Use of LIDAR-based Elevation Data for Highway Drainage Analysis: A Qualitative Assessment

APPLICATION OF ADVANCED REMOTE SENSING TECHNOLOGY TO ASSET MANAGEMENT

Final Report—October 2003

Sponsored by

the Research and Special Programs Administration,
U.S. Department of Transportation,
University Transportation Centers Project MTC-2001-02

and

the Iowa Department of Transportation
CTRE Management Project 01-98

Iowa Department of Transportation

MTC MIDWEST TRANSPORTATION CONSORTIUM

Iowa State University ~ University of Missouri-Columbia ~ Lincoln University
University of Missouri-Kansas City ~ University of Missouri-St. Louis ~ University of Northern Iowa

2901 South Loop Drive, Suite 3100 ~ Ames, Iowa 50010-8634

The Midwest Transportation Consortium (MTC) is housed at the Center for Transportation Research and Education (CTRE) at Iowa State University. CTRE's mission is to develop and implement innovative methods, materials, and technologies for improving transportation efficiency, safety, and reliability while improving the learning environment of students, faculty, and staff in transportation-related fields.

Technical Report Documentation Page

1. Report No.	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Use of LIDAR-based Elevation Data for Highway Drainage Analysis: A Qualitative Assessment		**5. Report Date** October 2003 **6. Performing Organization Code** MTC-2001-02
7. Author(s) Zachary Hans, Shauna Hallmark, Reginald Souleyrette, Ryan Tenges, and David Veneziano		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Midwest Transportation Consortium c/o Iowa State University 2901 South Loop Drive, Suite 3100 Ames, IA 50010-8634		**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.**
12. Sponsoring Organization Name and Address U.S. Department of Transportation Research and Special Programs Administration 400 7th Street SW Washington, DC 20590-0001		**13. Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code**

15. Supplementary Notes

This report was prepared as part of the following project: Application of Advanced Remote Sensing Technology to Asset Management, co-sponsored by the Iowa Department of Transportation (CTRE Project 01-98).

16. Abstract

US Geological Survey (USGS) based elevation data are the most commonly used data source for highway hydraulic analysis; however, due to the vertical accuracy of USGS-based elevation data, USGS data may be too "coarse" to adequately describe surface profiles of watershed areas or drainage patterns. Additionally hydraulic design requires delineation of much smaller drainage areas (watersheds) than other hydrologic applications, such as environmental, ecological, and water resource management. This research study investigated whether higher resolution LIDAR based surface models would provide better delineation of watersheds and drainage patterns as compared to surface models created from standard USGS-based elevation data. Differences in runoff values were the metric used to compare the data sets. The two data sets were compared for a pilot study area along the Iowa 1 corridor between Iowa City and Mount Vernon. Given the limited breadth of the analysis corridor, areas of particular emphasis were the location of drainage area boundaries and flow patterns parallel to and intersecting the road cross section.

Traditional highway hydrology does not appear to be significantly impacted, or benefited, by the increased terrain detail that LIDAR provided for the study area. In fact, hydrologic outputs, such as streams and watersheds, may be too sensitive to the increased horizontal resolution and/or errors in the data set. However, a true comparison of LIDAR and USGS-based data sets of equal size and encompassing entire drainage areas could not be performed in this study. Differences may also result in areas with much steeper slopes or significant changes in terrain. LIDAR may provide possibly valuable detail in areas of modified terrain, such as roads. Better representations of channel and terrain detail in the vicinity of the roadway may be useful in modeling problem drainage areas and evaluating structural surety during and after significant storm events. Furthermore, LIDAR may be used to verify the intended/expected drainage patterns at newly constructed highways. LIDAR will likely provide the greatest benefit for highway projects in flood plains and areas with relatively flat terrain where slight changes in terrain may have a significant impact on drainage patterns.

17. Key Words asset management—highway drainage analysis—LIDAR—remote sensing technology		**18. Distribution Statement** No restrictions.	
19. Security Classification (of this report) Unclassified.	**20. Security Classification (of this page)** Unclassified.	**21. No. of Pages** 50	**22. Price** N/A

USE OF LIDAR-BASED ELEVATION DATA FOR HIGHWAY DRAINAGE ANALYSIS: A QUALITATIVE ASSESSMENT

Authors
Zachary Hans, Shauna Hallmark, Reginald Souleyrette, Ryan Tenges, and David Veneziano
Center for Transportation Research and Education
Iowa State University

This report was prepared as part of the following project:

Application of Advanced Remote Sensing Technology to Asset Management

MTC Project 2001-02
CTRE Project 01-98

Principal Investigator
Shauna Hallmark
Center for Transportation Research and Education
Iowa State University

Preparation of this report was financed in part
through funds provided by the U.S. Department of Transportation
through the Midwest Transportation Consortium
and through funds provided by the Iowa Department of Transportation
through its research management agreement with the
Center for Transportation Research and Education.

Midwest Transportation Consortium
c/o Iowa State University
2901 South Loop Drive, Suite 3100
Ames, IA 50010-8634
Phone: 515-294-8103
Fax: 515-294-0467
www.ctre.iastate.edu/mtc/

Final Report • October 2003

TABLE OF CONTENTS

LIST OF FIGURES

ACKNOWLEDGMENTS

This research was supported in part by the Iowa Department of Transportation, the Midwest Transportation Consortium, and Federal Highway Administration. Appreciation is expressed to Alice Welch and other individuals from the Iowa Department of Transportation.

EXECUTIVE SUMMARY

US Geological Survey (USGS) based elevation data are the most commonly used data source for highway hydraulic analysis; however, due to the vertical accuracy of USGS-based elevation data, USGS data may be too “coarse” to adequately describe surface profiles of watershed areas or drainage patterns. USGS data are too coarse to defined roadbeds and other transportation structures that would affect drainage patterns around existing facilities. Additionally hydraulic design requires delineation of much smaller drainage areas (watersheds) than other hydrologic applications, such as environmental, ecological, and water resource management. This research study investigated whether higher resolution LIDAR based surface models would provide better delineation of watersheds and drainage patterns as compared to surface models created from standard USGS-based elevation data. Differences in runoff values were the metric used to compare the data sets. The two data sets were compared for a pilot study area along the Iowa 1 corridor between Iowa City and Mount Vernon. Given the limited breadth of the analysis corridor (approximately 18 miles long with LIDAR data available immediately proximate to the road centerline, 0.25 to 1.5 miles), areas of particular emphasis were the location of drainage area boundaries and flow patterns parallel to and intersecting the road cross section.

Traditional highway hydrology does not appear to be significantly impacted, or benefited, by the increased terrain detail that LIDAR provided for the study area. In fact, hydrologic outputs, such as streams and watersheds, may be too sensitive to the increased horizontal resolution and/or errors in the data set. However, a true comparison of LIDAR and USGS-based data sets of equal size and encompassing entire drainage areas could not be performed in this study. Differences may also result in areas with much steeper slopes or significant changes in terrain.

LIDAR may provide possibly valuable detail in areas of modified terrain, such as roads. Better representations of channel and terrain detail in the vicinity of the roadway may be useful in modeling problem drainage areas and evaluating structural surety during and after significant storm events. Furthermore, LIDAR may be used to verify the intended/expected drainage patterns at newly constructed highways. Knowledge of existing drainage structures can also be very important.

LIDAR will likely provide the greatest benefit for highway projects in flood plains and areas with relatively flat terrain where slight changes in terrain may have a significant impact on drainage patterns.

1. BACKGROUND

Hydrology is the science that deals with the occurrence, circulation, and distribution of water (Bedient and Huber 1998). The primary emphasis of hydrology for highway engineering is collection, transport, and disposal of water originating on, near, or adjacent to the roadway right-of-way or flowing in highway stream crossings. Adequate hydraulic design is paramount to successful highway engineering. However, provision of adequate drainage is costly. Approximately one-fourth of all highway construction dollars are spent for culverts, bridges, and other drainage structures (Hicks and Oglesby 1982). On the other hand, insufficient design may also be very costly since inadequate drainage can result in significant damage to highway structures. Additionally, water accumulation on the pavement surface reduces capacity. Inadequate drainage affects pavement performance and slope stability and may contribute to safety problems if water crosses or stands on the roadway surface. Accidents may result if vehicles hydroplane or vision is reduced by splash and spray (Garber and Hoel 2002). Consequently, the ability to more accurately model drainage may improve a highway engineer's ability to cost-effectively plan drainage facilities for new projects as well as identify and mitigate potential deficiencies in existing projects.

Highway drainage structures provide locations for traffic to cross natural waterways. During the design period, drainage structures are sized to be sufficiently large enough to discharge anticipated water flow through the structure. Flow depends on watershed area, amount of rainfall, runoff coefficient, and the time of concentration (T_c). Time of concentration is the amount of time it takes for runoff from the hydraulically most distant point to flow to a specified point of interest. Time of concentration depends on size, shape, and slope of the drainage area, rainfall intensity, surface type, and whether any portion of the flow is channelized. Once structures are in place, adequacy of drainage structures can also be assessed. For instance, assessment of drainage conditions for existing conditions allows evaluation of whether bridges are performing adequately in terms of expected versus actual drainage conditions. It may also assist in determining both where lower cost/lower performance bridges will suffice as well as where higher cost/higher performance bridges are necessary and justified.

1.1. USGS Surface Elevation Models

USGS-based elevation data are the most commonly used data source for delineation of watershed boundaries, delineation of existing drainage patterns, and determination of watershed slope. Digital elevation models (DEMs) are digital files in raster format consisting of terrain elevations for ground positions at regularly spaced intervals. The US Geological Survey (USGS) produces several digital elevation products that vary by sampling interval, geographic reference system, areas of coverage, and accuracy. Nearly all of the United States has been digitized into grids of elevation values or DEMs over the past few decades by the USGS. The USGS has recently begun creating 7.5-ft DEMs at a 10 by 10 m resolution with a vertical resolution of 1 ft. USGS DEMs have been used extensively in hydrologic modeling, including drainage basin delineation, storm event modeling, hydrograph creation, and the routing of floods down rivers and through reservoirs. DEMs have also been used in the design of culverts, dams, and detention basins. Specific examples include the following:

- Calculating subbasin parameters (e.g., slope and slope length) and defining the stream network for the Great Salt Plains Basin (White, Storm, and Smolen 1997).
- Creating a flash flood prediction model for rural and urban basins in New Mexico, which included delineation of the basin and calculating the slope and aspect within the basin (Snell and Gregory 2002).
- Designing discharge for flow conveyance structures on Texas highways (Bao, Maidment, and Olivera 1997).
- Improving the understanding of drainage areas and hydrological flow paths in urban areas adjacent to the San Francisco Bay (Wittner and McKee 2002).

USGS DEMs, however, do have limitations. One recent study compared 30-m USGS DEMs with field data and found that they correctly predicted slope gradient at only 21% and 30% of the field sampling locations in two study sites (Hammer et al. 1994). Several other studies have found similar results (Srinivasan and Engel 1991; Zhang and Montgomery 1994; Mitasova et al. 1996). Numerous authors have argued that DEMs with spatial resolutions of 2 to 10 m are required to represent important hydrologic processes and patterns in many agricultural landscapes (Wilson 1999).

USGS-based elevation data are the most commonly used data source for highway hydraulic analysis; however, due to the vertical accuracy of USGS-based elevation data, USGS data may be too “coarse” to adequately describe surface profiles of watershed areas or drainage patterns. Additionally, USGS data are too coarse to defined roadbeds and other transportation structures that would affect drainage patterns around existing facilities. Additionally, hydraulic design requires delineation of much smaller drainage areas (watersheds) than other hydrologic applications, such as environmental, ecological, and water resource management. For example, a commonly used method in Iowa to determine peak discharge for culvert design (Iowa runoff chart) is applicable for rural areas less than 1,000 acres in size. By contrast, the smallest surface hydrologic unit code (HUC) currently being delineated by the USGS is 10,000 to 40,000 acres in size (12-digit HUC). As a result, highway engineers may require more detailed topographic data to assess impacts due to new construction or evaluate existing designs.

1.2. LIDAR Surface Elevation Models

Since the early 1970s, light detection and ranging (LIDAR) has been used for terrain definition. The LIDAR instrument transmits a beam of light to a target. Some of this light is reflected/scattered back to the instrument. The time for the light to travel out to the target and back to the LIDAR is used to determine the range to the target. LIDAR works best with low vegetation, but even in heavy vegetation some light pulses penetrate and are returned so that the distance to the ground can be measured. Algorithms are then used to “filter” out the vegetation and buildings, leaving what is referred to as a “bare earth” model, which contains precise ground elevations. The resolution and accuracy of aerial-based LIDAR vary among vendors, but a reported horizontal resolution of 2 m is common. Reported horizontal accuracies of 1-m root mean square error (RMSE) and vertical accuracies of 15-cm RMSE or greater are also common.

LIDAR terrain data have been used for a number of different applications, including generating contours, creating three-dimensional terrain views, determining fault locations, modeling steep slopes, critical areas, and streams, and delineating drainage basins (City of Seattle 2003). LIDAR data have recently been used in two extensive hydrologic projects in Texas and North Carolina. Specifically, LIDAR data are being collected to assist in the creation of a drainage system model for Corpus Christi, Texas, and in the development of flood insurance rate maps in North Carolina. LIDAR data were also used to capture very small drainage features, such as narrow ditches and potential areas where ponding of water might occur. These LIDAR data were used to interpret drainage patterns, producing a detailed drainage network that was highly representative of all actual water features (Caruso 2003).

1.2.1. Description of Technology

The acronym LIDAR stands for “light detecting and ranging.” LIDAR is an active remote sensing system that utilizes a laser beam as the sensing carrier (Wehr and Lohr 1999). Laser scanners measure three-dimensional points that are distributed over the terrain surface and on objects rising from the ground (Haala and Brenner 1999). In short, the laser beam makes distance measurements to and from the surface of the earth from the sensing platform, from which elevations can be derived.

The manner in which LIDAR works is fairly straightforward. A platform (usually an airplane) has a laser ranging system mounted onboard, along with other equipment including a precision global position system (GPS) receiver and accurate Inertial Navigation System (INS) to orient the platform (Shrestha et al. 1999). The platform is flown over the area in which data are to be collected while scanned by the laser. The lasers utilized in this process typically emit thousands of pulses (up to 25,000) per second while in use. The travel time of these pulses is timed and recorded between the platform, the ground, and the platform again (round trip), along with the position and orientation of the platform to determine range (distance) (Shrestha et al. 2001). Figures 1.1 and 1.2 illustrate the process.

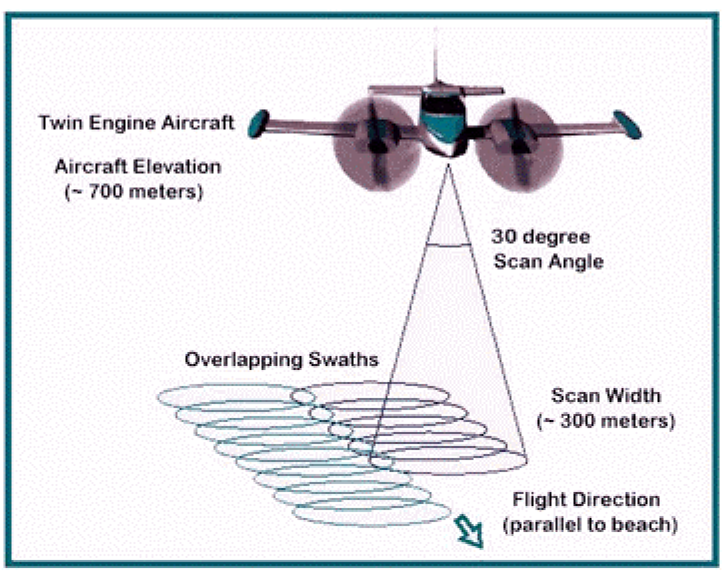

Figure 1.1. LIDAR data collection (image source: http://www.csc.noaa.gov/ products/sccoasts/html/tutlid.htm)

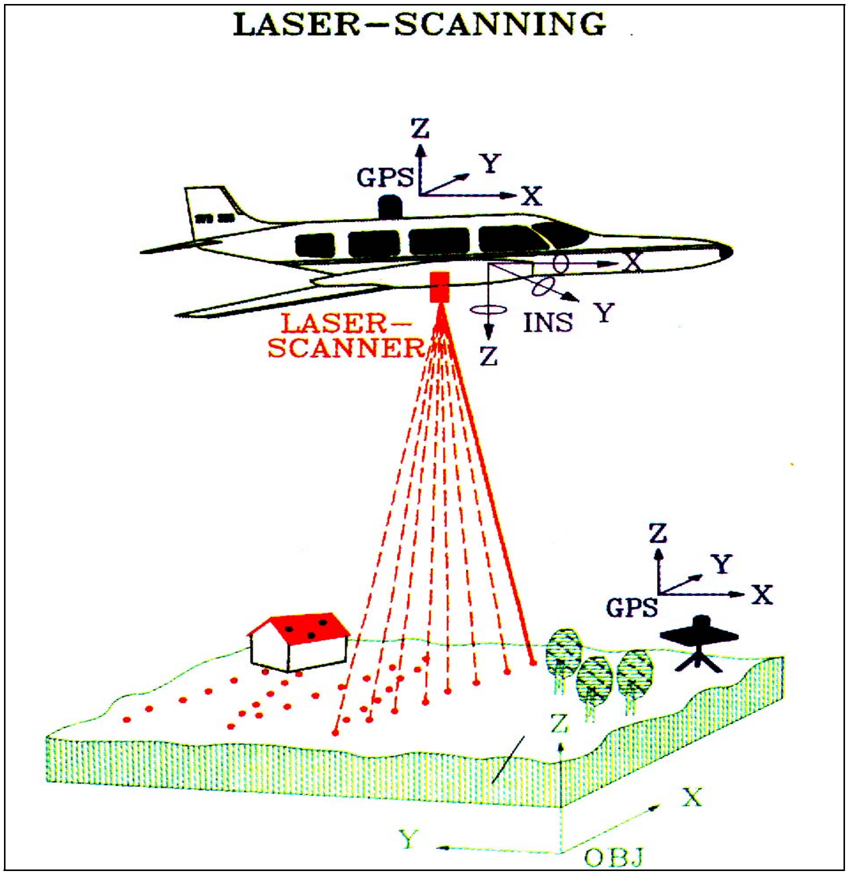

Figure 1.2. LIDAR data collection (image source: http://www.sbgmaps.com/lidar_technologies.htm)

Distance is calculated using the measured variable, travel time, and the known constant for the velocity of light. Onboard GPS measurements are collected and then combined with the measurements made by the INS and used to adjust the distance measurement for each pulse, allowing calculation of corrected surface coordinates (x, y, z). Further data processing can extract measurements of the bare ground (removal of vegetation, snow cover, etc.), allowing creation of digital elevation models or surface terrain models. Vertical accuracy is typically 15 cm. If flight layouts are optimized for GPS, vertical accuracies of 7 to 8 cm are possible (Brinkman and O'Neill 2000). Horizontal accuracy depends on flying height with accuracies up to 0.4 m. Digital aerial photography can also be collected at the same time as LIDAR data, providing an additional layer of data, assuming conditions such as cloud cover are favorable.

The processing of data collected during a LIDAR flight involves a series of steps. The first step is the computation of points along the trajectory of the aircraft (done in-flight) (Carter et al. 2001). Next, coordinate transformations and interpolation are performed to determine the position and orientation of the sensor head at the precise time of each laser pulse (Carter et al. 2001). From this task, laser scanner angle and range values are used to compute vectors from the sensor to the reflective surface for each measurement, which are then combined with sensor head position and orientation values to obtain the coordinates of the surface points (Carter et al. 2001). These coordinates furnish the xyz data. Depending on the desired final product, additional processing may be performed to filter out unwanted items such as vegetation and buildings.

The characteristics of flights performed to collect LIDAR data vary depending on the project. Even the platform itself can vary; some laser scanners are mounted to helicopter while other scanners are mounted in airplanes. The determination of what platform will be used for collecting laser data often depends upon the project itself, as well as the capabilities of the organization chosen to perform the collection.

One of the primary uses of LIDAR data is in the creation of digital models of the earth's surface. Traditional methods for producing such models (photogrammetry, field survey) are very time consuming and therefore costly, especially in areas with dense vegetation, and often additional measurements are later required (Petzold, Reiss, and Stossel 1999). Through the use of filtering techniques, vegetation can be removed from LIDAR data, producing suitable results even in areas with dense vegetation. One study found that the accuracy of LIDAR derived models was equal or better to those produced by traditional photogrammetry (Petzold, Reiss, and Stossel 1999).

