Use of LiDAR-Based Elevation Data for Highway Drainage Analysis: A Qualitative Assessment

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ABSTRACT

Small-scale elevation models may not provide the accuracy and detail necessary to accurately delineate small watersheds. Moreover, they may not accurately reflect the impact of roads and their ditches on these small watersheds, particularly in flat areas. This research study investigates the differences of utilizing high resolution LiDAR and standard USGS-based elevation data for watershed and drainage pattern delineation 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 are the location of drainage area boundaries and flow patterns parallel to and intersecting the road cross section.

Key words: highway engineering—hydrology remote sensing—LiDAR

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SECTION 1: INTRODUCTION

Hydrology is the science that deals with the occurrence, circulation, and distribution of waters of the earth (*1*). The primary emphasis of hydrology for highway engineering is collection, transport, and disposal of waters 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. Approximately one-fourth of all highway construction dollars is spent for culverts, bridges, and other drainage structures. (*2*). Insufficient design may also be very costly from the standpoint of mobility and infrastructure deterioration. Therefore, improving the highway engineer's ability to cost effectively accommodate drainage and identify possible deficiencies in existing design may provide significant savings while limiting potential disruption of service due to flood-related road closers.

SECTION 2: PROJECT OVERVIEW

2.1 Scope of Work

Several key components of the hydraulic design for highways are the size, topography, land use, channels/streams, and rainfall of the drainage area. This research study qualitatively assesses whether the use of higher resolution terrain information from Light Detection and Ranging (LiDAR) to better define three of these components; size, topography, and channel location, impacts hydraulic design and deficiency (surety) assessment.

USGS-based elevation data is the most commonly used data source for watershed and drainage pattern delineation. However, USGS data may be too "coarse" to adequately describe surface profiles of watershed areas or drainage patterns around new construction that have been disrupted. 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 1000 acres in size. By contrast, the smallest surface hydrologic unit (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. LIDAR provides such a dataset.

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. The study area is the Iowa 1 corridor between Iowa City and Mount Vernon in Johnson and Linn Counties (Figure 1). Iowa 1 is two-lane roadway throughout the 18 miles of the corridor. The corridor is characterized by a variety of terrain, including rolling farmland and developed (or urban) area. Additionally a river is present which causes significant changes in elevation in portions of the study area. Elevations of the study area range from approximately 650 to 900 feet. Of particular interest is 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 Department of Transportation (DOT) and Iowa Department of Natural Resources (DNR).

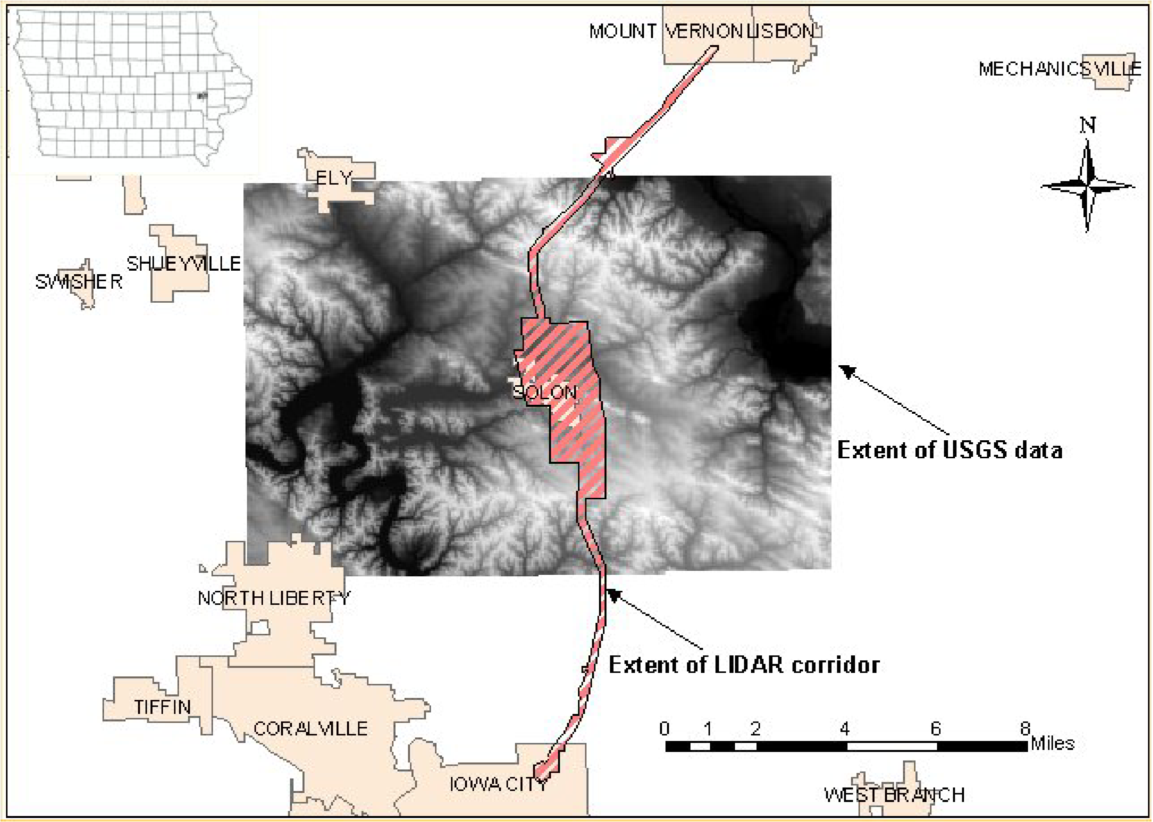

FIGURE 1. Corridor Map

2.2 Potential Benefits

The primary benefit of this study is 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.

