Interim Guidance on Acquisition of Culvert Geospatial Data

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Minnesota Digital Elevation Committee

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Table of Contents

1. INTRODUCTION

There is considerable interest in making use of the new LiDAR-derived digital elevation models (DEMs) in Minnesota[2] for water resource projects. LiDAR DEMs provide a very precise depiction of the land surface. However, LiDAR captures the topography of the landscape and all human-created features *upon* it. LiDAR DEMs do not inherently include important information about *subsurface water conveyance* connections such as culverts, drain tiles, and storm sewers. As a result, bridges, roads and other structures on the landscape effectively act as virtual dams ("**digital dams**"), preventing terrain analysis algorithms from properly routing the flow of water across the DEM landscape. Figure 1 below identifies many LiDAR DEM digital dams caused by culverts. This figure illustrates the magnitude of the problem, especially when all the culverts in the state are considered. The digital dam problem and other related issues have been documented by numerous scientific investigators (Poppenga et al. 2010; Maidment 2002; Hutchinson and Gallant 2000; Hutchinson 1989).

Hydrologic analyses conducted using DEMs that do not account for subsurface water conveyance are generally suspect. As a result, LiDAR DEMs need to be manipulated to allow the passage of water through digital dams. Fortunately, there are methods for modifying DEMs

[1] http://www.mngeo.state.mn.us/committee/elevation/research_education/index.html
[2] http://www.mngeo.state.mn.us/chouse/elevation/lidar.html

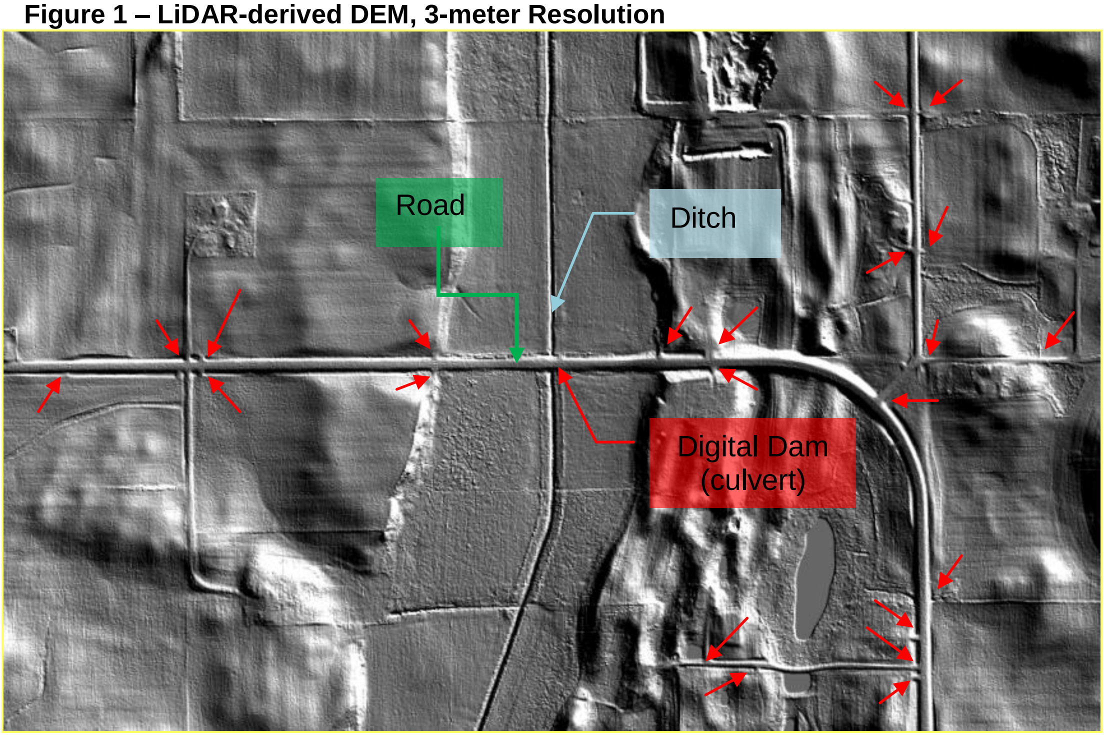
to account for subsurface water conveyance features. This process is known as **hydrological conditioning**.

