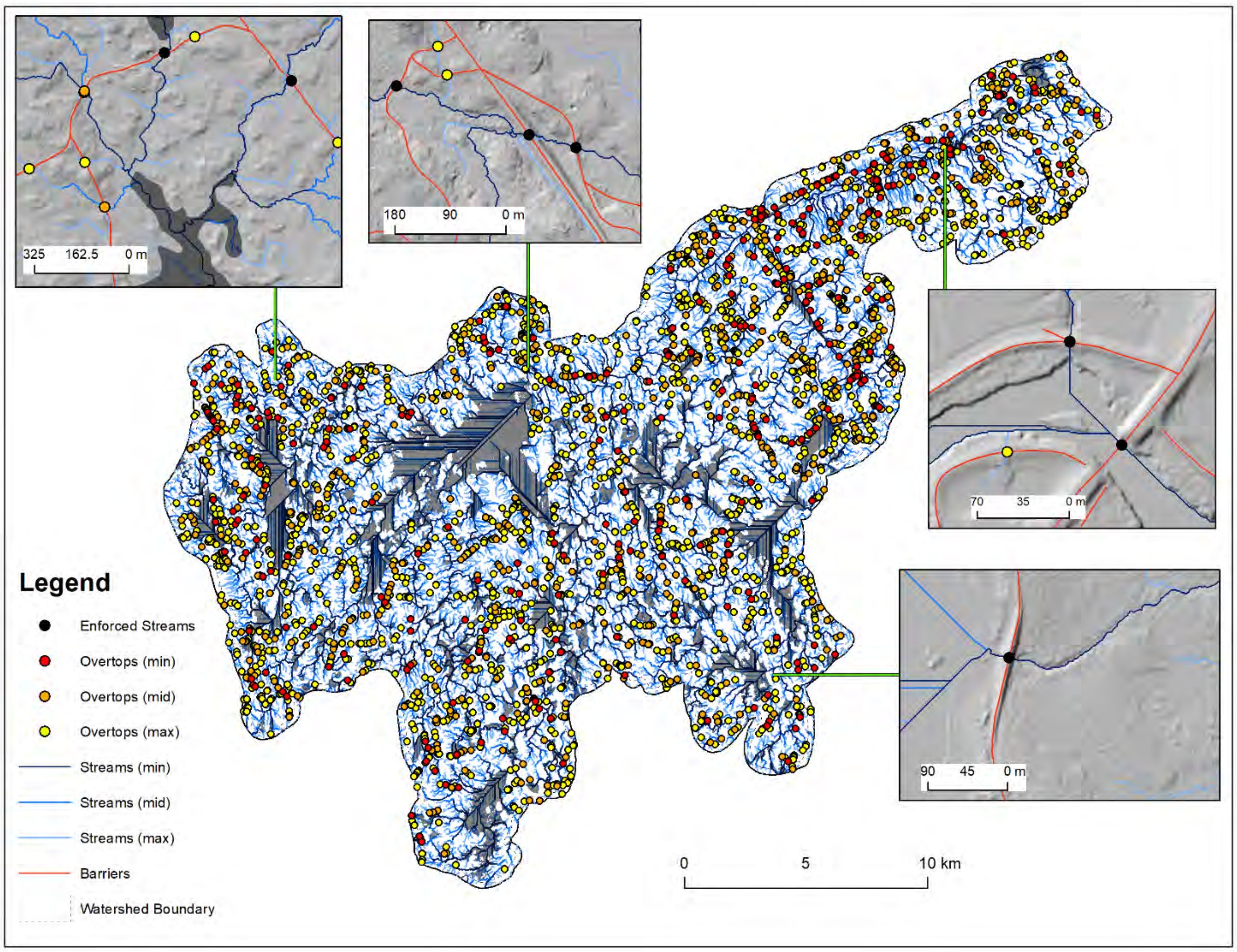
Analysis of Lidar Data for Improved Flood Risk Mapping:

Methods to Construct Hydrologically Correct Lidar Elevation Models for Flood Risk Modelling, Report 2/2.



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Executive Summary

The province of Nova Scotia has recently been surveyed with airborne topographic lidar. The lidar point clouds have been minimally classified into ground, water and non-ground. Lidar grids have been constructed in the form of raw bare-earth Digital Elevation Models (DEMs), all legitimate points as Digital Surface Models (DEMs), the lidar Intensity of the DSM, and a hydro-flattered DEM. The DSM was subtracted from the DEM to form a normalized height model, referred to as a Canopy Height Model (CHM). Although these data have many uses for several practical applications, they are currently limited for use in flood risk assessment and flood line mapping. This project examined how the lidar DEMs for the Gaspereau watershed can be used in conjunction with other provincial mapping data, mainly the Hydrographic Network (NSHN) and Topographic Database (NSTDB) for streams, roads, and culverts and bridges, to produce more accurate hydro-enforced DEMs. These hydro-enforced DEMs can then be used with GIS tools to conduct hydrological analysis resulting in flow direction and flow accumulation grids which can be used to derive a synthetic stream network. The resultant stream network and watershed can then be used for additional hydrologic and hydraulic modelling required for flood line mapping studies. The high resolution of lidar causes roads and other features to appear as barriers in the terrain that can obstruct the flow of water along valleys where streams are located. The process of hydro-enforcing a DEM involved mapping these intersections of streams and roads and constructing a synthetic culvert or bridge that was used to “burn” or notch the DEM to allow water to flow through the road. Once the DEM is conditioned the hydrologic GIS tools were then executed to calculate new stream locations. In this report we separated these procedures into three different levels of effort, that resulted in three levels of hydro-enforced DEM accuracies: Minimum, Mid-level, and High. The highest accuracy is achieved with the highest level of effort and processing time. We concluded that the Minimum accuracy was relatively easily achieved using existing provincial stream and road layers and produce a significantly improved hydro-enforced DEM and stream network. The Mid-level enhanced this by calculating areas of sinks and pools where culverts probably exist but are not mapped. The highest level of accuracy was achieved through automated tools to identify areas where the stream will breach the road if no culvert exists. We found this level of effort to achieve the highest accuracy came with diminishing returns and the computational time was significant. Care was taken to measure the time and effort involved at each step and accuracy level for the Gaspereau watershed. These results were then extrapolated to the provincial scale to attempt to quantify the level of effort required to produce hydro-enforce DEMs.

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1 Introduction

1.1 Project Background

Given the high accuracy, spatial precision, and availability of topographic lidar data, it is not surprising it is the gold standard data source for generating precise and accurate DEMs for hydrological models from the scale of individual neighbors to entire watersheds. These models are used for conducting overland flood risk analysis, contaminant mapping, storm water infrastructure assessment, watershed delineation among others. Basically, lidar data is preferred for any analysis where detailed and accurate mapping of the overland flow of water is required. To best utilize the accuracy of the lidar data in this manner, it is critical to account for all infrastructure such as dams, culverts, bridges, etc. appropriately which effect the computed pathway of water at the accuracy of lidar data (which typically has a spatial resolution of 0.5 m – 2 m and vertical accuracy between 5-15 cm in cleared areas). Generally, to account for these types of infrastructure in this manner, they are identified and simply 'burned' into the elevation raster such that the simulated flow can pass appropriately across a road, or overpass for example which would otherwise provide a barrier to the simulated flow of water and thus adversely affect the modelled direction of the flow of water. This approach was discussed for coastal applications using lidar DEMs by Webster et al. (2004) and then implemented more extensively in a larger coastal flood assessment study (Webster et al. 2006a) where the DEM was modified to allow free connection of elevated coastal waters in low lying inland areas. Webster et al. (2006b) described "notching" the DEM where culverts exist to properly construct watershed boundaries and the stream network from a lidar DEM. Furthermore, in some instances errors in the lidar or discrepancies in water elevations across multiple lidar collections may create obstructions to flow which may have to be accounted for in even natural environments. However, most significant obstructions to flow in this manner occur around man-made structures. With the province of Nova Scotia now having complete topographic lidar coverage and beginning to issue flood risk mapping projects for municipalities, potential improvements to the basic delivered lidar products to the province was the focus of this study.

1.2 Purpose of This Study

This portion of the study was undertaken to answer the following questions:

- What methodology should be used to hydrologically correct the provincial lidar DEMs using the existing provincial data?

- What inputs are required for a highly accurate Hydro Enforced DEM? Does the province have sufficient data, or what additional data needs to be collected? What are the costs for this version, and how much time is required?
- What inputs are required for a mid-level accuracy Hydro Enforced DEM? Does the province have sufficient data, or what additional data needs to be collected? What are the costs for this version, and how much time is required?
- What are the minimum data input requirements for a Hydro Enforced DEM? Does the province currently have sufficient data to do this? What are the costs for this version, and how much time is required?
- What additional techniques can be used to understand hydraulic barriers if no mapping data exists for them?
- Estimate of costs and how long it would take to do the entire province if we chose High/Mid/Low Accuracy Hydro Enforced DEMs.
- The Gaspereau Watershed was selected as our test case to address these issues.

