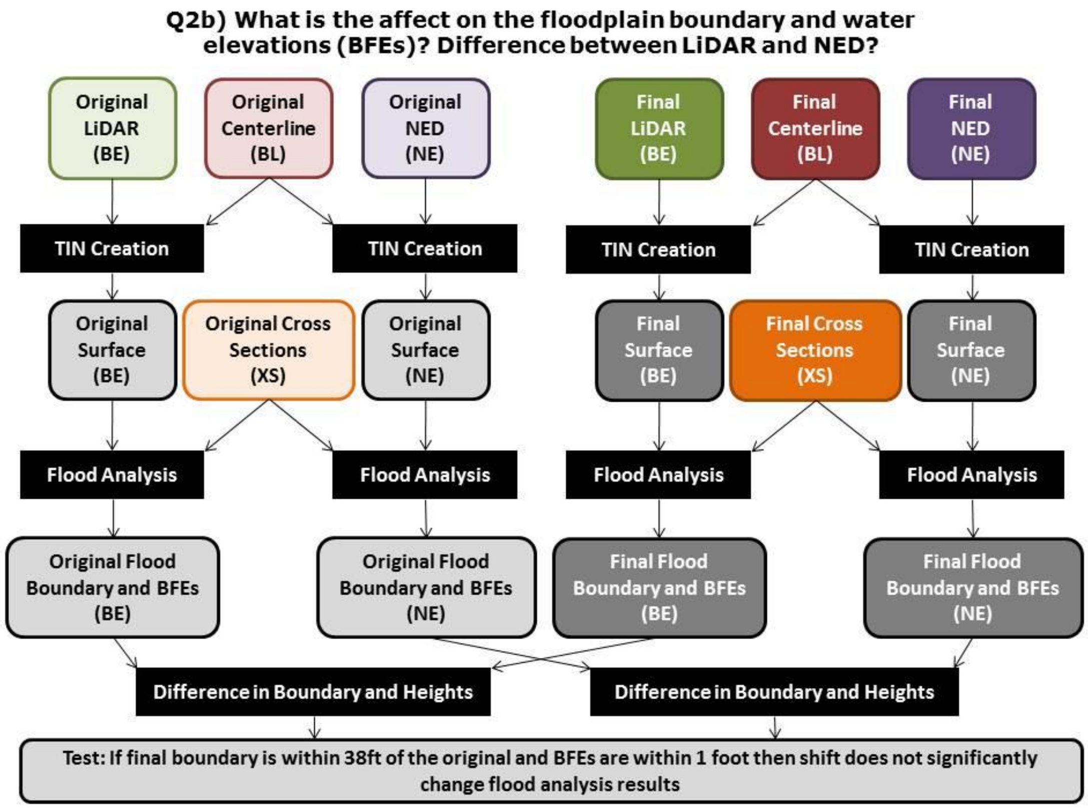


Figure 7: Method flowchart for Question 2b) What is the effect on the floodplain boundary and water elevations (BFEs)?

2.4.3. Effect on Surveying for Floodplain Mapping

Surveying and mapping standards are set by a variety of groups, including FEMA and state regulatory agencies. In the case that error bars are published on bench mark heights, these standards would influence when the use of published heights is acceptable. A literature review of the FEMA standards was conducted to identify the most stringent requirement, but it is also important to consider state or local requirements that may also influence surveying practices.

To supplement the current published guidance, a quantitative test on the effect of changing survey heights was conducted. Since flood analyses are highly sensitive to surveyed structures, a bridge was added into the model using transformed survey data. Since this analysis is focused on the sensitivity of the floodplain to structure height the original data was used to eliminate any errors introduced with the transformation. The bridge was added to the model using the same engineering parameters as the effective model. The heights on the structure were adjusted up and down to determine the tolerance of the models to errors. The minimum height change which caused a 1 foot change in BFE or a 38 foot change horizontally was considered the acceptable limit in bench mark error (Figure 9).

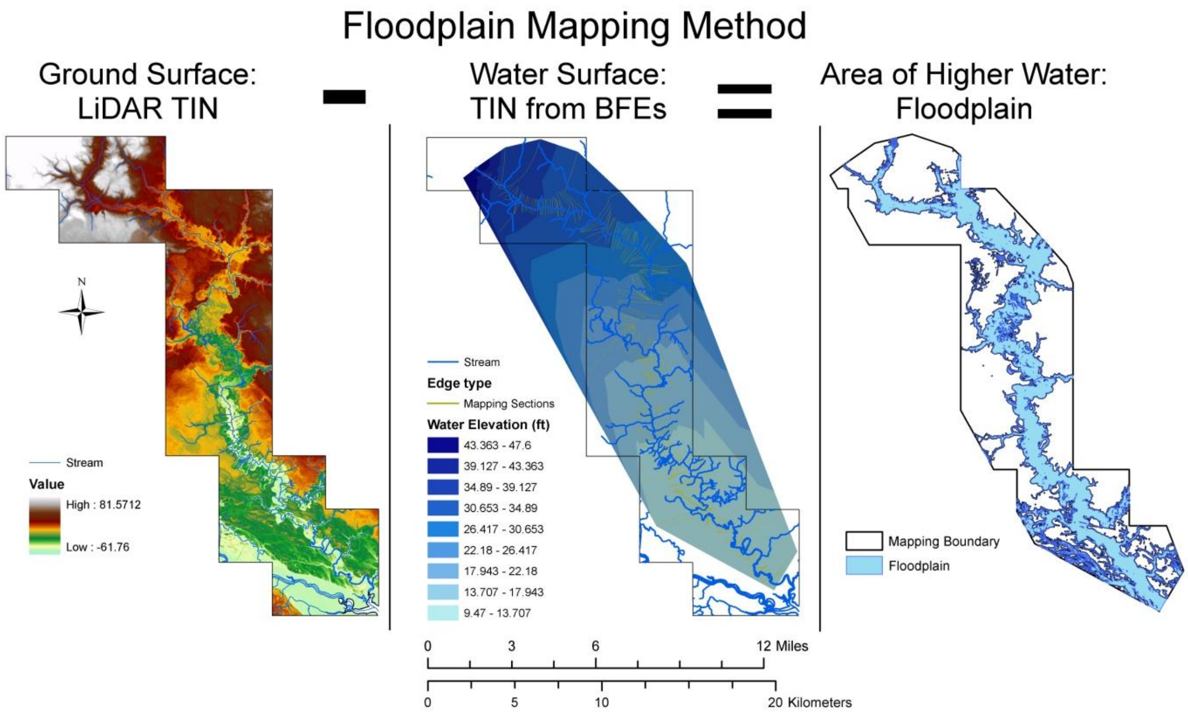


Figure 8: Graphical Representation of Floodplain Mapping Method

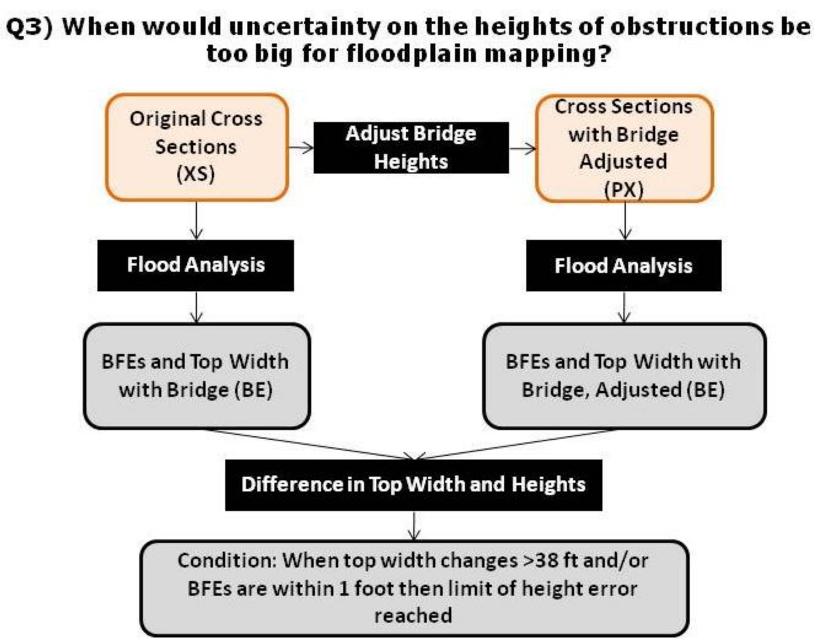


Figure 9: Method flowchart for Question 3) When would uncertainty on the heights of obstructions be too big for floodplain mapping?