1.2.2. Preliminary Review of Current LIDAR Research

Experimental research work with LIDAR has been performed by researchers at the US Department of Defense and National Aeronautics and Space Administration (NASA) for a number of years; however, the size, weight, and power requirements of early LIDAR systems required them to be operated from large, four engine aircraft (Shrestha et al. 2001). This made its widespread use difficult and expensive. With recent advances, LIDAR systems have reduced size, weight, and power requirements, while the accuracy of essential GPS systems has improved. Furthermore, advances in computer memory and processing speeds now allow the vast quantities of data collected by LIDAR to be stored and processed more quickly and efficiently.

Since the practical application of LIDAR is recent, no information was available on its' specific use in extracting asset-related data. For transportation in general, two related applications were found. Researchers at the University of Florida evaluated LIDAR data to create airport layout plans. LIDAR data have also been used in a route selection model developed to compare new rail alternatives (Cowen et al. 2000). In other fields, LIDAR data have been used to create baseline coastal topographic data for evaluation of coastal erosion, storm damage, and shoreline stabilization by the National Oceanic and Atmospheric Administration (2001). Additionally, the Federal Emergency Management Association is using the technology to create flood insurance rate maps, which are used for proactive flood hazard mitigation, risk assessment, preparation for floods, and recovery from flooding. FEMA estimates that LIDAR is providing the agency with high-resolution, high-accuracy terrain data less expensively than currently used aerial photography methods (FEMA 2000). LIDAR data have also been used for the following:

- Hydraulic computer modeling (Miotto 2000)
- Pipeline and power utilities

- Oil and gas exploration
- Environmental evaluations
- Beach erosion studies
- Open pit mining
- Land resource management
- Construction planning
- Creation of topographic maps for drainage basins (Stone 1999)

1.2.3. LIDAR Errors

Research conducted by Huising and Piereira classified LIDAR errors into broad groups including laser, GPS/INS, and filtering induced, as well as errors caused by other problems (Huising and Pereira 1998). Laser induced errors stem from changes in height for the points on the terrain surface at a narrow angle (ridges and ditches), and grain noise, which makes a smooth surface (beaches) appear rough (Huising and Pereira 1998). GPS/INS errors stem from equipment initialization errors and variances in the measurements taken by the instruments (Huising and Pereira 1998). Filtering errors stem from the incomplete and/or unnecessary removal of features, which may or may not be desired in the final data set (vegetation, buildings, rock outcroppings). Other causes of error can stem from incomplete coverage of the survey area from improper flying and water bodies reflecting beams instead of absorbing them, producing a false reading (Huising and Pereira 1998).

1.2.4. Use of LIDAR in Transportation Applications

Al-Turk and Uddin examined the combination of LIDAR-derived DTM and digital imagery for digital mapping of transportation infrastructure projects. The authors state that such applications include asset management, right-of-way alignment, terrain modeling, and other transportation applications (Al-Turk and Uddin 1999). The application of remotely sensed digital data (both LIDAR and imagery) would accelerate data collection and processing efforts, which are essential for full and timely implementation of geographic information system (GIS) based infrastructure asset management systems (Al-Turk and Uddin 1999). In addition, such data could be loaded into terrain mapping or computer-aided design software, allowing further applications to be developed. The horizontal accuracy of the laser data was calculated to be 1 m (3 ft) and the vertical accuracy was better than 7 cm (2.75 in).

In a similar application, Pottle (1998) discusses the combination of LIDAR and video imagery to asset management for the capture of terrain and asset position information along busy rail corridors. The data were used to locate features such as mileposts, track centerlines, road crossings, switches, bridges, electrification, and culverts for mapping purposes and DTM development. The data allowed engineers to analyze drainage conditions, measure distances between rails and clearances between overhead power lines, and model areas along the surveyed corridor.

Highway Mapping

Research conducted at the University of Florida evaluated the use of LIDAR-derived terrain data for highway mapping. A 13-mile test flight over Interstate Highway I-10 in Leon County, Florida, was flown (Shrestha et al. 2000). Ground returns were processed to produce shaded relief maps, among other products. Roadway details revealed included an overpass, the directional lanes of the divided highway, the median divider, drainage ditches, and trees. In the un-edited data, it was also possible to identify vehicles on the roadway. The horizontal resolution and positioning of the points were at the few centimeter level, so if profiles were taken along and across the highway, the grade and crown of the interstate, along with the height of the overpass, could be determined.

Additional research examined the accuracy of elevation measurements derived from laser data. This examination involved a comparison of heights derived from laser mapping and low altitude (helicopter based) photogrammetry data collected in November 1997. Laser data were collected along a 50-km (31 mi) corridor consisting of State Road 200 and Interstate Highway I-95. The elevations produced by laser data were found to be accurate to within ±5–10 cm (± 2–4 in). The mean differences between photogrammetric and laser data were 2.1 to 6.9 cm (0.82 to 2.71 in) with a standard deviation of 6 to 8 cm (2.36 to 3.15 in) (Shrestha et al. 1999).

Railroad Lead-track Route Location

Cowen et al. (2000) examined the inclusion of LIDAR data into an econometric model to determine the least cost path for a new railroad spur. A traditional field survey was also performed to assist in evaluating the accuracy of the LIDAR data. The data were examined to find the relationship between canopy closure, LIDAR canopy penetration, and scan angle (Cowen, Jensen, and Hendrix 1999). The research concluded that LIDAR appears to be a useful method to obtain xyz data, even during growing seasons, although completely closed canopies in forested areas led to lower DEM accuracies (Cowen et al. 2000). Where canopy closures were 30% to 40%, LIDAR pulses reached the ground 80% to 90% of the time. However, in areas where canopy cover was 80% to 90% closed, only 10% to 405 of LIDAR pulses reached the ground (Cowen et al. 2000).

Road Planning and Design

Investigations into the application of LIDAR-derived DTMs have been conducted in both the Netherlands and Canada to determine their suitability in highway planning and design (Berg and Ferguson 2000, 2001; Pereira and Janssen 1999). The traditional mapping method being used by the agencies involved was photogrammetry, supplemented by ground surveys. The research conducted in these cases examined the use of LIDAR as a means to speed up data collection and surface mapping. In each case, the accuracy of the data was examined to determine if it compared to the accuracies of data currently derived by photogrammetric means.

Research conducted in the Netherlands examined not only the applicability of laser data in highway planning and design, but also what additional information (both semantic and geometric) could be extracted (Pereira and Janssen 1999). This work included the detection, identification, modeling, measuring, and labeling of such information (Pereira and Janssen 1999). The extraction research performed by the researchers focused extensively on the identification of break lines, an important component in the planning and design process.

To assess the accuracy of the data, three additional sets of reference measurements were collected: two tachymetric (ground survey) data sets and one photogrammetrically derived data set (derived from imagery collected in March 1996) (Pereira and Janssen 1999). For existing planning and design applications, a height accuracy of 25 cm (9.85 in) was required, with 7.5-cm (3 in) accuracy required for hard surfaces such as roads (Pereira and Janssen 1999). Assessment of the laser data found that its height (z) accuracy was 29 cm (11.4 in) RMSE. The accuracies obtained from tachymetry and photogrammetry (in soil with low grass) were 16 cm (6.3 in) and 15 cm (5.9 in), respectively. Laser data provided similar accuracies in similar areas; however, the RMSE of the laser data was affected by high inaccuracies in areas containing features such as ditches and slopes. This suggests that further research is required to address the shortcomings of LIDAR in these measurements.

The Ministry of Transportation Ontario (MTO), in Canada, also conducted research into the application of LIDAR data in the highway planning and design process. The focus of this research was to determine if LIDAR data compared to data derived from photogrammetric mapping techniques, and whether it would perform better than photogrammetry when leaves and ground vegetation were present (Berg and Ferguson 2001). In order to make this determination, an examination of the horizontal and vertical accuracies of LIDAR was performed to see if they met the MTO specifications of 15 cm (5.9 in) for hard surfaces and 20 cm (7.87 in) for soft surfaces (Berg and Ferguson 2001). To perform this analysis, data were collected during the summer under leaf-on conditions.

Analysis revealed that LIDAR data had an accuracy of 15 cm or better on hard surfaces, such as pavement (Berg and Ferguson 2000). The accuracies on other surfaces were variable up to 0.5 m, while low vegetation, rock, and ditches led to discrepancies of over 1 m in some cases (Berg and Ferguson 2001). Under forested canopy, the accuracy of LIDAR data ranged from 0.3 to 1 m (Berg and Ferguson 2000, 2001). LIDAR data were compared to MTO audit (ground surveyed) data, and no direct comparison was made to photogrammetric data produced under leaf-off conditions.

The MTO project presented a number of issues pertaining to the use of LIDAR data in highway planning and design. Most notably, difficulties were encountered with the ability of LIDAR to hit and define narrow features, such as ditches (Berg and Ferguson 2001). This is particularly significant since the identification of such features is critical to define break lines. The researchers also found that LIDAR was unable to penetrate low ground vegetation (Berg and Ferguson 2000). Comparisons to MTO audits revealed a number of discrepancies of up to 0.5 m in areas covered with tall grass (Berg and Ferguson 2001). Another point of concern was caused by rock cuts. During the classification process, such features were assumed to be buildings by the software and were automatically extracted (Berg and Ferguson 2001). Since rock features are important factors in determining highway construction costs, they must be properly identified (Berg and Ferguson 2000).

2. PROJECT SCOPE

USGS-based elevation data are the most commonly used data source for highway drainage analysis. However, the data may not have sufficient accuracy to properly delineate watershed boundaries, define the watershed area surface, and delineate roadway features that affect drainage patterns around roadway facilities. LIDAR data provide higher resolution terrain information. Although collection of LIDAR data is currently rather expensive and may not be feasible only for hydraulic analysis, a number of state departments of transportation and other state and local agencies are planning large-scale collection of LIDAR data for other applications, providing an additional surface terrain data set for highway drainage analysis. The research presented in this report compares the use of terrain models resulting from LIDAR data to USGS terrain models for assessing the adequacy of existing highway drainage structures.

This study investigates the differences between high-resolution LIDAR and standard USGS-based elevation data. In order to evaluate whether terrain data from LIDAR resulted in significant changes in drainage patterns, particularly flow, as compared to USGS terrain data, a pilot study was conducted as discussed in the following sections.

2.1. Scope of Work

Several key components of the hydraulic design of new or analysis of existing highways are the size, topography, land use, channels/streams patterns, and rainfall intensity of the drainage area. This research study qualitatively assesses whether the use of higher resolution terrain information from LIDAR better defines three of these components (size, topography, and channel location) and impacts hydraulic design and deficiency (surety) assessment.

2.2. Pilot Study Area

In order to evaluate LIDAR-derived terrain information compared to USGS terrain information, a study corridor was selected. The corridor was selected from existing Iowa Department of Transportation (Iowa DOT) projects that already had initial data, such as high-resolution aerial imagery, available. The Iowa Highway 1 corridor through Solon, Iowa, met all the requirements and was selected for a pilot study.

The study area is the Iowa 1 corridor between Iowa City and Mount Vernon in Johnson and Linn counties as shown in Figure 2.1. Iowa 1 is a two-lane, undivided state highway oriented north-south located in the east-central portion of the state. Iowa 1 is a two-lane roadway throughout the 18 miles of the corridor. The study segment begins at an interchange with Interstate 80 near Iowa City and ends at the junction with US Highway 30 outside the town of Mount Vernon. The highway passes through the town of Solon, the location of a proposed bypass, at about the midpoint of the corridor, as shown. The corridor is characterized by a variety of terrain, including rolling farmland and developed (urban) area. Additionally, a river is present that causes significant changes in elevation in portions of the study area. Elevations of the study area range from approximately 650 to 900 ft. Of particular interest is the drainage area size and placement of the drainage area boundaries and streams parallel to and crossing the highway. Stream paths were derived from the USGS and LIDAR data using hydraulic modeling, and then the accuracy of these locations was also compared to aerial images from the Iowa DOT and Iowa Department of Natural Resources (Iowa DNR). Extent of USGS and LIDAR data available for the study area are shown in Figure 2.2.

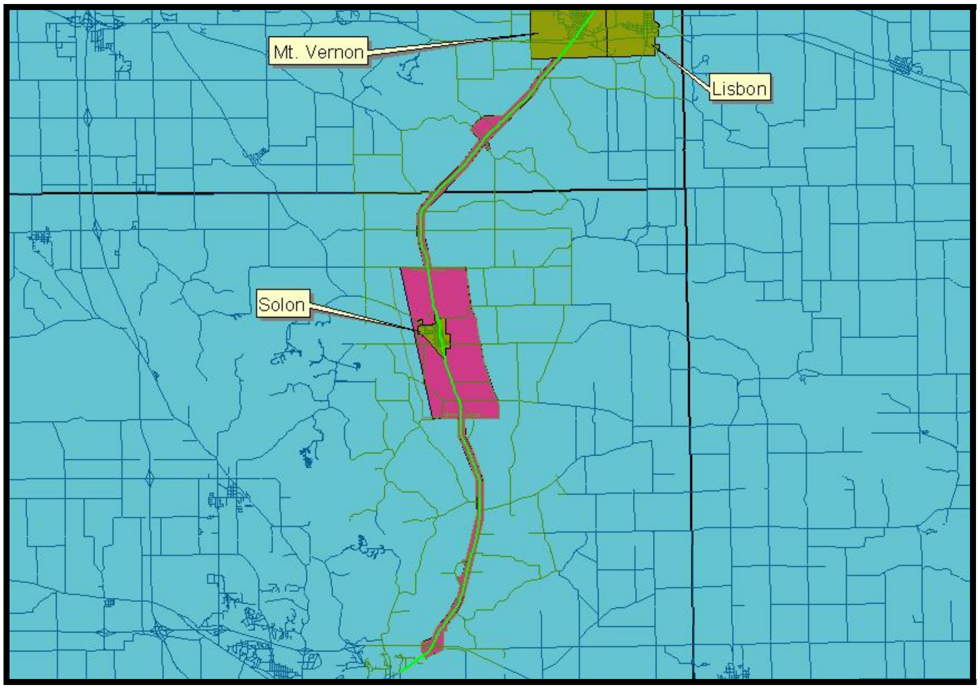

Figure 2.1. Iowa 1 corridor

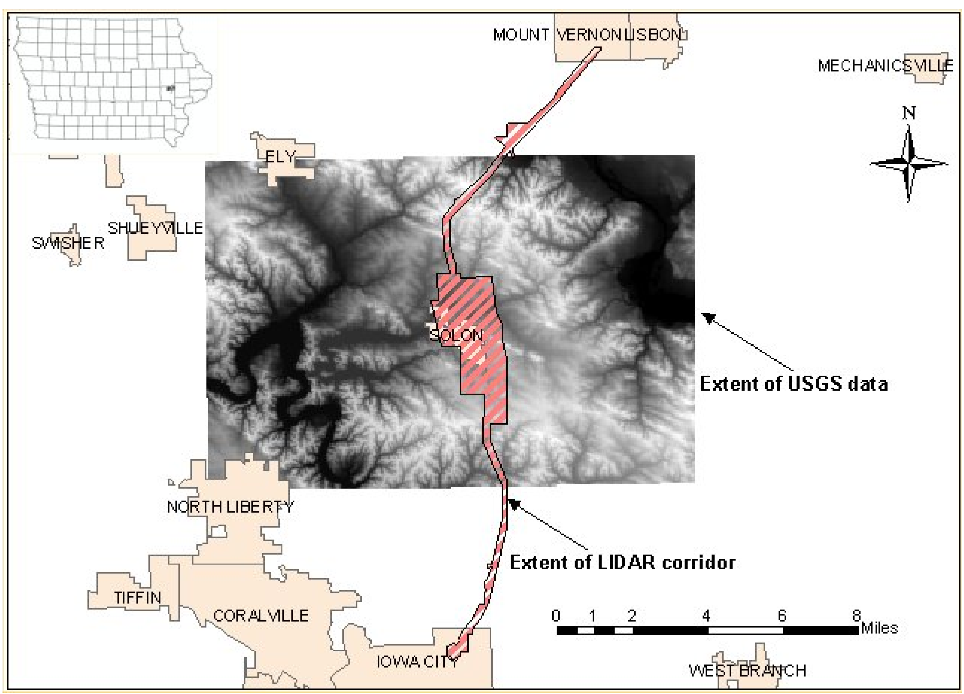

Figure 2.2. Map of corridor

2.3. Description of Data

Two sources of terrain data were obtained for the pilot study area, LIDAR and USGS DEMs. Additionally, sets of aerial imagery were obtained for the location of existing drainage structures.

2.3.1. USGS DEMs

Two 7.5-minute USGS DEMs **(**10 by 10 m data) were obtained for the corridor from GISDataDepot (data.geocomm.com). The reported accuracies for the DEMs were 7 m (23 ft) vertical and 10 m (33 ft) horizontal (US Geological Survey 2002). The USGS data covered the 18-mi length of the Iowa 1 and were 21,000 m (69,000 ft) wide and extended at least 8,200 m (27,000 ft) on both sides of the roadway as shown in Figure 2.2.

2.3.2. LIDAR

LIDAR data for the study area were collected by a private vendor in October 2002. The vendor provided LIDAR-derived digital elevation data in the form of a point cloud consisting of an easting, northing, and elevation (xyz) with an average spacing of 2 m. Three data sets were provided: first return pulses, last return pulses, and bare earth. To produce a bare earth DEM, last return LIDAR pulses were processed with vegetation filters. Later work by the vendor produced a gridded DEM of 5 ft. All DEM data were delivered in comma-delimited ASCII format.

The laser unit utilized by the vendor sent out 4,000 pulses per second and scanned across the aircraft's flight path. Additionally, GPS and Inertial Measurement Unit (IMU) data were collected to record the aircraft's position, as well as its roll, pitch, and yaw at the time each pulse was fired by the laser. Digital orthophotos were also collected during a separate flight from the LIDAR data collection. Digital images were of 1-ft resolution, with a horizontal accuracy of 2 m. Imagery was orthorectified using airborne GPS data, platform attitude, and LIDAR DEM data. All data were projected in the Iowa State plane south coordinate system. The horizontal datum was NAD83, and the vertical datum was NAVD88, with units in meters.

A bare earth model from the LIDAR data was available to the study team. The reported accuracy of the LIDAR data was 1-m RMSE horizontal and 15-cm RMSE vertical. Horizontal resolution was 2 m. Although USGS data were available for 27,000 ft around Iowa 1, LIDAR data were collected for a different purpose and were available for the length of the study corridor but the data only extended 0.25 to 1.5 mi on both sides of Iowa 1 depending on the location. Data for the largest area were available near Solon, at the site of the proposed bypass as shown Figure 2.2.

2.2.3. Aerial Imagery and Planimetric Data

Planimetric data and two sets of aerial images were also obtained for the study corridor. Digital planimetric files, including culvert locations and aerial photographs for the corridor were obtained from the Iowa DOT. Color infrared (CIR) aerial photographs for Johnson and Linn counties were obtained from the Iowa DNR. The images were acquired between March and May 2002. The images have a scale of 1:40,000 and meet all standards and specifications of the National Aerial Photography Program (NAPP) (http://www.iowadnr.com/epc/03sep15/6.pdf).

2.3. Potential Benefits of Research

The primary benefit of this study was to determine whether the use of high-resolution terrain data (LIDAR) improves drainage area delineation and the corresponding flow estimates, and how this may influence design of hydraulic features such as culverts. If the increased terrain detail can improve hydraulic design, structures may be more accurately and cost effectively designed and possible deficiencies in existing design may be identified. Possible benefits of deficiency identification include limiting future system failure and the mobility issues accompanying it and the deterioration of pavement and structures resulting from improper drainage. Additionally, it would provide the ability to assess the surety of existing structures particularly since USGS data do not adequately delineate existing roadway facilities.

3. METHODOLOGY

Hydraulic design entails several key components. The components affected by use of terrain models are drainage area size, topography, and channel location. Differences between size, topography, and location of streambeds that resulted from uses of USGS and LIDAR-derived surface elevation models were the focus of this study. Implications of differences in size, topography, and channel location were also addressed. The methodology to compare results of the two data sets is presented in the following sections.

3.1. Software Tools

Two software tools were used for the study: ArcView version 3.3 and HEC-GeoHMS version 1.0. ArcView is a GIS created by ESRI. The Geospatial Hydrologic Modeling Extension (HEC-GeoHMS) is a software package developed by the Army Corps of Engineer's Hydrologic Engineering Center that utilizes ArcView and its Spatial Analyst extension to develop hydrologic modeling inputs. HEC-GeoHMS analyzes digital terrain data and transforms the resulting drainage paths and watershed boundaries into a hydrologic data structure representing the watershed response to precipitation (US Army Corps of Engineers 2003).