1.3 Hydrological Analysis

To understand the importance of hydrological enforcement (hydro-enforcement) regarding lidar elevation data, one must first understand the mechanisms of standard hydrological analysis. The basic procedure for computing an accurate stream vector or watershed boundary from lidar or other elevation data is based on a simple flow direction calculation (Figure 1.1). This direction is derived directly from the slope direction of the elevation data within a given raster cell. Typically, flow directions coded with a simple cardinal direction (D8) (Jenson and Dominque,1988; Costa-Cabral and Burges, 1994). To compute streams from a DEM, the flow is accumulated across the raster domain by tallying up the flow direction cells. In a flow accumulation grid, each given cell is assigned a value representing the total combined number of grids cells which cumulatively drain into it. The flow accumulation values increase monotonically toward the final watershed outlet at the main river branch. The flow accumulation raster can then simply be used with an accumulation area threshold and stream networks can be vectorized directly. Watershed boundaries can then be computed as the full extent of all raster cells which cumulatively drain via their flow direction toward a given stream location such as the outlet of a given river.

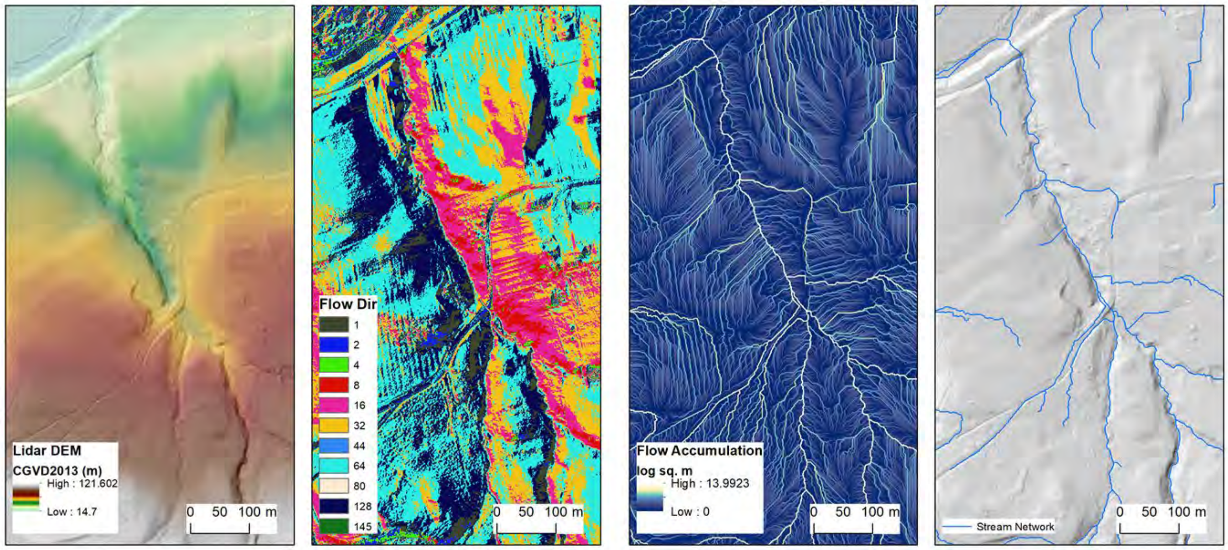


Figure 1.1 The basic procedure of a lidar digital elevation model (DEM) based hydrological analysis. From left to right: A example one- meter lidar DEM colorized by elevation and shaded by a sun angle from the northwest. The flow direction grid calculated from lidar DEM. The flow accumulation grid showing the drainage area from the flow direction gird. The resulting stream network from the flow accumulation grid overlaid a shaded relief lidar DEM.

1.4 Understanding Hydro Enforcement

The fundamental assumption when conducting flow accumulation calculations is that all flow directions converge toward the outlet correctly for tributaries and the main stem of the river. If a flow direction raster contains local *sink* areas where flow is only directed inward, the subsequent flow accumulation raster will resolve each local sink and result in stream vectors terminating there (Figure 1.2). The existence of local sinks, which are exceedingly common in high resolution lidar data, have a catastrophic effect when conducting hydrological analysis. The standard method to counteract the effect of sinks is to identify the full extent of these local depressions and simply fill the area with an overtopping elevation. This simple hydro-enforcement technique is highly effective at resolving small inconsequential depressions such as those that commonly manifest in the rough elevations found in lidar DEMs of forested areas. Were more significant depressions do exist however, the filling technique can have a deleterious effect on the accuracy of the resulting stream vector calculation due to the flattening and loss of local elevation information (Figure 1.2). In some cases, the resulting stream vector may escape larger depressions in the wrong location and result in significant discrepancies for both the watershed area and stream locations. Typically, the most critical of such depressions exist at the intersection of roads and streams where some culvert, bridge or other structure directs the water under the structure but is not visible to the lidar (Figure 1.2). As such, to maintain a high accuracy of hydrological analysis from the lidar DEM, it is critical that flow altering structures are accounted for so that significant filling can be avoided during the generation of hydrological products.

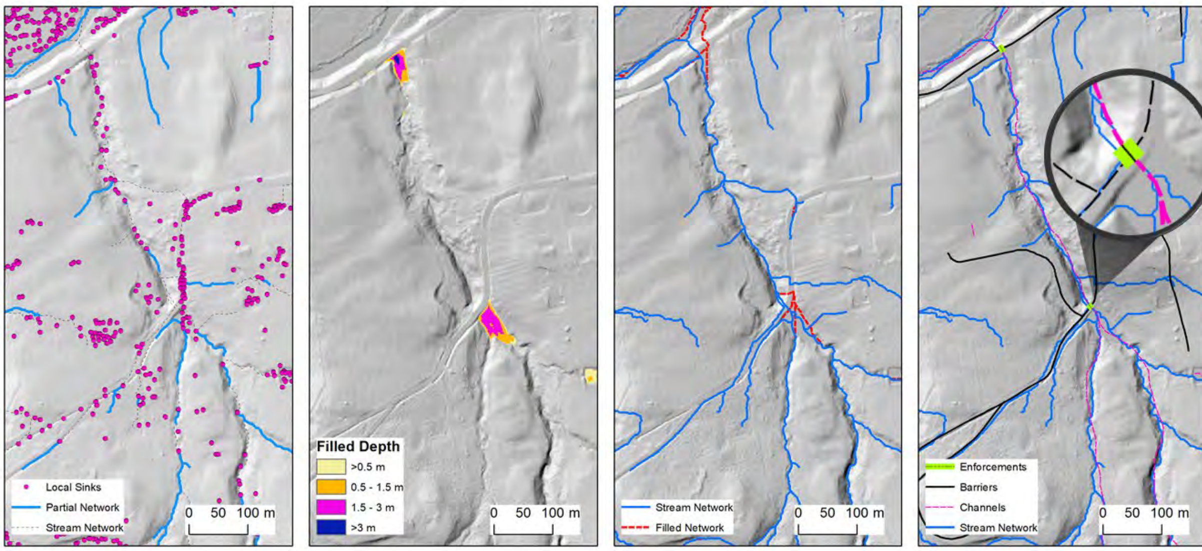


Figure 1.2 Various hydro-enforcement features and techniques and their effect on hydrological analysis. From left to right. Local sinks (pink) if left unfilled terminate any modelled stream vectors (blue). Filled sink depressions (yellow-blue) enforces the flow but affects the stream accuracy. The resultant streams (red lines) for these cases are not accurate at these large depressions. Identified critical infrastructure (culvert location in green) is key to avoiding extensive filling and the production of an accurate hydro enforced DEM.

1.5 Advanced Hydro Enforcement Techniques

The most efficient and ideal method for hydro-enforcing a lidar DEM is to directly burn-in the required flow structure lines from an extensive and spatially accurate set of known locations. If sufficiently accurate data exist, such as road and stream vectors, flow structures can be inferred from the stream vectors where they cross the road, and where a buffer distance can be applied to capture that section of stream.

When such data are absent or are insufficient, manual interpretation of such structure locations can be conducted to generate similar data for hydro-enforcement. This analysis can be supported by any available information or data such as aerial photography and by interpreting the relief of the lidar data itself. This process can be supported by iteratively computing a complete hydrological analysis and observing areas of significant filling. When considering computational time, these techniques may help target efforts for digitizing features where the greatest hydro-enforcement impact can be made, which is often for large tributaries and the main stem of the river.

A third more computationally intensive option for hydro-enforcement, which can be quite effective, is to model the precise location of missing flow structures directly from the lidar data. This can be done using a least-cost type analysis where the path of least resistance downslope is computed to enforce flow pathways across topographic highs. Alternatively, simply by extending local sink locations to a nearby lower raster cell within some tolerable distance is also an effective alternative. However, both these techniques can create havoc in certain instances depending on the complexity of the flow structures involved and are certainly not a replacement for quality vector data of known flow pathways.

In the strictest sense, the *fill* operation described above is the standard technique for ensuring the hydrologic flow is enforced and is generally always executed to ensure all small local sinks are filled to ensure continuous flow. As such, all the described breaching and burning enforcement techniques are typically followed by a filling operation to check for completeness and elevation continuity. The absolute elevation value used to burn these features into the DEM needs to be lower than the value resulting from the fill and lower than the lidar elevation at the downstream outlet of the feature.

1.6 Minimizing Hydro-enforcement Impact

The key to accurately modelling stream vectors with lidar elevation data is to balance: (1) limiting the impact of the fill operation by hydro-enforcing known flow pathways, and (2) limiting the extent of hydro-enforcement modifications to the lidar.