This document does not explicitly address the technical methods used to modify a LiDAR DEM. Rather; it offers guidance for developing subsurface hydrography data via a culvert inventory that can subsequently be utilized to hydrologically condition a DEM.

Culverts and LiDAR-derived DEMs

Standard transportation engineering practices have long called for elevating rural roadbeds above the surrounding landscape in an effort to prevent water from ponding on the road surface. Culverts are installed under these roads to allow water to move across the landscape from one side of the road to another (see locations marked by red arrows in Figure 1). Without considering such connections, many roads represented in LiDAR derived data act as digital dams and adversely affect the prediction of water flow patterns.

Figure 1 – LiDAR-derived DEM, 3-meter Resolution



2. PURPOSE

The purpose of these guidelines is to create a framework for geospatial information for subsurface water systems that allows data transfer and linkage of data developed by different entities. The guidelines specify the names and definitions for subsurface water system components that can be geospatially depicted as features (points and lines) with attributes.

Requirements of a culvert inventory may vary depending upon the intended use of the data. Because conducting such an inventory typically has relatively high initial costs for mobilization, but relatively low costs for collecting additional data attributes, this document outlines a set of requirements robust enough to support most hydrologic applications. It should be noted that some local projects may have neither the resources nor requirements to complete every element outlined below.

3. APPLICABILITY

These guidelines are intended to improve collection, sharing and exchange of information about subsurface water conveyance features in Minnesota. Organizations involved in data transfer are not required to include all features and attributes listed in the guidelines and may choose instead to only populate the features and attributes applicable to their use. The guidelines apply to both how data is stored internally in an organization and how it is transferred to other entities.

While there are a variety of subsurface water connections that may influence the flow patterns predicted using DEMs, this document focuses solely on developing culvert inventory data. Culverts are a particularly important class of subsurface water conveyance feature associated with LiDAR DEM conditioning.

4. SPECIFICATIONS

These culvert inventory guidelines are composed of five specification parts:

- Feature representation
- Feature descriptions and domains
- Positional accuracy
- Acquisition methods
- Completeness and maintenance

4a. FEATURE REPRESENTATION

Any water conveyance feature (culvert) data collected should be consistent with the applicable elements of the Minnesota Standard for Digital Stormwater System Data Exchange (SDSSDE).[3]

Features inventoried in the field should be represented as points in a spatial dataset. If post-processing back in the office is possible, line features representing culvert pipes should be developed from the points. This is because Global Positioning Systems (GPS) is the primary means of recording field locations, and capturing line features in the field is more difficult and cumbersome than capturing points alone.

- The Point feature dataset:
    - Should include both inlets and outlets

- The Line feature dataset:
    - Should represent pipes that connect inlets and outlets
    - Should be digitized (or created) from upstream to downstream to indicate direction of flow (if known)
    - Should NOT include other feature types from the SDSSDE because they are not applicable to a culvert inventory:
        - channels
        - artificial paths
        - constructed basins
        - other stormwater devices (aside from inlet/outlet)
        - natural water features

4b. FEATURE DESCRIPTIONS AND DOMAINS

The requirements for feature descriptions and domains will vary somewhat according to the primary intended application. Table 1 below defines an attribute template to use when creating a culvert spatial dataset. Field names and attributes will allow integration with the SDSSDE.

Point features collected in the field should have attributes entered while on site. Note the fields required for detailed hydraulic and hydrologic modeling.

[3] http://www.mngeo.state.mn.us/committee/standards/stormwater/stormwater_standard.html