3. RESULTS

The results of the data analysis are reported below. In most cases results are reported in both feet/square miles and meters/square kilometers based on the conventions of floodplain mapping and geodesy, respectively.

3.1. EFFECT ON COORDINATES

There were significant shifts horizontally and vertically. Based on the bare-earth LiDAR points, the average horizontal shift to the proxy datum was 2.72 feet (0.828 m) in the west northwest direction. The average vertical shift was -0.95 feet (0.289 m) in the vertical down from NAVD 88. The ranges and standard deviation are reported in Table 1. While the range of values is small, there is not a normal distribution of horizontal and vertical shifts as shown in Figure 10 and Figure 11. This is not surprising since the differences are systematic rather than random.

Table 1: Statistics on LiDAR Coordinate Change

US feet	Average	Max	Min	Std Dev
dx	0.947036	0.9580	0.937	0.003752
dy	-2.54529	-2.535	-2.564	0.004917
dxy	2.715762	2.737	2.705302	0.005598
dH	-0.94695	-0.9168	-1.0873	0.028079

Meters	Average	Max	Min	Std Dev
dx	0.288657	0.2920	0.285598	0.001143
dy	-0.7758	-0.77267	-0.78151	0.001499
dxy	0.827766	0.834171	0.824578	0.001706
dH	-0.28863	-0.27944	-0.33141	0.008559

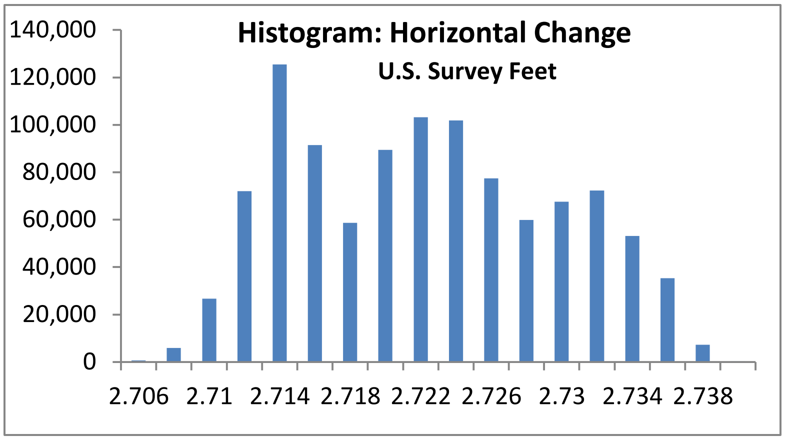


Figure 10: Distribution of Horizontal Change of LiDAR points

Although the standard deviation is relatively small, the shift is spatially correlated with larger horizontal and vertical shifts occurring in the northwest area (Figure 12).

The analysis of the derived 50 foot DEM shows that if the stream centerline is ignored that 96% of the points fall within 2 feet of the 50 foot DEM from the transformed LiDAR. The errors are reported for 1, 2, and 3 foot tolerances in Table 2. Figure 13 shows the spatial distribution of the differences. A large portion of the significant differences between the two are at the stream centerline. This is because the transformed DEM was hydro-corrected, but the DEM from transformed LiDAR was not. It was not possible to fully recreate the hydro-correction process that was used in the original 50 foot DEM, so statistics are reported with and without the centerline. In the case that the DEM would be recreated from the LiDAR it would be hydro-corrected, so the "without centerline" statistics are considered the most appropriate. Based on the accuracy of the LiDAR data a 2 foot tolerance is appropriate and over 95% of the points fell within this range.