SECTION 3: BACKGROUND

3.1 USGS DEM

Digital elevation models (DEM) are digital files in raster format consisting of terrain elevations for ground positions at regularly spaced intervals. The U.S. Geological Survey (USGS) produces several digital elevation products which 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' DEMs at a 10 x 10 m resolution with a vertical resolution of 1 foot. 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:

- Calculating subbasin parameters, e.g. slope, slope length, and defining the stream network for the Great Salt Plains Basin (*3*).
- 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 (*4*).
- Designing discharge for flow conveyance structures on Texas highways (*5*).
- Improving the understanding of drainage areas and hydrological flow paths in urban areas adjacent to San Francisco Bay (*6*).

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 (*7*). Several other studies have found similar results (*8*) (*9*) (*10*). Numerous authors have argued that DEMs with spatial resolutions of two to ten meters are required to represent important hydrologic processes and patterns in many agricultural landscapes (*11*).

3.2 LiDAR

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 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 that can be determined after. The resolution and accuracy of aerial-based LiDAR vary among vendors, but a reported horizontal resolution of two meters is common. Reported horizontal accuracies of 1m root mean square error (RMSE) and vertical accuracies of 15cm RMSE, or greater, are also common.

LiDAR terrain data have been used for a number of different applications, including generating contours, creating 3D terrain views, determining fault locations, modeling steep slopes, critical areas and streams and delineating drainage basins (*12*). 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, which was highly representative of all actual water features (*13*).

SECTION 4: METHODOLOGY

4.1 Software tools

Two software tools were used in this study: ArcView Version 3.3 and HEC-GeoHMS Version 1.0. ArcView is a geographic information system (GIS) created by ESRI. The Geospatial Hydrologic Modeling Extension (HEC-GeoHMS) is a software package developed by the Army Corp 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 (*14*).

4.2 Data Assimilation

As was discussed previously, hydraulic design entails several key components. The primary components investigated in this study are drainage area size, topography, and channel location. The primary data element used to derive and/or assess these components is the digital terrain data. Two sources of terrain data were obtained, LiDAR and USGS DEM. Two 7.5-Minute USGS DEMs (10- x 10-meter data) were also obtained for the corridor. These DEMs possessed reported accuracies of 23 feet (7 meters) vertically and 33 feet horizontally (10 meters) (*15*). The USGS data covered the 18-mile length of the Iowa 1 and was 69,000 feet (21,000 meters) wide and extended at least 27,000 feet (8200 meters) on both sides of the roadway (Figure 1).

LiDAR data for the study area was collected for another research project by EagleScan Corporation. A bare earth model from the LiDAR data was available to the study team. The reported accuracy of the LiDAR data was one meter RMSE horizontal and 15 centimeters RMSE vertical. Horizontal resolution was two meters. Although USGS data were available for 27,000 feet 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 miles 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 (Figure 1).

Planimetric data and two sets of aerial images were also obtained for the study corridor. Planimetric CAD 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.

4.3 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.

1. Depressions are removed from the source DEM to allow water to flow across the landscape.
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.
3. Flow accumulation is calculated for each cell by determining the number of upstream cells that drain into it.
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.
5. Streams are segmented between successive junctions, a junction and an outlet, or a junction and a drainage divide.
6. Watersheds, or subbasins, are delineated for each stream segment.
7. Stream and watershed grids (raster) are converted to vector representations.
8. Aggregated watersheds are created by merging upstream subbasins at every stream confluence. (*16*)

4.4 Terrain Data Sets

Four distinct 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.

4.4.1 LiDAR Bare Earth. Using the LiDAR bare earth data sets, an elevation grid of 10m-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 (1 every 25 m2), the 10m-grid was selected for processing efficiency and consistency with the USGS data set. The processing time required to create a 5m 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 5m grid for a portion of the corridor is presented later in this document.) The 10m-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 consist comparison of the USGS data could be performed. Areas of emphasis were watershed and stream delineation in the immediate vicinity of the highway.

Using HEC-GeoHMS, watershed, stream configuration, and flow accumulation grids were created for this elevation grid. An area threshold value of one percent, or approximately six acres, was used for stream definition (Figure 2).