The purpose of using lidar to model the stream networks is to either capture river state at the time of the lidar collection, or to generate a new and more accurate stream network vector. In either case, if the lidar DEM is enforced too extensively it can have a counter productive impact on the hydrological analysis. Therefore, it is a best practice to restrict hydro-enforcement from existing vectors to limit this impact. For example, enforcing a complete river vector could create a long-flattened pathway in which a significant length of adjoining cells would be forced to be accumulated into flattened areas. When short lines are used as enforcements, however, their flat pathways have a restricted effect. In fact, if multiple enforcements from various sources with slight spatial misalignments are used to represent a given culvert, the resulting hydrological analysis will be minimally impacted as the main branch of accumulated flow will simply follow the enforcement line nearest or with the lowest flattened fill height.

1.7 Definitions

This report will cover a variety of topics from different perspectives. For the purposes of clarity in this report, the following definitions related to hydrologic features will be adhered to:

1.7.1 Pools

- Local depressions or areas within a lidar elevation model which would be filled during hydro-conditioning (i.e. sink filling). It is assumed that because these areas were not observed to be inundated with water during the lidar survey that some drainage feature or pathway exists that was not adequately observed by the lidar such as a culvert.

1.7.2 Enforcements

- Line features generated by users, automation, or other source which are used to modify lidar elevations to enforce drainage along a given path. *Examples: culverts, ditch, or other flow structures.*

1.7.3 Streams

- Lines representing continuous flow pathways derived from hydrological analysis of lidar elevation data where a modelled accumulation of drainage has reached some threshold.

1.7.4 Overtops

- Locations where a modelled accumulation of drainage representing a significant area (*streams*) crosses a known road feature in a location where no hydro-enforcement was conducted. These locations often indicate an error or gap in data. For example, a lidar flow accumulation grid may indicate a large area drains across a road where no culvert is known to exist.

1.7.5 *Barriers*

- Line features which indicate a topographic high or discontinuity co-incident with lidar elevations which fully interrupts the otherwise continuous downward progression of a modelled or known drainage pathway. For example, the provincial dataset of roads, dams, dykes, etc.

1.7.6 Channels

- A continuous line feature representing the general location of a known drainage pathway. For example, the provincial hydrography network, culverts, river centerlines, etc.

1.7.7 Breaches

- The result of an automated hydro-enforcement process which forces flow pathways to escape local depressions within an elevation model.

1.8 Hydro-Enforcement Process and Tools

A significant effort was put forth to test various techniques and to establish various workflows to recommend best practices for conducting hydro-enforcement at various accuracy levels. Note that all the toolsets described below also include the standard D-8 tools required for conducting a typical hydrological analysis (Flow Direction, Flow Accumulation, Stream to Feature, Watershed Delineation).

1.8.1 Spatial Analyst ArcGIS

A standard suite of relevant hydrological processing tools can be accessed with an additional Spatial Analyst licence from ArcGIS. This will give access to the Hydrology Toolset which can be used in various ways to conduct the following operations:

1.8.1.1 Detect Sinks

In the context of hydro-enforcement and hydro-conditioning, sinks are any raster cell which all neighboring cells flow into. These cells may include the lowest cell of a local depression, an isolated no-data cell, or the valid lowest edge of the raster dataset such as the mouth of a river. Detecting sinks is a straightforward and efficient raster computation available in all major hydrological analysis GIS toolsets. The identification of isolated sinks can provide insight into the required effort to properly hydro-condition a given DEM. A properly hydro-conditioned DEM should contain no sinks within the interior of the dataset as they would terminate the computed flow and thus restrict portions of a watershed from properly reaching the mouth of the river. In certain high accuracy situations, local isolated sinks may be specifically re-enforced where storm drains exist, and these structures correctly terminate the flow water. These types of structures must be considered in a highly developed and urban landscapes where such features artificially alter the surface flow of water. We did not consider these structures in this analysis.

1.8.1.2 Fill Sinks

Once sinks have been identified, the associated localized depressions may be filled iteratively with a fill sink algorithm which results in a flattened area on the DEM such that simulated flow will escape the area of the local depression. This technique is standard for hydro-conditioning, requires a medium level of processing time, and is available in all major hydrological GIS packages. While this technique will enforce that modelled flow escape and no supplementary information is required. However, this method does not ensure that the correct pathway is maintained as the water will simply overtop the filled localized depression, known as the spill point, and continue to the lowest elevation of the DEM**.** This is a fundamental technique for hydro-enforcement and underpins much of the analysis conducted in this report.

1.8.1.3 Fill Difference

To further analyze that character or impact of a *Fill Sinks* operation, it is useful to conduct a simple raster subtraction with the original DEM such that the filled area is computed. This simple operation provides a great deal of visual and analytical insight into the state of the DEM with respect to hydro-conditioning. For example, the size and depth of the resulting raster *pools* can be used directly to assess the overall level of hydro-enforcement required for the DEM. Furthermore, each pool can form the basis of a location where a given structure, such as a culvert, must be enforced and maybe missing from supplementary vector data.

1.8.1.4 Fill Burn

This approach represents the most basic attempt to enforce the correct hydrological pathways in the DEM based on supplementary vector data. In this technique, known stream vectors are *burned* into the DEM by a vector to raster process. The elevation of the streams may be set to some constant low value, or the stream raster may be computed to be a constant offset from the DEM elevations. If the spatial quality of the stream vector is poor relative to the DEM, the impact on the resulting accuracy of the hydro-conditioning can be significant and erroneous. If these burned segments do not reach the outer extent of the DEM, a *Fill Sinks* operation must be executed to ensure the flow continues along the length of the burned stream raster.

1.8.2 WhiteboxTools

WhiteboxTools is an Open Source and freely available geospatial software package developed by Dr. John Lindsay with assistance from the research commercialization program at the University of Guelph (WhiteboxTools Geospatial Inc., 2022). In addition to the general capabilities as the ArcGIS hydrologic toolset, Whitebox Tools contains some specific and robust hydro-enforcement routines which are listed below.

1.8.2.1 Burn Streams at Roads

Generally used to conduct a *Fill Burn* with minimum impact from lower accuracy vector data. For example, the channel location used to burn the stream may be restricted and only utilized in areas of significant barriers to flow such as the road-stream intersections (such as culverts or bridges) or at key complex infrastructure like pipes, flumes, or spill ways. Note that once a DEM has been *burned* in this way, a *Fill Sinks* is required to ensure flow continues through the burned segments. This technique exists explicitly in the WhiteboxTools Hydrological Analysis toolset but can be simulated in ArcGIS using a series of vector/raster tools.

1.8.2.2 Breach Depressions Least Cost

The Breach Depressions Least Cost tool (BDLC) offers a lower impact, computationally intensive alternative to the hydro-enforcement method to fill sinks. The BDLC uses a least cost algorithm whereby the minimum elevation required to join a given sink to a nearby lower elevation cell is used. This algorithm can be set to operate with a limited search radius and a maximum allowable cost for the operation which is then followed by a standard fill operation to ensure complete hydro-enforcement (Lindsay and Dhun, 2015). This tool provides the basic methodology for achieving the highest accuracy hydro-enforcement results outlined in the methods of this report.

1.8.2.3 Breach Depressions

Breach depressions is a legacy tool with a similar conceptual operation to BDLC with potentially greater computational costs and produces less favorable output. The tool remains available in WhiteBoxTools, as an alternative over the BDLC in some instances (Lindsay, 2016)

1.8.3 Custom Implemented Tools

Researchers at AGRG have significant experience conducting hydro-enforcement type DEM conditioning for various partners and projects throughout the region (e.g. Webster, Ferris, McGuigan and Kodavati, 2021). As such several customized tools continue to be developed to assist in detecting flow obstructions accurately and efficiently to either hydro-enforce automatically or assist in manual interpretation and digitization of flow structures. Some of these tools include:

1.8.3.1 Nearest Lower

This method is a robust technique for breaching local depressions. It takes a simple and efficient raster-based approach and is easily modelled in ArcGIS. This method avoids costly iterations over a potentially large number of local depression points in favor of two focal statistic computations on the DEM, whereby the elevation value of a given pool is compared to elevation in the DEM for a set distance (Figure 1.3). These raster comparisons are aggregated in their overlap by the maximum height and again by the minimum height. The technique then exploits the efficiency of the *nearby* operation to join each pool to a maximum of two sets of nearby points (one possibility from each aggregate calculation). Any adjoined points that both lie within a single pool are discarded. The resulting tool provides a minor efficiency improvement over other possible techniques to breach pool barriers using only functions available in ArcGIS (Figure 1.3). Significant improvements to the overall efficiency can be obtained by converting the tool to a pure python environment. This approach is used extensively in the methods of this report to conduct semi-automatic enforcement detection that facilitated the requirements of the mid-level accuracy hydro-enforcement case.