Table 1 – Attribution Template

Field	Name	Description	Data Type	Length / Precision	Scale	Domain	H&H Use[4]
ID	PIPE_ID	Unique identifier	Text	20			N
Quantity	QUANTITY	Pipes working as one at crossing / location	Number	3	0	>0	Y
Flow End	US_DS	Upstream or Downstream End	Text	4		US, DS	Y
Pipe Type	TYPE	Pipe material and shape	Text	6		CMP, CMPA, SMP, RCP, RCPA, CBOX, WBOX, MBOX, SPP, CPP, Span-Bridge, other	Y
Span	SIZE_SPAN	Length of Span (width)	Text	6		>0 (indicate units of measure)	Y
Rise	SIZE_RISE	Length of Rise (height)	Text	6		>0 (indicate units of measure)	Y
Pipe Length	LENGTH	Length of pipe	Number	6	0	*GIS Derived length in feet	Y
End Type	END_TYPE	Type of End Section	Text	12		none, apron, trap, wing-wall, other	Y
Restrictor	RESTRICTOR	Presence of a man-made flow restrictor	Text	3		No, Yes *if 'Yes', describe in comments	Y
Invert Elevation US	ELEV_US	Upstream Invert Elevation	Number	8	2	*GPS captured elevation in feet (NAVD 88)	Y
Invert Elevation DS	ELEV_DS	Downstream Invert Elevation	Number	8	2	*GPS captured elevation in feet (NAVD 88)	Y
Comments	COMMENTS	Surveyor comments	Text	250			Y
Horizontal Accuracy	HPA	Horizontal Positional Accuracy	Text	10		<0.5m, 0.5-3m, 3-9m, >9m	Y
Vertical Accuracy	VPA	Vertical Positional Accuracy	Text	10		<0.03m, 0.03-1m, >1m	Y
Survey Date	DATE	*GPS timestamp, yyyymmdd	Date	8		yyyymmdd	Y
Surveyor	SURVEYOR	Name of surveying entity/agent	Text	30			N
Ownership Type	OWN_TYPE	Type of entity owning the pipe	Text	30		private, state, county, city, township, other	N
Ownership Name	OWN_NAME	Name of entity owning the pipe	Text	30			N
Maintenance Type	MAINT_TYPE	Type of entity maintaining the pipe	Text	30		private, state, county, city, township, other	N
Maintenance Name	MAINT_NAME	Name of entity maintaining the pipe	Text	30			N
Hyperlink	HYPERLINK	Hyperlink location of photo, schematic, etc.	Text	300			Y

[4] H&H Use = Detailed hydraulic and hydrologic modeling use

4c. POSITIONAL ACCURACY

Positional accuracy is defined by the location of an object both horizontally (X and Y axis) and vertically (Z axis). Positional accuracy of culvert locations should be consistent with the desired use(s) of the data. It is also important to use and store the data in a known horizontal coordinate system (user or location defined) and vertical datum (NAVD 88).

Two examples of positional accuracy are described below:

- A minimal level of accuracy for stream and watershed delineation projects, and
- A more stringent accuracy requirement for detailed hydrologic and hydraulic modeling projects

1. POSITIONAL ACCURACY FOR STREAM AND WATERSHED DELINEATION

Sub-meter accuracy of culvert locations is not an absolute requirement for this level of analysis. For example, a horizontal positional accuracy better than 1 meter will not improve analyses utilizing 3-meter DEMs. If 1-meter DEMs are the primary elevation data source, sub-meter positional accuracy of culverts may enhance stream and watershed delineation projects.

The recommended horizontal positional accuracy of culvert inventories for this level of analysis is 1-3 meters. This level of accuracy can be achieved using a mid-range GPS and software package capable of real-time and/or post-processed differential correction (e.g., Novatel, Sokkia, Trimble, Topcon).

* Recreation-grade GPSes (e.g., Delorme, Garmin, Lowrance, Tom-Toms, smartphones with GPS apps) are unable to capture highly accurate data, but can sometimes reach accuracies of 1-3 meters (3-10 feet), especially if the unit is WAAS-enabled. While use of recreation-grade GPSes is discouraged, if this type of hardware will be used, mission planning for peak satellite visibility and point averaging are advised to improve accuracy.

Vertical accuracy with recreation-grade GPSes is poor (>3 meter); this may be the deciding factor for the data collection method.

2. POSITIONAL ACCURACY FOR HYDROLOGIC AND HYDRAULIC MODELING

Detailed hydrologic and hydraulic modeling applications will require highly accurate horizontal and vertical elevation data for culverts. GPS accuracy requirements for hydrologic and hydraulic modeling are typically driven by the need for very accurate measurements of the invert elevations for culverts. This will typically require survey-grade GPS hardware using real-time kinematic (RTK) or post-processing; though some mid-range GPSes with post-processing software are capable of sub-meter accuracy.

