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Article

Drainage Structure Datasets and Effects on LiDAR-Derived Surface Flow Modeling

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Abstract: With extraordinary resolution and accuracy, Light Detection and Ranging (LiDAR)-derived digital elevation models (DEMs) have been increasingly used for watershed analyses and modeling by hydrologists, planners and engineers. Such high-accuracy DEMs have demonstrated their effectiveness in delineating watershed and drainage patterns at fine scales in low-relief terrains. However, these high-resolution datasets are usually only available as topographic DEMs rather than hydrologic DEMs, presenting greater land roughness that can affect natural flow accumulation. Specifically, locations of drainage structures such as road culverts and bridges were simulated as barriers to the passage of drainage. This paper proposed a geospatial method for producing LiDAR-derived hydrologic DEMs, which incorporates data collection of drainage structures (*i.e.*, culverts and bridges), data preprocessing and burning of the drainage structures into DEMs. A case study of GIS-based watershed modeling in South Central Nebraska showed improved simulated surface water derivatives after the drainage structures were burned into the LiDAR-derived topographic DEMs. The paper culminates in a proposal and discussion of establishing a national or statewide drainage structure dataset.

Keywords: LiDAR; DEM; drainage structure; culvert; watershed; metadata

1. Introduction

Digital Elevation Models (DEMs) are the most critical datasets to the success of surface hydrologic modeling applications [1–3]. These datasets can be used to produce critical topographic and hydrologic derivatives, such as slope, aspect and flow accumulation. The accuracy of derived hydrological features is largely dependent on the quality and resolution of DEMs [4]. DEMs were traditionally derived by the US Geological Survey (USGS) photogrammetrically or from topographic maps with relatively coarse resolution (usually > 10 m) and low vertical accuracy (±2.44 m) [5]. As an emerging modern terrain data production technology, Light Detection and Ranging (LiDAR) has been increasingly applied to produce a new generation of DEMs with higher resolution and accuracy. LiDAR densely samples the ground surface and produces point clouds with highly accurate three-dimensional positions, which can then be used to derive these high-resolution DEMs. Compared with conventional USGS DEMs derived photogrammetrically or from topographic maps, LiDAR-derived DEM datasets possess higher horizontal and vertical accuracy [6–8], and thus are suitable to depict minor topographic variations that control surface water flow across low-relief landscapes [9]. For example, LiDAR-derived DEMs are capable of modeling low-order drainage lines and fine-scale headwater channels that were not present on topographic maps or even orthorectified aerial photographs [10,11]. LiDAR-derived DEMs have been found to significantly improve the accuracy of wetland-stream connectivity determined at the landscape scale [12] and boost topo-hydric data accuracy [13,14].

However, the DEMs typically derived from airborne LiDAR only reflect the topographic features on the ground and are therefore explicitly topographic DEMs. Such LiDAR-derived topographic DEMs are, in some cases, not suitable to use for hydrologic modeling [7]. For example, ground features such as bridges and roads over drainage structures may be modeled as “digital dams” [15] in a topographic DEM, affecting the modeled drainage passage and flow accumulation over the land surface. The absence of drainage structures in a topographic DEM effectively disconnects areas upstream of culverts from the watershed outlet [16]. Barber and Shortridge [7] acknowledged that ground features such as bridges and graded roadbeds over culverts can result in larger sinks and affect the simulated watershed boundaries in a GIS-based watershed modeling. Cook and Merwade [17] found that the flooding risk of a flood-prone area may differ substantially, depending on whether bridges are modeled as flow obstructions in the model. The problem becomes more acute for hydrologic features derived at the local scale. For instance, it was found that the LiDAR-derived surface flows could spill erratically in the wrong location if flow barriers were not removed from the elevation data [15]. Therefore, it is preferable to have hydrologic DEMs without flow obstructions at culvert locations for hydrologic modeling [18]. A hydrologic DEM allows surface flow through the drainage structures that are generally unrepresented in a topographic DEM.

Hydrologic DEMs can be derived by burning ancillary hydrographic breaklines, such as those from the National Hydrography Dataset (NHD), into topographic DEMs [2]. Burning, in this context, involves trenching a DEM to allow surface flows. However, to create a LiDAR-derived hydrologic DEM, such ancillary breakline datasets with accuracy comparable to LiDAR-derived DEMs are often nonexistent or not quality-assured. For example, the best resolution of the NHD dataset is based on USGS 1:24,000-scale topographic maps, and any mapping of streams and canals at finer scales is expected to be extremely costly. One potential solution to produce LiDAR-derived hydrologic DEMs is to burn only drainage structures which are generally unrepresented in the LiDAR-derived topographic DEMs. For example, it has been found that incorporation of culverts under roads in the LiDAR-derived topography can affect the simulated spatial extent and distribution of contributing areas in a prairie wetland region of North Dakota [19]. Burning drainage structures into the DEM can decrease the elevation at locations of bridges and culverts under graded roadbeds to allow for flow passage. In this paper, drainage structures are specifically referred to as both culverts and bridges. A culvert is defined as a conduit for the passage of drainage water under highways, roads or other embankments. A bridge is a structure carrying a roadway or railway over a water course.