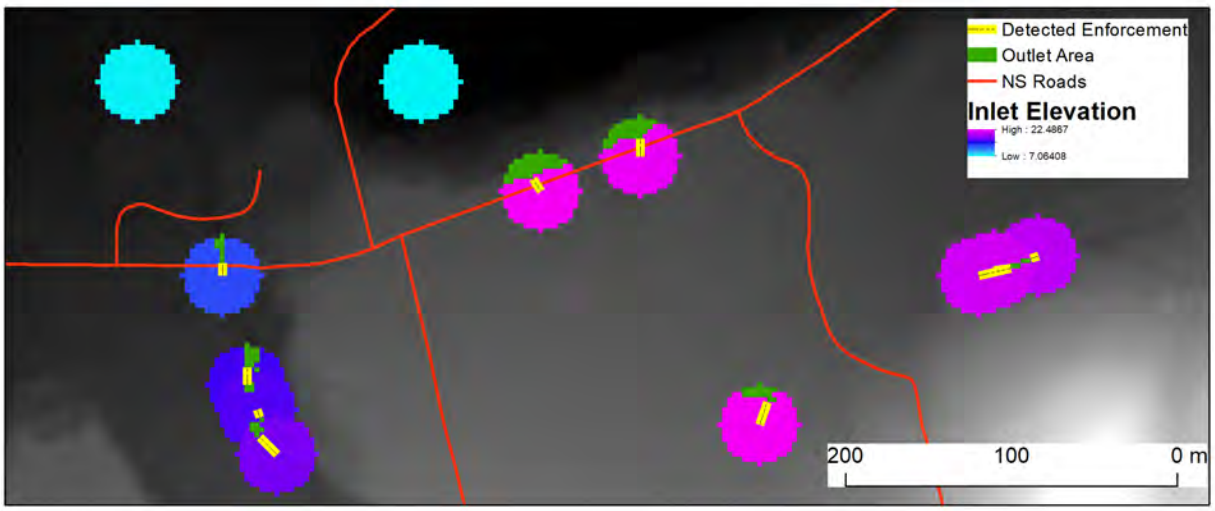


Figure 1.3 Example output from the custom enforcement (culvert) detection tool. Enforcement features identified as pools (center of circular buffer), where their elevation is compared to lowest neighboring DEM cells within 30 m (blue-pink elevation of the upstream buffer and green for downstream) a line feature (yellow) is constructed to the nearest lower cell.

1.8.3.2 Ditch Detection

Based on previous experience developing highly scrutinized drainage area products in the Halifax Regional Municipality Area, regions with a significant number of undocumented minor culverts, such as driveway culverts along ditches present a particular challenge to hydro-enforcement when striving for a maximum accuracy (Webster et al., 2021). Techniques were developed at AGRG to facilitate driveway culvert mapping by first vectorizing ditch structures along road features through a specially designed feature detection process utilizing the lidar DEM. These vectors were then joined to represent a significant number of new culverts. These data were delivered to the municipal water utility to update their culvert inventory and were inspected for quality assurance. This technique can be improved and perhaps can be used to contribute to updating the Nova Scotia Hydrographic Network to facilitate DEM hydro-enforcement to the highest level of accuracy. This technique was not used in the methods of this report but may play a significant role supporting rapid and effective culvert detection in the future, especially in urban areas with a high degree of impervious surface materials where ditch drainage plays a significant role.

1.8.3.3 Pool Characterization

Automatic flow obstruction and culvert detection can be more accurate when connecting only the lowest area of a given pool to nearby lower external areas (Figure 1.4). Furthermore, by observing the standard deviation of elevation within a given pool, certain pools can be considered critical or not during a manual quality assurance assessment of hydro-enforcement. These techniques were not directly used in the methods of this report.

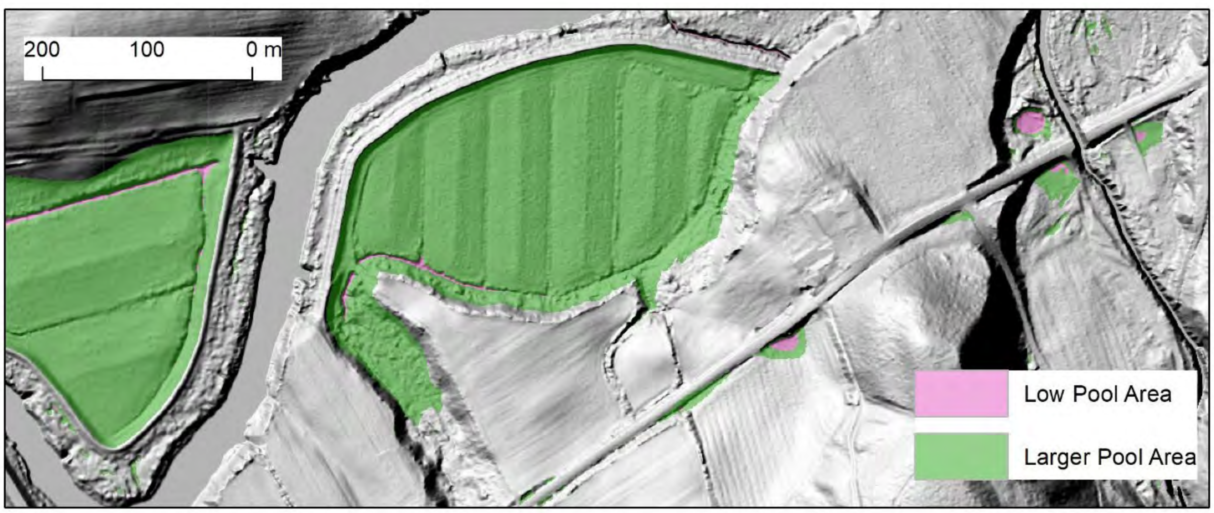


Figure 1.4 A section from the north-eastern portion of the Gaspereau watershed which contains some dyke structures. Possible pooling landward of the dyke is caused by the fill operation. The pool areas can be further subdivided based on the relative heights to better target a potential inlet location for a missing flow structure (e.g. aboiteau or culvert).

1.8.3.4 Snap Pour Points

Snap pour points is a tool that exists in the standard hydrological toolset for ArcGIS. Its intended use is to snap a user created point to a raster cell of maximum flow accumulation within a set distance to ensure that the proper drainage area is computed for a given outlet point. This tool provides an efficient method to compute a nearest conditional value. This tool can be exploited to increase the spatial accuracy of supplemental hydrographic vector data to best match the lidar. In the case of culverts, we can compute the end points of a culvert segment, negate the DEM (flip the elevations to negative), and snap each culvert endpoint to the 'lowest' elevation within a given tolerance distance (Figure 1.5). This technique shows great promise and can perhaps be used to increase the accuracy of the provincial culvert data relative to the provincial lidar data. However, care will need to be taken about setting the tolerance distance to ensure unintended consequences are avoided such as culvert outlets migrating too far down stream. This tool was not used in the methods of this report and requires additional testing.

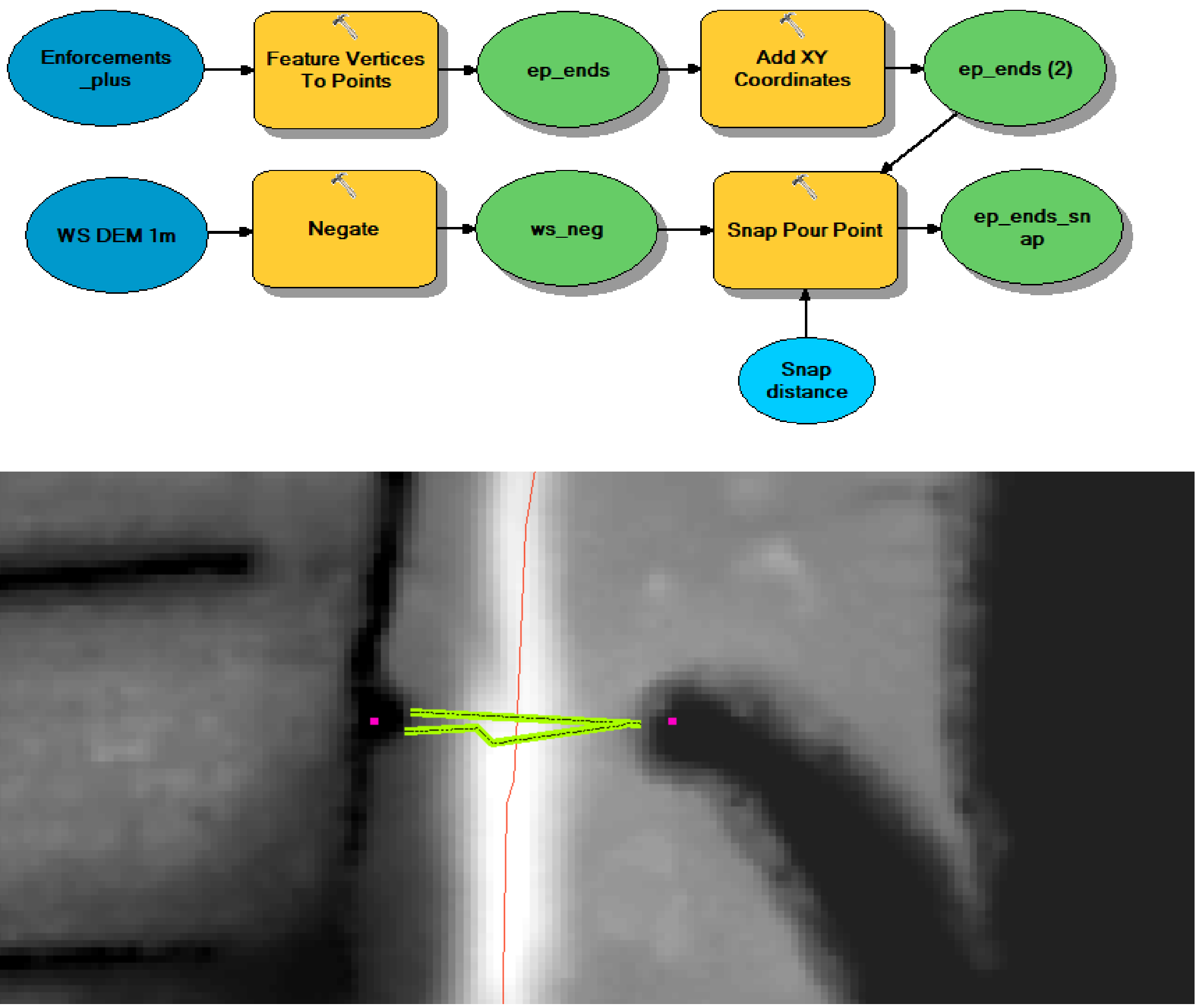


Figure 1.5 The figure demonstrates the snap pour point tool, where linear features representing culverts (green line) can be snapped to match points (pink) with the lidar elevation data. A simple model 'flips' the lidar DEM (above) and detects more accurate culvert points withing a tolerance distance.