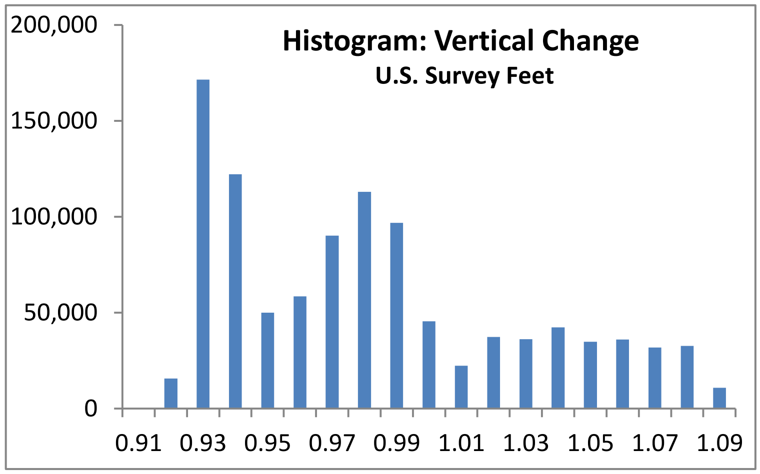


Figure 11: Distribution of Vertical Change of LiDAR Points

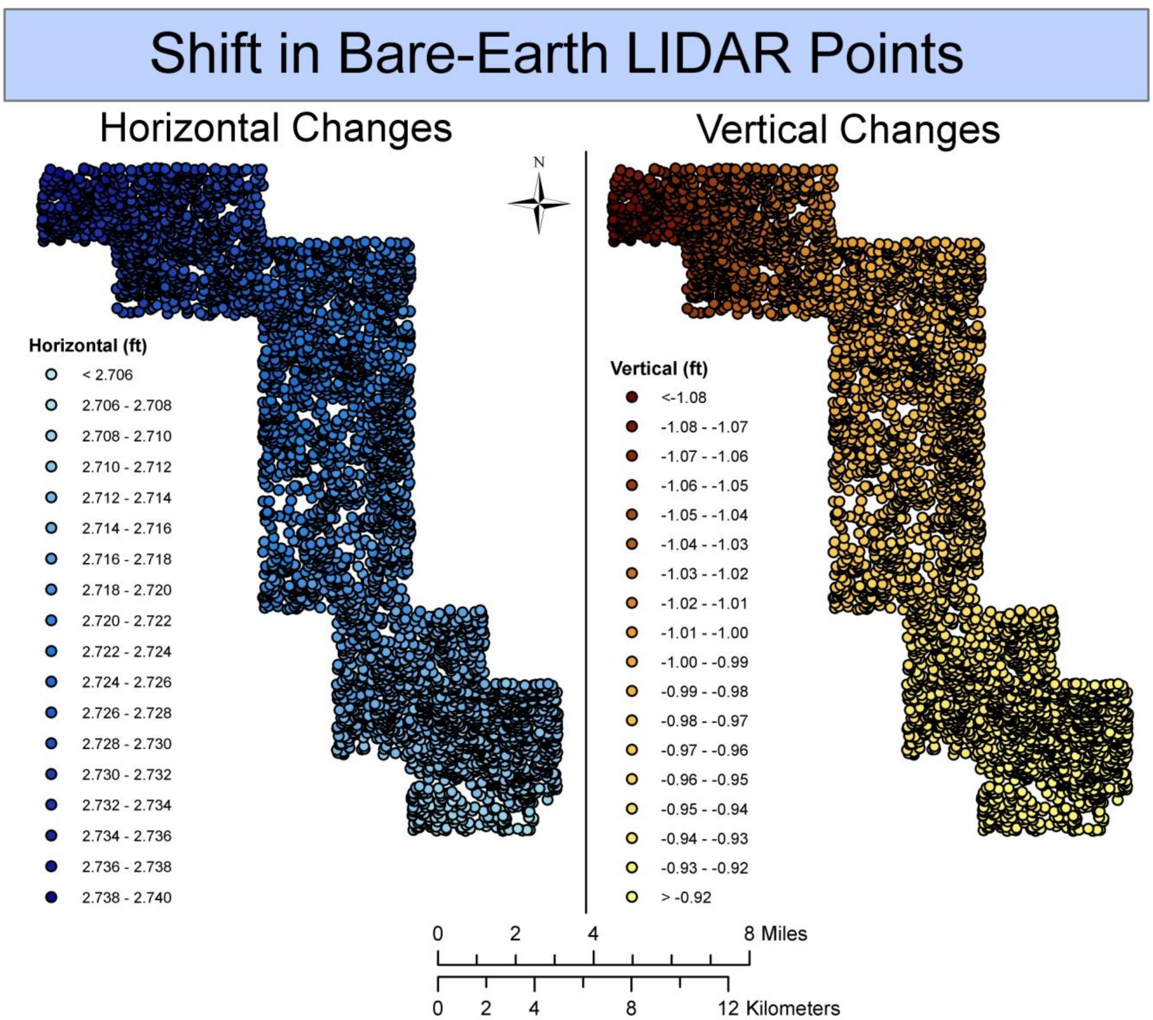


Figure 12: Spatial Distribution of Horizontal and Vertical Changes of Bare-Earth LiDAR Points

Table 2: Evaluating the Difference in Transformed DEM and DEM from Transformed LiDAR Based on a 1, 2, and 3 foot Tolerance

DEM Elevation Differences Transformed - LiDAR				
	Average	Max.	Min.	Std Dev.
Feet	-0.449	17.313	-52.109	3.087
Meters	-0.137	5.277	-15.883	0.941

1 foot tolerance				
Range (ft)	Area (sq. ft)	Area (sq. km)	Percent	w/o Stream
< -10	15794100	1.467	2.0%	0.0%
-10 to -1	50019300	4.647	6.3%	6.5%
-1 to 1	681786000	63.340	86.3%	88.0%
1 to 10	42644700	0.396	5.4%	5.5%
> 10	26100	0.002	0.0%	0.0%

2 foot tolerance				
Range (ft)	Area (sq. ft)	Area (sq. km)	Percent	w/o Stream
< -10	15794100	1.467	2.0%	0.0%
-10 to -2	17238600	1.602	2.2%	2.2%
-2 to 2	744003000	69.120	94.1%	96.1%
2 to 10	13208400	1.227	1.7%	1.7%
> 10	26100	0.002	0.0%	0.0%

3 foot tolerance				
Range (ft)	Area (sq. ft)	Area (sq. km)	Percent	w/o Stream
< -10	15794100	1.467	2.0%	0.0%
-10 to -3	8595900	0.799	1.1%	1.1%
-3 to 3	761529600	70.748	96.4%	98.3%
3 to 10	4324500	0.402	0.5%	0.6%
> 10	26100	0.002	0.0%	0.0%

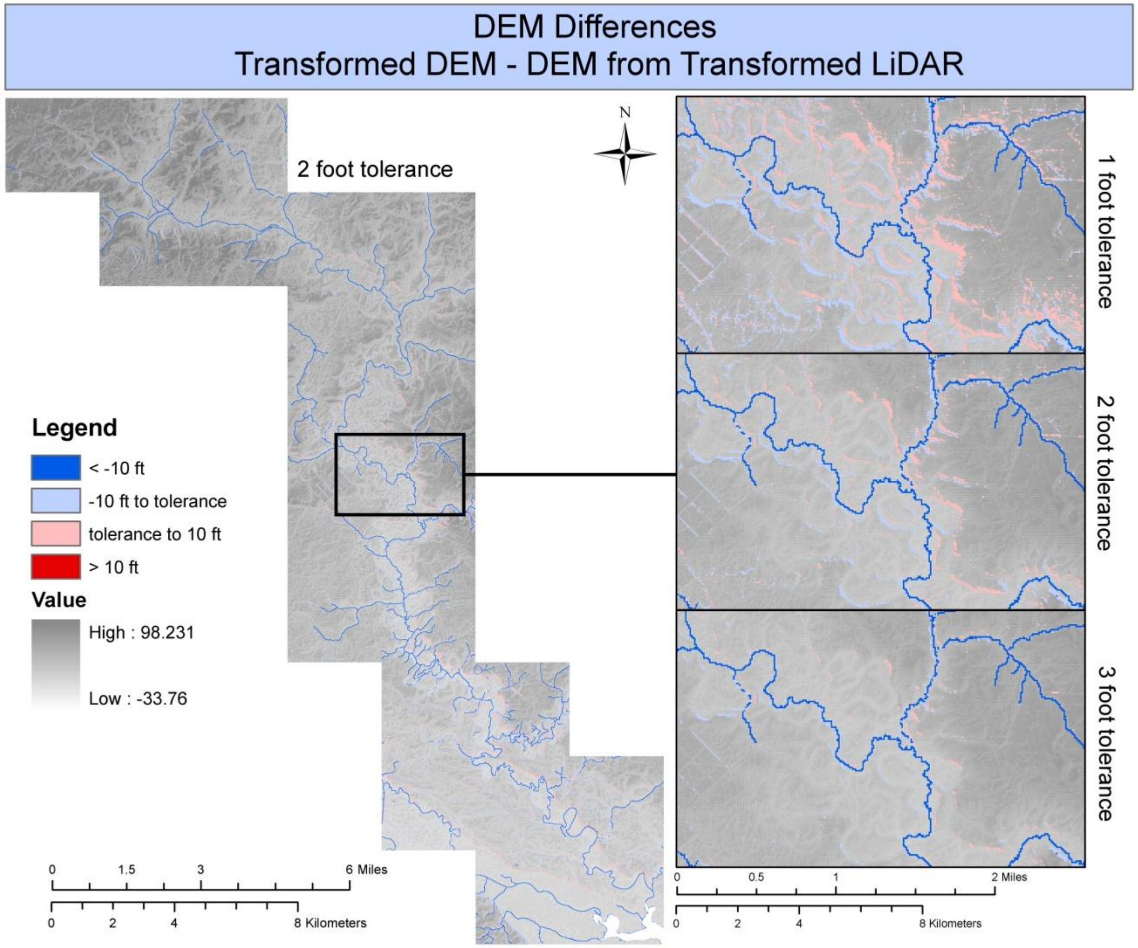
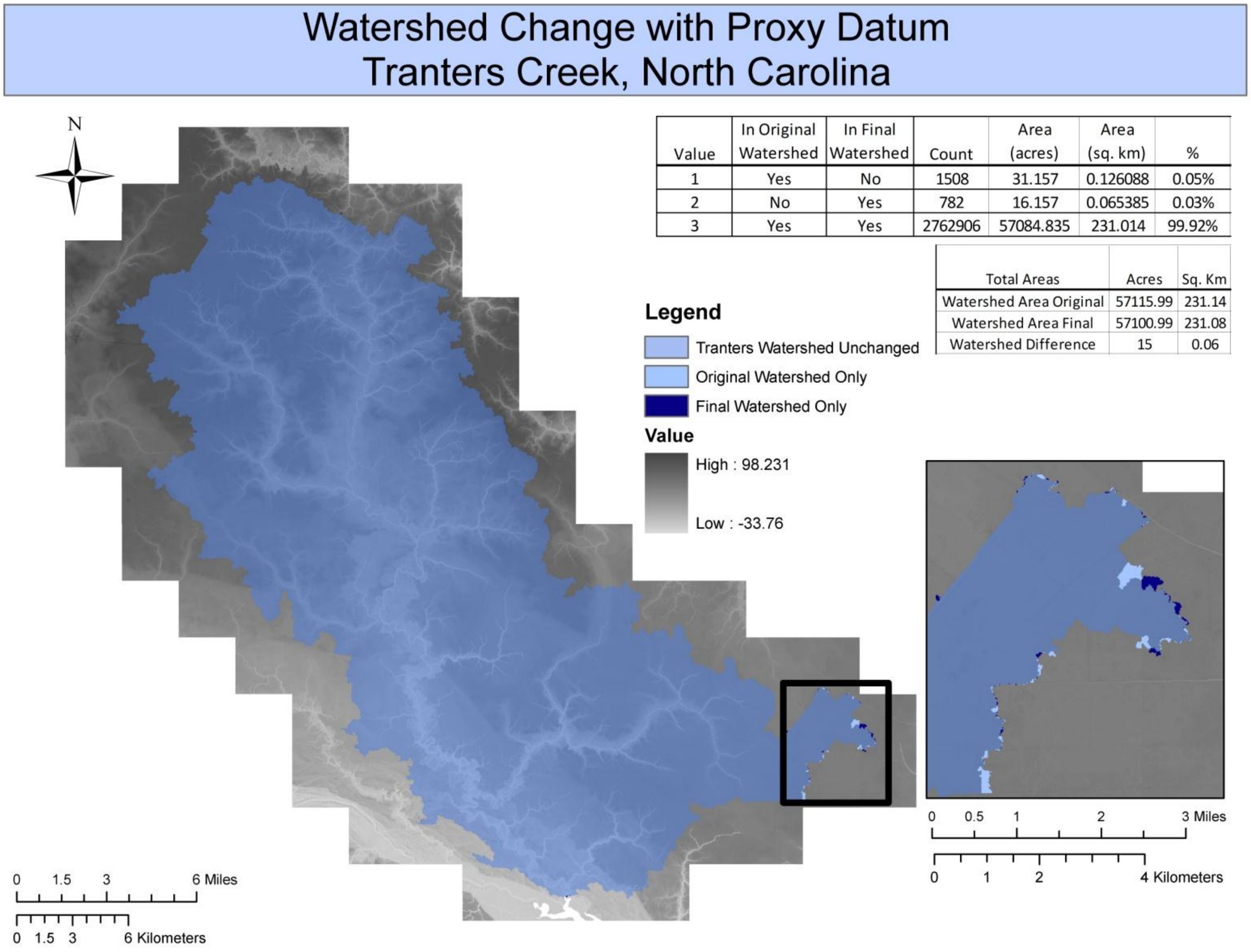