4.4.2 USGS DEMs. An elevation grid of 10m-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 one percent, or 200 acres, was used as the stream threshold. 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 initiate a stream. (Figure 3)

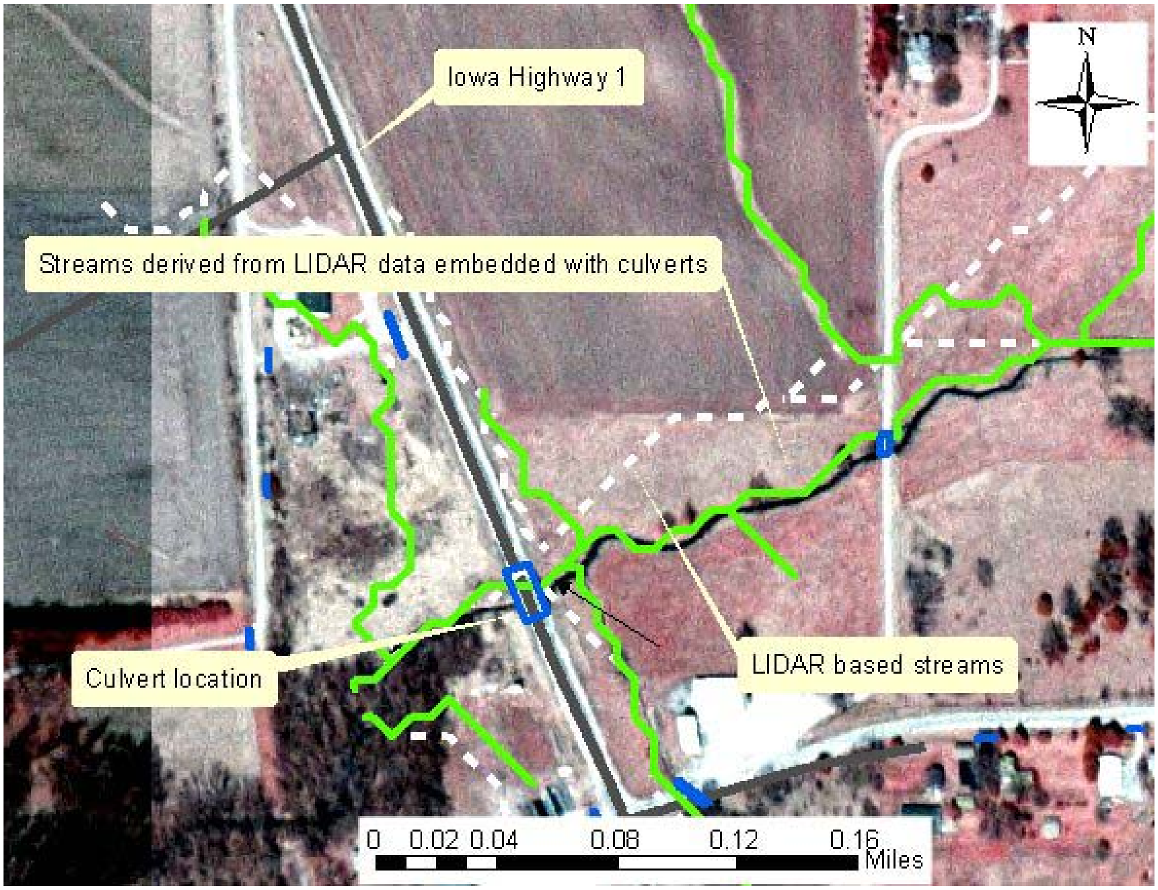

FIGURE 2. Lidar-Based V. Lidar Embedded with Culverts-Based Stream Coverage, Six Acre Threshold for Stream Initiation

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 six acres (0.018 percent) for stream definition was used to be consistent with the watersheds generated from the LiDAR terrain data.

4.4.3 LiDAR Bare Earth Supplemented with Culverts. In an attempt to influence stream flow through known hydrologic structures, a 10m-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 feet, 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 one percent (approximately six acres) was used as the stream initiation threshold (Figure 2).

4.4.4 LiDAR Bare Earth Supplemented with Culverts and USGS DEMs. A final 10m-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 six acres (0.018 percent of the largest drainage area).