1.8.3.5 Refine Streams

Based on the processing efficiency observed using the Snap Pour Points tool in ArcGIS, experiments were conducted adjusting the entire Nova Scotia Hydrographic Network to best match the lidar. Results are encouraging though counterproductive effects have been observed in some cases. This can certainly be explored further and perhaps a robust and efficient method to increase the accuracy of the stream network can be established based on this technique. For example, using the hydrographic network and applying the snapping operation iteratively results in preserving the overall shape of the stream and locating it in the lowest local valley more consistently (Figure 1.6). This tool requires further development and was not used in the methods of this report.

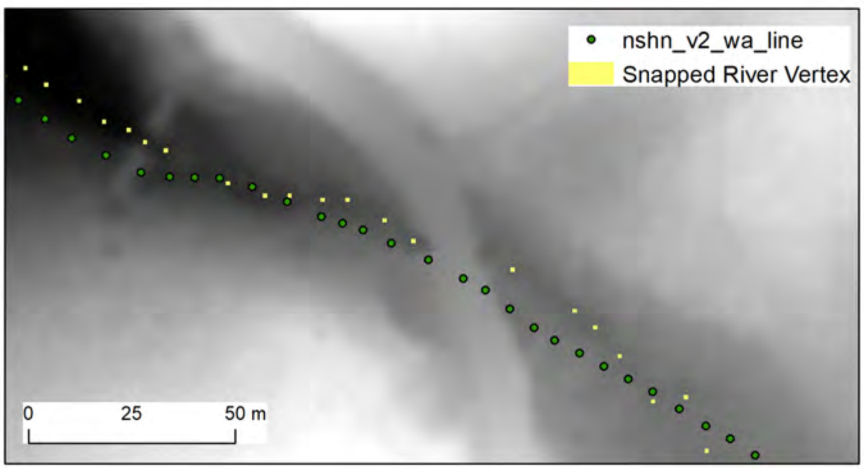


Figure 1.6 Snap pour point can be used to snap the entire river line (by vertex) to the local lowest lidar elevation.

1.8.3.6 Overtop Detection

Once a hydrologic analysis is conducted on a lidar DEM, a resulting river vector or flow accumulation raster can be overlaid with a roads layer to detect significant road overtopping calculated by the model. If these overtops are not at the location of known culverts, they can provide a powerful and systematic metric to conduct hydro-enforcement quality assurance and direct the user to areas of interest and probable culvert locations.

1.9 Levels of Hydro-Enforcement Accuracy

AGRG has developed three methods for hydro-enforcing the provincial lidar DEMs with High, Mid-level, and Minimum accuracy. Each method should utilize the most accurate and highest precision lidar data and provincial hydrographic and road data available. The ranging accuracy for each method comes directly from an increasing level of scrutiny required for the hydro-enforcement features (i.e., culvert locations). This can be accomplished by setting increasingly higher benchmarks for manual quality assurance, increased manual digitization of features, and with the addition of automated tools assisting in generating features. Specifically at each level, we measure the scale of impact from the sink filling operation and the number of new road feature intersections with modelled streams. To minimize the exponential increase in the frequency of these metrics with each level, we introduce semi-automated tools to assist in generating new culvert features at the medium-level, and a comprehensive hydro-enforcement technique for breaching depressions via a least cost function at the highest required accuracy. Even with these tools, the manual quality assurance time required for each level increases significantly.

When considering all levels of detail for hydro enforcement (High/Mid-level/Minimum) one needs to consider the relative impact of individual flow structures on the hydrologic network and not simply on the percentage of the total infrastructure being accounted for. For example, large infrastructure impacting significant areas in terms of flow such as bridges and overpasses crossing a major river must certainly be accounted for at all levels of accuracy, whereas less significant features such as individual driveway culverts may be omitted from lower accuracy analysis with minimal impact. On the local scale however, each individual culvert may play a role in the resulting modelled flow direction and should ideally be accounted for when conducting a highly accurate analysis such as flooding within a specific suburban area.

Through exploratory analysis of the Gaspereau watershed data, suitable threshold levels for the following hydro-enforcement quality assurance metrics were established and form the basis of differentiating the various requested levels of accuracy/effort (High/Mid/Min). To complete a hydro-enforcement of a given accuracy level, users should incorporate hydraulic features into the DEM through either manual digitization, or utilizing external sourced data and accompanying visual inspection, or fully automated modification using the criteria in Table 1.

Table 1. These metrics form the basis for achieving hydro-enforcement accuracy of Minimum, Mid-level, and High accuracy levels as outlined in the methods section of this report.

	Accuracy Level Tolerances		
	Minimum	Mid-level	High
Pool Depth (maximum)	< 3.0 m	< 1.5 m	< 0.5 m
Pool Area (>30 cm)	< 10,000 sq. m	< 1000 sq. m	< 50 sq. m
Overtop Drainage Area	< 150,000 sq. m	< 50,000 sq. m	< 10,000 sq. m

To achieve a Minimum accuracy hydro-enforcement product, pools which are less than 3 meters maximum depth and are less than 10,000 sq. meters in area do not need to be accounted for or inspected. Similarly, a properly hydro-enforced product with a Minimum accuracy can allow for stream features overtopping roads with a drainage area of less than 150,000 sq. meters. The magnitude of these metrics is designed to be consistent across levels of effort/accuracy (i.e. a few hundred instances for each minimum threshold, under a thousand for mid-level, and several thousand for high). It certainly is important regardless that quality assurance for hydro-enforcement be conducted with diligence as the complex nature of modelling these systems can pose unique and unforeseen challenges case by case.

1.10 Relevant Data

Key to the success of the proposed methods in this report rely on highly accurate and precise lidar data. These data should be under 2 metres in spatial resolution and preferably below 1 metre. This precision helps ensure adequate representation of key flow structure such as ditches leading to culverts. Ideally lidar data will be hydro-flattened, where the typical rough and noisy water surface elevations have been removed and made smooth or flat, as these features may significantly impact various hydro-enforcement routines such as sink filling operations. Lidar data should span the extents of a continuous watershed boundary to ensure an accurate hydrologic analysis is possible. Care must be taken when integrating variable lidar datasets (different years, different seasons, lidar systems, etc.) across a watershed to ensure internal continuity of the elevations.

With the vertical accuracy of the lidar, supplementary vector data for features such as culvert locations, roads and stream vectors need only be represented in two-dimensions. Note that road features can be used to generate additional enforcement vectors through their intersection with accurate river channel information. Roads are additionally used as a basis for the accuracy assessment of overtopping.

In terms the scope of this project, accurate hydro-flattened lidar DEMs at 1-metre resolution were used from the GeoNova Elevation Explorer website (https://nsgi.novascotia.ca/datalocator/elevation/).

2 Methods

A test case watershed was selected so that various approaches to DEM hydro-enforcement could be examined and tested in the context of High, Medium, and Minimum accuracies with regards to the level of effort required to process the entirety of the province in a similar manner. The watershed of the Gaspereau River (Kings County) was selected and a continuous lidar DEM (hydro-flattened) of 1 m spatial resolution was compiled from available provincial GeoNova lidar tiles such that the entirety of the watershed was represented.

To assess the state of the supplementary provincial data which are relevant to rapid and accurate hydro-enforcement (barriers, channels, etc.) a download of the complete set of available vector data from the GeoNova Geographic Data Directory was conducted and the data were inspected for the inclusion of relevant features. These features were identified, clipped to the extent of the Gaspereau Watershed, and integrated appropriately.

Following the provincial data assessment, hydro-enforcement was conducted on the 1 metre DEM of the Gaspereau watershed with a minimum, mid-level, and high level of accuracy.

2.1 Provincial Data Assessment

Of the data collected from the feature layers publicly available in the GeoNova Geographic Data Directory, the two main datasets deemed critical to assisting in hydro-enforcement analysis are the Nova Scotia Hydrographic Network (NSHN) and the Nova Scotia Topographic Database (NSTDB) layers (Table 2). Collectively these data were observed to contain highly accurate line features including the location of critical infrastructure relevant to hydro-enforcement including roads, stream networks, dam, dykes, etc. The Nova Scotia Road Network appears to be the most up to date source for roads, but the NSTDB road layer contains more flow obstructions compared to the NSCAF database (Table 2). Water features from the NSTDB appear to be of a similar or of a lesser quality to those contained in the NSHN.