3.2. Watershed and Stream Creation

HEC-GeoHMS employs a multi-step process to define streams and watershed boundaries from terrain data. The user may employ either a step-by-step or batch processing approach to derive the stream and watershed coverages. The user has more control in the step-by-step approach, allowing interactive review and verification of the incremental results. The batch process develops all incremental and final data sets, allowing only limited user input. This study utilized both approaches.

Before watersheds and streams can be delineated, elevation grids were created from the point-based LIDAR elevation data. An elevation grid consists of a grid of cells, square or rectangular, in raster format having land surface elevation stored in each cell. Four distinct elevation grids were created for this study. These grids will be discussed in the next section. Upon creation of the grids, HEC-GeoHMS employs the following eight steps to create watershed and stream coverages from the input terrain data (Doan 2000):

Step 1. Depressions are removed from the source DEM to allow water to flow across the landscape.
Step 2. The direction of flow for each cell is determined by the direction of the steepest descent. Possible directions of flow are the eight cardinal directions.
Step 3. Flow accumulation is calculated for each cell by determining the number of upstream cells that drain into it.
Step 4. Streams are defined based on a user defined threshold value (area or number of cells). The flow accumulation for a particular cell must exceed the threshold to be included in the stream network.
*Step 5***.** Streams are segmented between successive junctions, a junction and an outlet, or a junction and a drainage divide.

Step 6. Watersheds, or subbasins, are delineated for each stream segment.
Step 7. Stream and watershed grids (raster) are converted to vector representations.
Step 8. Aggregated watersheds are created by merging upstream subbasins at every stream confluence.

3.3. Surface Terrain Data Sets

Four distinct surface terrain data sets (elevation grids) were created from the LIDAR and USGS point-based elevation data. Given the limited breadth (area) of the LIDAR data set relative to the USGS DEMs, a strict comparison of the two terrain data sets could not be performed. For example, LIDAR data did not always cover a complete watershed or contributing area for a downstream stream. However, elevation grids were created in a manner that would best facilitate comparison of the available data. This section discusses the elevation grids and factors integral in their creation.

3.3.1. LIDAR Bare Earth

Using the LIDAR bare earth data sets, an elevation grid of 10-m cell size was created for the corridor. While a finer grid could be created from the LIDAR data set, given the density of data points (approximately 1 point per 25 m^2), the 10-m grid was selected for processing efficiency and consistency with the USGS data set. The processing time required to create a 5-m grid for the entire corridor was such that it was deemed unrealistic that this would be repeated in practice, with some exceptions without higher performance computers. (An example of a 5-m grid for a portion of the corridor is presented later.) The 10-m grid size was also a reasonable size for the USGS data. While some of the terrain detail provided by the LIDAR may be lost, a more consistent comparison of the USGS data could be performed. Areas of emphasis were watershed and stream delineation in the immediate vicinity of the highway. Two video clips of the terrain models created from the LIDAR data set are shown in Figures 3.1 and 3.2. Note the definition of the roadbed in the surface model.

Using HEC-GeoHMS, watershed, stream configuration, and flow accumulation, grids were created for this elevation grid. An area threshold value of 1%, or approximately 6 acres, was used for stream definition, as presented in Figure 3.3.

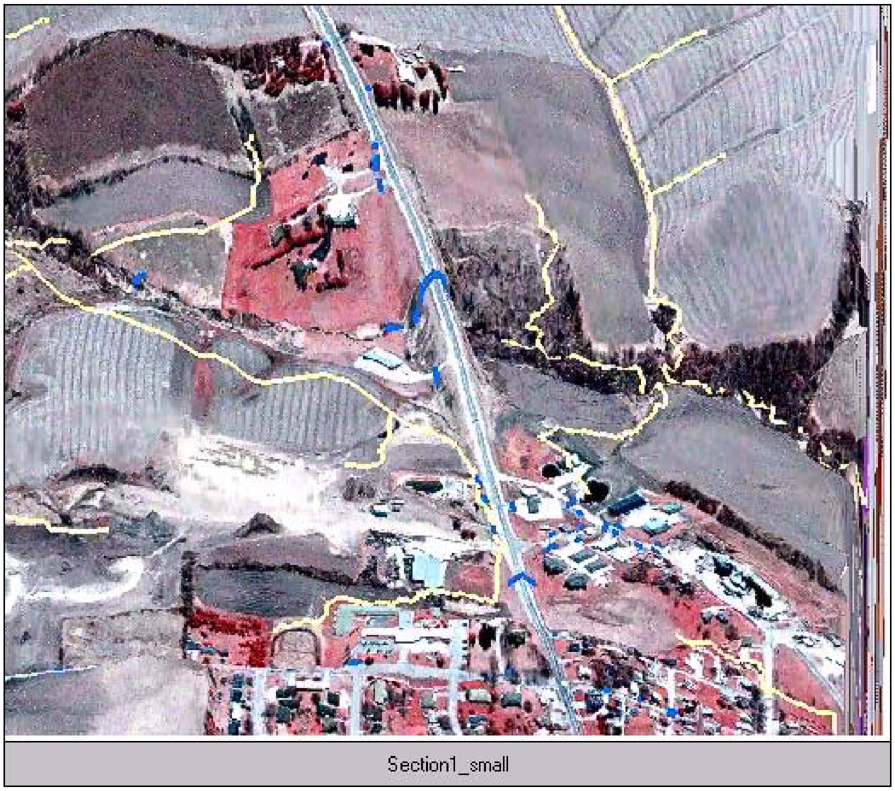

Figure 3.1. Video clip of LIDAR-based terrain model (section 1)

Figure 3.2. Video clip of LIDAR-based terrain model (section 2)

3.3.2. USGS DEMs

An elevation grid of 10-m cell size was created from the mosaiced USGS DEMs covering the Ely and Solon area. The area represented by these DEMs was much greater than that of the LIDAR data, encompassing both large and small watersheds. Using HEC-GeoHMS, two different sets of stream configurations, watersheds, and flow accumulation grids were derived. The first set was created using the batch-processing mode, and a default value of 1%, or 200 acres, was used as the stream threshold (Figure 3.3). These data sets were created to assess the sensitivity of watershed size to the input threshold value. As expected, the watersheds were much larger and the stream coverage was fairly sparse, limited to major streams or channels, because runoff over a greater area was required to define a stream in HEC-GeoHMS, as demonstrated in Figure 3.4. The second set of stream configurations, watersheds, and flow accumulation grids was created to compare to the LIDAR results. An area threshold value of approximately 6 acres (0.018%) for stream definition was used to be consistent with the watersheds generated from the LIDAR terrain data.

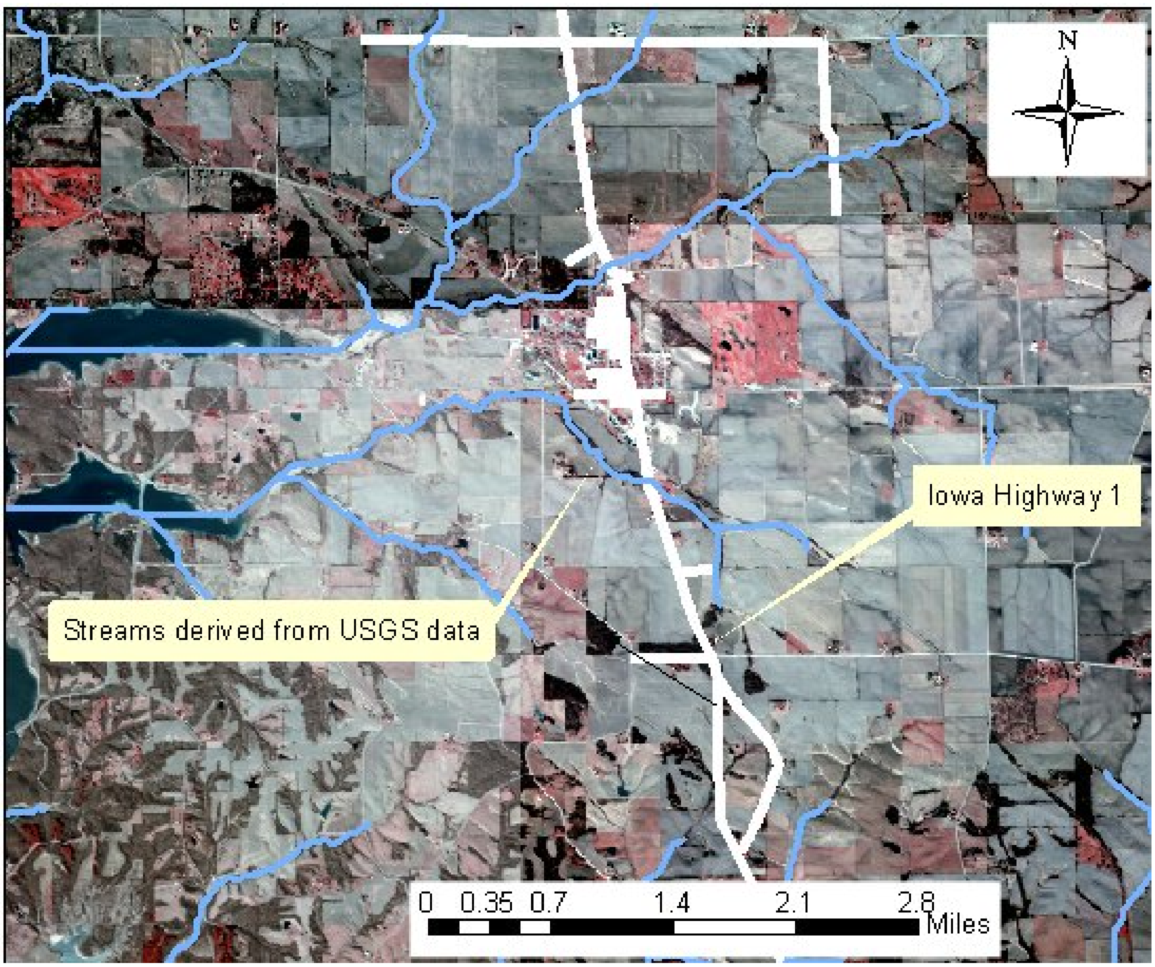

Figure 3.3. USGS-based stream coverage, 200-acre threshold for stream initiation

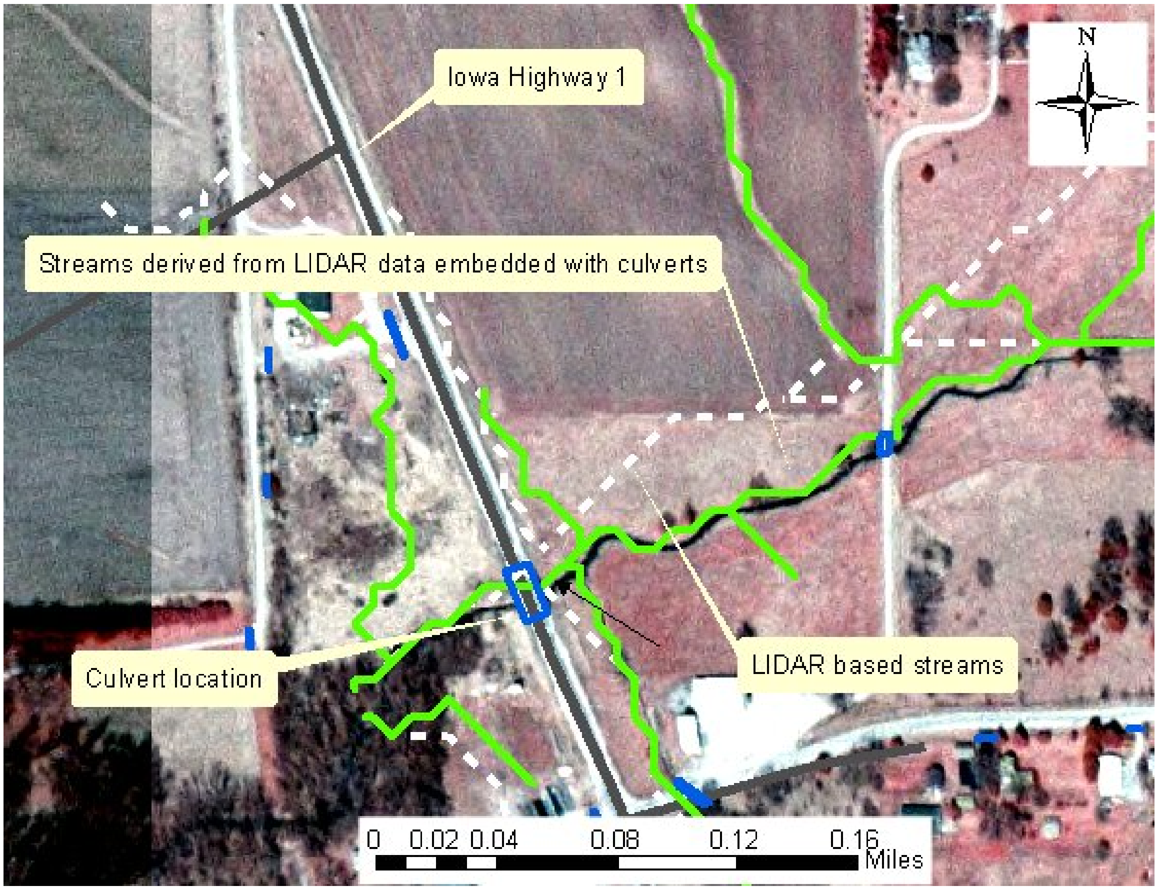

Figure 3.4. LIDAR-based vs. LIDAR-embedded with culverts-based stream coverage, 6-acre threshold for stream initiation

3.3.3. LIDAR Bare Earth Supplemented with Culverts

In an attempt to influence stream flow through known hydrologic structures, a 10-m grid file of existing bridge and culvert locations, identified from Iowa DOT planimetric CAD files, was created. The elevation of the grid cells at these locations was set to 600 ft, approximately the same elevation as the surrounding terrain, but lower than the surrounding pixels so as to force the streams to flow into the culverts. This grid was then merged with the elevation grid made from the individual LIDAR grids to create a LIDAR grid with culverts embedded. HEC-GeoHMS was used to derive watersheds, a stream configuration, and a flow accumulation grid. These were created using the batch-processing mode in which the default value of 1% (approximately 6 acres) was used as the stream initiation threshold, as shown in Figure 3.4.

3.3.4. LIDAR Bare Earth Supplemented with Culverts and USGS DEMs

A final 10-m elevation grid was created to assess the impact of utilizing the more detailed terrain data (from LIDAR) in the vicinity of the roadway in conjunction with the more extensive USGS data, which encompasses entire watersheds. The elevation grid created from the USGS elevation grid was merged with the LIDAR bare earth and culvert elevation grid. The combined LIDAR and culvert data were utilized at areas of coincidence or overlap with the USGS elevation grid, yielding more detailed terrain data in the vicinity of the highway. The resulting elevation grid consisted of data from the USGS, LIDAR, and culvert elevation grids. HEC-GeoHMS was used to derive watersheds, a stream configuration, and a flow accumulation grid with an area threshold value of approximately 6 acres (0.018% of the largest drainage area).

4. RESULTS

Several surface terrain models were created using the USGS and LIDAR data sets as described in the previous chapter. Comparison of those different models is presented in the following sections.

4.1. Stream Bed Locations

Since established drainage patterns are disrupted by highway construction, it is important to know the locations of existing streams, particularly for the design of new channels and structures to accommodate their flows. For existing transportation facilities, the location of both natural and created channels is necessary to determine drainage patterns.

Streambed locations were delineated for each surface terrain model using HEC-GeoHMS as discussed in Chapter 3. The accuracy and reasonableness of streambed locations from the surface terrain models were verified by identifying stream patterns using the aerial and color infrared images. In addition, stream location with respect to known culvert locations and the highway roadside was reviewed.

The streambed locations (drainage channels) produced from the LIDAR-based elevation grid appeared proximate (at varying levels of accuracy) to streams identifiable from the aerial images and known drainage structure locations. The stream coverage was also fairly dense, as a result of the relatively small drainage areas defined, but lacked curvilinear detail. Both intermittent channels as well as continually flowing streams appeared to be represented. Locations of possible drainage and base inundation parallel to the roadway were also visible. These locations could represent locations of potential base failure and, in turn, increased pavement deterioration.

Stream placement was not without spatial inaccuracies. Accuracies tended to vary throughout the corridor. Streams were generally parallel to visible streams but offset from a few meters to over 50 m. A possible explanation for these occurrences is sensitivity to subtle terrain changes and errors. Specifically, the LIDAR bare earth data set was found to occasionally contain non–bare earth features, such as buildings, trees, and other vegetation. The presence of these features yielded incorrect terrain representations. Furthermore, in areas of roadway fill the natural terrain provides no path for stream flow except for parallel to the roadway or terminating at the roadway. In these instances, the roadway essentially acts as a dike.

With the addition of the culvert locations to the LIDAR elevation grid, the alignments of natural streams appeared more accurate and detailed (meandering and curvilinear), again indicating sensitivity to subtle terrain changes. Inclusion of culverts appeared to supplement/enhance roadway cross-section information at locations where LIDAR may not be able to collect all terrain surfaces, e.g., ditch foreslope, bottom, and back slope. At approximately half of the culvert locations, the stream alignment was improved to the point that the stream now flowed through the culvert. Stream alignment also improved upstream from the culvert location, better mirroring the streams visible in the aerial photographs.

As mentioned previously, a 5-m elevation grid was created for a portion of the corridor. The stream coverages created from this grid and the 10-m grid from the LIDAR data are presented in Figures 4.1 and 4.2. As is apparent in these figures, the two stream coverages closely mirror each other. Alignment differences of approximately 50 m were present at several locations (in Figure 4.2), but the 10-m grid stream coverage was actually closer to the existing stream alignment. Therefore, the more finely defined elevation grid (5 m) did not appear to yield superior stream coverage and was more greatly impacted by terrain inaccuracies or false bare earth elevations.