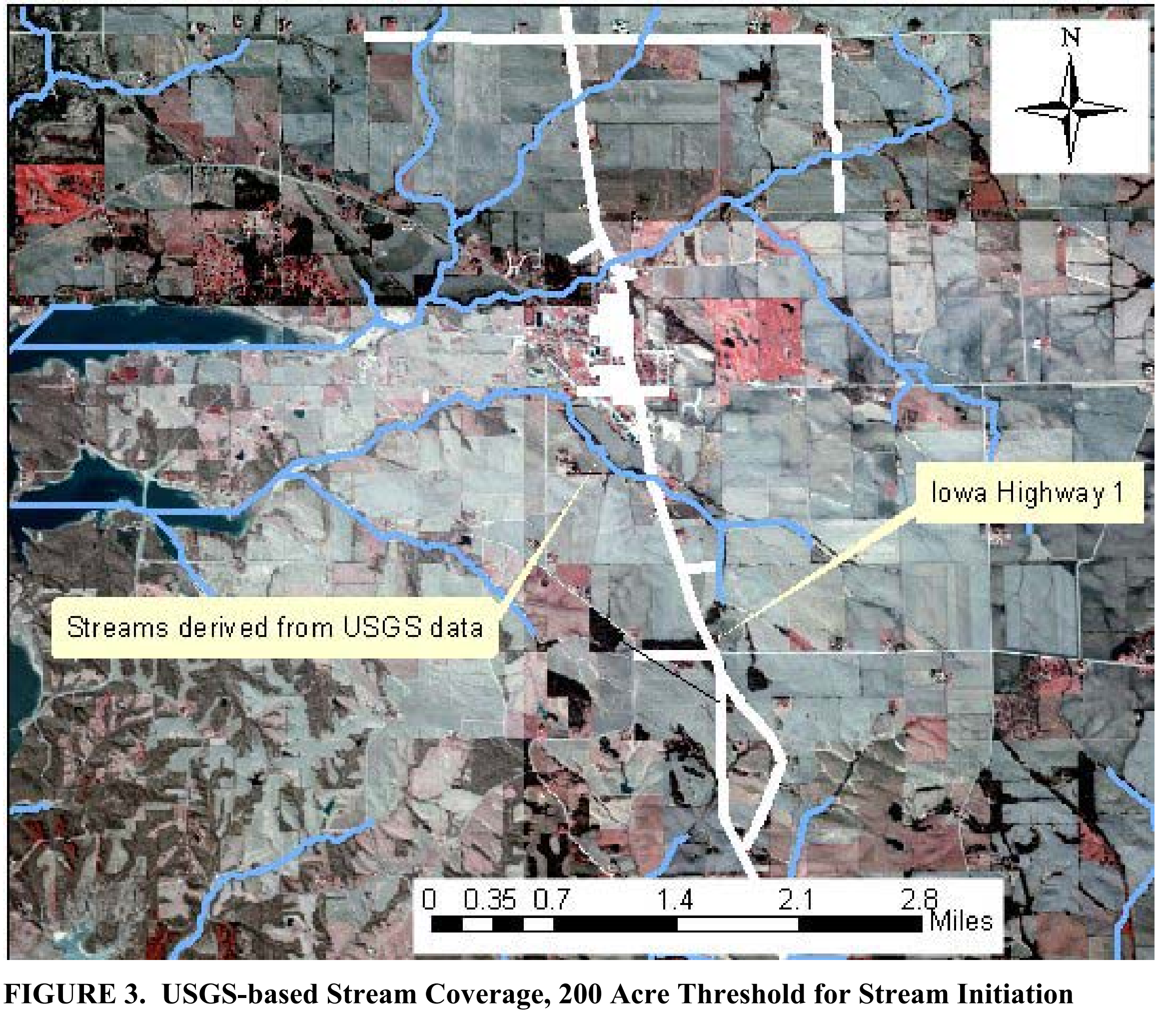

FIGURE 3. USGS-based Stream Coverage, 200 Acre Threshold for Stream Initiation

SECTION 5: RESULTS

5.1 Stream 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. Using the Iowa DOT corridor and Iowa DNR CIR aerial images, the relative accuracy and reasonableness of existing stream placement for each elevation grid created from HEC-GeoHMS was assessed. In addition, stream location with respect to known culvert locations and the highway roadside was reviewed.

The streams (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 meters. 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.

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 5m-elevation grid was created for a portion of the corridor. The stream coverages created from this grid and the 10m-grid from the LiDAR data are presented in Figures 4 and 5. As is apparent in these figures, the two stream coverages closely mirror each other. Alignment differences of approximately 50 meters were present at several locations, in Figure 5, but the 10-m grid stream coverage was actually closer to the existing stream alignment. Therefore, the more finely defined elevation grid (5m) did not appear to yield a superior stream coverage and was more greatly impacted by terrain inaccuracies or false bare earth elevations.