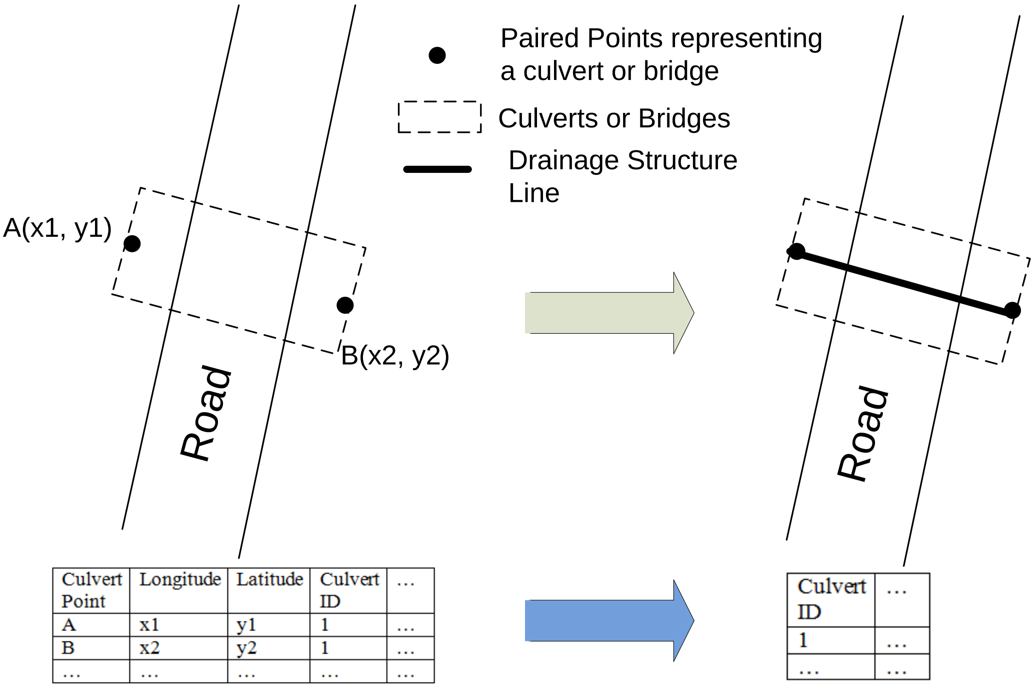
The major objective of this paper is to propose a method for developing LiDAR-derived hydrologic DEMs, which includes collecting data on drainage structures (*i.e.*, culverts and bridges), and the preprocessing and burning of the drainage structures. This method was demonstrated in a study area where surface runoff contributes to several wetlands. Based on the case study, a data model for a drainage structure dataset to be used for hydrologic burning is proposed. The hypothesis is that hydrologic burning of drainage structures such as culverts can result in differences in simulated surface water derivatives.

2. Research Methods

To create the drainage structure dataset, the geographic coordinates of inlets and outlets of culverts and/or center points of the edges of bridges (see Figure 1) were collected using a GPS unit along with their corresponding geometrical parameters (*i.e.*, diameter of the culvert pipe, bridge span and depth to bottom). Only geometrical parameters important for hydrologic modeling were collected during the fieldwork but other engineering parameters such as materials and culvert design critical for hydraulic modeling and structure maintenance could potentially be included in the attributes. The data were stored as vector point features. However, the point data are not directly applicable for burning LiDAR-derived DEMs since roads or bridges present significant width or spans. The point features must be converted into linear features before the burning process. In this study, the collected paired feature points were assigned with the same Structure IDs (e.g., 1, 2, 3, …, *etc*.) then converted to line features. This process can be implemented using the Points to Line tool of ArcToolbox in ArcGIS 10. The attributes collected for each drainage structure were joined to the attribute table of the new vector line features.

The linear drainage structure features can be burned into the DEMs using two potential approaches. For the first approach, the elevation of DEM grids corresponding to the drainage structures were reduced using specialized GIS tools, such as DEM Reconditioning in the ArcGIS Hydrology toolbox. The DEM Reconditioning tool was developed based on the AGREE algorithm which drops the elevation of the DEM cells corresponding to user-defined buffers of drainage structures [20]. The elevation drop and the number of cells for the stream buffer were determined based on the collected geometrical attributes of depth to bottom and culvert diameter and bridge span over the river channels. The number of cells (stream buffer) is equal to the rounded value of the half culvert diameter divided by the cell size of the DEM. If the diameter is smaller than the cell size, the number of cells for the stream buffer was assigned as 1. In the second approach, the DEM grids corresponding to the areas of buffered drainage structures were assigned the lowest elevation within the same areas. The lowest elevation can be calculated with zonal statistics. In this study, the DEM Reconditioning tool integrated in the ArcGIS toolbox was used to burn the drainage structures.

Figure 1. Conversion of point features to line features for a drainage structure.



Culvert Point	Longitude	Latitude	Culvert ID	…
A	x1	y1	1	…
B	x2	y2	1	…
…	…	…	…	…

Culvert ID	…
1	…
…	…

To illustrate the effectiveness of burning drainage structures into the LiDAR-derived topographic DEMs, hydrologic derivatives simulated directly using the LiDAR-derived topographic DEMs and hydrologic derivatives produced from hydrologic DEMs were compared for a low-relief landscape imbedded with numerous wetlands. In this hydrologic context, LiDAR-derived topographic DEMs represent the gentle variations in the local topography well, but present considerable hydrologic fragmentation caused by raised roadbeds. The focus of this study is to produce surface water derivatives, including catchments contributing water to the wetlands, drainage lines and depression storage volumes [21]. Catchments in this study are defined as the areas where rainwater can accumulate and flow into the large depressions (such as wetlands and lakes). Drainage lines indicate the path of flow accumulation. The depression storage volume affects the amount of water stored or intercepted by land depressions (such as impoundments along road ditches and water puddles). The following steps were implemented for the modeling [22]:

(1) Prefill spurious artifacts in the LiDAR-derived topographic DEM (e.g., Fill Sinks tool in ArcGIS). In DEM-based hydrologic modeling, small sinks were generally regarded as spurious artifacts

resulting from errors caused by the dense vegetation profiles and artifacts of DEM interpolation [15]. It was assumed that sinks smaller than or equal to an area of four cells (approximately 16 m^2) were erroneous sinks and should be excluded from the true land sinks/depressions. The removal of the sinks followed a standard procedure of filling them to the level of their lowest outflow points [23].