Figure 13: Difference between Transformed DEM and DEM from Transformed LiDAR

3.2. EFFECT ON FLOODPLAIN MAPPING

The effect of changing the datum on floodplain mapping was analyzed in two parts according to the two engineering processes: the change to the watershed (hydrologic modeling) and the change of the floodplain boundary (hydraulic modeling).

For hydrologic modeling based on using North Carolina rural regression methodologies, the most important factor is the size of the watershed. Thus, the first analysis looked at whether the size of the watershed changed significantly between the original and transformed 50 foot DEM. Figure 14 shows that there were no significant changes to the watershed boundary with 99.92% of the area remained the same. The changes that did occur were located in one spatial area where the terrain is very flat, agricultural land. Using the USGS rural regression equations (U.S. Geological Survey, 2001) the watershed area changes lead to an insignificant decrease of 1.42 cubic feet per second (-0.1% change) in the hydrology models. Since hydrology is not significantly affected by the datum change the original discharge values were used in the following analysis.



Value	In Original Watershed	In Final Watershed	Count	Area (acres)	Area (sq. km)	%
1	Yes	No	1508	31.157	0.126088	0.05%
2	No	Yes	782	16.157	0.065385	0.03%
3	Yes	Yes	2762906	57084.835	231.014	99.92%

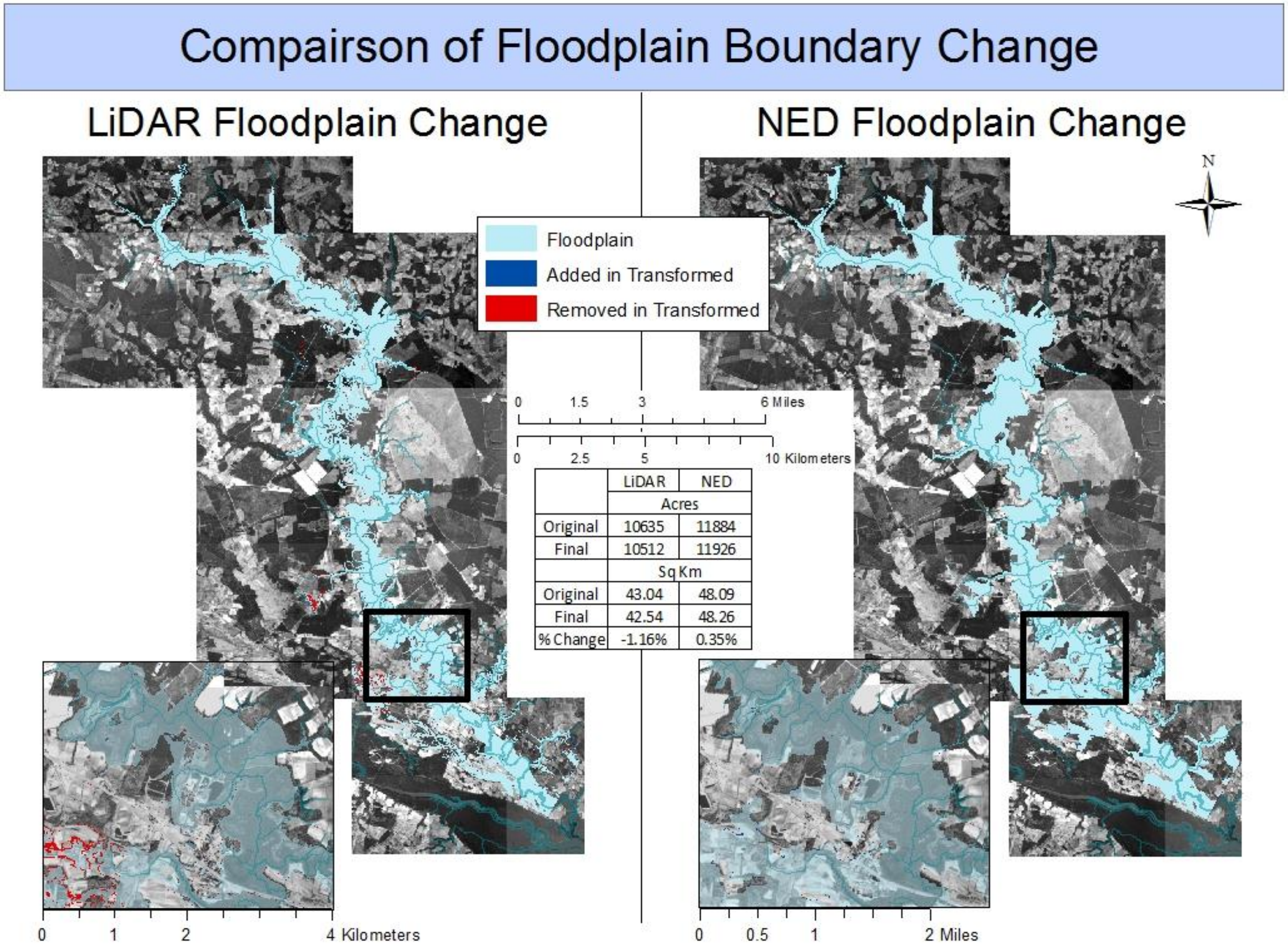
Total Areas	Acres	Sq. Km
Watershed Area Original	57115.99	231.14
Watershed Area Final	57100.99	231.08
Watershed Difference	15	0.06

Figure 14: A comparison of the watershed boundary between the original and transformed 50 foot DEM

The second part of the analysis focused on the floodplain boundary based on hydraulic modeling. The floodplains determined from the original and transformed surfaces from the NED and the LiDAR are shown in Figure 15. The final floodplains from the LiDAR and the NED were very similar. Since the LiDAR is more accurate the floodplain was more detailed and resulted in a smaller floodplain area than the NED-derived floodplain. However, the change between the original and final was very different between the two base data sets (Figure 15). The change in the NED floodplain with the datum shift was minimal and showed no systematic spatial pattern. For this case, the final floodplain area was 0.35% larger (42 acres or 0.17 square km) than the original.