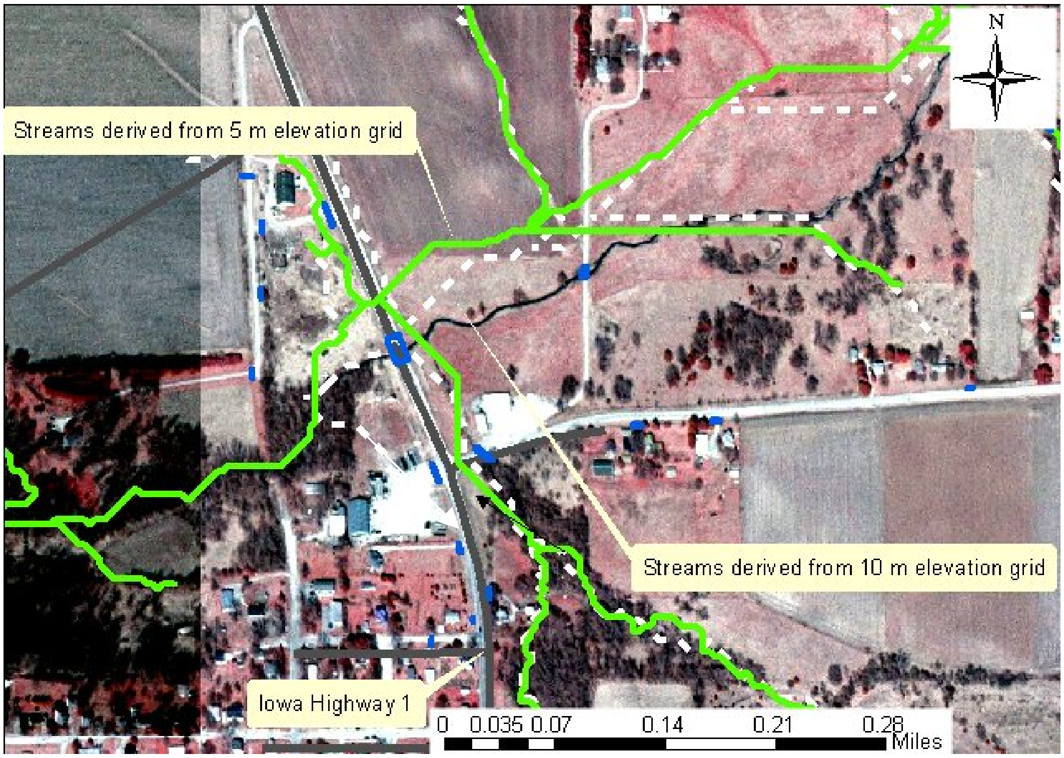

Figure 4.1. LIDAR-based stream coverage, 5-m vs. 10-m elevation grid (overview)

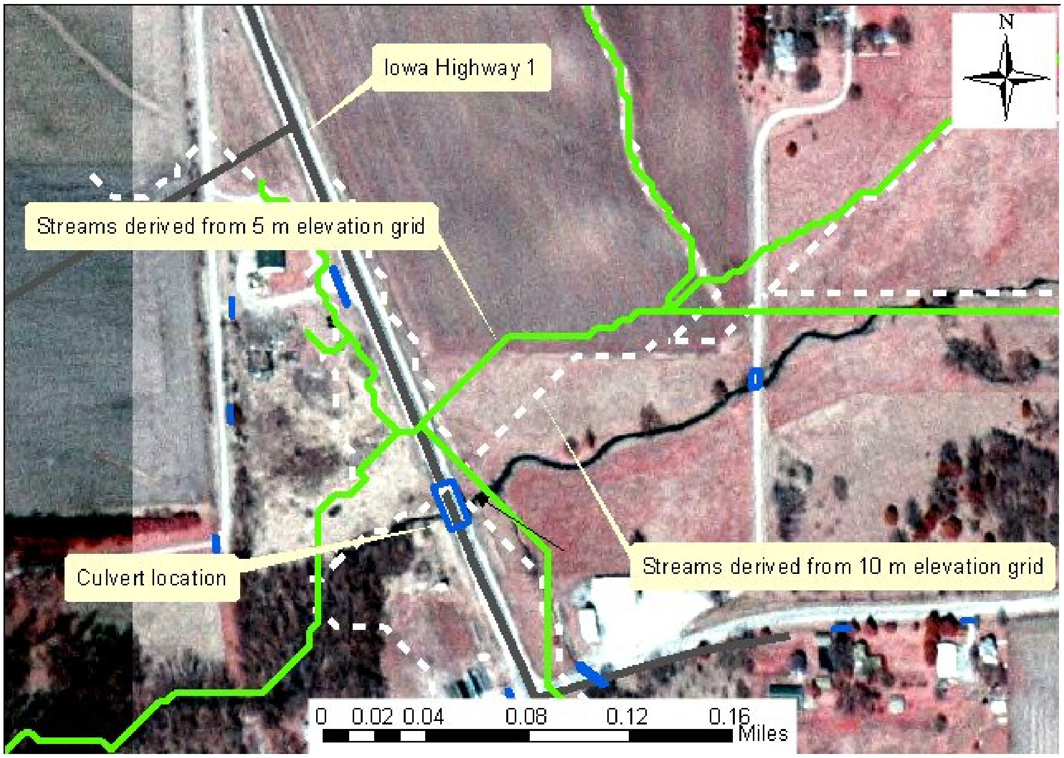

Figure 4.2. LIDAR-based stream coverage, 5-m vs. 10-m elevation grid (zoomed in)

The USGS elevation grid yielded similar stream coverages as the LIDAR elevation grid in the vicinity of the highway, as shown in Figures 4.3 and 4.4. Stream bed locations (drainage channels) were proximate to streams identifiable from the aerial images and the known culvert locations. The stream coverage was also dense but lacked curvilinear detail. Accuracies tended to vary throughout the corridor, from a few meters to over 50 m. In contrast to the LIDAR data (which may be too sensitive to terrain detail), this may result from errors in elevation or lack of terrain detail. Other than differences in stream alignment, the primary difference between the LIDAR and USGS-based stream coverages is definition of minor, feeder streams. The length and alignment of these streams differed as well as the presence (or absence) of these streams between the two coverages. As a whole, the USGS-based elevation grid yielded comparable results to the LIDAR data set without drainage structures.

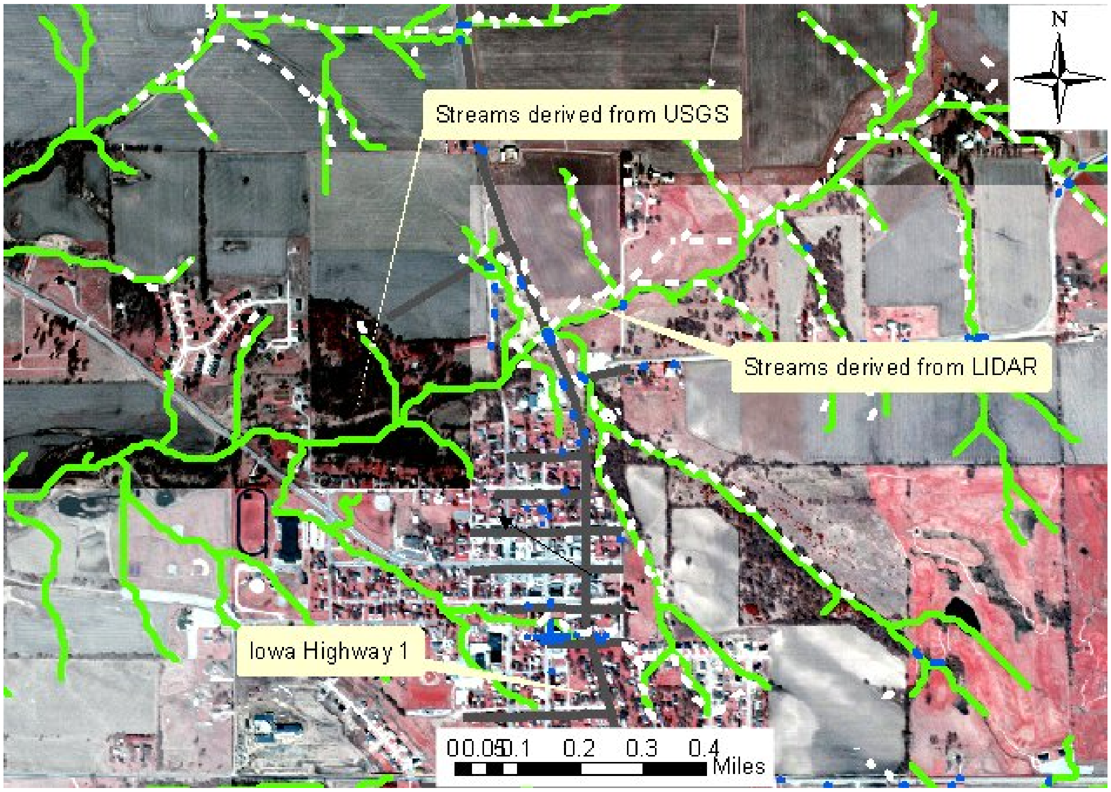

Figure 4.3. USGS-based vs. LIDAR-based stream coverages (overview)

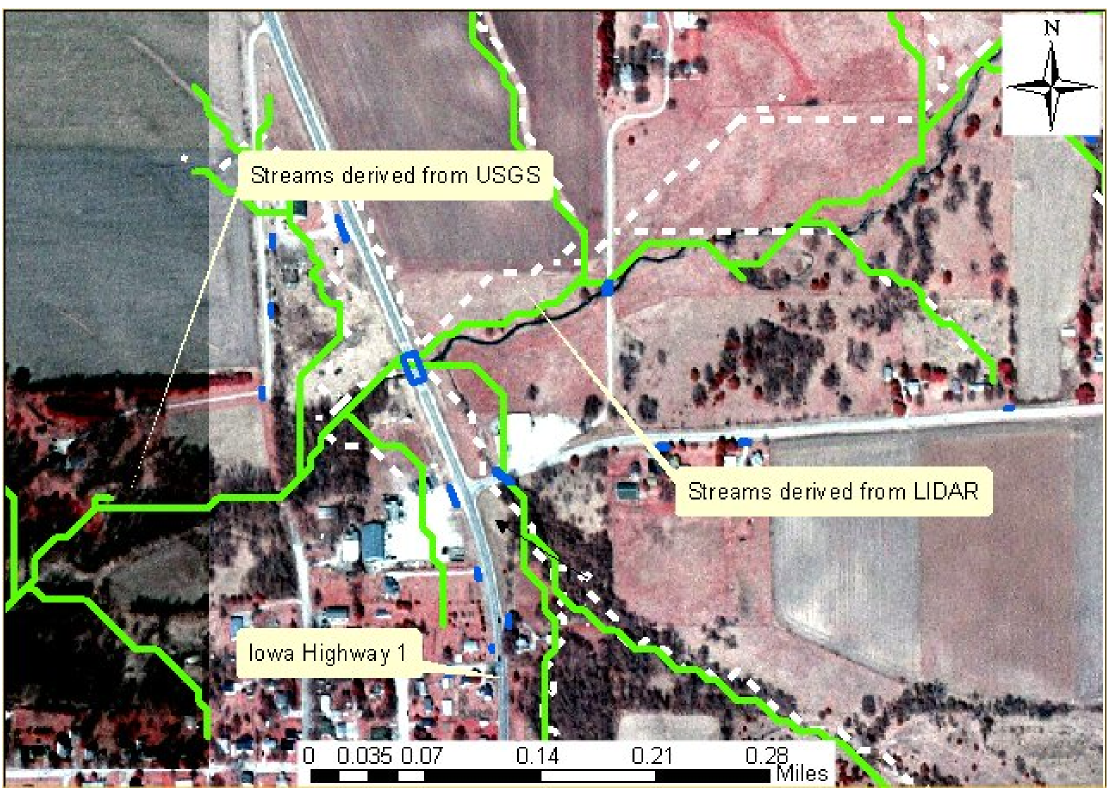

Figure 4.4. USGS-based vs. LIDAR-based stream coverages (zoomed in)

Lastly, many of the observations of the LIDAR grid supplemented with culvert locations are also applicable for the combined USGS, LIDAR, and culvert elevation grid as demonstrated in Figure 4.5. The stream coverage in the areas extending beyond the LIDAR data (USGS data only) appeared to possess the same relative accuracy and detail as the areas where LIDAR was present. Again, the streams (drainage channels) appeared proximate to streams identifiable from the aerial images and the known culvert locations. The benefit of this coverage is two fold. First, complete watershed or contributing areas, extending beyond the LIDAR coverage area, can be derived for downstream streams. Second, inclusion of the drainage structures, in both this elevation grid and the LIDAR grid alone, appeared to increase the accuracy of stream alignment at and upstream from the culvert. This was observed at approximately half of the locations, while minor/no improvement was observed at one-third of the locations, and a poorer alignment resulted at nearly 10% of the locations.

4.2. Watershed Boundaries

While knowledge of existing streams is important in highway design, the size of the drainage areas contributing to the flow in these streams is critical in the design of hydraulic structures. Of particular interest is the sensitivity of watershed delineation to improved terrain detail. In other words, can the size and nature of watersheds produced from different terrain models impact design inputs, such as flow accumulation.

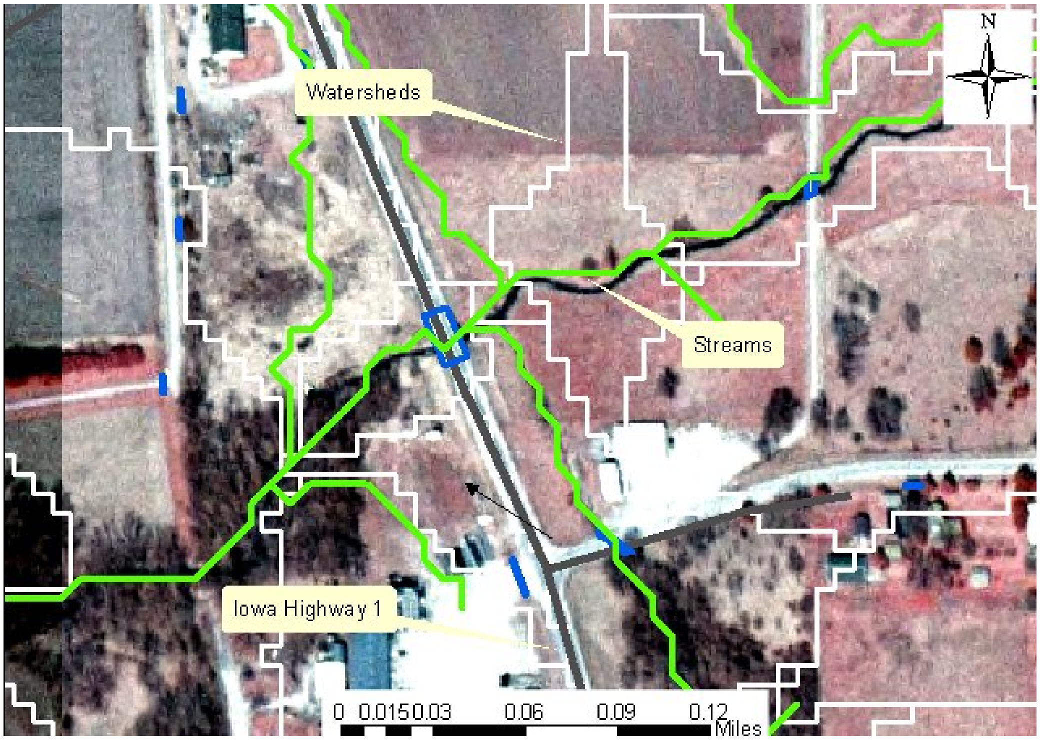

Figure 4.5. Combined LIDAR, USGS, and culvert stream coverage

Given the limited extent of the LIDAR data, only the small watersheds defined in areas where both LIDAR and USGS data existed could be compared. As presented earlier, a relatively small area threshold (6 acres) was used to define the streams. This, in turn, also yielded relatively small watersheds. Traditionally, highway engineers do not delineate watersheds using this area-based approach. Topographic maps are used to identify an outlet and all highpoints upstream from the outlet. The highpoints are then connected to define the watershed. Roadways, which are typically not visible on a topographic map, are also utilized to delineate the watershed.

HEC also used roadways to create watershed boundaries with the LIDAR data. This is possible because the horizontal resolution of the LIDAR data often facilitates detection of the roadway within the terrain, as shown in Figure 4.6. This, however, does not hold true for all watersheds along the roadway and seldom, if ever, holds true for the USGS-based data also shown in Figure 4.6. The horizontal resolution of the USGS DEM, at 10 m, is too great to detect a two-lane roadway, as demonstrated in Figure 4.6. The ability to define the roadbed is one of the significant benefits of using LIDAR over USGS.

Watersheds were affected by roadway alignments where LIDAR data were present, but near the edges of the LIDAR data set and in area described only by the USGS elevation data, the roadway did not affect the watershed configuration as demonstrated in Figure 4.7. In general, the watersheds delineated from the LIDAR-based elevation data appeared to very sensitive to changes in terrain, particularly in areas of modified terrain. This resulted in smaller, more irregularly shaped drainage areas. The USGS-based watersheds were typically larger and less complex. Yet, in many instances the LIDAR and USGS watersheds were similar in extent and/or border definition. The addition of drainage structures to the elevation grids yielded watersheds of limited differences.

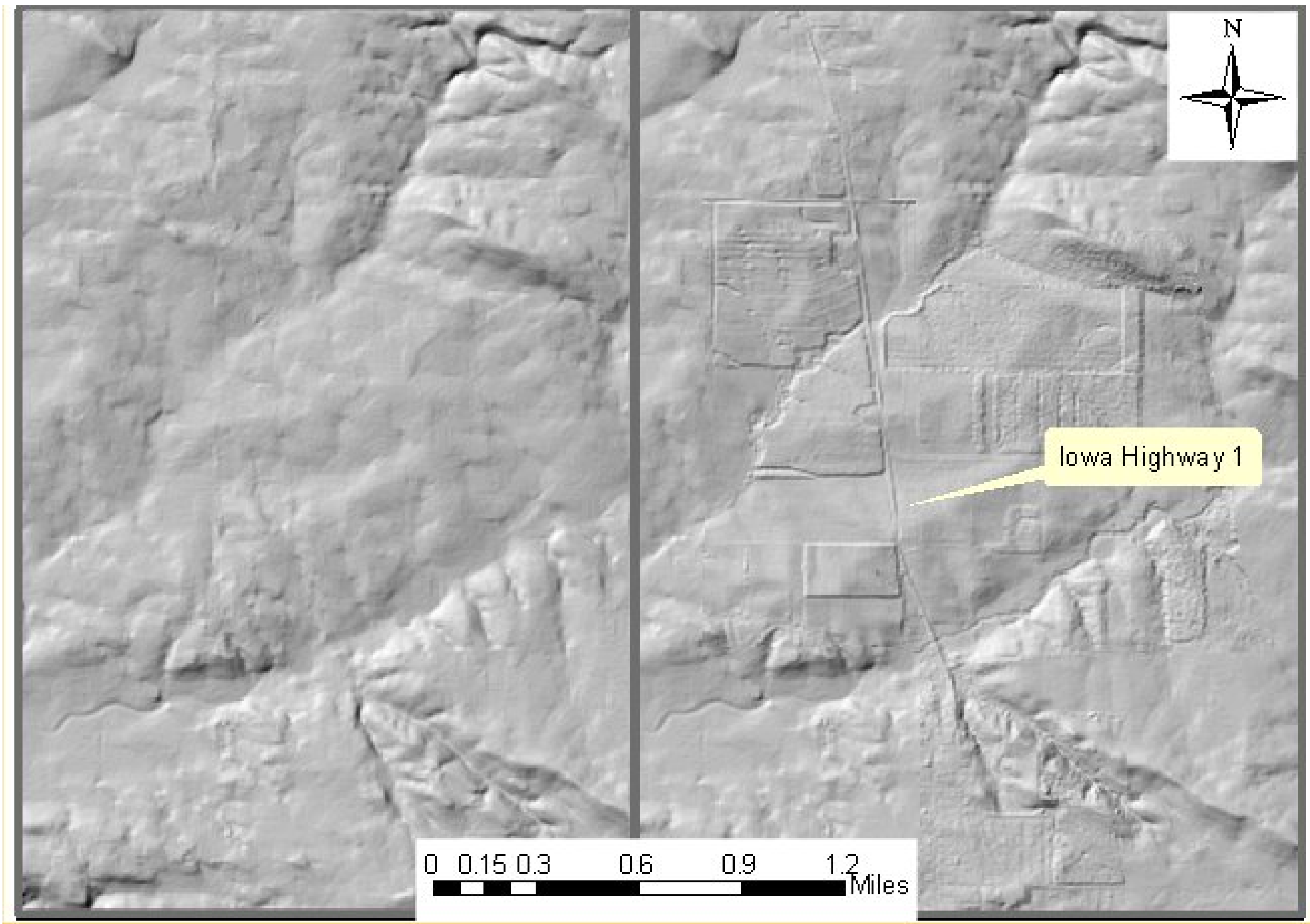

Figure 4.6. Comparison of surface model derived from USGS (left image) and LIDAR (right image) using 10-m grid

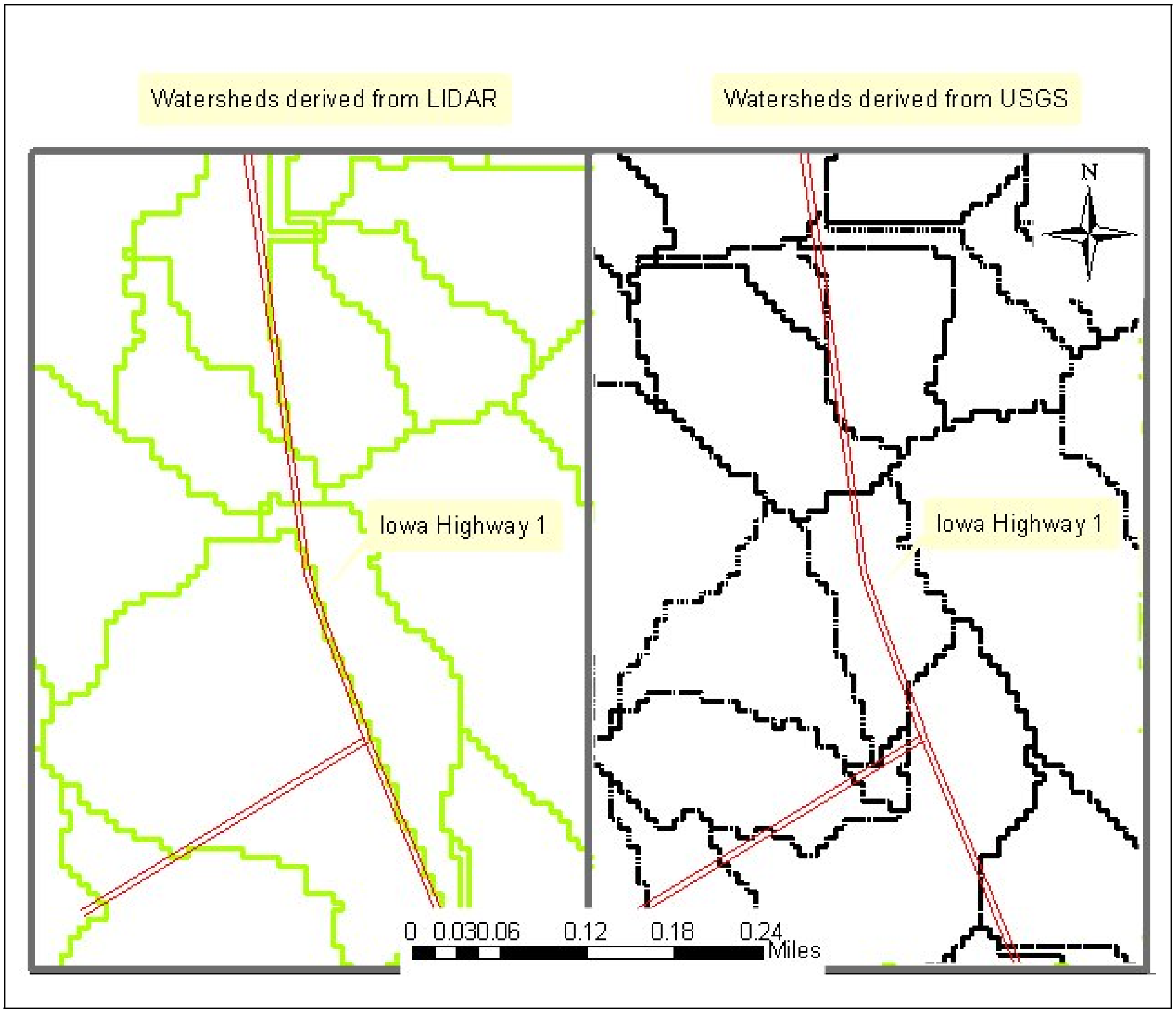

Figure 4.7. LIDAR-based vs. USGS-based watershed boundaries, 6-acre minimum watershed area

4.3. Flow Accumulation

Because no outlets were defined during watershed delineation, watershed size is not an appropriate measure to assess the possible impact of improved terrain detail on hydraulic design. Flow accumulation, which is the number of upstream cells that drain into a cell, is a more appropriate measure. By identifying the area contributing to flow at each drainage structure, design flow at each drainage structure can be calculated. Flow accumulation and the resulting design flow for the two different terrain models may then be used to assess the possible impact of terrain detail (resolution) on hydraulic design and existing structural surety.