The recommended horizontal and vertical accuracy of culvert inventories for this level of analysis is +/- 3 cm (0.1 ft).

4d. ACQUISITION METHODS

1. FIELD

The preferred method of conducting a culvert inventory is using a field-based survey, recording locations and attributes using GPS units. On-the-ground assessments will generally provide the most accurate data.

Field survey crews should collect GPS coordinates precisely at the inlet and outlet of each pipe (close to the barrel; not on the end of the apron). An aerial photo reference either as a background on the GPS or printed and carried along is recommended.

If the subsurface water conveyance at a particular road crossing is composed of multiple pipes, the inlet and outlet for each pipe should be recorded, as well as the other attribute information described in section 3.

GPS data should be differentially corrected, thus a mid- or survey-grade GPS is required (see section 4c).

2. OFFICE

While field-based data collection will generally be more accurate, field methods do have limitations. First, they are more time-intensive, therefore more costly. Second, while culverts along public roads can be easily accessed, there are many culverts located on private property that may also be important to include in a comprehensive inventory. Securing permission to inventory culverts on private land will also be more time-consuming (and thus costly) than those located along public roads.

In some instances an office-based inventory may be a cost-effective complement to field-based inventory. An office-based inventory can use highway construction plans, LiDAR-derived images and rasters (hillshade rasters, topographic position index (TPI) rasters, high-resolution digital aerial imagery) in a GIS, or an individual's firsthand knowledge. It should be noted that such inventories can only be used to derive positional information, not detailed attributes such as pipe size, pipe shape, and invert elevations (except in the case of construction plans). Reasonable uses of this office method would include:

- as a precursor to a field inventory to assess the scope of work required
- to inventory culvert features that cannot be readily accessed

Office-based methods will require careful heads-up digitizing of culvert inlet and outlet point features:

- Scale (zoom level) should be appropriate to ensure point placement falls within intended cells on the DEM

- Inlet points should typically be located in the deepest point (cell) of the upstream depression
- Outlet points should typically be located in the closest cell on the other side of the digital dam that has a lower elevation than the inlet point (Poppenga et al. 2010)

The accuracy of point data created using office-based methods will be dependent upon the accuracy of the remote sensing data used to digitize the locations of culverts. Minnesota's standard 3-meter LiDAR DEM product meets or exceeds an accuracy of <1 meter (95% CI). Recent high-resolution imagery datasets for Minnesota meet or exceed an accuracy of <3 meters (95% CI).

4e. COMPLETENESS and MAINTENANCE

Acquiring complete and accurate culvert data is a considerable challenge. Culverts occur not only under public roadways such as state, county, or township roads, but frequently under rural residential driveways, farm field roads, field approaches, and railways (to name just a few other categories). Experience has shown that culvert inventories typically capture only the information important to a respective local government unit (LGU) business need. For example, a county may only be interested in flow through culverts perpendicular to a county highway, while a township may be interested in culverts parallel to the county highway and perpendicular to the township road they manage. Therefore, coordinated inventory design and responsibilities between the different surveying entities (e.g., LGU's, consulting firms) in a region should take place to insure a complete coverage of the area is made in a cost effective manner.

Once the inventory is created, it is essential that a sustainable maintenance plan is developed and followed to help ensure the continued accuracy of the database. Updates should include culvert replacements, additions, and removals.

5. CULVERT INVENTORY and LiDAR APPLICATIONS for VALIDATION

The statewide LiDAR collect has expedited the need for a complete culvert inventory throughout the state. Once the culvert inventory is collected, the ability to enhance the LiDAR data for hydrologic applications as well as confirm the completeness of the initial inventory can take place. After modifying the original LiDAR DEM with the initial culvert inventory, various GIS analyses can be performed on the conditioned DEM for culvert location validation:

- Compare DEM-derived flow lines to real world watercourse locations and aerial photography.
- Compare original DEM surface to conditioned-DEM surface after filling sinks.
- Review GIS-derived sinks with real world depressions in the landscape.
- Compare GIS-derived subwatershed boundaries to known boundaries.
- Identify potential locations for un-inventoried culverts.