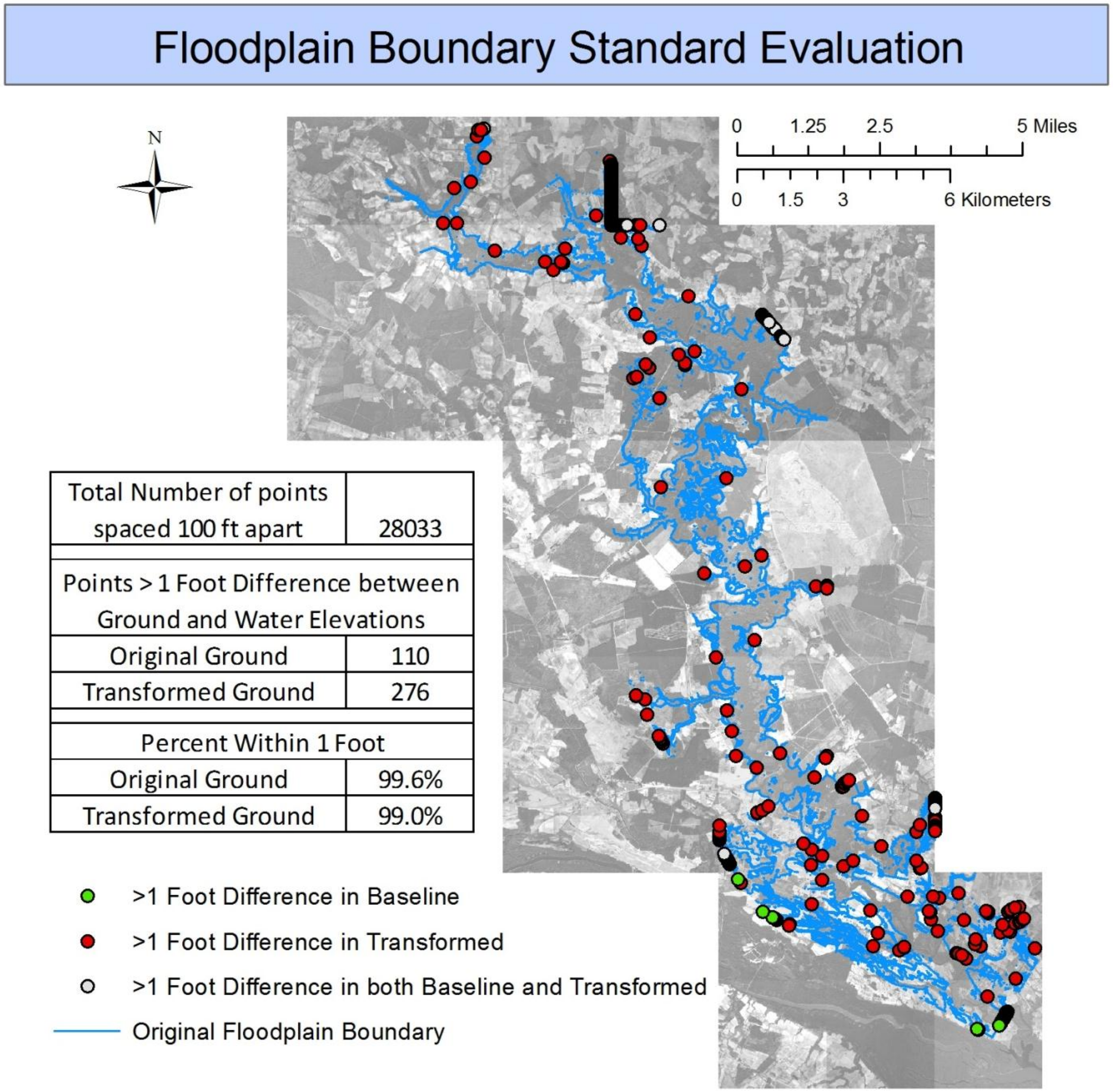
In contrast, the LiDAR floodplain had a -1.16% change (-124 acres or -0.5 square km) from the original to the transformed floodplain. However, this larger change may be a result of the automated mapping method using a water surface TIN generated from the engineering modeling cross sections (Figure 15). While the same mapping method was used for both the original and transformed surfaces, the areas that changed were in backwater finger locations where there was a large distance from the model stream centerline. The larger distance from the centerline likely introduced more water surface interpolation error over this area and may have influenced the result. The cross section problem would not normally be an issue in engineering practice, since these areas would likely be mapped by hand or individually. It is uncertain whether this change would be observed in a full study with the addition of individual judgment.

In addition, it is important to consider whether the original floodplain would pass the Floodplain Boundary Standard (FBS) audit procedure (FEMA, 2007). This is a two part procedure in which 95% of points along the boundary must pass at least one of two tests: 1) the difference between the water level elevation and ground level elevation is less than 1 foot or 2) the water level elevation is within 1 foot of the maximum-minimum range for points within a 38 foot buffer. For this study the original, or baseline, floodplain boundary was tested using the original ground surface and compared to the result using the transformed ground surface. As shown in Figure 16, using the original ground surface the floodplain boundary would pass the FBS with 99.6% of the water level points falling within 1 foot of the ground surface, all of these on the edge of the TIN models. Using the transformed ground surface this decreased to 99%, but still passed step one of the FBS. This result shows that for this study area the floodplain boundary will likely still be accurate to current FEMA standards with the datum modernization. However, before generalizing this result it will be important to test this in different areas of the country considering the impact on coordinates will vary.



	LiDAR	NED
	Acres	
Original	10635	11884
Final	10512	11926
	Sq Km	
Original	43.04	48.09
Final	42.54	48.26
% Change	-1.16%	0.35%

Figure 15: A comparison of the original and transformed floodplain boundaries from LiDAR and the USGS National Elevation Dataset (NED)



Total Number of points spaced 100 ft apart	28033
Points > 1 Foot Difference between Ground and Water Elevations	
Original Ground	110
Transformed Ground	276
Percent Within 1 Foot	
Original Ground	99.6%
Transformed Ground	99.0%

Figure 16: FEMA Floodplain Boundary Standard Evaluation

3.3. EFFECT ON SURVEYING FOR FLOODPLAIN MAPPING

Surveying for floodplain mapping is primarily done for two reasons: surveying obstructions and surveying cross sections of the stream. In the past, bench marks have been assumed to be a known starting point from which surveys could be reasonably conducted. FEMA requires that bench marks must be at least second order horizontally, at least third order vertically (Federal Geodetic Control Subcommittee, 1984) and have a stability classification ranking of A, B, or C (FEMA, 2002). However, the current definitions of vertical order and stability are based on how the bench mark was set and the leveling accuracy, but do not take into account changes that may have occurred over time (natural or anthropogenic). Additional standards must be examined in order to determine how information quantifying this change, such as original error bars and heights themselves that changed over time, would be treated in surveying for floodplain mapping.

It is difficult to quantify at what uncertainty a bench mark should not be used as it varies with the desired product. With any survey and subsequent product there is error in the control, error in the survey, and error in the derived product. While there is no existing clear answer to when a bench marks should not be used, there are some generalizations that can be made. 5 centimeters is commonly used with survey control and procedures. NGS defined survey procedures to contain absolute ellipsoid height errors from GNSS to 5 centimeters, and relative height errors to 2 centimeters (FEMA, 2003, pp. A-25; Zilkoski, D'Onofrio, & Frakes, 1997). FEMA specifies the mapping partner must use 5 centimeters or better GPS procedures or Third-Order (or better) differential leveling. Limiting the use of bench marks to those with an accuracy of 5 centimeter or better will likely satisfy all required products, although it is probably more accurate than required for some.

In addition, using control that is at least twice as accurate as the desired product is commonly used for aerial imagery and topographic surfaces (Geospatial Committee of Arizona Professional Land Surveyors Association, 2008). Based on that standard, for floodplain mapping in a flat area the desired vertical accuracy is 1.2 feet (36.576 centimeters) (FEMA, 2003), thus the survey accuracy would need to be 0.6 feet (18.288 centimeters) and the control used for that survey 0.3 feet (9.144 centimeters). If the vertical accuracy fails to meet these specifications, the expected error of the survey should be taken into account to determine whether the final product uncertainty would be unacceptable.