Unfortunately, a true comparison of flow accumulation resulting from LIDAR and USGS-based elevation data could not be performed. Since most drainage areas extended beyond the LIDAR coverage area, only a comparison of LIDAR data (embedded into USGS data) and USGS data alone could be performed. With a few exceptions (less than 10), the primary contributor to most flow accumulation values was the USGS-based data. Therefore, any possible differences in flow accumulation at a structure would be limited to the portion of the drainage area with LIDAR data present.

The flow accumulation for all of the hydraulic structures (bridges and culverts) was identified for the elevation grid and the combined LIDAR, USGS, and culvert elevation grid. The difference in flow accumulation at each location was then calculated. The USGS-based flow accumulation (area) for approximately 90% of these structures was less than 40 acres. The average difference in area between the combine LIDAR data and USGS data was less than 4 acres. Using the Iowa Runoff Chart to determine peak discharge, and assuming the same flood frequency (50 yr), land use (mixed cover), and slope (hilly), the average difference in peak flow was 16.4 ft^3/sec and the range of differences was from 0.4 to 100 ft^3/sec. By comparison, if rolling terrain is assumed instead of hilly terrain for a 40-acre drainage area, the difference in peak flow is approximately 25 ft^3/sec. Therefore, for the locations observed with the limited LIDAR data, the factors utilized to calculate peak discharge have as much, or more, impact as the flow accumulation area provided by different terrain models.

5. CONCLUSIONS AND RECOMMENDATIONS

Traditional highway hydrology does not appear to be significantly impacted, or benefited, by the increased terrain detail that LIDAR provided for the study area. In fact, hydrologic outputs, such as streams and watersheds, may be too sensitive to the increased horizontal resolution and/or errors in the data set. However, a true comparison of LIDAR and USGS-based data sets of equal size and encompassing entire drainage areas could not be performed in this study. Differences may also result in areas with much steeper slopes or significant changes in terrain.

LIDAR may provide possibly valuable detail in areas of modified terrain, such as roads. Better representations of channel and terrain detail in the vicinity of the roadway may be useful in modeling problem drainage areas and evaluating structural surety during and after significant storm events. Furthermore, LIDAR may be used to verify the intended/expected drainage patterns at newly constructed highways. Knowledge of existing drainage structures can also be very important.

LIDAR will likely provide the greatest benefit for highway projects in flood plains and areas with relatively flat terrain where slight changes in terrain may have a significant impact on drainage patterns.

REFERENCES

Bao, Juling, David Maidment, and Francisco Olivera. 1997. *Using GIS for Hydrologic Data-Processing and Modeling in Texas.* Texas: Center for Research in Water Resources.

Bedient, Philip, and Wayne Huber. 1988. *Hydrology and Floodplain Analysis.* New York: Addison-Wesley Publishing Company.

Caruso, Vincent. 2002. Use of light detection and ranging (LIDAR) technology for mapping hypsography and hydrology. Reston, VA: US Geological Survey. http://www.appalachianregionscience.usgs.gov/appal/pub/abstract.asp?ID=5.

City of Seattle. 2003. Hazard mapping using LIDAR technology. Seattle, WA: City of Seattle. http://www.cityofseattle.net/projectimpact/pages/whatsnew/pressrelease5.htm.

Doan, James H. 2000. *Geospatial Hydrologic Modeling Extension HEC-GeoHMS User's Manual.* U.S. Army Corps of Engineers, Davis, CA.

Hammer, R. D., F. J. Young, N. C. Wollenhaupt, T. L. Barney, and T. W. Haithcoate. 1994. Slope class maps from soil survey and digital elevation models. *Soil Science Society of America.*

Hicks, R., and Clarkson Oglesby. 1982. *Highway Engineering.* New York: John Wiley & Sons.

Mitasova, H., J. Hofierka, M. Zlocha, and L. R. Iverson. 1996. Modeling topographic potential for erosion and deposition using GIS. *International Journal of Geographical Information Systems*.

Snell, Seth, and Kirk Gregory. 2002. *A Flash Flood Prediction Model for Rural and Urban Basins in New Mexico.* New Mexico: New Mexico Water Resources Research Institute.

Srinivasan, R., and B. A. Engel. 1991. Effect of slope prediction methods on slope and erosion estimates. *Applied Engineering in Agriculture*.

US Army Corps of Engineers. 2003. Geospatial hydrologic modeling extension (HEC-GeoHMS). Davis, CA: US Army Corps of Engineers. www.hec.usace.army.mil/software/hec-hms/hechms-geohms.html.

US Geological Survey. 2002. National elevation data set. Reston, VA: US Geological Survey. http://gisdata.usgs.net/NED/AccuracyQ2.asp.

White, Michael, Daniel E. Storm, and Michael D. Smolen. 1997. *Hydrologic Modeling of the Great Salt Plains Basin.* Oklahoma: Environmental Protection Agency.

Wilson, J. P. 1999. Local, national, and global applications of GIS in agriculture. In *Geographical Information Systems: Principles, Techniques, Management, and Applications.* New York.

Wittner, Eric, and Lester McKee. 2002. *Mapping Urbanized and Rural Drainages in the Bay Area: A Tool for Improved Management of Stormwater Contaminants Derived from Small Tributaries.* San Francisco: San Francisco Estuary Institute.

Zhang, W., and D. R. Montgomery. 1994. Digital elevation model grid size, landscape representation, and hydrologic simulations. *Water Resources Research*.

APPENDIX: OTHER GRAPHICS USED TO ANALYZE LIDAR VS. USGS SURFACE TERRAIN MODELS

Figure A.1 depicts the differences in stream and watershed locations calculated from the use of the 5-m versus the 10-m LIDAR grid.

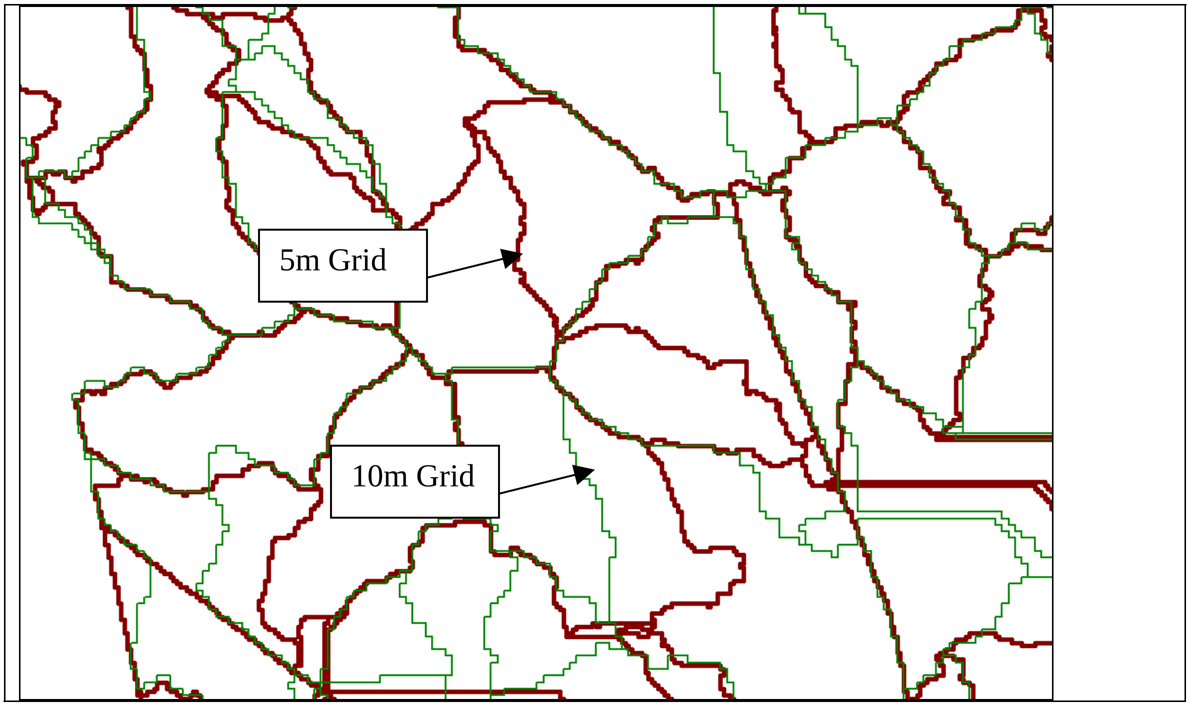

Figure A.1. Stream/WS 5-m grid vs. 10-m grid

Figure A.2 shows the differences in stream locations calculated from the use of the 5-m versus the 10-m LIDAR grid.

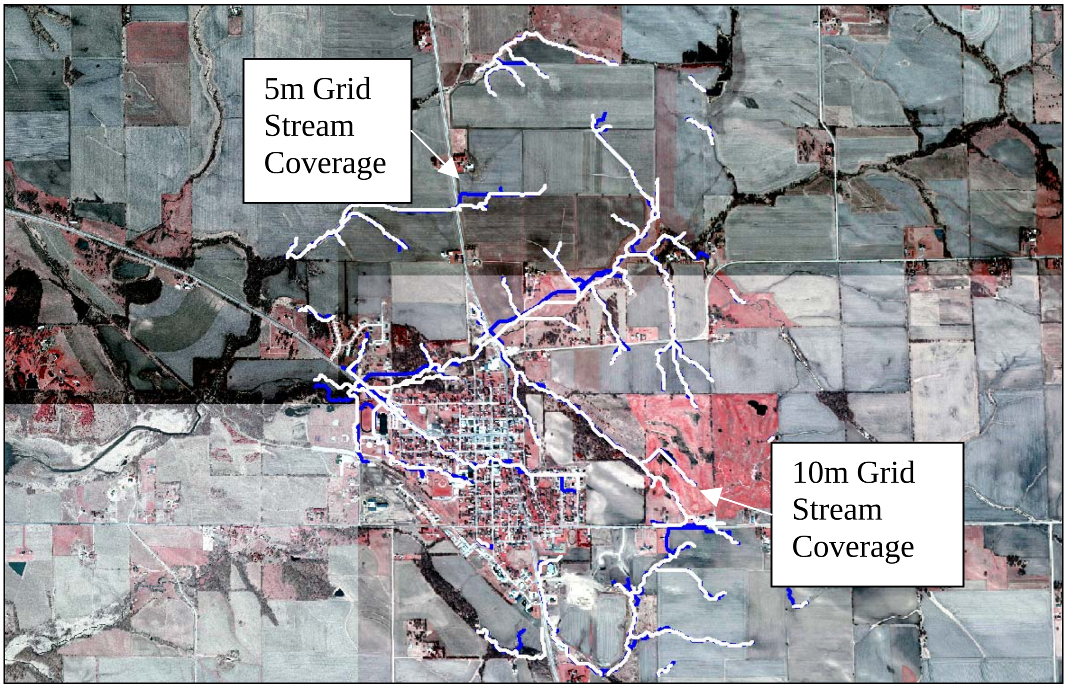

Figure A.2: Stream 5-m grid vs. 10-m grid

Figure A.3 shows the differences in stream locations calculated from the use of the 5-m versus the 10-m LIDAR grid.

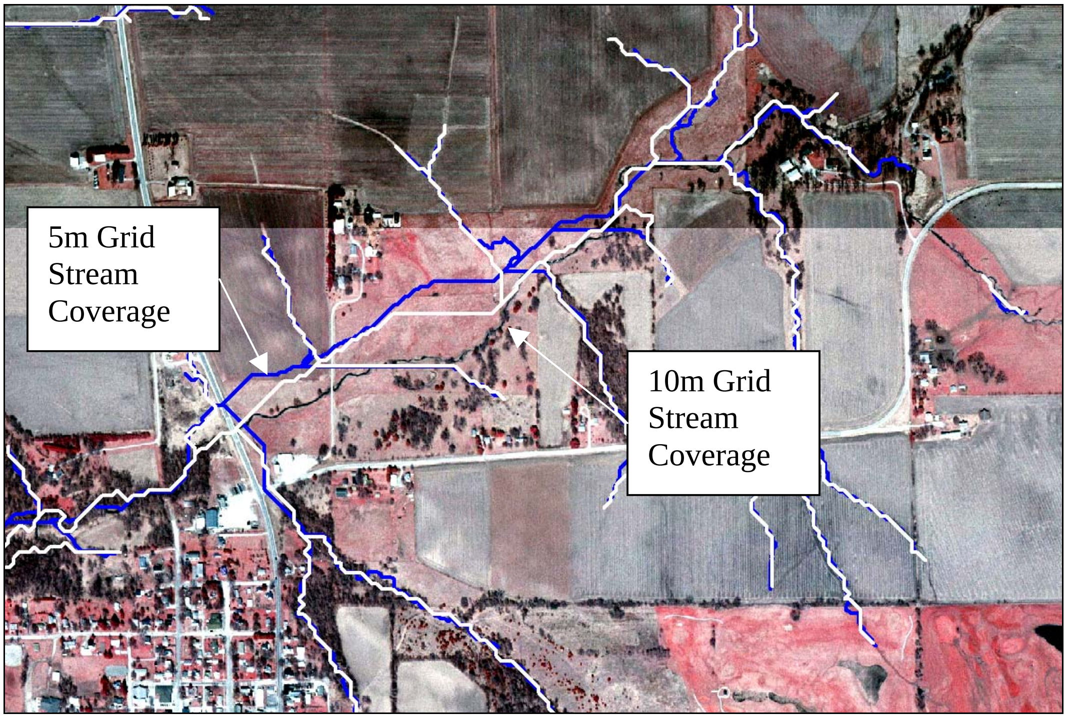

Figure A.3. Stream 5-m grid vs. 10-m grid

Figure A.4 depicts the differences in stream locations calculated from the use of the 5-m versus the 10-m LIDAR grid.

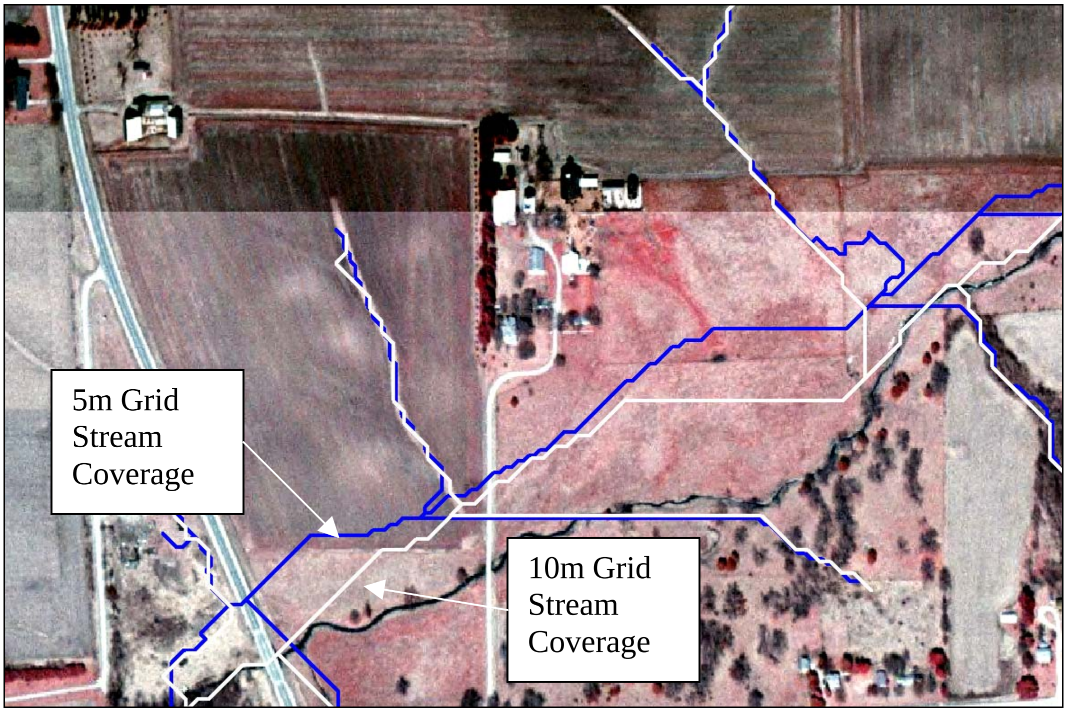

Figure A.4. Stream 5-m grid vs. 10-m grid

Figures A.5 and A.6 show the differences in stream locations calculated from the use of the 5-m versus the 10-m LIDAR grid.

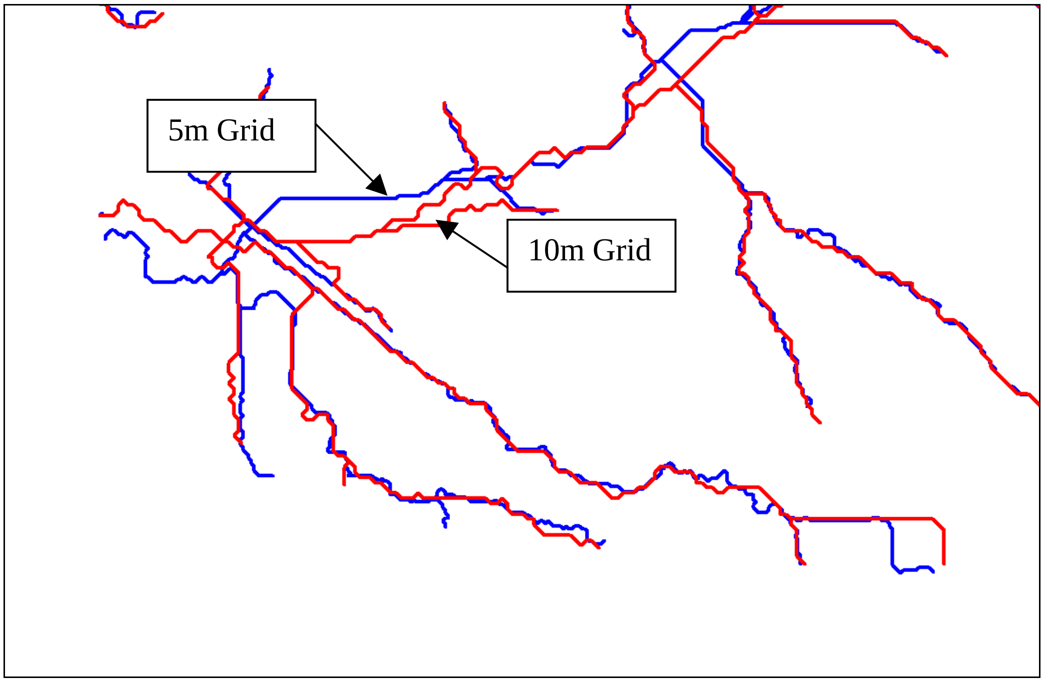

Figure A.5. Stream 5-m grid vs. 10-m grid

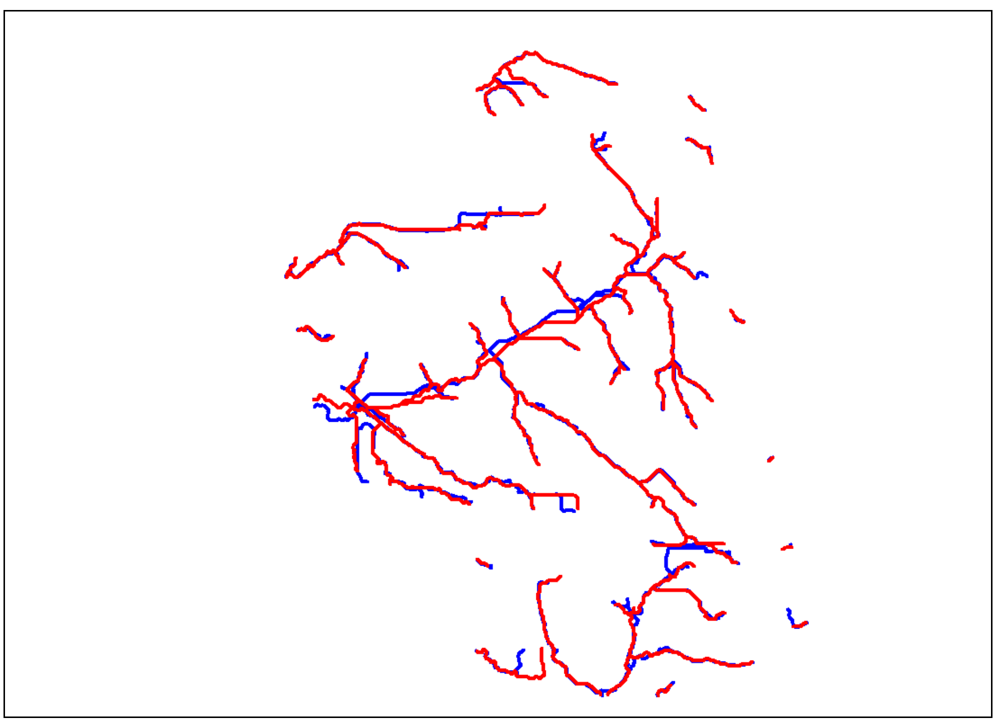

Figure A.6. Stream 5-m grid vs. 10-m grid

Figures A.7 and A.8 compare the streams calculated using the USGS and LIDAR grids with a threshold value of 10% of the watershed area.