(2) Identify the extent of wetland depressions. The National Wetland Inventory (NWI) dataset was overlaid with the relief-shaded DEM datasets and aerial photo imagery to identify the actual depressional wetland boundaries.

(3) Fill the sinks again on the burned and unburned DEMs. In this step, sinks and depressions were filled using the DEM Reconditioning tool except for large wetland depressions identified by overlaying the NWI dataset. This process produced depressionless DEMs. The filled sinks in this step were regarded as true sinks and depressions, including small water reuse pits, impoundments along road ditches and small water puddles. The volumes of these sinks equate to depression storage volumes.

(4) Produce flow direction grids with the wetlands as converging locations of surface runoff based on the LiDAR-derived topographic DEMs and the burned DEMs respectively. This process results in enclosed catchment areas that contribute runoff to wetlands. The Flow Direction with Sinks tool in ArcGIS can be used for this purpose.

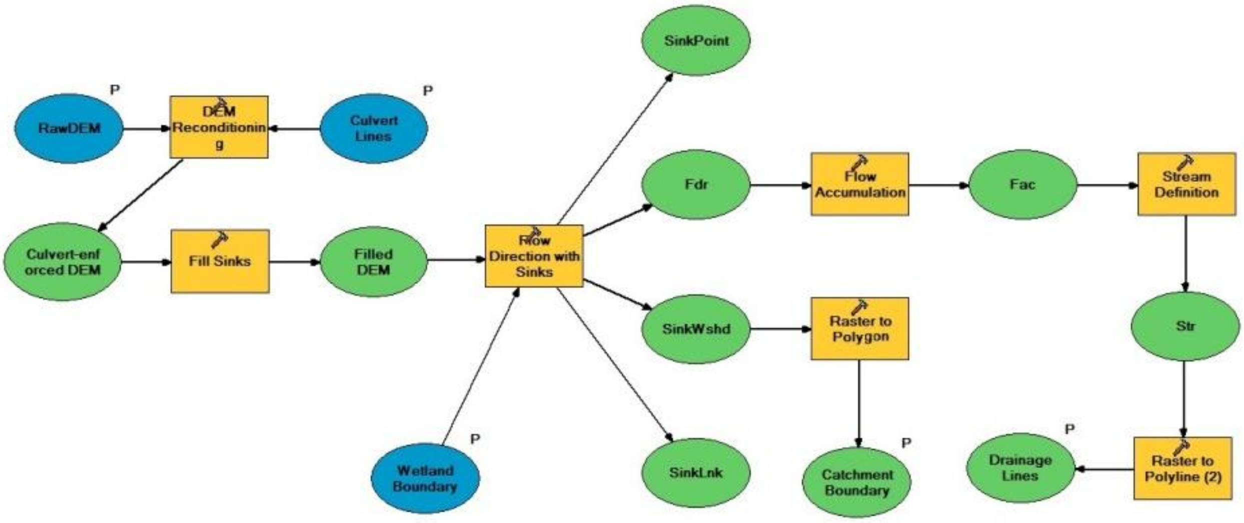
(5) Compute flow accumulation grids based on the flow direction grids. The Flow Accumulation tool in ArcGIS can be used.

(6) Generate drainage route grids from the flow accumulation grids based on a predefined drainage threshold. An overly large threshold number could miss small drainage channels; while too small a number can cause many spurious drainage artifacts. In ArcGIS, the Stream Definition tool can be used.

(7) Convert the raster datasets of drainage and wetland catchments into feature classes.

(8) Calculate the depression storage volume for each catchment of the wetlands. To do this, calculate the raster difference between the depression-filled DEMs and prefilled DEMs for both topographic DEM and hydrologic DEM. The end product represents the depression storage [21] in the land surface. In ArcGIS, the Zonal Statistics tool can be used to summarize the depression storage volume within each wetland catchment.

Figure 2. Geoprocessing tools for wetland catchments and drainage delineation in a ModelBuilder.



The above processes (Steps 1–7) were automated as a workflow in a ModelBuilder environment within an ArcGIS platform (Figure 2). ModelBuilder streamlined the processes and thus saved the execution time of running each function manually. Finally, the simulated catchment size, drainage channels and depression storage volumes resulting from the LiDAR-derived topography DEM and from the LiDAR-derived hydrologic DEM were compared based on our proposed method.