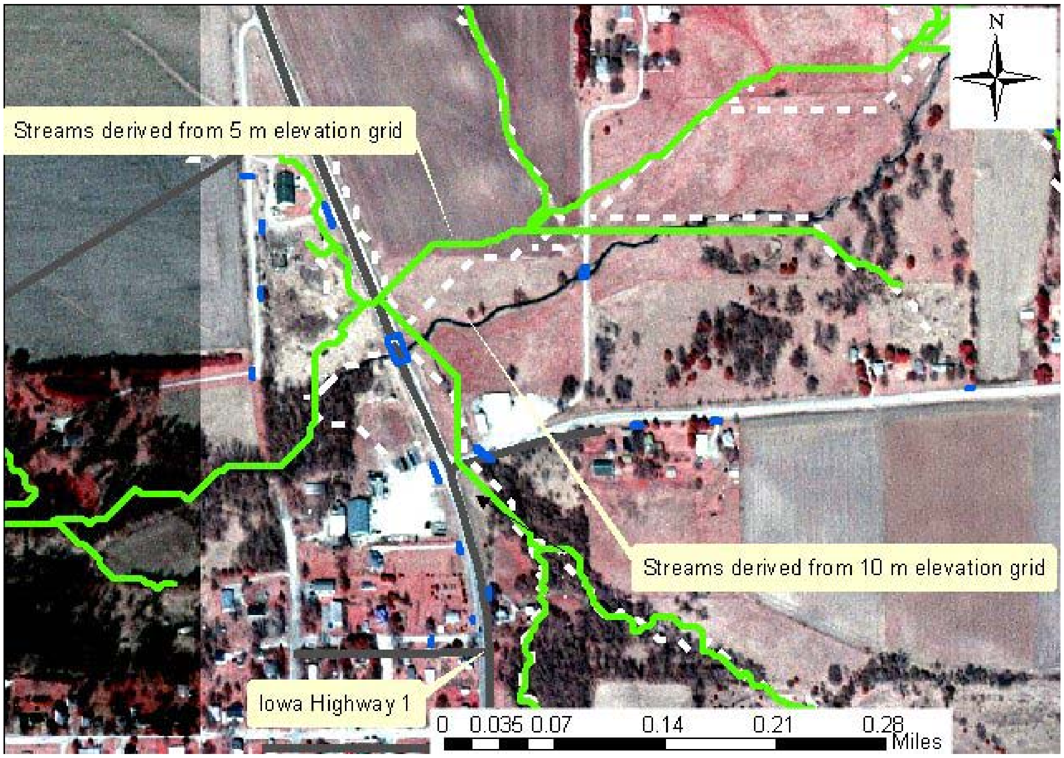

FIGURE 4. LiDAR-based Stream Coverage, 5m v. 10m Elevation Grid (Overview)

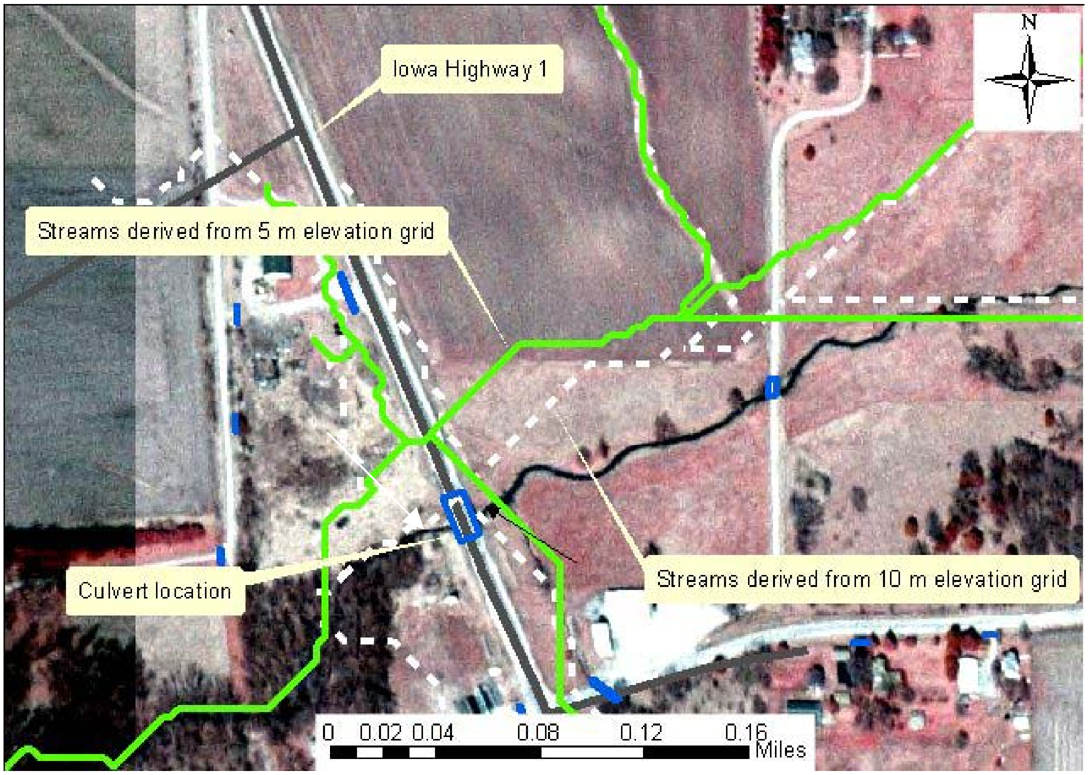

FIGURE 5. LiDAR-based Stream Coverage, 5m v. 10m Elevation Grid (Zoomed in)

The USGS elevation grid yielded similar stream coverages as the LiDAR elevation grid in the vicinity of the highway (Figures 6 and 7). Streams (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 meters. 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.