In order to explore quantitatively how heights influence the floodplain a bridge was added into the HEC-RAS model. Table 3 shows the changes in top width and BFE according to changes in the bridge height (+/-0.1, 0.5, 1 feet). An 11 foot tolerance was used based on the typical map scale of 1”=500’ (Maune, 2003). Although the standard is 11 feet at the 95% confidence level, the 11 feet is used as the cutoff for this general study. For Tranter’s Creek this standard is violated at 0.5 feet (Table 3).

It should be noted that in this particular model the sudden change in width at 1 foot was from the overtopping of the bridge (i.e., as a weir) to one side of the stream. This suggests that the effects will vary significantly depending on the shape of the channel and model characteristics. It is expected that there would be a greater and lesser effect in different locations. Further analysis would likely be worthwhile to test this hypothesis and explore the minimum height change that significantly changes the floodplain as the most conservative value.

While this conclusion is appropriate for current guidelines, FEMA may revise these specifications with the movement towards digital mapping and improvement in technology. It will be important to reexamine the effect of height uncertainty with any review of vertical or horizontal accuracy standards.

Table 3: Top width and BFE changes varying bridge height

Cross Section	Top Width Difference (feet)						BFE Difference (feet)					
	-1	**-0.5**	**-0.1**	**0.1**	**0.5**	**1**	**-1**	**-0.5**	**-0.1**	**0.1**	**0.5**	**1**
79651	-0.53	-0.16	-0.03	0.03	0.17	0.38	-0.09	-0.03	-0.01	0	0.03	0.06
78790	-0.75	-0.23	-0.05	0.04	0.24	0.54	-0.09	-0.02	0	0.01	0.03	0.07
78071	-1.45	-0.43	-0.09	0.09	0.32	0.52	-0.09	-0.02	0	0.01	0.04	0.07
77413	-15.8	-4.7	-0.98	0.99	5.24	11.45	-0.1	-0.03	-0.01	0	0.03	0.06
76565	0	0	0	0	0	0	-0.1	-0.03	-0.01	0	0.03	0.07
75732	-9.01	-2.68	-0.55	0.57	2.99	6.53	-0.1	-0.03	-0.01	0.01	0.03	0.07
74764	-2.92	-0.86	-0.18	0.19	0.97	2.12	-0.11	-0.03	-0.01	0	0.03	0.07
74084	0	0	0	0	0	0	-0.11	-0.04	-0.01	0	0.03	0.07
72896	-4.95	-1.47	-0.31	0.31	1.64	3.58	-0.11	-0.03	-0.01	0	0.03	0.07
71681	-0.76	-0.23	-0.05	0.05	0.25	0.55	-0.11	-0.04	-0.01	0	0.03	0.08
70889	-0.37	-0.11	-0.03	0.02	0.12	0.26	-0.11	-0.03	0	0.01	0.04	0.08
69357	-0.41	-0.12	-0.02	0.03	0.14	0.3	-0.12	-0.03	-0.01	0.01	0.04	0.08
67982	-0.3	-0.09	-0.02	0.02	0.1	0.21	-0.12	-0.04	-0.01	0.01	0.04	0.08
66311	1686.65	11.25	2.24	-2.24	-11.18	-22.21	-0.04	-0.03	-0.01	0	0.03	0.06
66125	BRIDGE CROSS SECTION											
65960	614.09	12.29	5.97	-3.21	-11.94	-22.88	-0.02	-0.01	0	0	0	0.01

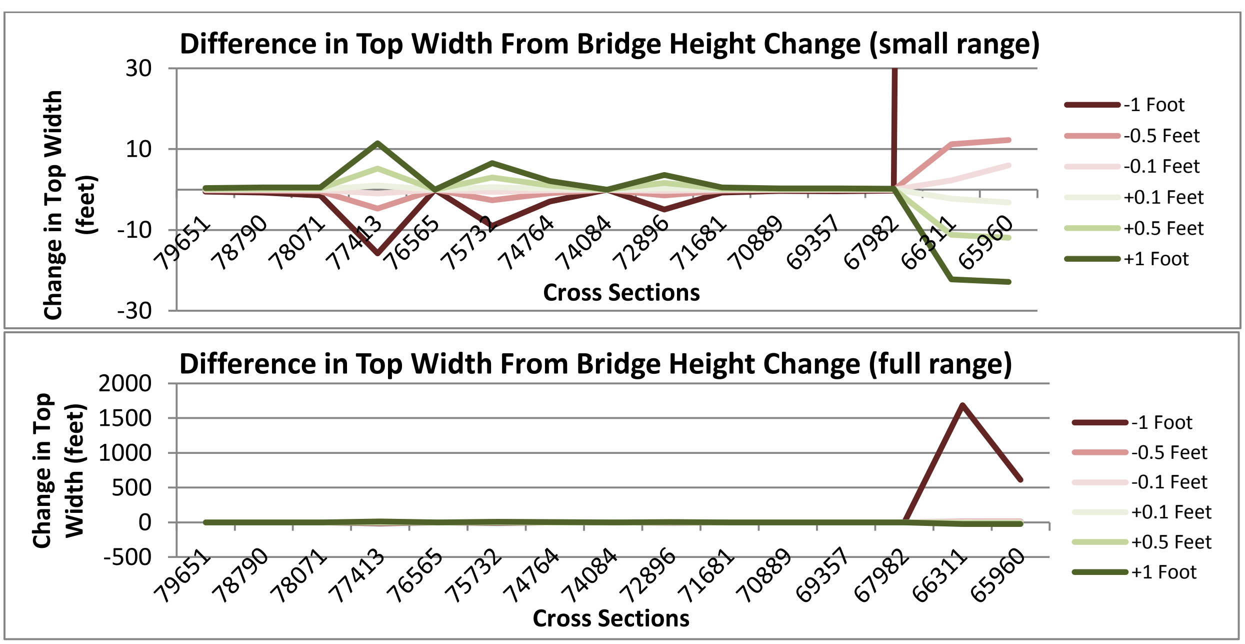


Figure 17: Difference in top width of floodplain based on varying height changes of a bridge

4. CONCLUSIONS

While the effective floodplain models and boundaries are not significantly changed by the datum shift, it is extremely important for floodplain mapping to understand and address height uncertainties. As reported previously (National Research Council, 2009, p. 62), hydraulic modeling is highly sensitive to obstruction heights. The datum modernization will increase the absolute accuracy of the geospatial data, but, more important to floodplain mapping, relative accuracy will be improved with a greater understanding of height uncertainties.

Since there is a significant shift in coordinates, the challenge in implementing the new datums will be the discontinuity between previously conducted flood studies and studies conducted in the new datums. This is both a data problem and a public relations problem. On the data side, it may be difficult to match up studies at boundaries. On the public relations side, constituents may have difficulty understanding why the coordinates are shifting and may not match up.

The floodplain impact will vary depending on the specific location and characteristics of the stream, surrounding area, and available data. High-accuracy elevation data will be more affected by the datum modernization than lower accuracy data. Further studies are warranted to better understand the impact of location-specific factors. Also important is clarifying how existing standards would treat error bars on bench marks.

Because of the significant coordinate shift and potential impact, the development of an implementation plan is extremely important for FEMA. An implementation plan would include guidance on how to phase in the new datums, prioritization, how to compare data in the two datums, and a constituent message on the change. Successful implementation will depend on a clear message and open communication to constituents to explain the changes. The following sections discuss some recommendations for further investigation into data collection, data discontinuity, and public relations.