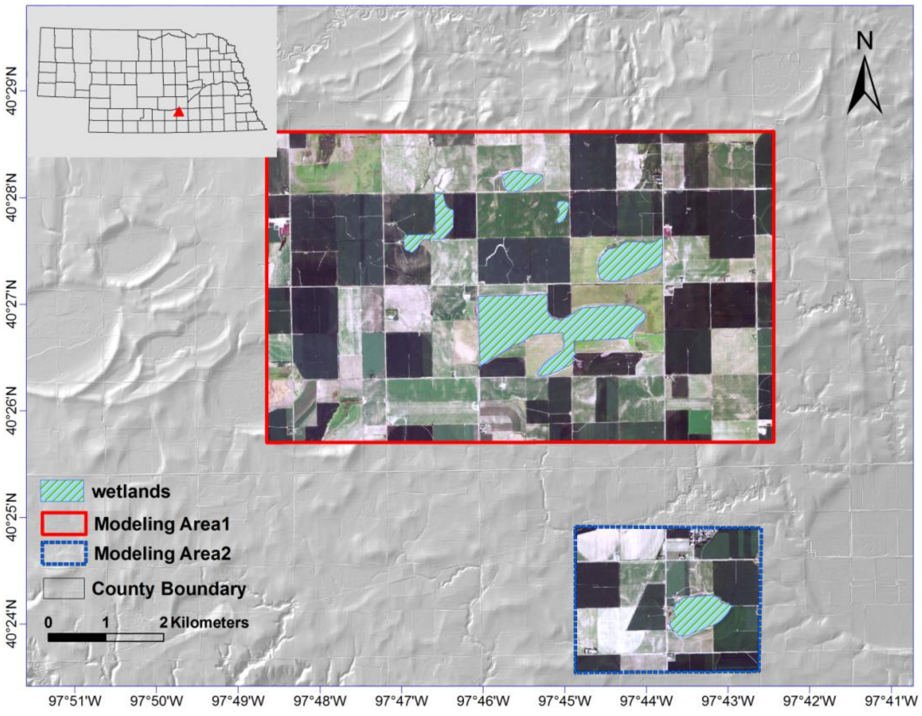
3. A Case Study in Nebraska

The proposed method to burn drainage structures in the LiDAR-derived topographic DEMs was applied to a case study in Nebraska. Differences between the simulated catchment size, drainage lines, and depression storage volumes were compared.

3.1. Study Area

The study area is Weis Lagoon, part of the Dry Sandy Creek watershed located in the southeast corner of Fillmore County, Nebraska (Figure 3). This region of Nebraska is known as the Rainwater Basin. The terrain of the watershed is a gently undulating loess plain, descending from the northwest to the southeast with the highest and lowest elevations at 525 m and 487 m, respectively. This region was formed by the deposition of wind-blown silts over silty and alluvial materials, and named for its abundant clay-bottomed depressional basins that hold rainwater and form playa wetlands [24]. The hydrology of the region is dominated by a poorly developed drainage system and large depressional wetlands with internal drainage patterns. These wetland depressions are generally shallow with important ecological functions, including flood mitigation, capture and filtering of surface runoff, aquifer recharge and enhancement of biodiversity [25,26]. This area is a focal point of millions of migratory waterfowl in spring [27] and provides important staging and migrating habitat for endangered species.

Figure 3. Locations of wetlands and the study area.



Like most agricultural areas, this region features a dense network of primary and secondary roads [24]. These roads fragment the agricultural landscape as well as many wetlands (and their corresponding catchments). Hydraulic drainage structures, such as culverts and bridges, play important roles in facilitating the runoff transport. The best existing digital elevation datasets were only available as topographic DEMs, in which surface flows can be blocked at locations of drainage structures.

3.2. Data Sources and Collection

The datasets used in this study included the LiDAR-derived topographic DEMs, NWI, 2012 Farm Service Agency (FSA) Digital Orthophoto for Fillmore County, Nebraska (1 m resolution), and collected culvert data for the study area. In the study area, no bridges were present and hence no bridge data were collected. LiDAR-derived topographic DEMs with a horizontal resolution of 2 m and a vertical accuracy (RMSE) of 0.15 m were obtained for this study [28]. Technical parameters of the raw LiDAR cloud points are shown in Table 1. The FSA aerial imagery was used to visually assist in quantitatively verifying the simulated drainage derivatives. The NWI dataset [29] was used to identify the location and extent of six major depressional wetlands. These wetlands functioned as converging locations of surface runoff in an internal drainage system. The geographic coordinates and geometrical parameters (e.g., span and depth) of the culverts upstream of the wetlands were collected using a Trimble GeoXH 6000 Series handheld GPS unit (with horizontal accuracy around 2.5 cm). The geographic coordinates of both ends of a culvert pipe were recorded and assigned the same Structure ID. Meanwhile, depth to bottom from the road and diameter of culvert pipes were measured using a tape ruler and recorded as extra attributes along with the geographic coordinates and StructureIDs. A total of 21 culverts were located in the vicinity of studied wetlands. Table 2 shows 12 records of the culvert attribute table collected for the case study. It is noted that no bridges were found in this study area.

Table 1. Specifications, resolution, and accuracy of Light Detection and Ranging (LiDAR) point clouds [22,30].

Items	Information
Ground sample distance	1.0 m
Collection conditions	Leaf off; Snow free
Accuracy required (Bare Earth)	Vertical: 0.15 m Root Mean Squared Error (RMSE) Horizontal: 1 m RMSE
Products (Mass Points)	First return; last return; bare earth; number of returns required is 5.
Datum	Vertical: NAVD 88 (default) Horizontal: NAD 83 (default)
Coordinate system	UTM Zone 14 Nebraska State Plane Zone 2600
Units	Meters: to 3 decimal places (meters is default for UTM) Feet: to 3 decimal places (feet is default for state plane)
Title size	2,000 m × 2,000 m (default meters) 2 m × 2 m (default feet)
Metadata required	FGDC (XML) in project level

Table 2. Field collected culvert data in the form of points (only the first six pairs listed).