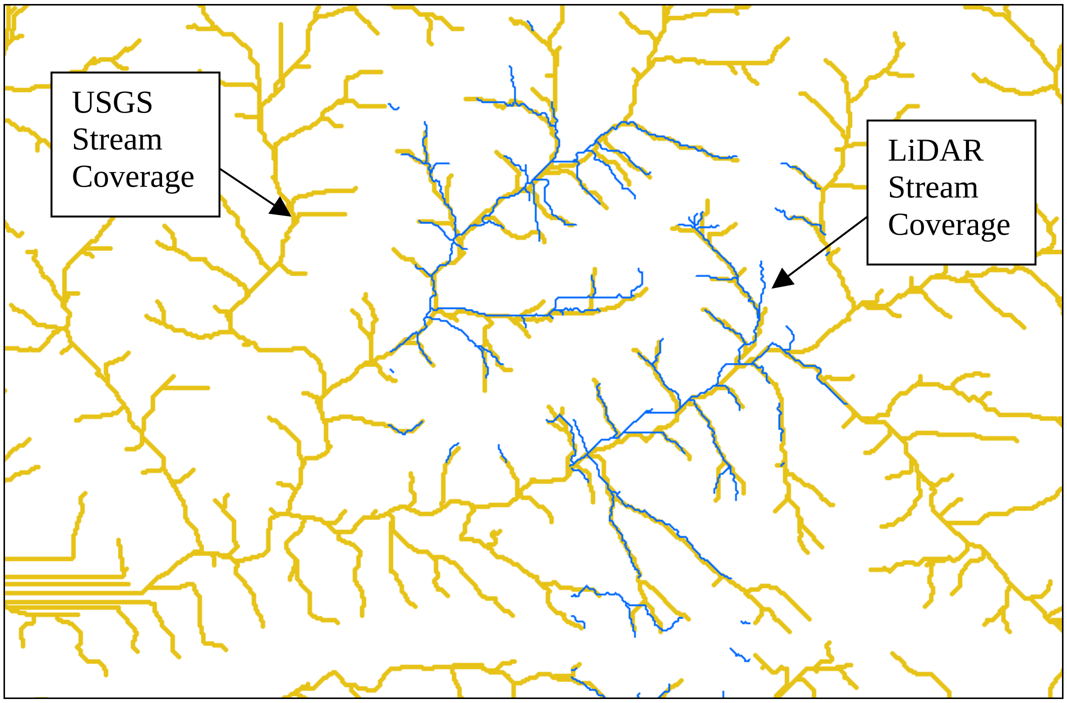

Figure A.7. Stream comparison of USGS vs. LIDAR

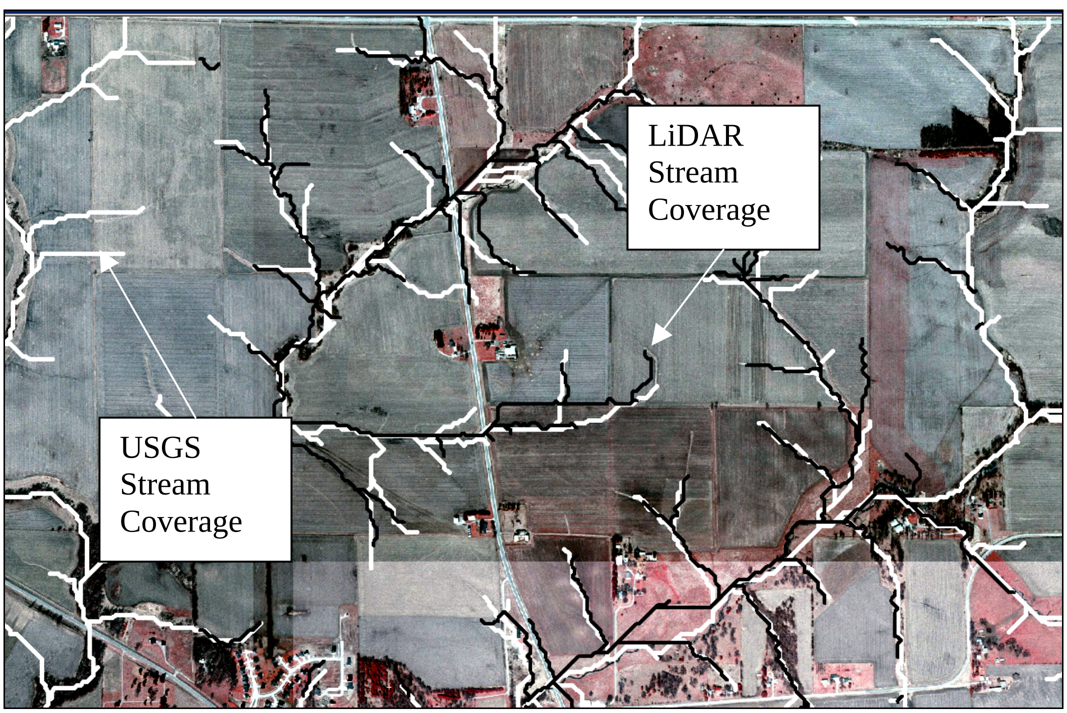

Figure A.8. Stream comparison of USGS vs. LIDAR

Figures A.9 and A.10 illustrate the difference between the streams calculated using the LIDAR grid mosaiced, just the USGS data, and just the LIDAR data.

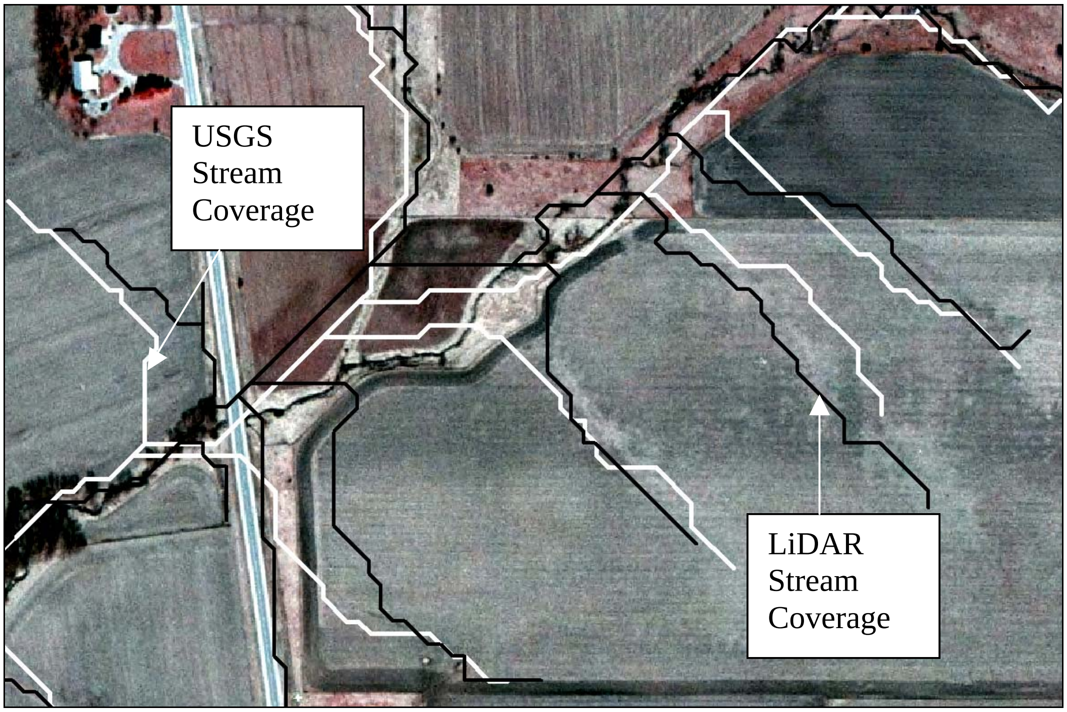

Figure A.9. Just LIDAR and culverts

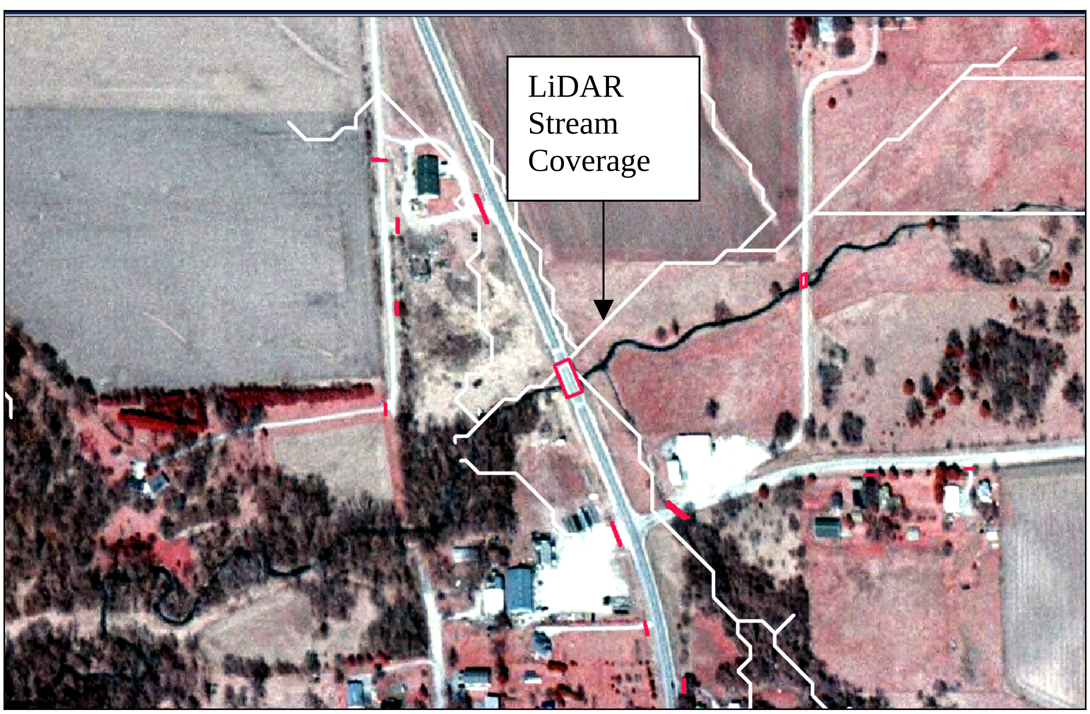

Figure A.10. WS edge difference of USGS vs. LIDAR

Figures A.11 to A.14 show watershed boundaries for just the LIDAR data and just the USGS data with a threshold value of 10% of the watershed area.

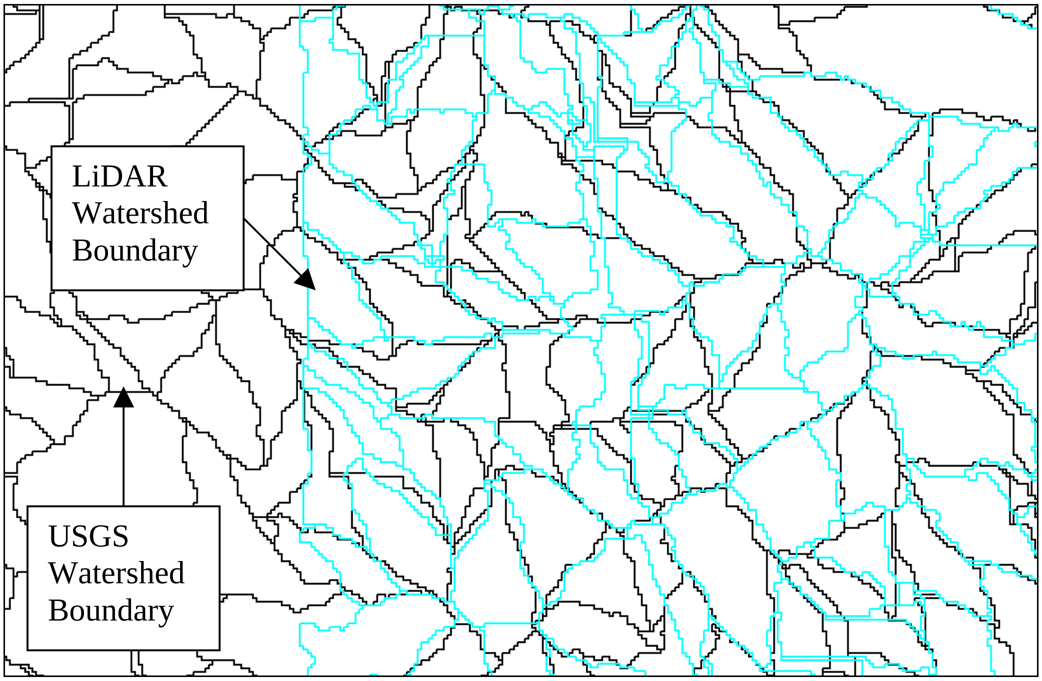

Figure A.11. LIDAR and USGS (no culverts involved)

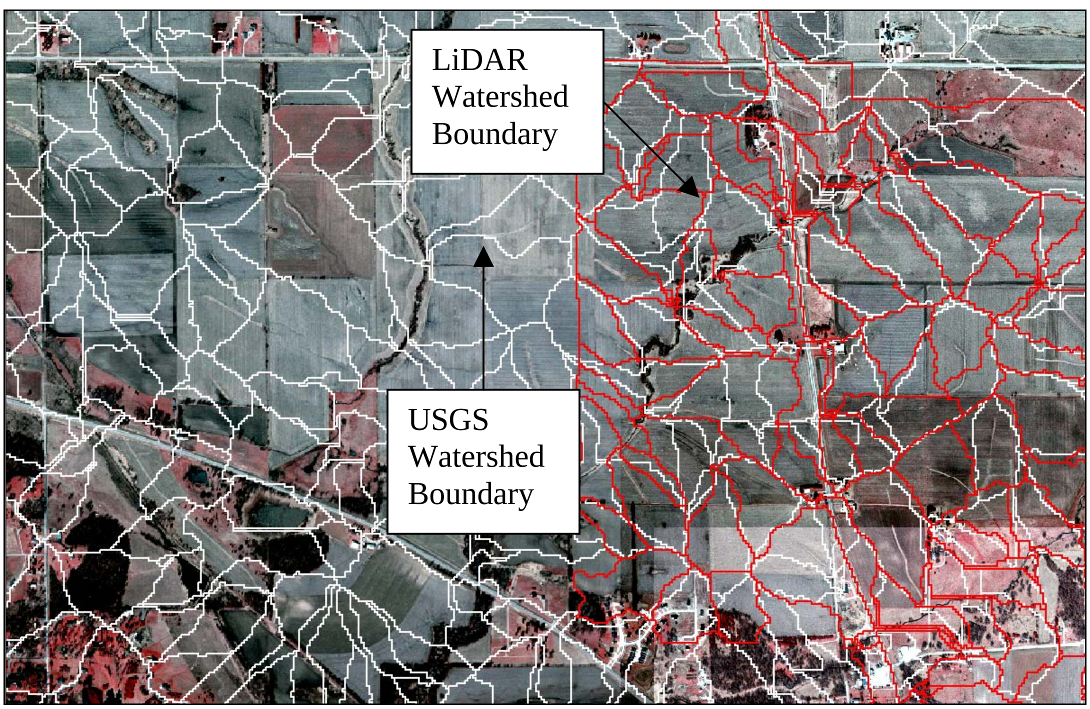

Figure A.12. LIDAR and USGS (no culverts involved)

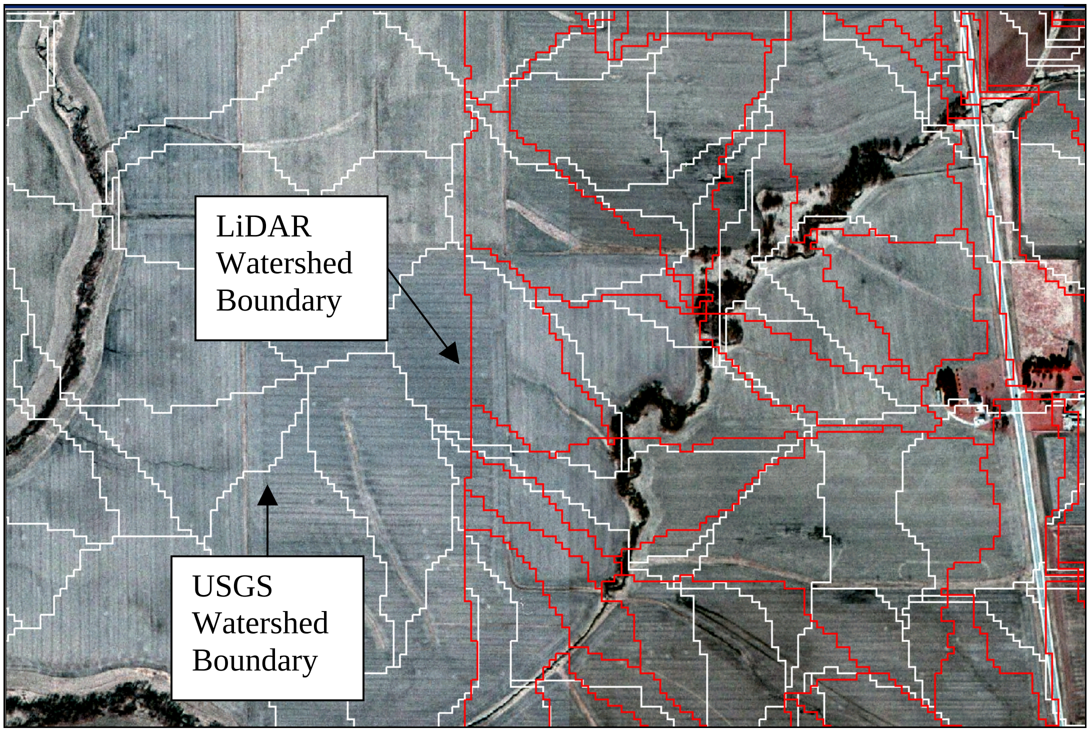

Figure A.13. LIDAR and USGS (no culverts involved)

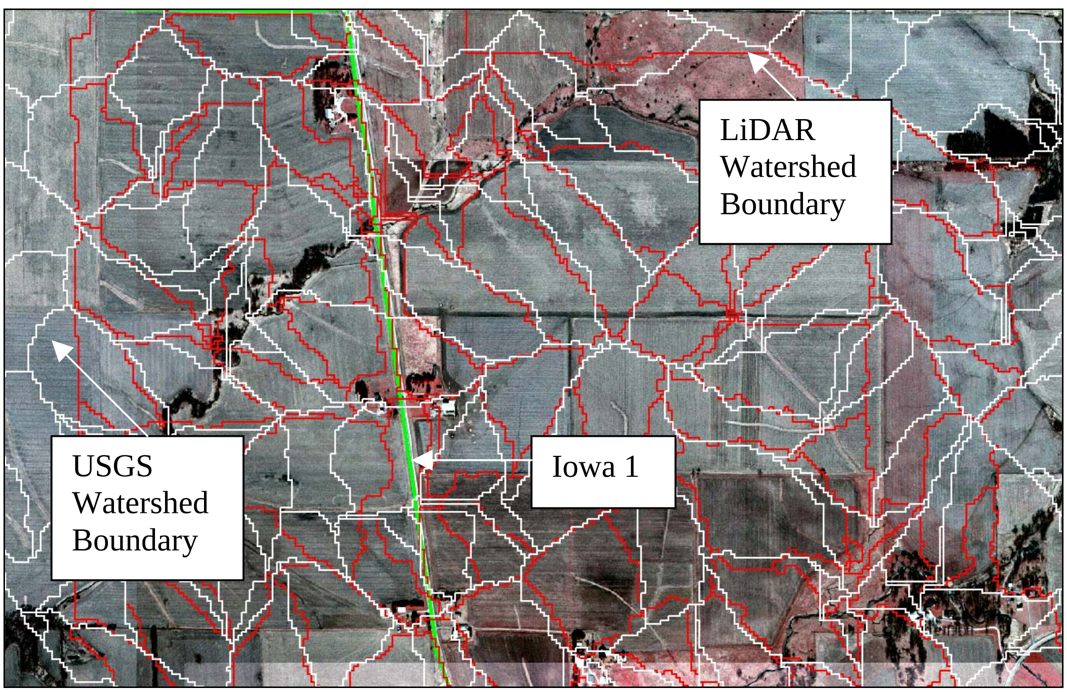

Figure A.14. LIDAR and USGS (no culverts involved)

Figures A.15 and A.16 illustrate the differences between the watershed boundaries calculated using just the USGS data and just the LIDAR data.