Table 2. Vector data obtained from the GeoNova Geographic Data Directory

Name	Source	Published Date	Layer Names
Nova Scotia Road Network - Addressed Roads (NSCAF)	GeoNova	2022-03-21	TRNS_NSRN
Nova Scotia Hydrographic Network (NSHN)	GeoNova	2020-12-18	nshn_v2_wa_line **nshn_v2_wa_junc*
Nova Scotia Topographic Database - Water Features	GeoNova	2020-12-18	WA_LINE_10K
Nova Scotia Topographic Database - Roads, Trails and Rails	GeoNova	2020-12-18	RR_LINE_10K RR_ROAD_LINE_10K
Nova Scotia Topographic Database - Utilities	GeoNova	2020-12-18	UT_LINE_10K

Some data are generally useful for hydrologic analysis, such as approximate watershed boundaries, but they were not explicitly used in the methods of this report.

2.1.1 Nova Scotia Hydrographic Network (NSHN)

Each of the available data layers from the NSHN were observed individually for their utility in lidar hydro-enforcement.

2.1.1.1 Water Tables

Data contained specifically in the line features of the NSHN water tables can provide a great deal of use for a province wide hydro-enforcement analysis (Table 3). Key features are listed in Table 3 highlight line features to provide known enforcement locations (culverts, aboiteaux etc.) for ensuring the most correct flow paths are generated by the breaching analysis. This can be accomplished by intersecting known water features (streams) with flow impediments (roads, dams, dykes, etc.). It has been observed that the accuracy of the stream features contained in the NSHN is of a higher quality near visible features such as road intersections than in less visible areas such as the forest, which is understandable since the streams were interpreted from aerial photography. There are different examples of features that can act as barriers both correctly (Figure 2.1) and incorrectly (Figure 2.2). For the most part drainage of inland water accumulation near dykes is accomplished with one-way valves (aboiteau) to only allow flow to the ocean and not reverse flow. The drainage in other areas with dams can sometimes be very complicated (Figure 2.3)

Table 3. All feature codes from the Nova Scotia Hydrographic Network V2 (NSHN) which intersect the Gaspereau Watershed Study Area. Features are depicted as Channels or Barriers such that where they intersect Enforcements can be imposed in the elevation model.

Feature Code	Description	Channel	Enforcements	Barrier	N/A
WABD50	*Beaver Dam*			**X*	
WACA10	Canal (left)				X
WACA20	Canal (right)				X
WACA59	**Canal Spine**	**X**			
WACORV20	Coast River (right)				X
WACORV59	**Coast River Spine**	**X**			
WACORVF0	Coast River Delimiter				X
WADI50	**Ditch**	**X**			
WADM50	*Dam*			*X*	
WADM59	**Dam Spine**	**X**			
WADYL0	*Dyke (left)*			*X*	
WADYR0	*Dyke (right)*			*X*	
WAFI50	**Fish Ladder**	**X**			
WAFU10	Flume (left)				X
WAFU20	Flume (right)				X
WAFU59	**Flume Spine**	****X**	**X**		
WALK20	*Lake (right)*			**X*	
WALK59	**Lake Spine**	**X**			
WALKF0	Lake Delimiter				X
WALKIS10	Lake Island (left)				X
WARS20	*Reservoir (right)*			*X*	
WARS59	**Reservoir Spine**	**X**			
WARV10	Double Line River (left)				X
WARV20	Double Line River (right)				X
WARV50	**River**	**X**			
WARV55	**River - Indefinite**	**X**			
WARV56	**River - Underground**	**X**	**X**		
WARV59	**River Spine**	**X**			
WARVF0	*Double Line River Delimiter*			**X*	
WARVIS10	River Island (left)				X
WARVSP50	**River Split**	**X**			
WATOF0	Toponymic Object				
WAWH50	Wharf				

* Some included barrier may decreace accuracy of generated Enforcements

** insufficient Barrier data exists to generate minimal impact Enforcement segment

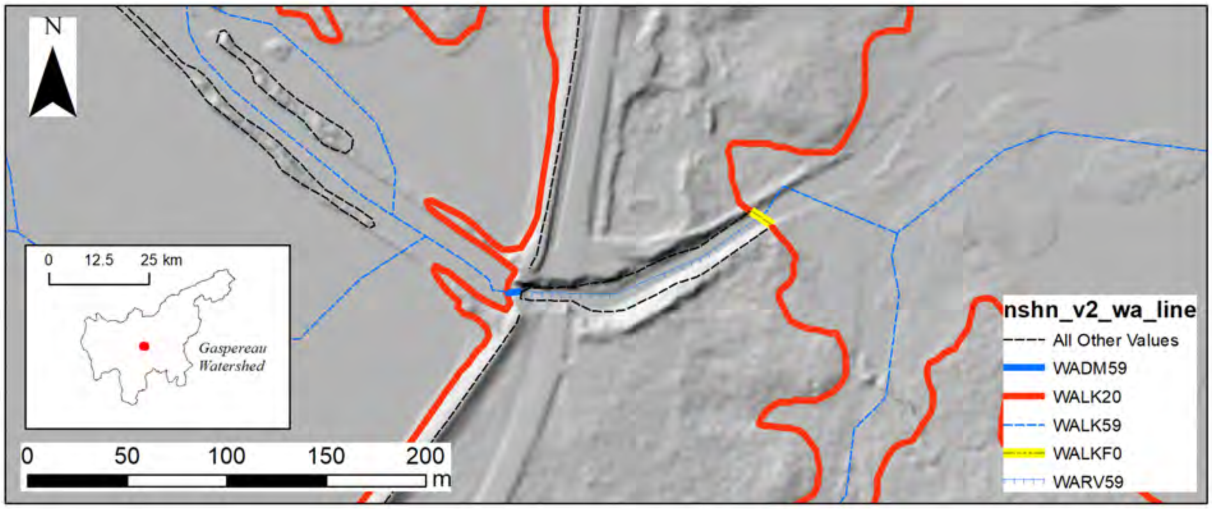


Figure 2.1 This figure shows Beaver Brook (Highway 12). Here we see that lake boundary (WALK20 in red) is depicted as a *Barrier*. This will ensure *Channel* features (blue) will be maintained where they intersect the lake features. Lake Delimiters (yellow) that do not act as *barriers* to imposing *Channel* features were unnecessary.

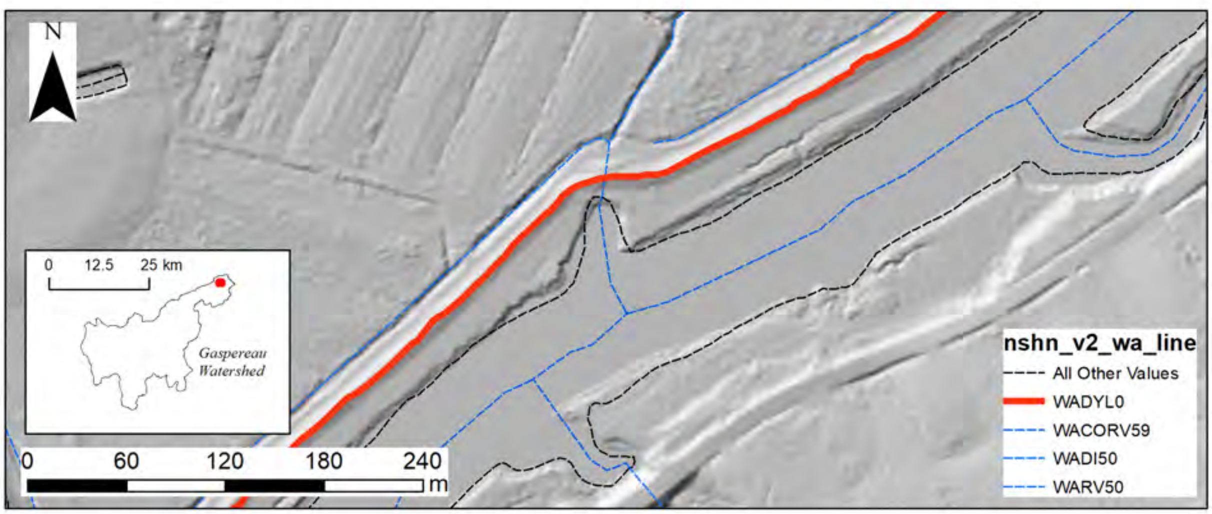


Figure 2.2 NSHN Dyke features (WADYL0) are depicted as *barriers* (in red) such that *Channels* (blue) will intersect to establish known flow *Enforcements*. These data are essential inputs to reduce errors produced by the breaching analysis.

Both left and right Dyke features (WADYL0 and WADYR0) seem to trace the top of the dyke in both cases and provide good intersecting *Barriers* (Figure 2.2).