No	Lat	Long	Culvert ID	Depth (m)	Diameter (m)	Notes
1	40.45510	−97.78576	1	0.6	1	twin culverts
2	40.45510	−97.78564	1	1	1.2	twin culverts
3	40.43758	−97.76812	2	0.8	0.8	in the middle of wetlands
4	40.43748	−97.76808	2	0.8	0.8	in the middle of wetlands
5	40.44774	−97.76671	3	0.7	0.5	This culvert was newly replaced
6	40.44779	−97.76663	3	0.7	0.5	This culvert was newly replaced
7	40.46039	−97.76667	4	0.9	0.6	No drainage path was visible upstream side
8	40.46047	−97.76656	4	0.9	0.6	No drainage path was visible upstream side
9	40.46789	−97.76656	5	0.9	0.6	no wetland found nearby
10	40.46788	−97.76667	5	0.9	0.6	blocked by corn stalks
11	40.45208	−97.77881	6	2.2	2	
12	40.45199	−97.77881	6	2.2	2	
…	…	…	…	…	…	…

3.3. Data Processing and Modeling

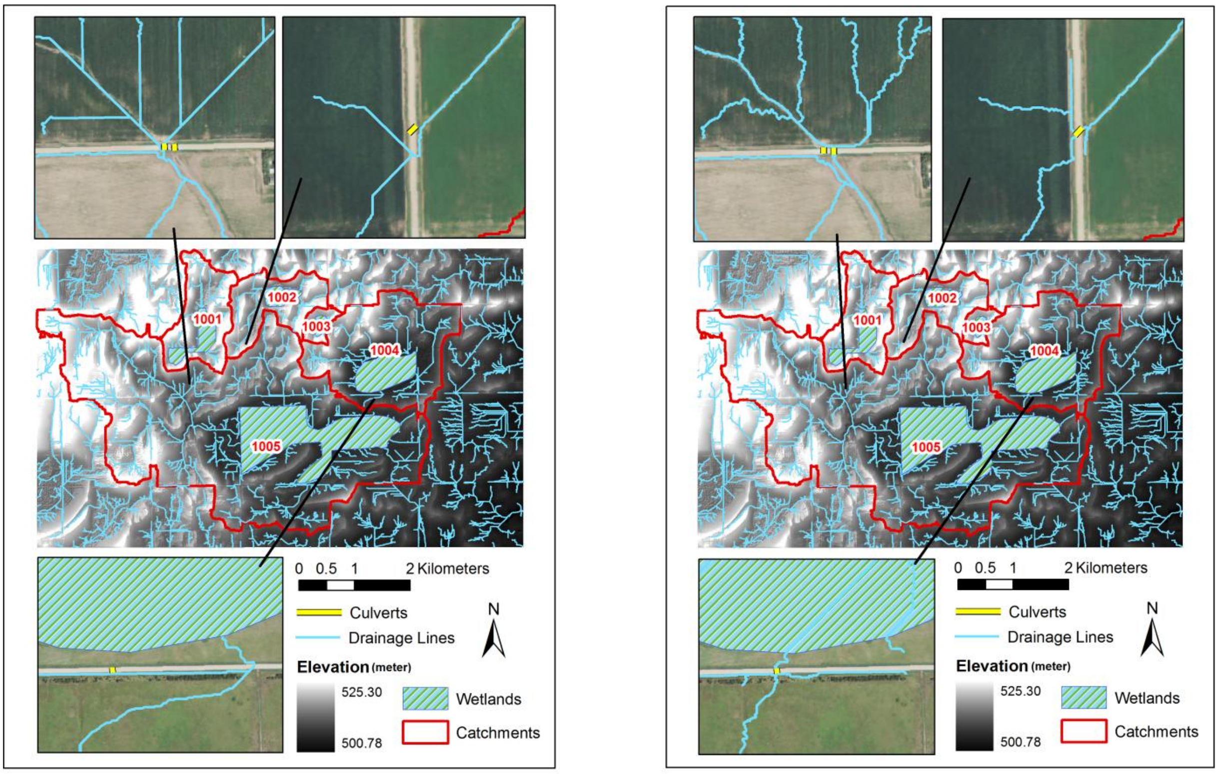
The DEM data were subset to the two Modeling Areas illustrated in Figure 3, which include major wetlands (*i.e.*, Modeling Area 1 and 2 bounded by solid boxes). The purpose of subsetting the DEMs was to isolate the internal drainage areas from the dendritic drainage systems, as the study focus was to produce hydrologic derivatives that are related to wetlands.

The collected culvert point features were converted into line features using the Points to Line tool. Each subset of LiDAR-derived topographic DEM was then burned using the derived culvert lines. The modeling procedure detailed in the Methods Section above was then run for the unburned and burned DEMs, respectively. The produced hydrologic derivatives, including catchments, drainage lines and depression storage volumes, were compared. It is noted that the drainage lines were derived from grids with values greater than a certain flow accumulation threshold. In this case study, the threshold to initiate a drainage route was arbitrarily set as 2,500 grids (approximately 0.01 km^2).