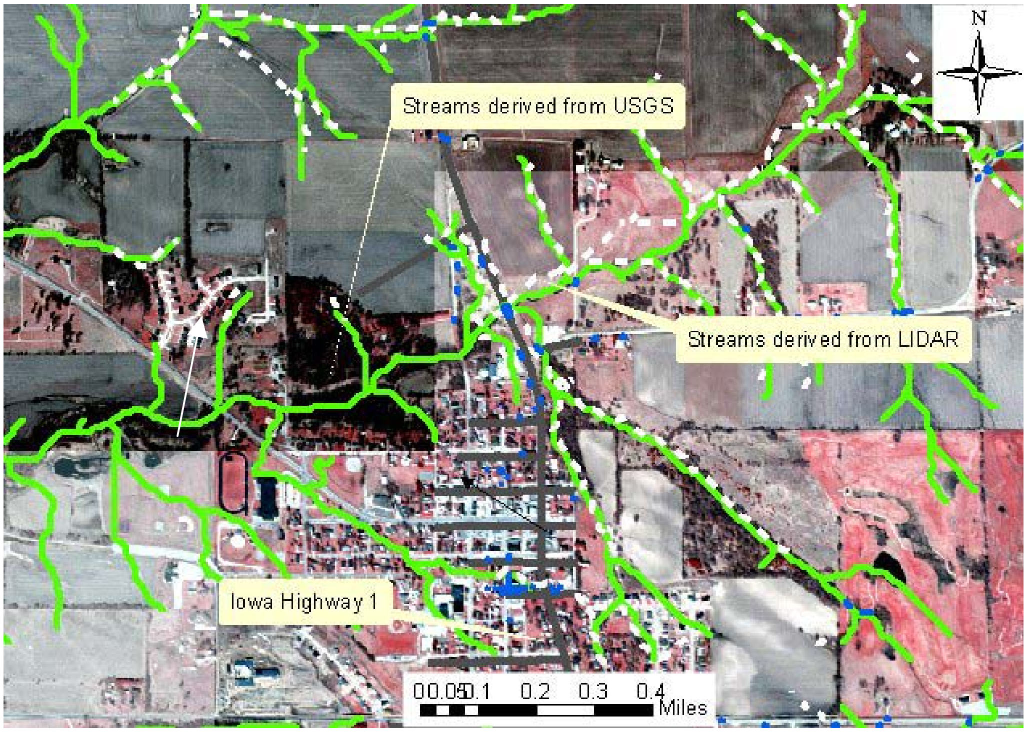

FIGURE 6. USGS-based v. LiDAR-based Stream Coverages (Overview)

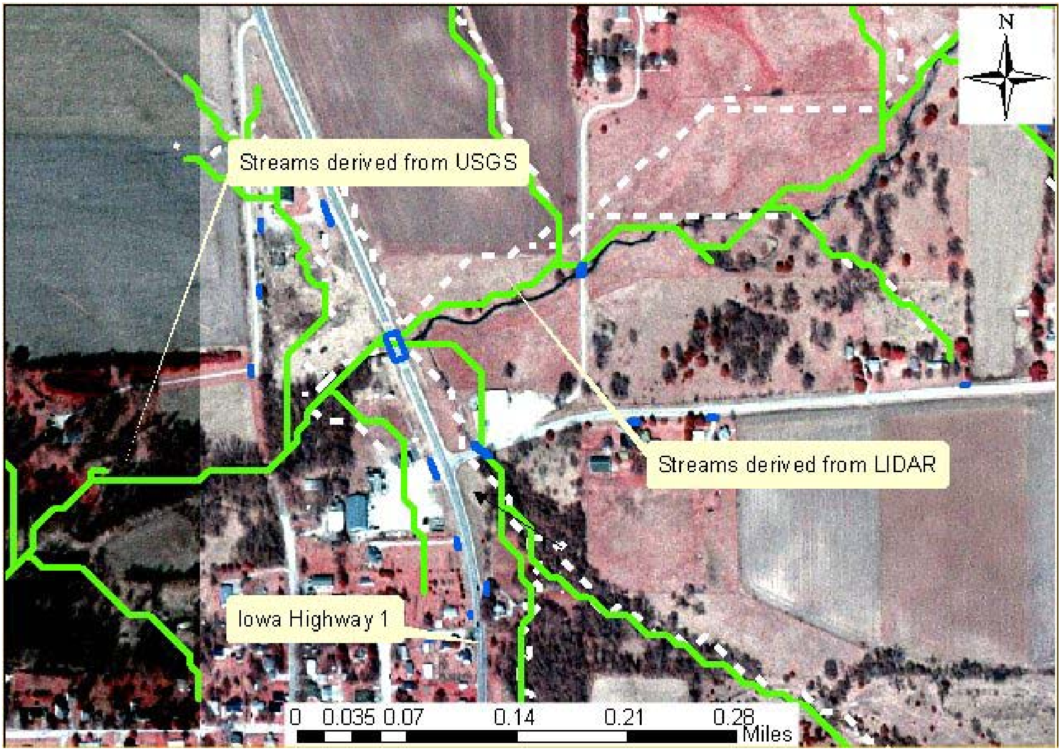

FIGURE 7. USGS-based v. LiDAR-based Stream Coverages (Zoomed in)

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 (Figure 8). 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.