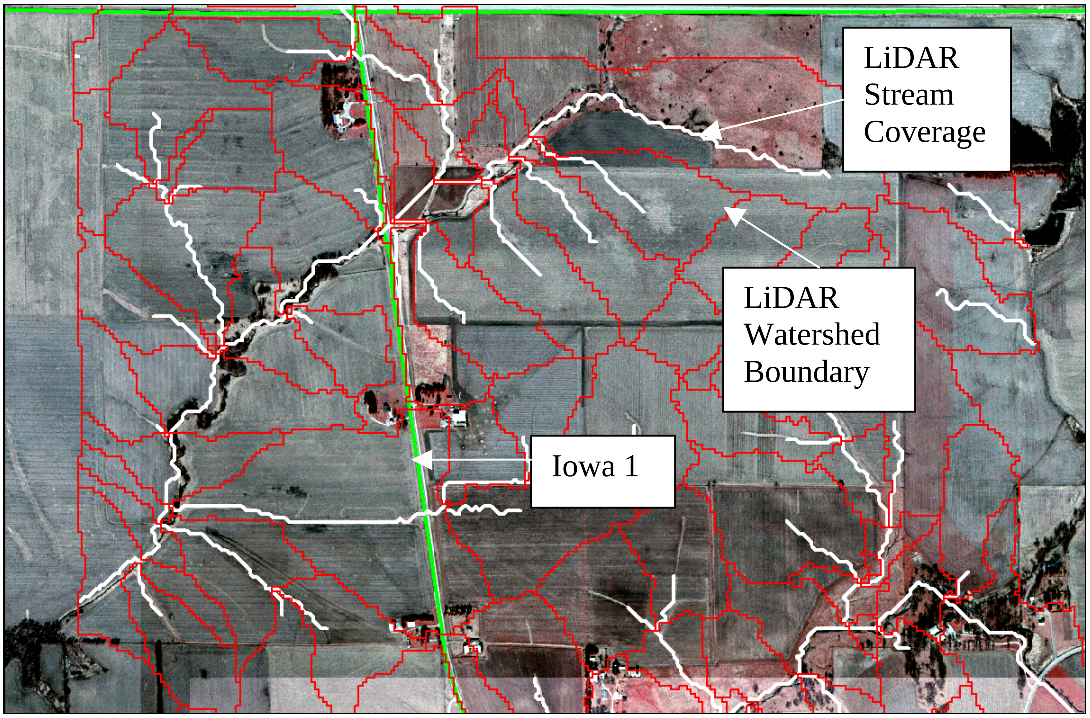

Figure A.15. USGS alone

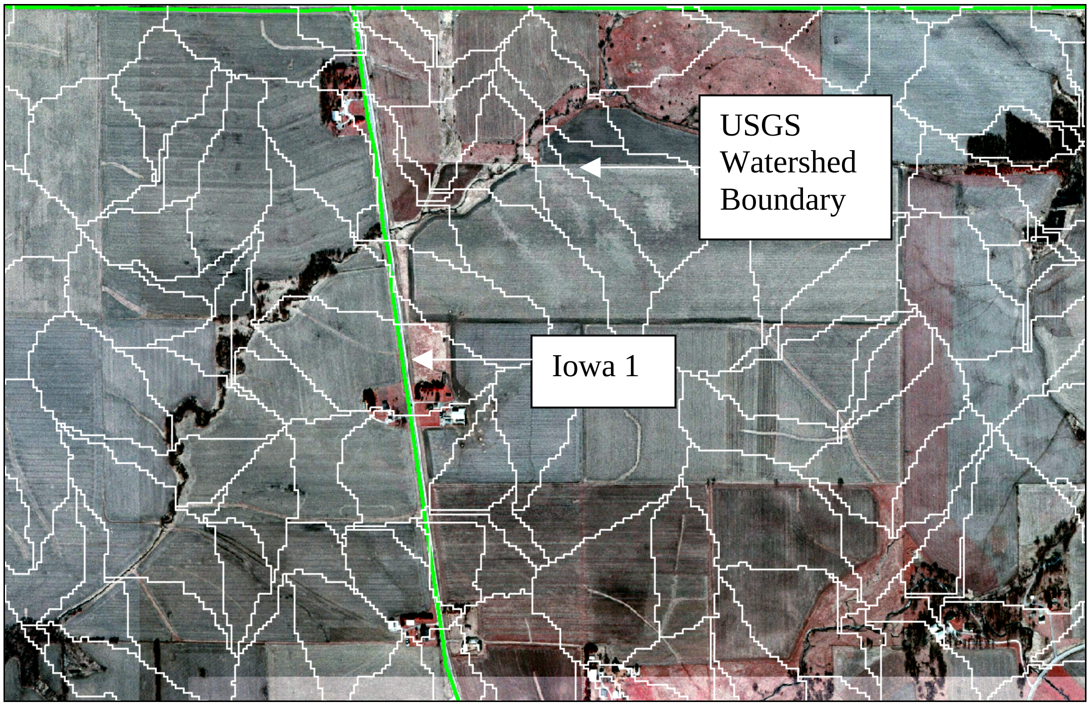

Figure A.16. LIDAR alone

Figures A.18 through A.24 depict the hillshades and slopes derived using the LIDAR data. It is important to notice that Iowa 1 is visible in each picture.

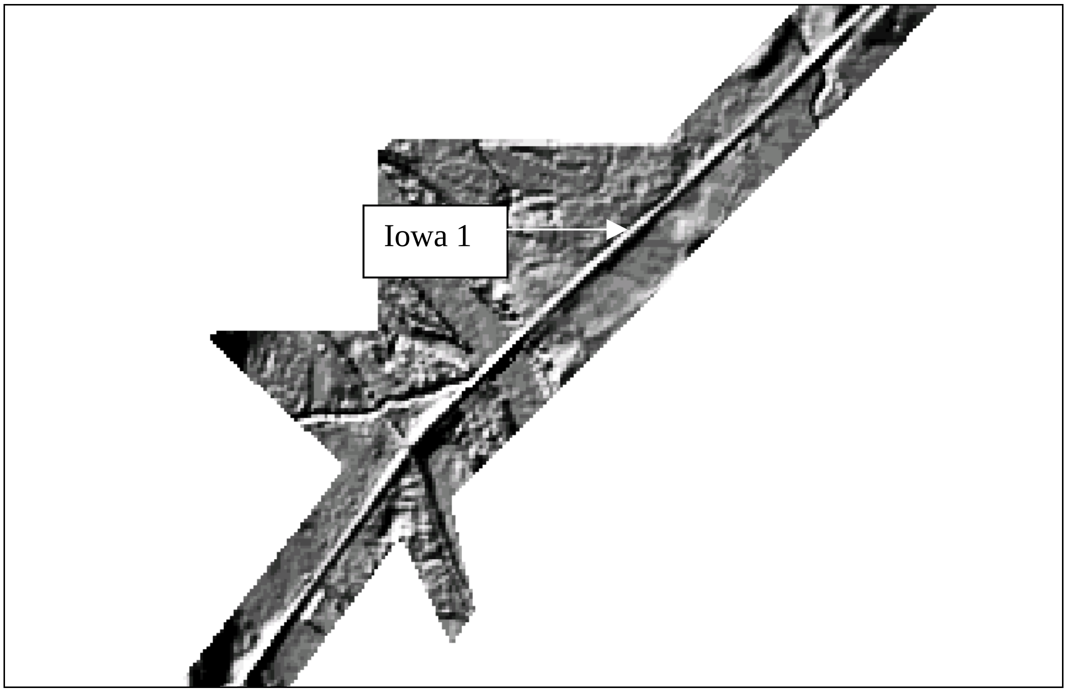

Figure A.18. Road definition in LIDAR for Iowa 1

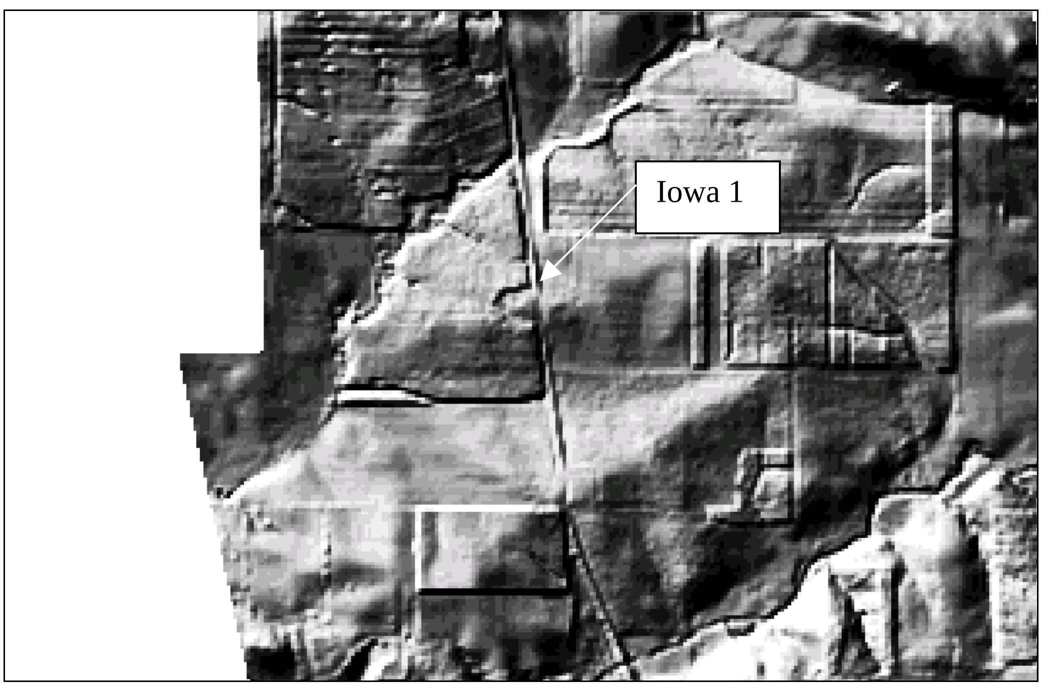

Figure A.19. Road definition in LIDAR for Iowa 1

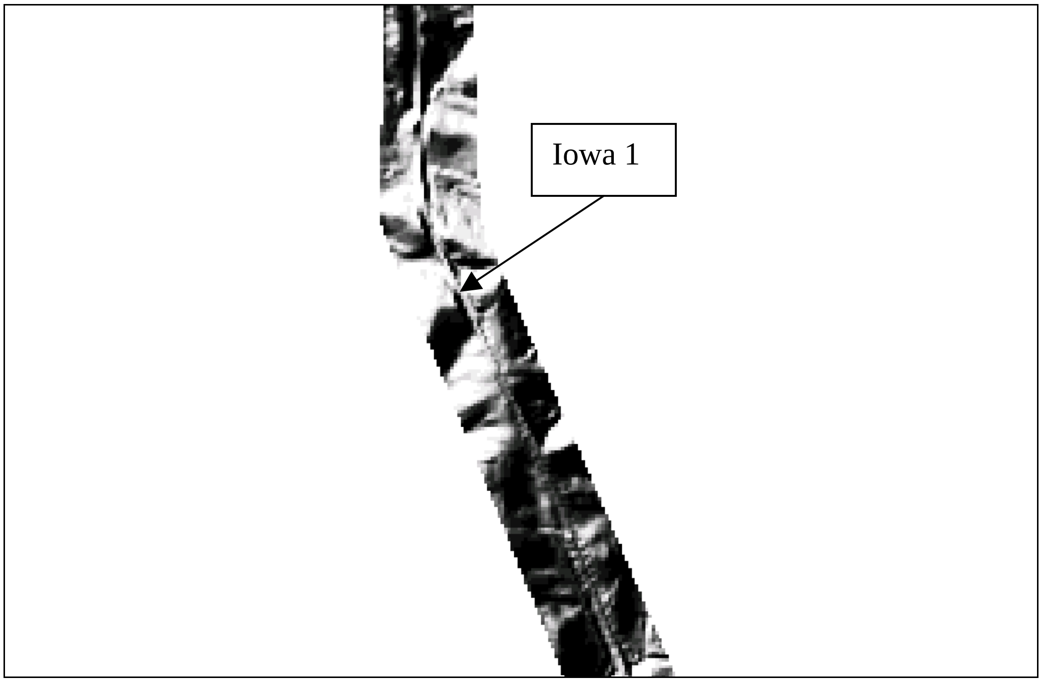

Figure A.20. Road definition in LIDAR for Iowa 1

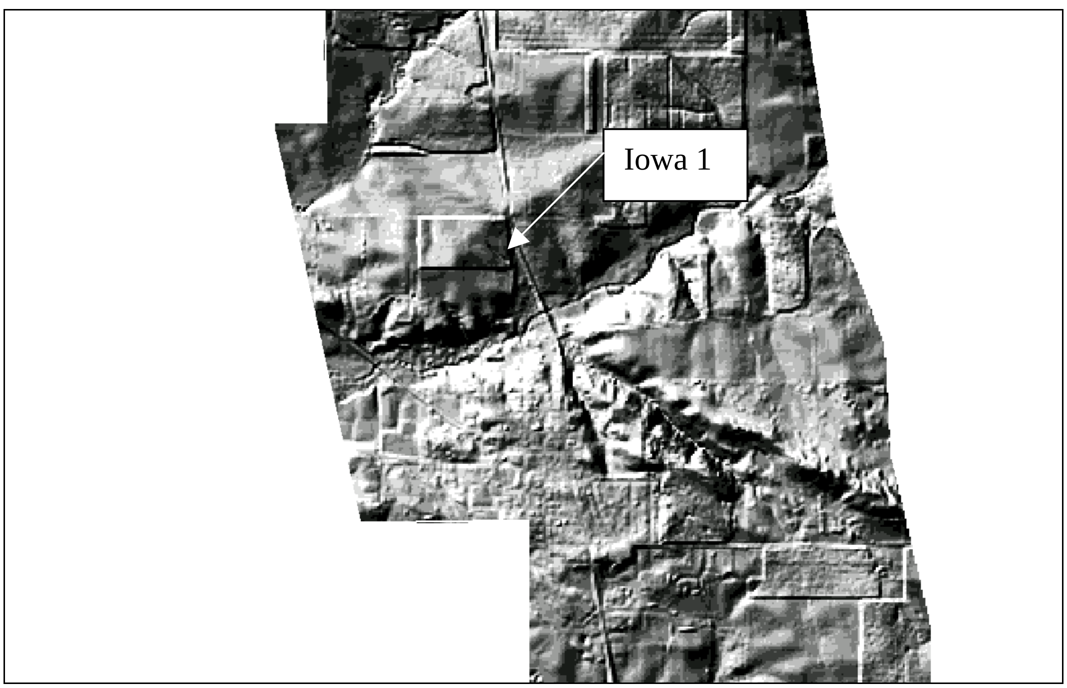

Figure A.21. Road definition in LIDAR for Iowa 1

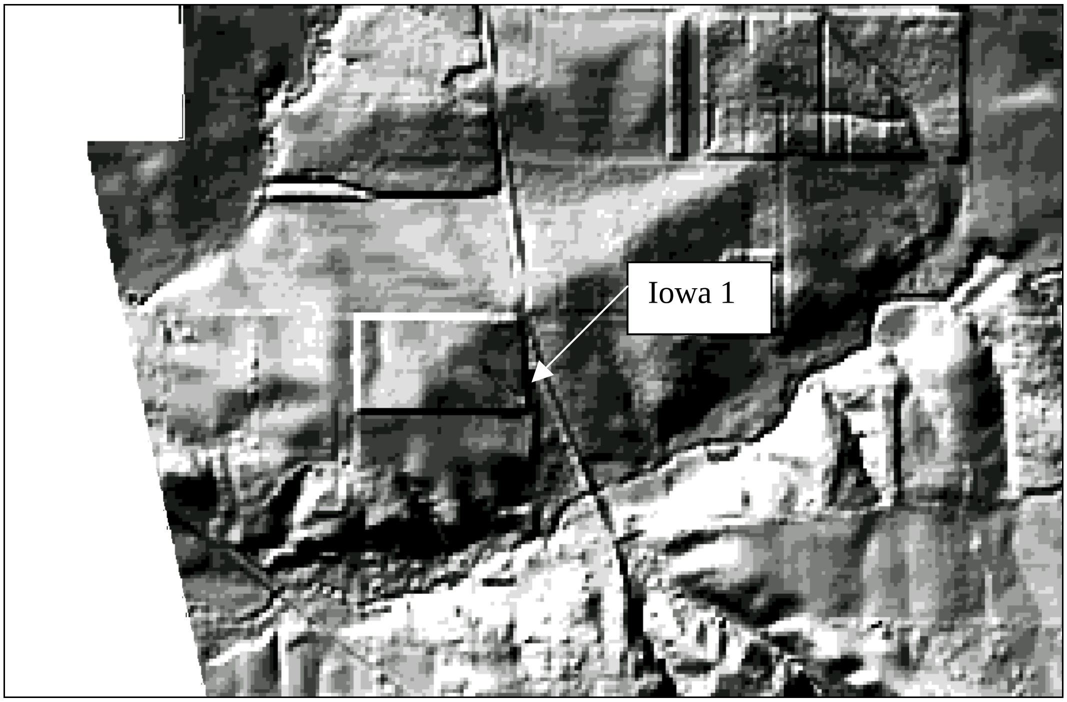

Figure A.22. Road definition in LIDAR for Iowa 1

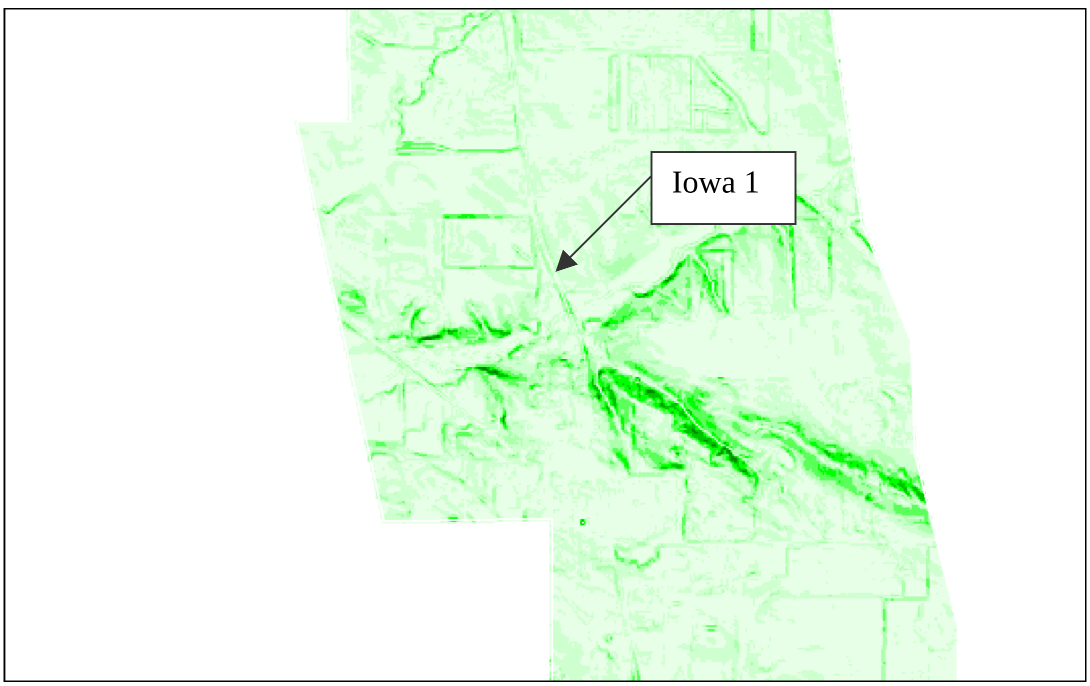

Figure A.23. Slopes derived from LIDAR

Figure A.24. Slopes derived from LIDAR

Figures A.25 through A.32 depict the hillshades and slopes derived using the USGS data. It is important to notice that Iowa 1 is not visible in any picture.