3.4. Results of the Case Study

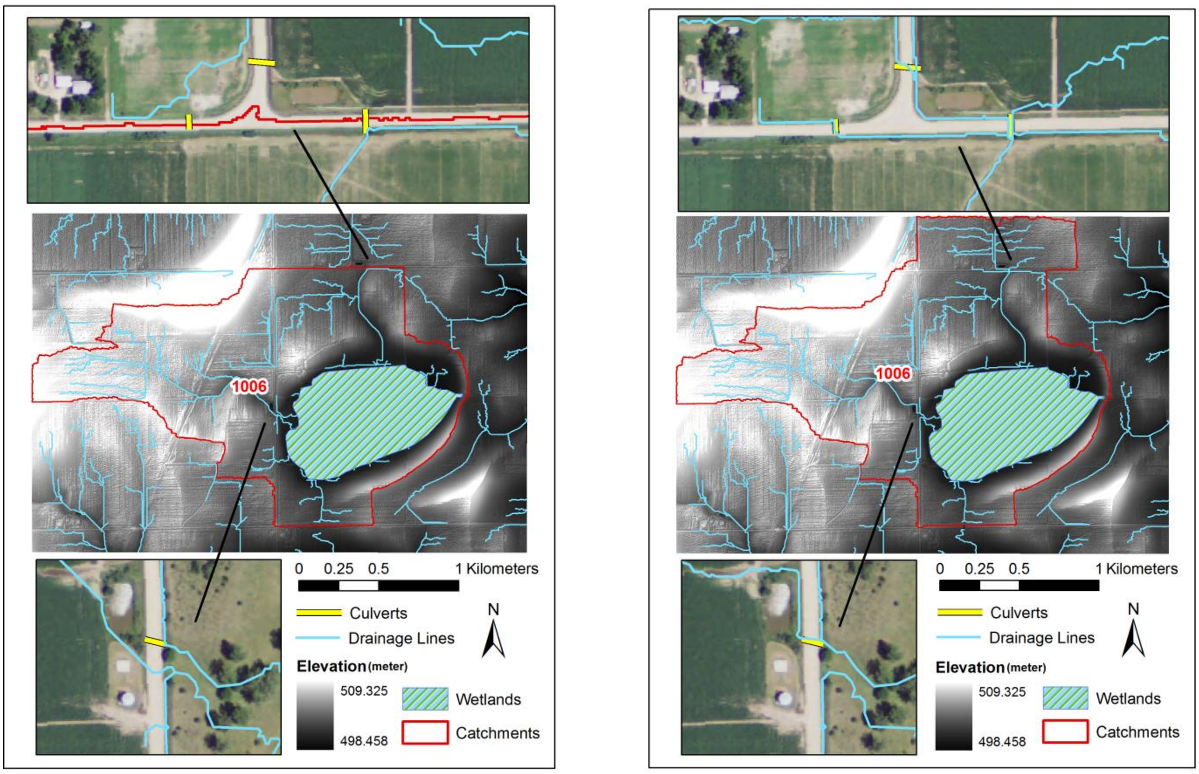
Figures 4 and 5 show the modeled wetland catchments and drainage lines for the two types of DEMs. There were five wetland catchments in Area 1 and one catchment in Area 2. In Area 1, identical catchment areas were simulated with and without burning culverts. However, a close examination shows that the location of the channels modeled from the topographic DEM did not coincide with the location of the surveyed culverts. In contrast, the culverts-burned DEMs resulted in correct drainage routes based on a visual comparison with aerial imagery. Table 3 shows that depression storage volumes simulated using the culvert-burned DEMs are mostly smaller than those modeled using the LiDAR-derived topographic DEM for each wetland catchment. A topographic DEM presented more land depressions, mainly caused by flow obstructions near roads, than a hydrologic DEM.

Figure 4. Simulated catchments and drainage lines for Modeling Area 1. (**a**) Did not incorporate culvert information, and (**b**) incorporated culvert information in modeling.



(**a**) (**b**)

Figure 5. Simulated catchments and drainage lines for Modeling Area 2. (**a**) Did not incorporate culvert information, and (**b**) incorporated culvert information in modeling.



(**a**) (**b**)

Table 3. Depression Storage Volumes simulated using LiDAR-derived digital elevation models (DEM) with (Hydrologic DEM) or without (Topographic DEM) culvert information incorporated (unit: m^3).

Wetland Catchment	Topographic DEM	Hydrologic DEM	Difference
1,001	155	155	0%
1,002	49,908	46,644	−7%
1,003	49,299	49,299	0%
1,004	109,035	33,124	−229%
1,005	137,851	105,812	−30%
1,006	16,536	12,619	−31%

In Area 2, the catchments simulated using the LiDAR-derived topographic and hydrologic DEMs had different sizes. In the hydrologic DEM, the wetland catchment extended to the northern portion of the study area because the road was breached by burning the culverts. But without the burning, the road acted as a digital divide of catchments (see Figure 5). Similar to Area 1, the culvert-burned DEM produced drainage lines well aligning with the drainage channels, while the drainage lines modeled using the LiDAR-derived topographic DEM did not follow the identifiable channels based on an interpretation of aerial imagery.

4. Discussions

4.1. The Impacts of Drainage Structures on Hydrologic Modeling

The modeling results shown in the case study confirmed the hypothesis that burning hydraulic structures, such as road culverts, can affect hydrologic modeling using LiDAR-derived DEMs. The simulation conducted in Area 2 shows that the catchment size can be affected by incorporating the culverts into the LiDAR-derived topographic DEMs. For both modeled areas, the simulated drainage lines aligned well with the locations of the culverts that were burned into the LiDAR-derived topographic DEMs. The topographic DEMs (without culverts burnt) resulted in drainage lines with incorrect placement, because the process of filling sinks caused by road obstruction tends to create continuous surface flow spilling over the roads at the wrong locations or rerouted erratically along the road ditches [15]. For both areas, DEMs without burning culverts resulted in more depressions, most of which were bounded by roads.

Although LiDAR-derived topographic DEMs have high resolution and vertical accuracy, greater surface roughness leads to more complex patterns of flow accumulation and presents challenges to automated drainage channel mapping [10]. Compared to a hydrologic DEM, graded roads present in the topographic DEMs can affect the passage of water flows [15,31]. The case study showed that a LiDAR-derived hydrologic DEM created by burning drainage structures best performed in hydrologic modeling. At the macro level, incorporating drainage structures in LiDAR-derived topographic DEMs improved the accuracy of catchment boundary delineation. For instance, the northern boundary of catchment 1006 was simulated aligning with a road in the topographic DEM in Area 2 (Figure 5). After culvert incorporation, the catchment divide along that road dissolved and shifted northward. At the micro level, both Figures 4 and 5 revealed the detailed differences in modeled drainage routes at selected culvert locations. After the LiDAR-derived topographic DEM was burned, those roads were breached to allow the flow passage under roads.