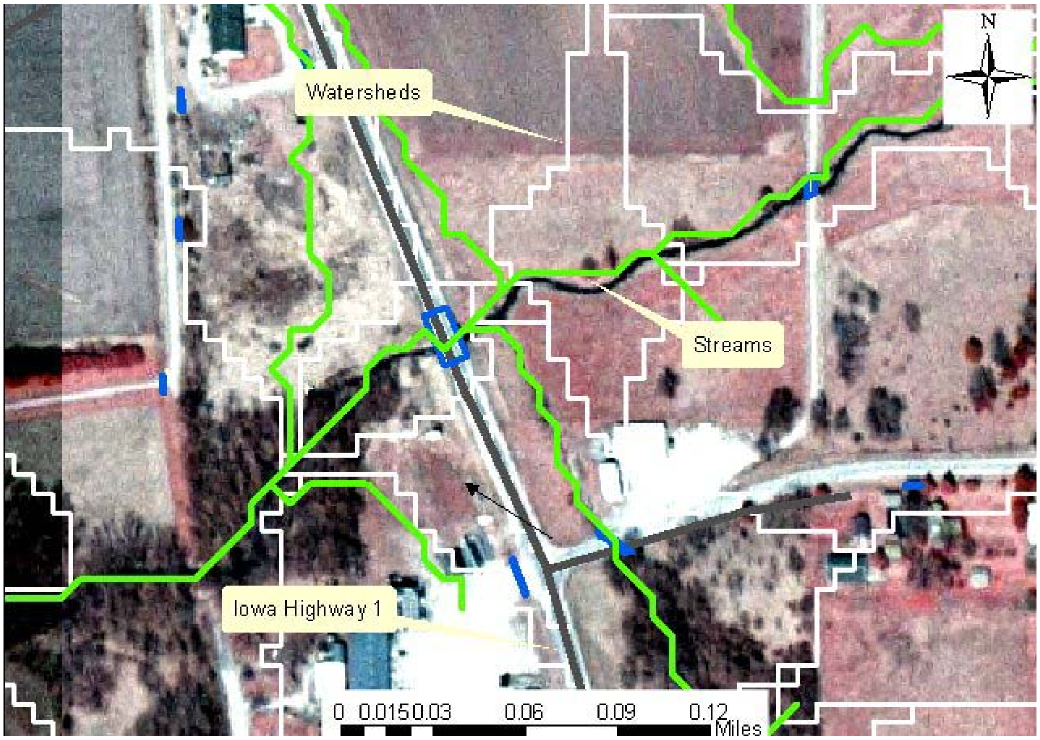

FIGURE 8. Combined LiDAR, USGS, and Culvert Stream Coverage

5.2 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?

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 (six 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 (Figure 10). This, however, does not hold true for all watersheds along the roadway and seldom, if ever, holds true for the USGS-based data (Figure 10). The horizontal resolution of the USGS DEM, at 10m, is too great to detect a two-lane roadway (Figure 14).