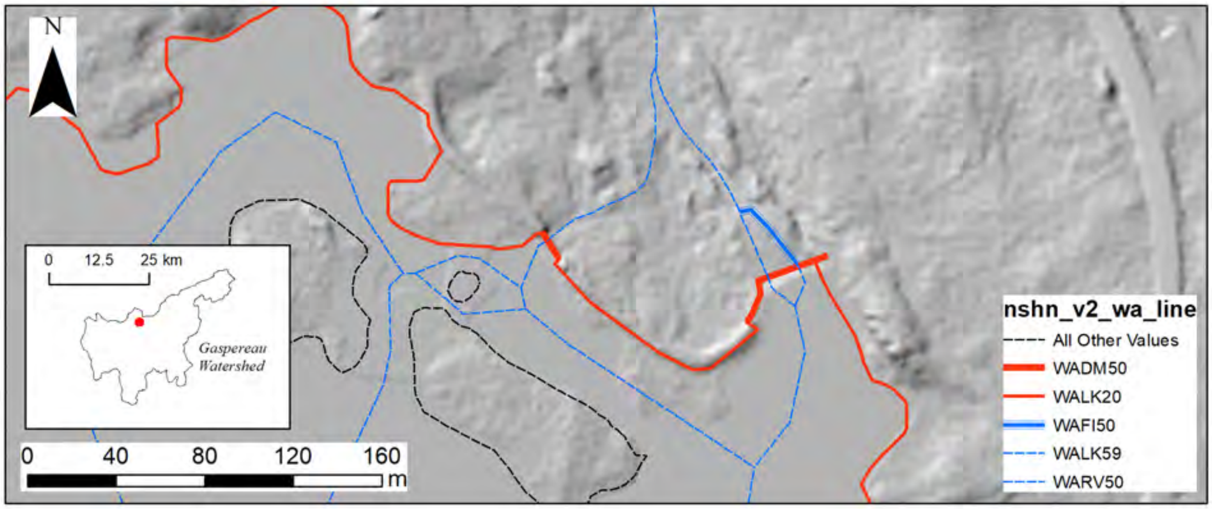


Figure 2.3 The complicated drainage network located at the north-east portion of Gaspereau Lake, Highway 12 at Welton Landing. NSHN features WAFI50 (Fish Ladders – Thick blue line), WALK59 (Dam Spines – dashed blue line), and WARV50 (Rivers blue dashed) indicate *channel* features. Intersection *barriers* are indicated in red including NSHN features WADM50 (Dams) and WALK20 (Lake Delimiters).

Initially, Lake delimiters were considered as barriers to ensure intersecting channel features were represented as enforcements. But errors in these relationships were observed and the lake delimiters were later described as optional barriers.

The Flume Spine features were included as enforcements as the simplest method for ensuring that the downstream outlet of the various flume structures was correctly represented (Figure 2.4). These features were limited to long dammed areas exclusively and thus the impact from including very long enforcements such as this in terms of altering the flow of the neighboring lidar derived flow were deemed negligible. Other water reservoirs had to be treated specifically as well to ensure correct flow paths (Figure 2.5). Other indefinite drainage features must also be considered during the process (Figure 2.6). Other areas such as highway overpasses where surface rivers have been diverted underground over large stretches of land must be incorporated correctly (Figure 2.7).

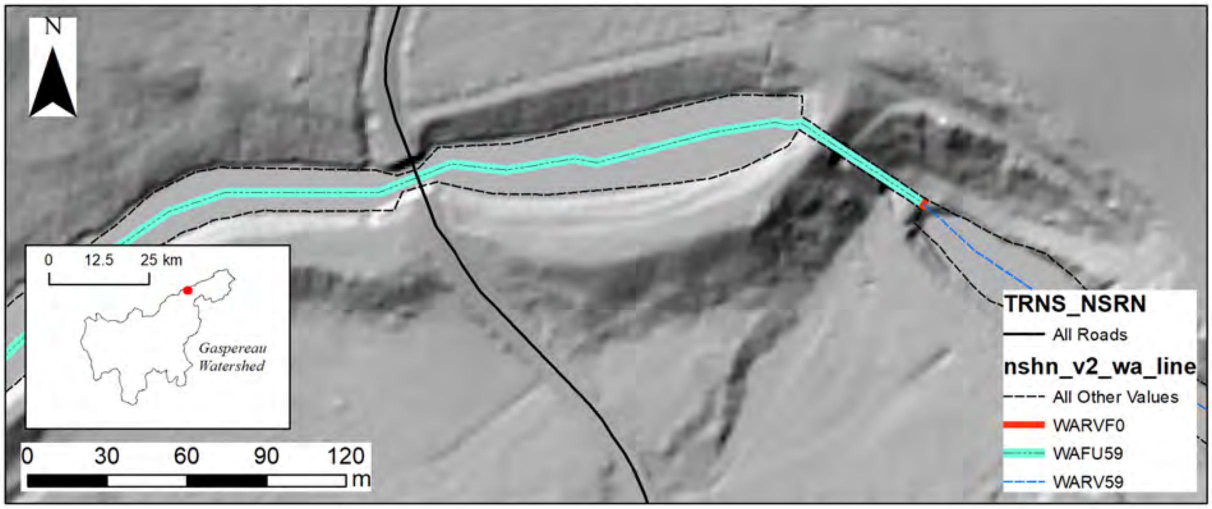


Figure 2.4 The flow structure terminating White Rock Pond, Black River Road Gaspereau. The NSHN feature WAFU59 (Flume Spine) continues to WARV59 (River) where it intersects WARVF0 (Double Line River Delimiter). No suitable barrier exists in the NSHN line or junction dataset to represent the inlet to this flow structure.

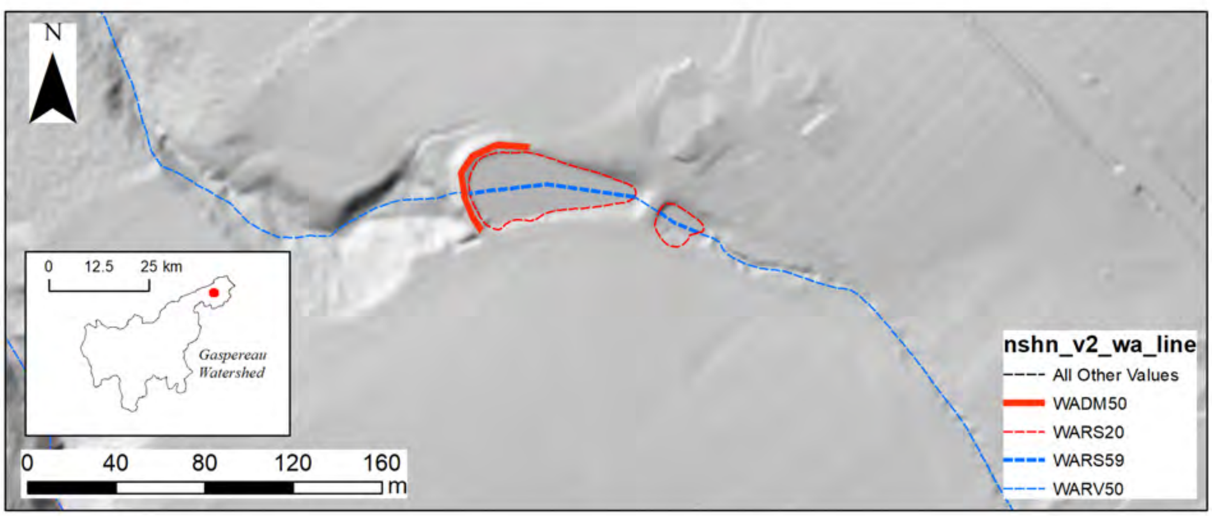


Figure 2.5 A reservoir located on a private vineyard, Grand Pre Rd. Wallbrook. NSHN features include WARS59 (Reservoir Spine) and WARV50 (River) which represent the water channel (blue) as well as WADM50 (Dam) and WARS20 (Reservoir boundary).

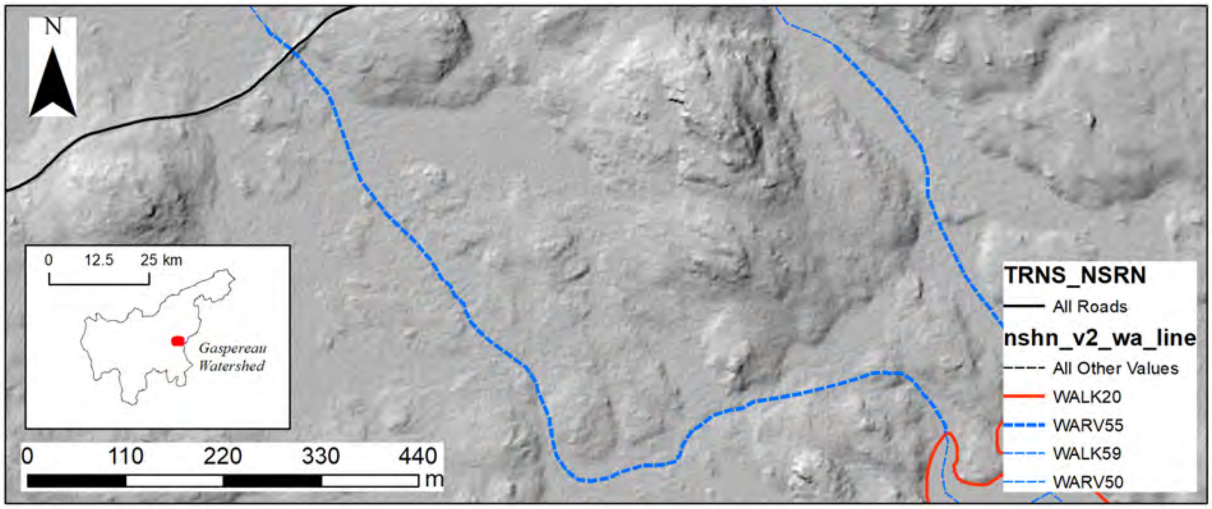


Figure 2.6 An 'Indefinite River' (WARV55) runs between Melthals Rd. (north) Black River Lake (WALK20) (south) in the Sunken Lake Area. The indefinite river feature forms a continuous channel with additional NSHN features WARV50 (River) and WALK59 (Lake Spine). Considering the NSRN roads and NSHN WALK20 (Lake Boundary) as *barriers,* the Indefinite Features would provide useful additional *enforcements* at road-stream intersections.