The accuracy of surface water derivatives is not only associated with the quality of DEMs but can also be affected by high-quality ancillary drainage structure data. With increased availability of drainage structure data, the surface water derivatives can be simulated with improved accuracy. This case study assumed that data on all culverts surrounding the wetlands had been comprehensively collected. However, there could potentially be some culverts which were undiscovered during the data collection since many road culverts were found covered by dense riparian vegetation. Furthermore, a mismatch between the time periods that NWI, aerial imagery and LiDAR-derived DEMs datasets cover could potentially bring uncertainties to the simulated surface water derivatives. For example, the simulated drainage paths at the field level could vary from those visually identifiable in the most recent aerial imagery because of farming operations such as land leveling conducted after the LiDAR data collection. Some wetlands listed in the NWI were found partially converted into cropland during the field site visit. However, these issues were not the focus of this study. Future work will focus on the development of quantitative indices that can be used to quantitatively account for the improvement from culvert burning.

4.2. Potential Ways for Producing LiDAR-Derived Hydrologic DEMs

The effects of the road culverts or bridges on the uncertainty of hydrologic modeling have been well observed and documented [7,15,17,31]. A typical solution is the application of hydrologic enforcement using known stream features. For a coarser-resolution DEM (10 m or 30 m), the NHD dataset is often used as digital breakline to enforce the drainage paths through those raised roadbeds or bridges. However, this method is generally ineffective for burning LiDAR-derived topographic DEMs, because (1) the NHD dataset possesses much lower spatial accuracy than LiDAR-derived DEMs and often aligns off the actual channels; (2) the NHD dataset is unavailable for minor drainage features at the field level (e.g., this study area); and (3) the NHD dataset, compared to LiDAR dataset, is outdated and temporally incompatible. Also, it is well anticipated that mapping minor drainage features is extremely time-consuming and economically infeasible. Therefore, another approach to conduct drainage enforcement is needed for hydrologic modeling using LiDAR-derived topographic DEMs.

Compared with mapping minor drainage features, using drainage structure data appears to be relatively economically feasible and applicable. Several methods have been proposed to identify the culverts or bridges and breach the digital dams on LiDAR-derived topographic DEMs in automated or semi-automatic approaches [15,32]. Poppenga *et al.* [15] proposed the Selective Drainage Method, which identifies the deepest cell inside a depression upstream of the flow obstruction and the closest downstream location with elevation lower than the deepest cell. However, the assumption of this method that the deepest cell in a depression corresponds to the location of runoff passage may not be universally true. In the case of culverts installed between road ditches, the deepest points may not correspond to the water crossings. Further, this method requires the known up-downstream order of the depressions caused by raised roadbeds, which could not be automatically identified in many cases. Schiess *et al.* [32] proposed an ArcGIS-based interactive tool, CULvert Locator for SEDiment Reduction (CULSED), to optimally design the culvert crossing placement to help reduce the sediment load to the river network. However, it is a tool for optimal siting of the culverts, and local hydrological characteristics may not necessitate the installation of culverts based on the rules [31]. Data intensive approaches usually require a collection of accurate spatial coordinates of hydraulic structures. Barber and Shortridge [7] used a version of LiDAR-derived topographic DEM from which the flow obstacles were removed manually for watershed modeling. Although labor-intensive, the data-intensive approach merits the advantage of reflecting a landscape's hydrologic reality. In this study, a method was proposed for generating LiDAR-derived hydrologic DEMs, which incorporates data collection of drainage structures, data preprocessing and burning of the drainage structures.

The method proposed in this study can further hydrologic modeling with the following advantages: (1) It can pinpoint the exact locations of drainage crossings through roads or bridges in a way useful for burning LiDAR-derived topographic DEMs; (2) it can produce a quality-assured drainage structure dataset which can be useful for the management and maintenance of drainage structures; (3) it can potentially be used as breakline features to produce LiDAR-derived hydrologic DEMs directly from LiDAR point clouds; and (4) it can be used to simulate the scenarios when one or several culverts are blocked by sedimentation or corn stalks and surface runoffs inundate and spill out of the depressions. Such scenario development is important for land use planners and risk management agencies interested in identifying potential geographic areas prone to flooding [15]. Figure 6 shows the pictures of culverts that were partially silted in the study area.

Figure 6. Culverts silted by (**a**) corn stalks and (**b**) sedimentation.

(**a**) (**b**)

A disadvantage of the proposed method is still the relatively higher costs of data collection. However, this cost could potentially be addressed through the construction of a drainage structure information system by a coordinated multi-agency effort in the form of cost sharing. Those government agencies responsible for the installation and maintenance of drainage structures, flood risk management and wetland protection/restoration could be among participating members of this data collection effort.