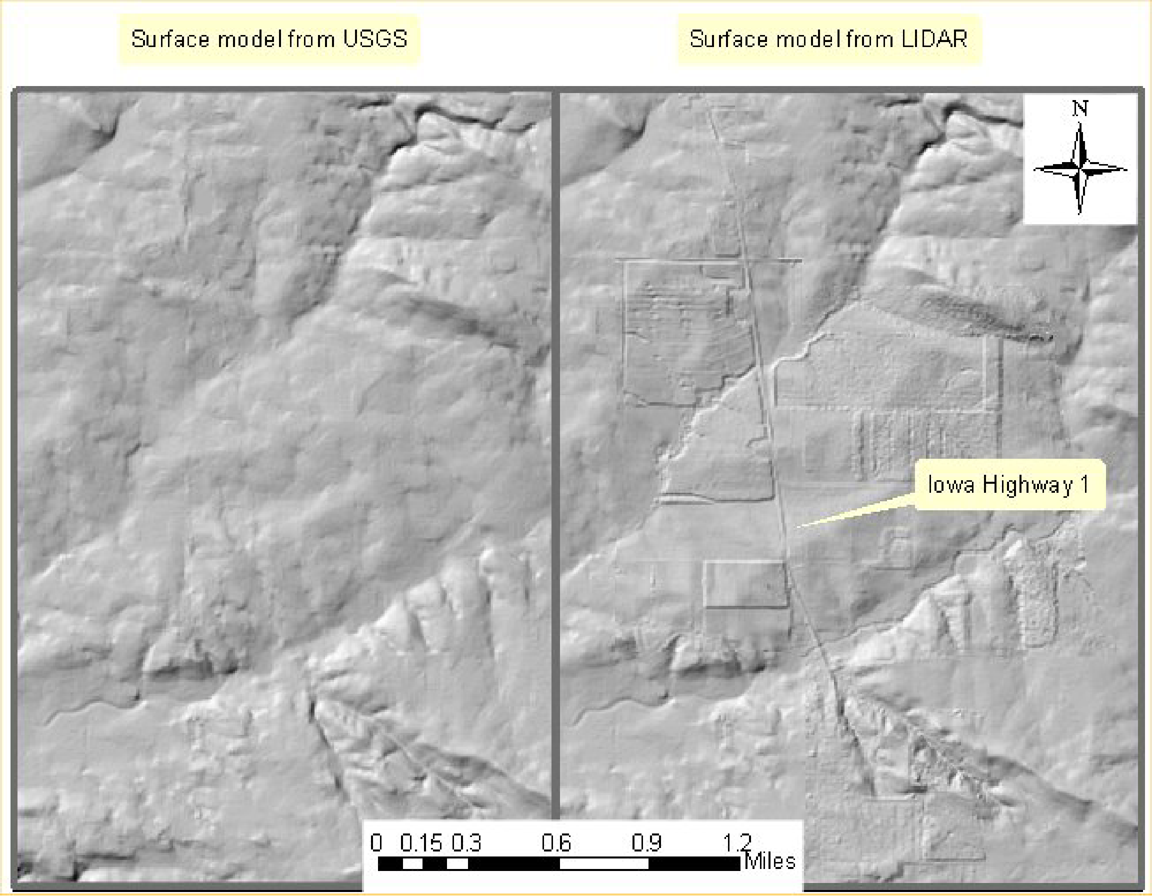

FIGURE 9. Comparison of surface model derived from USGS and LIDAR (10m-grid)

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.

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.

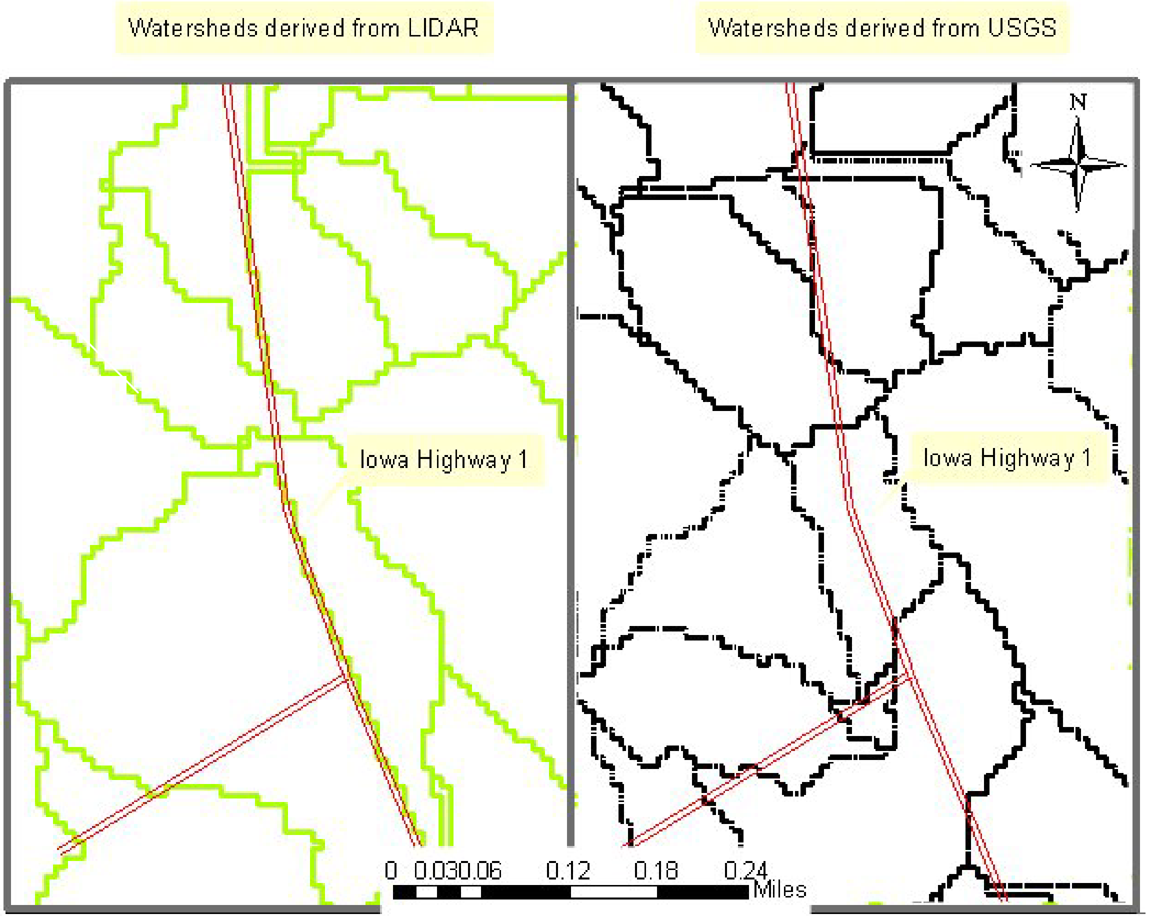

FIGURE 10. LiDAR-base v. USGS-base Watershed Boundaries, Six Acre Minimum Watershed Area

5.3 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 ten), 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 four acres. Using the Iowa Runoff Chart to determine peak discharge, and assuming the same flood frequency (50 year), 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.

SECTION 6: CONCLUSIONS/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.

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.

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