Suspect areas identified in the DEM can be field verified and a subsequent DEM conditioning process can be initiated to refine the hydrologic performance of the LiDAR DEM. This iterative process results in a robust and useable hydrologically conditioned LiDAR-derived DEM.

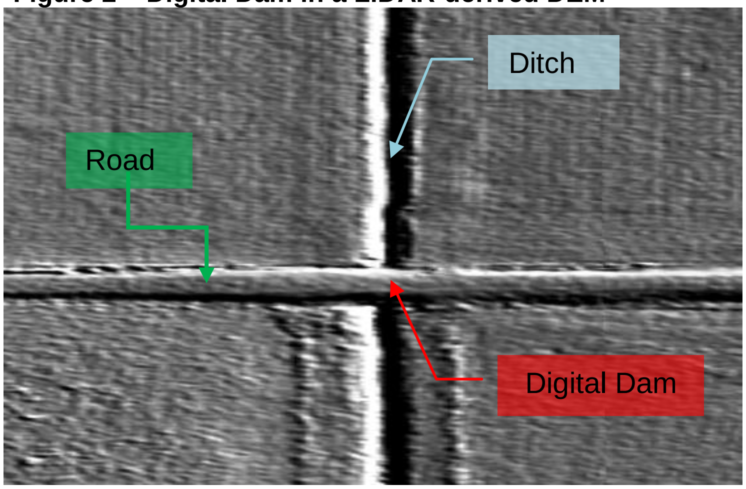
6. DEFINITIONS

Culvert - A structure used to convey surface water flow through embankments, such as roads, driveways, dikes, railroads etc.

Digital Elevation Model (DEM) - A digital file consisting of terrain elevations evenly spaced in a continuous gridded plane representing a mapped surface. Colors applied to the various elevation values and other data symbolization techniques give the DEM a depth perspective resulting in a 3-dimensional visual effect of the earth's surface. DEMs, also known as rasters and grids, can be used as background displays for other data, manipulated for three dimensional effects, and used for computations.

Digital Dam – LiDAR-captured features on the landscape that impede the modeled flow of water within a DEM such as bridges, roads and other structures that block predicted waterflow across a DEM.

Figure 2 – Digital Dam in a LiDAR-derived DEM



Hydrologic Conditioning - Hydrologic conditioning is the process of modifying the elevation values in a DEM through raster processing and or interpolation to make the DEM more suitable for most hydrologic analyses. The modification process typically involves breeching digital dams (lowering the outlet) and elevating user-selected sinks to ensure that water flow paths are accurately represented in the conditioned DEM. Hydrologic conditioning is sometimes referred to as hydrologic correction; however, the LiDAR Research and Education Subcommittee of the Minnesota Digital Elevation Committee has indicated that "hydrologic conditioning" is the preferred term for this type of DEM modification.

Invert Elevation - Invert elevation is the elevation at the bottom of a conveyance structure at which flow will begin to occur.

LiDAR - "Light Detection and Ranging”. LiDAR is a three-dimensional laser scan that provides high definition surveying of the landscape. In most instances the system is used to collect high-definition elevation data. There are many permutations of LiDAR equipment, software, collection parameters, and data processing, thus there are many variations of LiDAR products.

Sink - Sinks are cells within a DEM that have a low elevation relative to surrounding cells.

7. REFERENCES

Poppenga, S.K, B.B. Worstell, J.M. Stoker, and S.K. Greenlee. 2010. Using Selective Drainage Methods to Extract Continuous Surface Flow from 1-Meter LiDAR-Derived Digital Elevation Data. U.S. Geological Survey Scientific Investigation Report 2010-5059. 12 pp. http://pubs.usgs.gov/sir/2010/5059/

Hutchinson M.F. (1989) A new procedure for Gridding Elevation and Stream Line Data with Automatic Removal of Spurious Pits. *Journal of Hydrology* **106**, 211-232.

Hutchinson M.F. and Gallant J.C. (2000) Digital Elevation Models and Representation of Terrain Shape. In 'Terrain Analysis'. (Eds. JP Wilson and JC Gallant) pp. 51-85. John Wiley & Sons, Inc.: New York.

Maidment, D.R. (2002) Arc Hydro: GIS for Water Resources. ESRI Press. Redlands, CA. 224 pages.