4.3. Future Perspectives on National or Statewide Drainage Structure Dataset

In the case study, field-collected culvert data was used rather than the preexisting dataset for this area. A comparison of the available culvert dataset and FSA digital orthophoto indicates that the existing culvert data contained a few serious quality problems critical to hydrologic modeling. The quality issues included: (1) incomplete inventories, *i.e.*, some culvert locations were not included in the dataset; (2) inaccurate geospatial locations, e.g., some culverts were located far off the roads; (3) one single point represents a two-dimensional drainage structure, and the drainage structures have to be manually digitized as lines for hydrologic enforcement; (4) lack of key geometrical attributes such as culvert diameter and depth to bottom; (5) duplicate culvert records; and (6) a lack of metadata regarding the field names. In addition, the data availability is also an imperative issue to be addressed. For example, among 23 counties in South Central Nebraska, only two counties have data coverage of drainage structures with the aforementioned quality issues. Similar problems have also been reported for other geographic locations [15]. The current drainage structure datasets are maintained by different levels of government agencies responsible for the construction and maintenance of county, state and federal roads. However, there is no holistic and quality-assured dataset or database, which incorporates all of the culverts from various management authorities. With increasing popularity and availability of LiDAR-derived topographic DEMs, it may be imperative to establish an initiative to collect and compile a quality-assured a statewide or even national level drainage structure dataset. The necessity and utility of building such a drainage structure dataset was partially illustrated through the case study.

In establishing a broad-scale drainage structure dataset, road culverts and bridges should be surveyed and compiled through joint multi-agency efforts in a way to conserve the most important attributes and at the same time maximize its uses. The dataset should at least include unique identifiers, accurately surveyed geographic coordinates and critical cross-section parameters such as diameter and depth. Other potential attributes could include design parameters of the drainage structures, depending on the goals and tasks of funding agencies. The drainage structures should be surveyed at a level of accuracy matching the LiDAR-derived DEMs to best serve hydrologic applications. Currently, very few efforts have been taken to develop quality-assured culvert dataset at the national or state level echoing increasing efforts for LiDAR data collection. Among the sparse examples, the LiDAR Research and Education Subcommittee of the Minnesota Digital Elevation Committee published an Interim Guidance on Acquisition of Culvert Geospatial Data, which proposed detailed specification on feature representation, feature descriptions and domains, positional accuracy, acquisition methods and completeness and maintenance [33]. More research and investment need to be conducted to establish a high-quality culvert dataset.

Based on this case study, a preliminary template for the attributes of quality-assured culvert dataset is proposed as shown in Table 4. The dataset can be collected and compiled using a data model of vector point features with the same Structure ID for the paired inlet/outlet of a culvert and center points of bridge edges. Compared with a single culvert point, paired points can save geometrical attributes unique to each side of the structure and allow the derivation of culvert orientation and length as shown in this case study. The dataset should also be regularly updated to reflect the field reality. For example, if a culvert is blocked by sedimentation or replaced with new culverts, the attribute information should be updated. In the end, metadata should be developed for the dataset in accordance with ISO Metadata Standards [34].

Table 4. Template for the major attributes of a drainage structure dataset.

Name	Alias	Data Type	Description
ID	Feature ID	Text	Unique ID of the surveyed point
Str_ID	Structure ID	Text	Unique ID for each drainage structure
Lat	Latitude	Number	Latitude of the surveyed point (Datum: NAD 83)
Long	Longitude	Number	Longitude of the surveyed point (Datum: NAD 83)
Str_shp	Structure Shape	Text	The shape of a culvert (e.g., round)
Str_typ	Structure Type	Text	The type of the drainage structure (e.g., road or bridge)
Material	Construction Materials	Text	The material to build the drainage structure
Diameter	Structure Diameter	Number	The diameter of a culvert opening or the span of a bridge
Depth	Depth to Bottom	Number	Depth of the bottom a culvert opening or the span of a bridge
Date	Survey Date	Date	Date of this survey
Blocked	Blocked or Not	Number	Different Integer numbers indicate different levels of blockage
Comment	Comments	Text	Other comments
Hyperlnk	Hyperlink	Text	Links to photos and engineering drawings

In the future, it may be preferable to produce LiDAR-derived hydrologic DEMs directly out of the LiDAR point clouds and accurately surveyed breaklines, with the increasing availability of the breaklines and capability of GIS software to process the LiDAR point clouds. Authorities or data vendors may produce the LiDAR-derived DEMs in both topographic and hydrologic versions.

5. Conclusions

The finding of this study supports the hypothesis that burning drainage structures can benefit the simulated surface water derivatives from LiDAR-derived topographic DEMs. The study demonstrates the usefulness and necessity of a quality-assured drainage structure dataset for hydrologic modeling using LiDAR-derived topographic DEMs. A case study was conducted to compare the surface water derivatives from hydrologic modeling with or without burning culverts into LiDAR-derived topographic DEMs, showing that burning culverts can improve the simulated catchments, drainage routes and depression storage volumes. A potential format of such a dataset was also proposed in this study. Although this study focused more on local-scale hydrologic applications, the method can potentially benefit broader-scale hydrologic applications such as flooding risk mapping.

With unprecedented efforts to promote LiDAR-derived topographic DEMs availability at the national level (e.g., National LiDAR Dataset) [35], there is still a general lack of LiDAR-derived hydrologic DEMs for hydrologic applications. To address the field-level hydrologic problems as demonstrated in this study, it is important to develop and enhance ancillary drainage structures datasets matching the precision and resolution of LiDAR-derived topographic DEMs. Availability of quality-assured drainage structure data may become the bottleneck of broader application of LiDAR by the hydrologic scientific community. In the future, more funding may be needed to allocate toward the collection of better-resolution hydrologic breaklines rather than improvement of LiDAR accuracies. In a new era with increasing availability of LiDAR-derived topographic DEMs, establishing a national or statewide drainage structure dataset could be imperative in concert with the national LiDAR efforts [35] for land use planners, hydrologists, water resource managers and civil engineers. More work related to the needs and techniques for collecting these datasets are still needed to advance the development of LiDAR-derived hydrologic DEMs.

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Conflicts of Interest

The authors declare no conflict of interest.

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