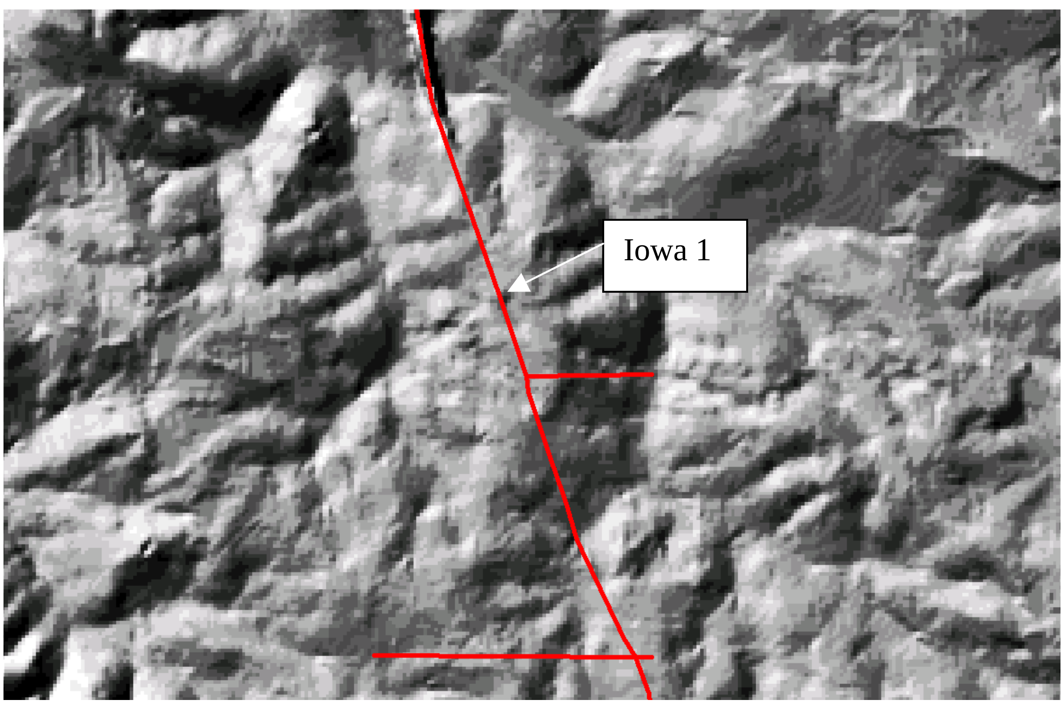

Figure A.25. Road definition in USGS for Iowa 1

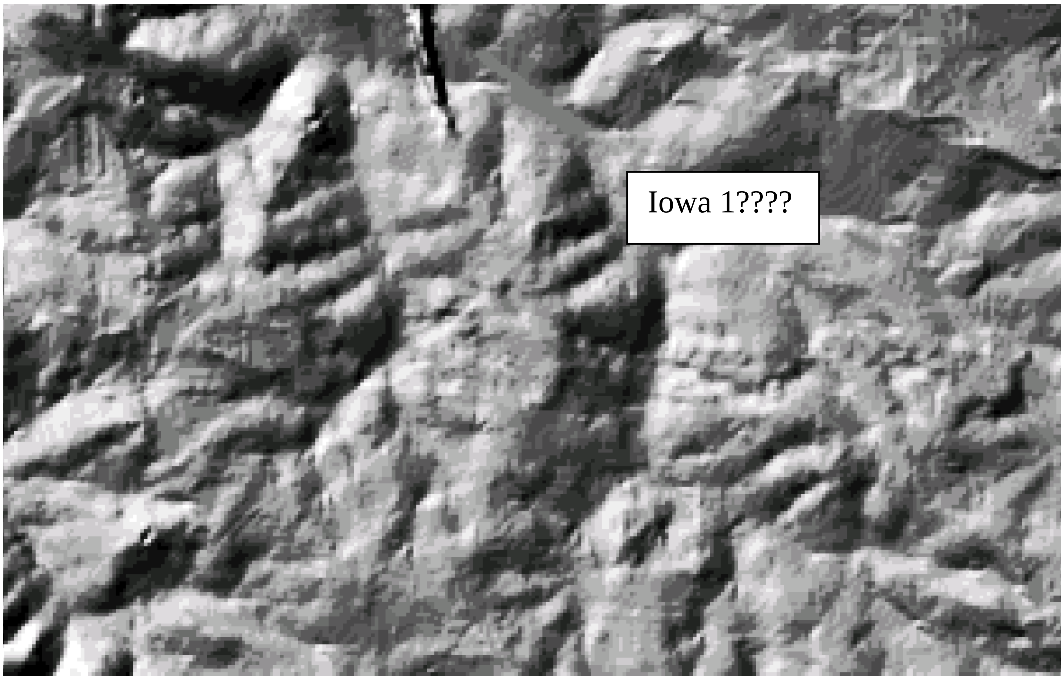

Figure A.26. Road definition in USGS for Iowa 1

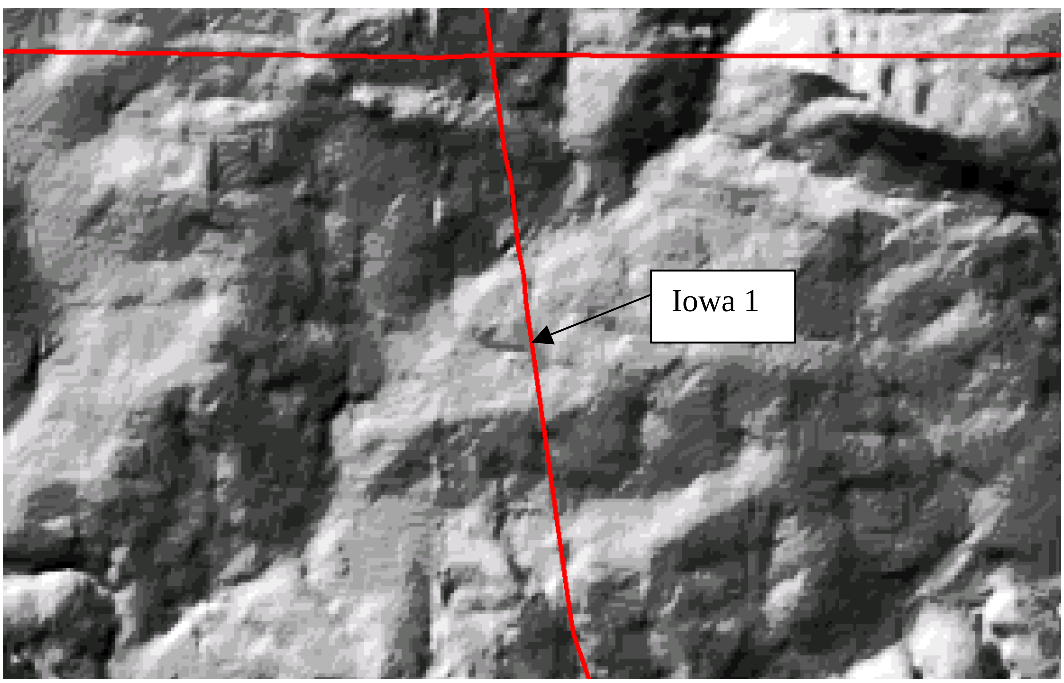

Figure A.27. Road definition in USGS for Iowa 1

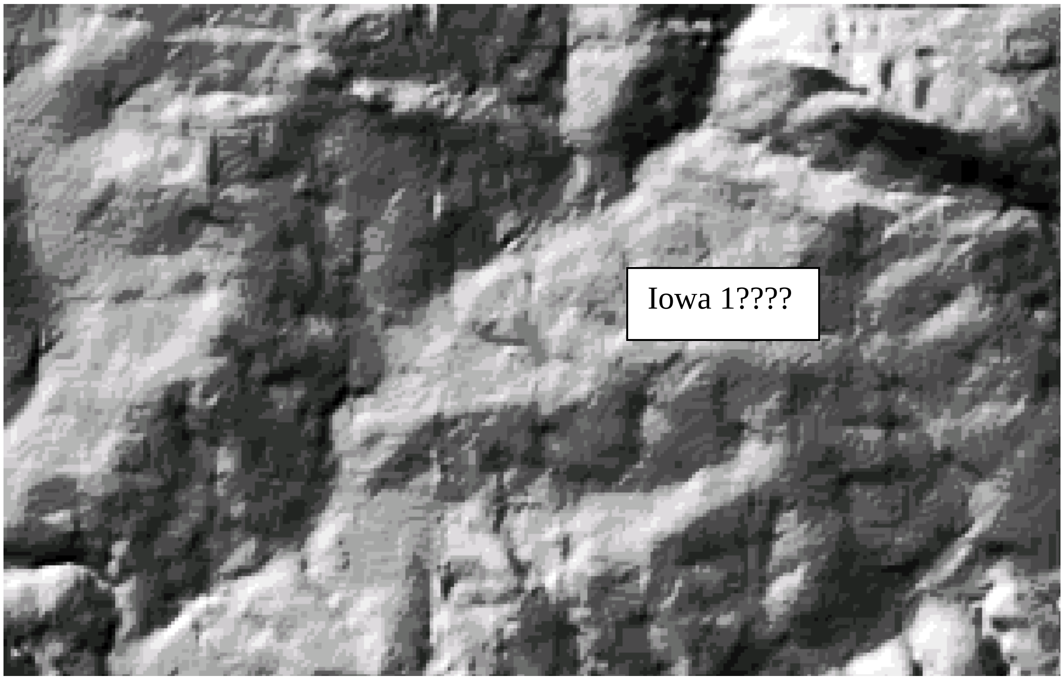

Figure A.28. Road definition in USGS for Iowa 1

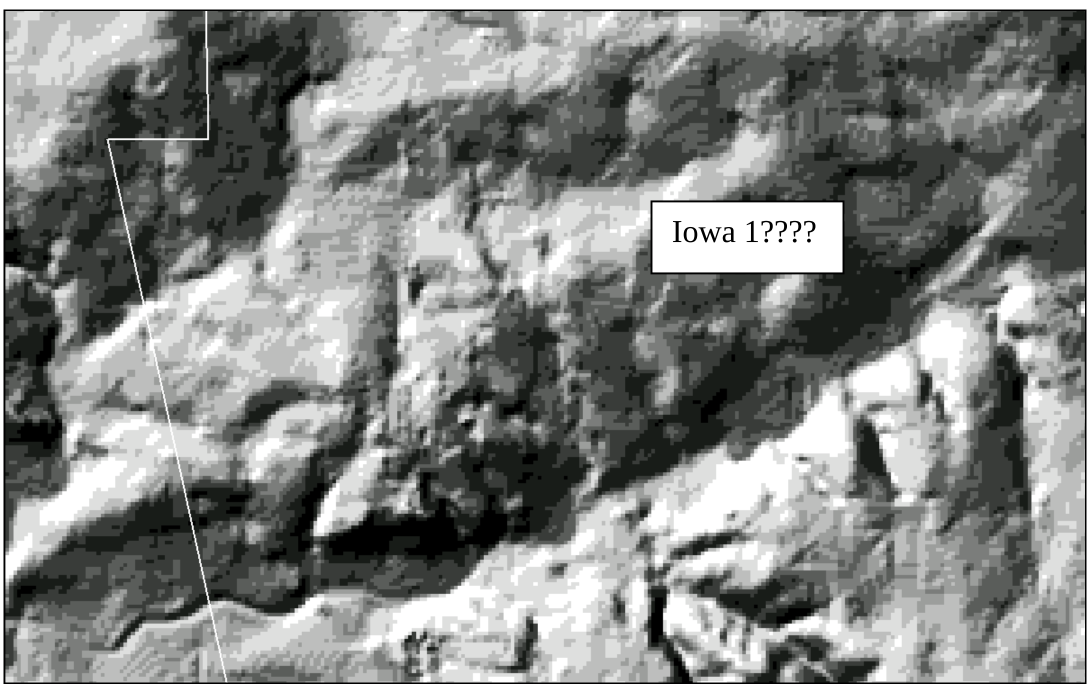

Figure A.29. Road definition in USGS for Iowa 1

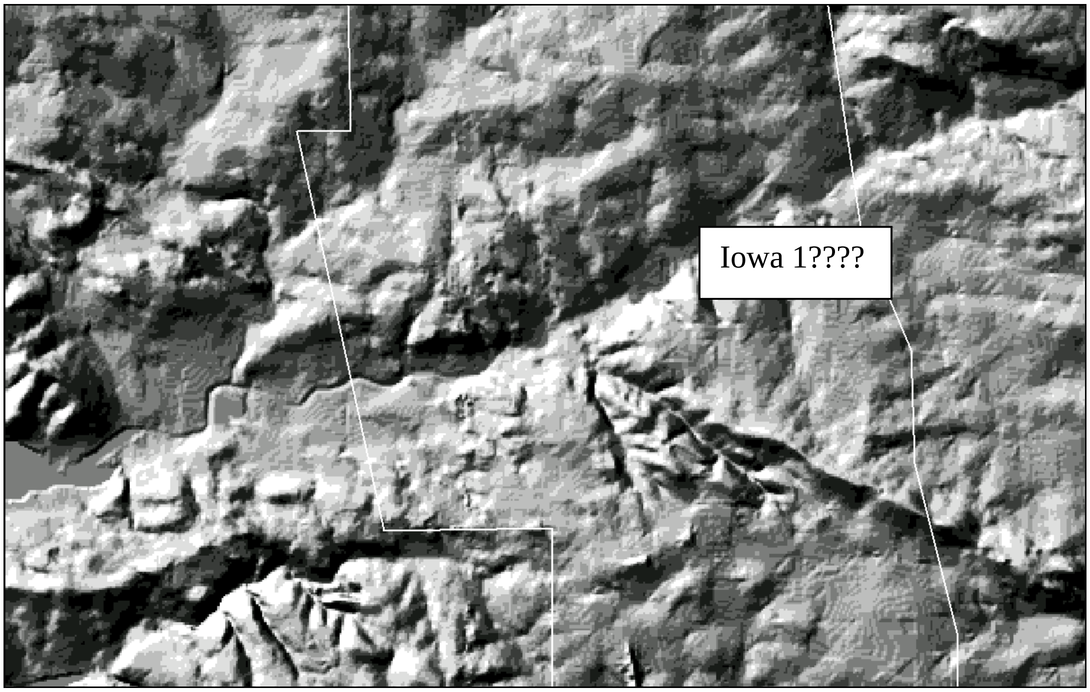

Figure A.30. Road definition in USGS for Iowa 1

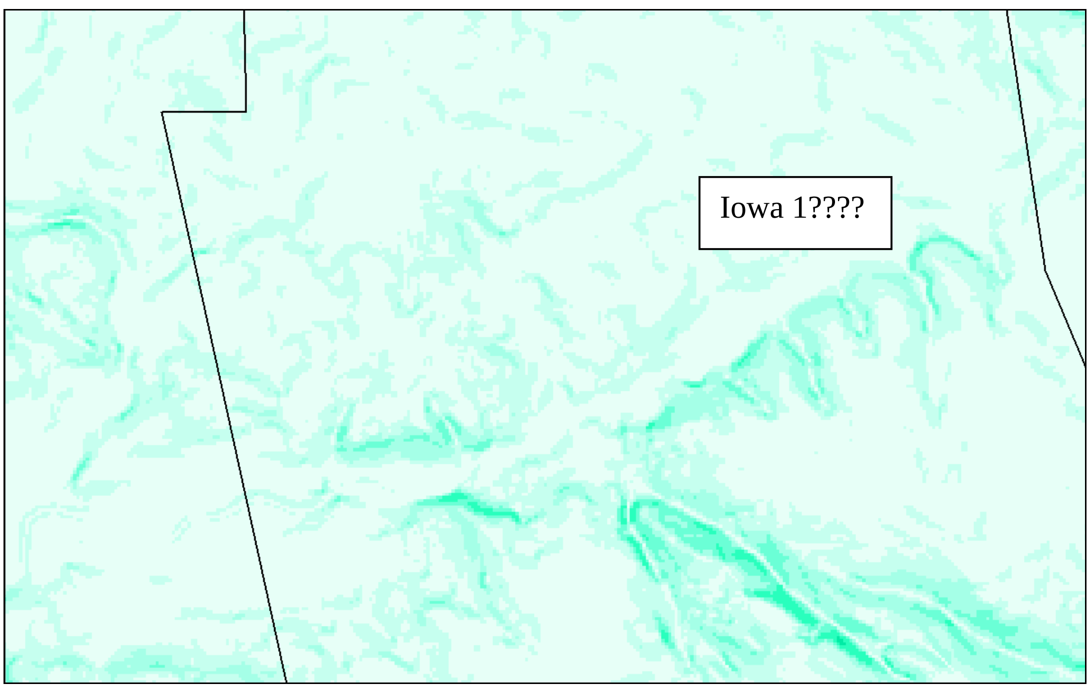

Figure A.31. Slopes derived from USGS

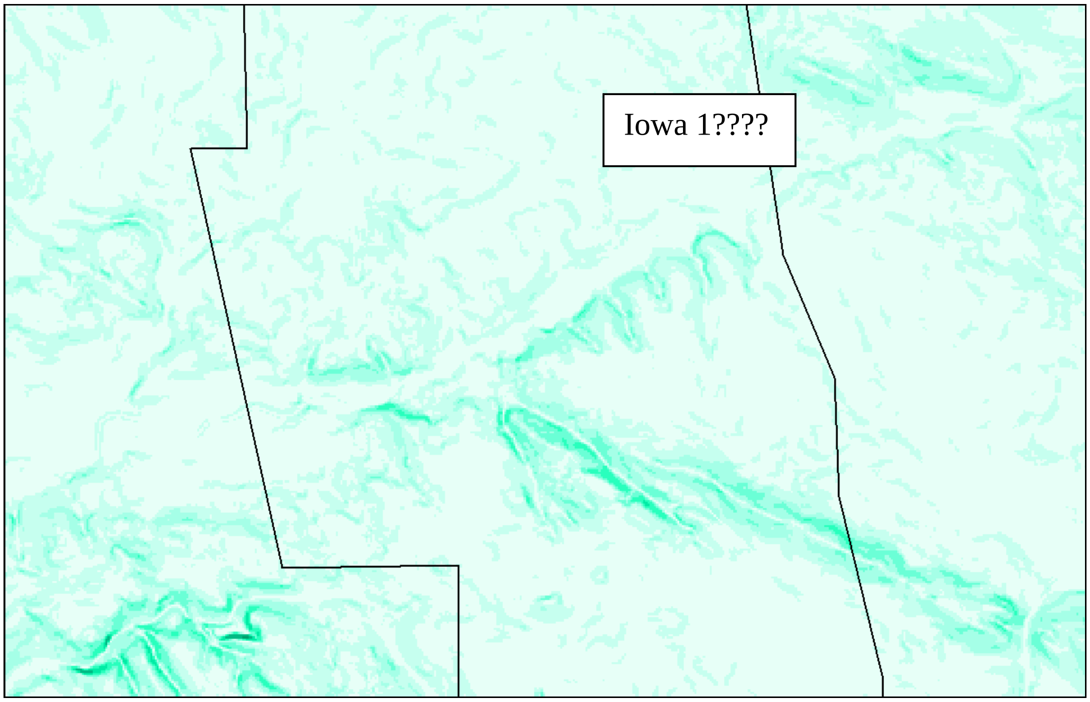

Figure A.32. Slopes derived from USGS