4.1. DATA COLLECTION

The collection of survey data for floodplain mapping will need to change to reflect a better understanding of height uncertainties and limitations. As shown above, uncertainties on heights will have a significant impact on the floodplain and BFEs in some locations. As additional information is published on bench mark heights, it is recommended that the guidelines and specifications be updated to provide guidance on when monuments can be used without re-surveying the point and how control is transferred to a survey site to limit propagation of errors. This would need to take into account the required accuracy of floodplain maps in the future considering the move towards digital data. While this study showed the importance of this uncertainty floodplain mapping, it is recommended that further studies test the sensitivity of height uncertainties in a variety of geographical locations. This would help inform a broad policy on the use of bench mark heights.

4.2. DATA DISCONTINUITY

In data maintenance and comparison it will be extremely important to provide metadata and correctly apply a transformation when necessary. While implementation of the datum change will be easier with the FEMA move towards studies at the watershed level (rather than at the county or municipal level), it will still be important to address how to treat adjacent watersheds that have studies in different datums. The datum difficulties will require an education initiative for the professional community, including scientists, engineers, and GIS specialists. We recommend any transformation developed be GIS-friendly with education directed specifically to engineers and the GIS community.

4.3. PUBLIC RELATIONS

In addition to the professional community, the general public affected by the floodplain mapping products will also be concerned. The data presented in this report will be most relevant to the first group as they will be responsible for appropriately working with data and producing products. However, appropriately preparing local officials and the public will also be important for successful implementation. NGS and FEMA should work together to develop an outreach and education plan that describes in layman's terms why this change is happening, how heights will be monitored in the future, and how the new datums will be implemented in floodplain mapping.

4.4. NEXT STEPS

While this study focused primarily on the scientific impact of the datum shift, a more in-depth analysis of how FEMA will implement the new datums should be conducted. An implementation plan should include, but not be limited to, identifying all specifications, guidelines, and policies that need to be revised, preparing a data management plan that includes the databases that would need to be updated, and organizing an outreach and education plan. While the release of the new datums is years away, adequately preparing for this change well in advance will assist in a timely and smooth transition, allow for the preparation of necessary resources, and help realize roughly $2.2 billion in benefits to the nation (Leveson, 2009). Successful cooperation and communication on the implementation of geospatial data will improve the accuracy of floodplain maps that are vital to saving lives and property.

REFERENCES

Federal Geodetic Control Subcommittee. (1984). *Standards and Specifications for Geodetic Control Networks.* Retrieved from http://www.ngs.noaa.gov/FGCS/tech_pub/1984-stds-specs-geodetic-control-networks.htm

FEMA. (2002). *Guidelines and Specifications for Flood Hazard Mapping Partners, Volume 1: Flood Studies and Mapping.*

FEMA. (2003). *Guidelines and Specifications for Flood Hazard Mapping Partners, Appendix A: Guidance for Aerial Mapping and Surveying.*

FEMA. (2007). *Flood Map Modernization Floodplain Boundary Standard Audit Procedures Version 2.0.*

Garber, N. J., & Hoel, L. A. (2009). *Traffic and Highway Engineering.* Cengage Learning.

Geospatial Committee of Arizona Professional Land Surveyors Association. (2008). *Arizona Spatial Data Accuracy and Georeferencing Standards.*

Leveson, I. (2009). *Socio-Economic Benefits Study: Scoping the Value of CORS and GRAV-D.* Jackson, NJ: Leveson Consulting.

Maune, D. F. (2003). *FEMA's Mapping and Surveying Guidelines and Specifications.* Fairfax, Virginia: Dewberry & Davis LLC.

National Geodetic Survey. (2007). *The GRAV-D Project: Gravity for the Redefinition of the American Vertical Datum.* Silver Spring, MD: NOAA/National Geodetic Survey.

National Geodetic Survey. (2008). *The National Geodetic Survey Ten-Year Plan.* Silver Spring, MD: NOAA/National Geodetic Survey.

National Research Council. (2007). *Elevation Data for Floodplain Mapping.* Washington DC: The National Academies Press.

National Research Council. (2009). *Mapping the Zone: Improving Flood Map Accuracy.* Washington, DC: The National Academies Press.

North Carolina Geodetic Survey. (n.d.). *Frequently Asked Questions (FAQs) Regarding NAD 83(NSRS2007).* Retrieved March 2, 2011, from North Carolina Department of Environment and Natural Resources: http://portal.ncdenr.org/web/lr/geodetic-survey/faqs

Office of Managmenet and Budget. (2002, August 19). Coordination of Geographic Information and Related Spatial Data Activities. *OMB Circular A-16*. Washington, DC.

U.S. Geological Survey. (2001). *The National Flood-Frequency Program--Methods for Estimating Flood Magnutide and Frequency in Rural and Urban Areas in North Carolina.*

Weaver, J. C., Feaster, T. D., & Gotvald, A. J. (2009). *Magnitude and Frequency of Rural Floods in the Southeastern United States, through 2006: Volume 2, North Carolina.* Reston, Virginia: U.S. Geological Survey.

Zilkoski, D. B., D'Onofrio, J. D., & Frakes, S. J. (1997). *Guidelines for Establishment GPS-Derived Ellipsoid Heights.* Silver Spring, MD: National Geodetic Survey.

APPENDIX A: GLOSSARY

Accuracy – agreement between a measurement and the true or corrected value

$Accuracy_r$ – the accuracy in the horizontal (radial) direction
$Accuracy_z$ – the accuracy in the vertical direction

Adjustment – the process of changing the values of a given set of quantities so that results calculated using the changed set will be better than those calculated using the original set. "Better" is most commonly interpreted to mean that the difference between calculated and measured values is minimized

Bare-Earth – a model of the Earth's surface with all vegetation and infrastructure removed

Base Flood – the flood having a 1 percent chance of being equaled or exceeded in any given year. It is also known as the 1 percent chance or 100-year flood

Base Flood Elevation (BFE) – the height at which there is a 1 percent chance or greater of flooding in a given year. The BFE is used for flood insurance policy rating

Bench Mark – known geodetic locations permanently marked with a brass disk, metal rod, cement or stone platform, or other permanent structure. This term is typically reserved for vertical control.

Breakline – linear feature with height information marking a distinct or abrupt change in elevation

Contours – a line marking locations of the same height

Coordinate System – a set of rules specifying how coordinates are to be assigned to points

Geodetic Coordinate System – coordinates designating the location of a point with respect to the reference ellipsoid and with respect to the planes of the geodetic Equator and a selected geodetic meridian.

Geographic Coordinate System – A generic term for a geodetic coordinate system.

Projected Coordinate System – a set of rules that maintains either constant lengths, constant angles, or constant areas across two dimensions (but not all of these). Projected coordinate systems are always based on a geodetic coordinate system and are used to map coordinates on a two dimensional surface. Examples include the State Plane Coordinate System (SPCS) and Universal Transverse Mercator (UTM)

Datum – a point, line or surface that serves as the "zero reference" to provide consistency in a coordinate system.

Horizontal Datum – A datum used for defining latitude and longitude. Most traditionally "horizontal" datums are now three dimension due to the prevalence of GNSS, and are therefore more frequently being called "geometric reference frames"

Vertical Datum -- A datum used for defining heights. A traditionally vertical datum may be one component of a larger “geopotential reference frame” which would encompass all aspects of heights and gravity.

Datasheet – a report provided by NGS that is the official recorded position for a bench mark. It details the current and historical positional information (horizontal and vertical) and metadata for a bench mark. Accessible at: http://www.ngs.noaa.gov/cgi-bin/datasheet.prl

Detailed Study - (*see Flood Study, Detailed*)

Digital Elevation Model (DEM) – a digital file consisting of terrain elevations for ground positions at regularly spaced horizontal intervals

Digital Terrain Model (DTM) – a digital model of the topographic surface created from a mass points that is typically augmented with additional information, such as breaklines

Effective Model – the basis of the current regulatory standard and the starting point for the modeling of any proposed development in the floodplain

Ellipsoid – *(see Reference Ellipsoid)*

Ellipsoid Height (*see Height, Ellipsoid*)

Elevation – generally interchangeable with the term “height”, but used by FEMA specifically to mean “orthometric height”

Epoch – the data at which data was collected

Floodplain Boundary Standard (FBS) – a method published by FEMA that evaluates the reliability of the floodplain boundary by comparing the computed flood elevation to the ground elevation

Flood Insurance Rate Map (FIRM) – the map that displays shaded areas in the community that are subject to flooding

Flood Study –

Detailed – a study method that involves collecting, creating, and reviewing survey data, engineering models, and using the best available elevation data

Limited Detail – a study method that involves creating or revising engineering models but includes some data collected in the field, such as sketches of bridges

Approximate – a study method that relies on models and mapping tools without any field survey data

Redelineation – a method of revising a flood study where only the elevation data is updated

Floodplain – any land area susceptible to being inundated by water from any source

Floodway – the channel of a river or other watercourse and the adjacent land areas that must be reserved in order to discharge the *base flood* without causing any cumulative increase in the water surface elevation. The floodway is intended to carry the dangerous and fast-moving water

Geoid – the equipotential surface of the Earth's gravity field that most closely fits global mean sea level

Gravimetric Geoid Model – a model of the geoid based solely on gravity, and attempting to model the shape of the actual geoid

Hybrid Geoid Model – a model of the geoid which does not attempt to model the geoid's true shape, but rather the shape of the geoid influenced by the known systematic differences in NAVD 88 and NAD 83, and used as a transformation between these two datums.

Geographic Information System (GIS) – a computer system for storing, manipulating, analyzing, and presenting geographic information

Global Navigation Satellite System (GNSS) – any navigational and positioning system by which the location of a position on or above the Earth can be determined by a special receiver at that point interpreting signals received simultaneously from several satellites in a constellation. Includes or will include GPS (U.S.), GLONASS (Russia), Galileo (EU), COMPASS (China)

Global Positioning System (GPS) – navigational and positioning system by which the location of a position on or above the Earth can be determined by a special receiver at that point interpreting signals received simultaneously from several of a constellation of satellites developed by the U.S. Department of Defense

Geodetic Reference System 1980 (GRS-80) – an ellipsoid model of the Earth used by NAD 83 and recommended by the IERS to use in conjunction with the ITRF. While the ellipsoid model is the same for NAD 83 and ITRF the two systems define location of the center of the ellipsoid at different locations

High Accuracy Reference Network (HARN) – a statewide or regional upgrade in accuracy of NAD 83 coordinates using Global Positioning System (GPS) observations. The upgrade project was done cooperatively between Federal and state government between 1986 and 1997.

Height – distance measured from a reference surface to a point of interest (usually at the topographic surface)

Orthometric Height – colloquially referred to as "height above mean sea level," the distance between the geoid and a selected point along the (curved) plumb line, often on the Earth's surface

Ellipsoid Height – distance between the reference ellipsoid and a selected point along the ellipsoidal normal (perpendicular to the ellipsoid surface), often on the Earth's surface

Horizontal Time Dependent Positioning (HTDP) - publically available software produced by NGS that predicts velocities of points based plate tectonics. Also converts coordinates between many different reference frames, such as NAD 83 (NSRS2007) and the various realizations of ITRF

Hydro-corrected DEM – DEM models that are edited to force streams to flow downhill

Interpolation – method of estimating new data points within the range of a discrete set of known data points

International Terrestrial Reference Frame (ITRF) – an international high accuracy reference frame established by the International Earth Rotation and Reference System Service

INTG – publically available software produced by NGS that interpolates geoid heights at specific locations from NGS geoid models (e.g., GEOID09, USGG2009)

Leveling – the process of determining relative height differences between points. Typically refers to optical differential leveling, which yields leveled height differences that can be converted to orthometric height differences.

Light Detection and Ranging (LiDAR) – remote sensing system used to collect topographic data using laser technology

Limited Detail Study – (*see Flood Study, Limited Detail*)

Metadata – "data about data". Information that captures the basic characteristics of data or information resource, representing the "who," "what," "when," "where," "why," and "how" of the resource

National Spatial Reference System (NSRS) – consistent national coordinate system in the United States that specifies latitude, longitude, height, scale, gravity, and orientation, as well as how these values change with time

North American Datum of 1983 (NAD 83) – current "horizontal" control datum for the United States, Canada, Mexico, and Central America, fixed to specific tectonic plates (North American, Pacific and Marianas, depending on the user's location), based on a geocentric origin and the Geodetic Reference System of 1980

North American Vertical Datum of 1988 (NAVD 88) – current vertical control datum established in 1991 by the minimum-constraint adjustment of the Canadian-Mexican-U.S. level observations. The adjustment held fixed the height of the Father Point/Rimouski bench mark in Quebec, Canada

Orthometric Height (*see Height, Orthometric*)

Precision – repeatability of a measurements, relates to the quality of the method by which the measurements were made but does not require one to know the correct or true value

Projection (see *Coordinate System, Projected*)

Real Time Kinematic (RTK) Positioning – employs GNSS or GPS technology to produce and collect three-dimensional positions relative to a stationary base station

Real Time Network (RTN) – an established network of stationary base stations that enable RTK positioning within the network

Realization – a realization connects the definition of a datum to physical land measurements or monuments and facilitates access to the datum

Redelineation – (*see Flood Study, Redelineation*)

Reference Ellipsoid – An ellipsoid of revolution, used as a simple model of the Earth for defining latitude, longitude, and ellipsoid heights. Examples include the Geodetic Reference System of 1980 (GRS-80), used by NAD 83, and the Clarke 1866 ellipsoid, used by NAD 27

Reference Frame, Geometric – See Horizontal Datum

Reference Frame, Geopotential – See Vertical Datum

Riverine Flooding – flood areas that are characterized by rivers, streams, or creeks. Often flooding is characterized in terms of riverine flooding or coastal flooding

State Plane Coordinate System (SPCS) – a set of coordinate systems for specific regions of the United States that mostly uses either the Lambert Conformal Conic or Transverse Mercator projections

SPCS83 – publically available software produced by NGS that converts between State Plane Coordinate and geographic coordinates

Superseded Survey Control – coordinates established on a control station that have been replaced by newer, more accurate coordinates

Triangulated Irregular Network (TIN) Model – a model that uses nodes with 3-dimensional coordinates to form triangles to create a surface

Transformation – in geodetic applications, a mathematical method to convert coordinates between two systems

Topography –the Earth's surface, usually at the interface between the solid surface and air

VDatum – publically available software produced by NOAA that transforms data among a variety of tidal, orthometric and ellipsoidal vertical datums

APPENDIX B: ACRONYMS AND ABBREVIATIONS

BFE	Base Flood Elevation
DEM	Digital Elevation Model
DFIRM	Digital Flood Insurance Rate Map
DTM	Digital Terrain Model
FBS	Flood Boundary Standard
FEMA	Federal Emergency Management Administration
GEOID99	Hybrid Geoid Model of 1999
GIS	Geographic Information System
GPS	Global Positioning System
GNSS	Global Navigation Satellite Systems
GRS-80	Geodetic Reference System of 1980
HARN	High Accuracy Reference Network
HEC-RAS	Hydrologic Engineering Center-River Analysis System
HEC-HMS	Hydrologic Engineering Center-Hydrology Modeling System
HTDP	Horizontal Time Dependent Positioning
INTG	Geoid Interpolation
ITRF2005	International Terrestrial Reference Frame of 2005
LiDAR	Light Detection and Ranging
MHIP	Multi-year Flood Hazard Identification Plan
NAD 27	North American Datum of 1927
NAD 83	North American Datum of 1983
NAVD 88	North American Vertical Datum of 1988
NCFMP	North Carolina Floodplain Mapping Program
NCGS	North Carolina Geodetic Survey
NED	National Elevation Dataset
NGS	National Geodetic Survey
NGVD 29	National Geodetic Vertical Datum of 1929
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NSRS	National Spatial Reference System
RTK	Real Time Kinematic
RTN	Real Time Network
SPCS	State Plane Coordinate System
TIN	Triangulated Irregular Network
USACE	United States Army Corps of Engineers
USGG2009	United States Gravimetric Geoid of 2009
USGS	United States Geological Survey
VDatum	Vertical Datum Transformation