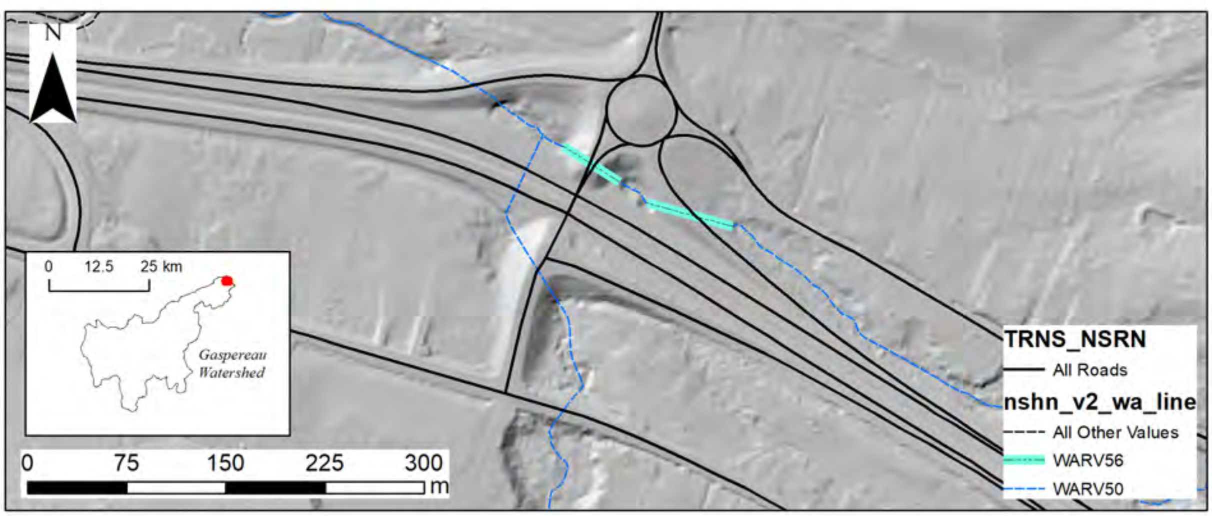


Figure 2.7 Highway 101 Exit 9 overpass for Avonport. The only two examples of WARV56 (Underground Rivers) from NSHN found in the Gaspereau Watershed exist here (cyan). These features join WARV50 (Rivers) which will form enforcements where they intersect with NSRN roads. WARV56 features provide critical knowledge of flow paths within this complex area, and they are included as enforcements in their entirety to reduce errors in the subsequent breaching analysis.

2.1.1.2 Basin Tables

All data contained in shapefiles labelled “nshn_v2_ba” pertain to basins. It is noted that these basins contain multiple individual watersheds in many cases. For example, the ‘Gaspereau’ basin contains the extent of the Gaspereau, Cornwallis, Habitant watershed and other minor ones. The metadata which accompanies the NSHN deems these administrative boundaries representing primary watersheds. These boundaries may provide a good basis for breaking up the analysis as they tend to have a comparable size and shape which may facilitate consistent computational resources if they depict the edge of some amalgamated catchment boundary which could avoid errors in flow accumulation calculations.

2.1.2 Nova Scotia Road Network Nova Scotia Topographic Database (NSTDB)

The following features were observed in the Gaspereau watershed in the **RR_LINE_10K** line layer from the NSTDB *BASE_Roads_and_Railroads* shapefile and included in the analysis appropriately (Table 4).

Table 4. Features from the RR_LINE_10K layer.

Feature Code	**Description**	**Enforcements**	N/A
RRCL50	CULVERT Line	X	
RRFB50	FOOT BRIDGE		X

As described, the intersection of road, dykes, and dams with known hydrographic features such as streams can precondition the lidar elevation to ensure most correct flow paths are maintained in a breached depression analysis. The following features were observed in the Gaspereau watershed in the **RR_ROAD_LINE_10K** line layer from the NSTDB *BASE_Roads_and_Railroads* shapefile and included in the analysis appropriately (Table 5).

Table 5. Features from the RR_ROAD_LINE_10K layer

Feature Code	**Description**	**Barriers**	N/A
ALL	CULVERT Line	X	

The NSTDB provides the suitable road locations which are useful for providing this known intersection. The effect of intersecting the roads with these features is to limit the use of hydrographic features in this way to areas directly surrounding roads so that the lower accuracy of the NSHN stream network does not impact the resulting channel established in the lidar elevation model from the breaching analysis.

2.2 Hydro-Enforcement Methodology

2.2.1 Provincial Vector Layer Processing

The Gaspereau 1 meter DEM was used in conjunction with the relevant supplementary vector data, to conduct an exploratory analysis to test a set of custom designed hydro-enforcement tools and techniques with the objective of finalizing a recommended methodology for High, Medium, and Low accuracy results. In total, the provincial data were assessed and merged into 3 categories in terms of their use in hydro-enforcement: *Barriers*, *Channels*, and *Enforcements* (Figure 2.8).

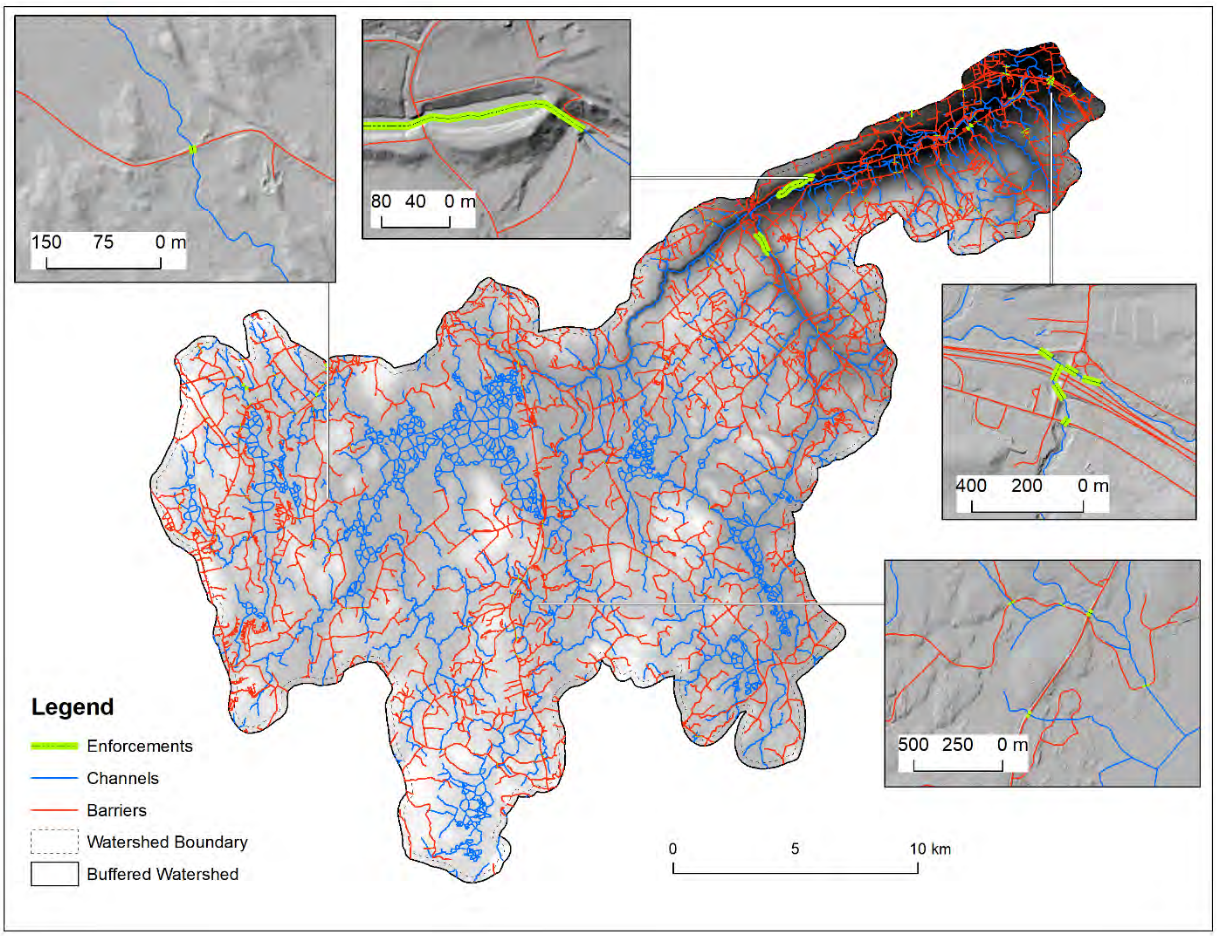


Figure 2.8 Output from model which includes buffered enforcements as well as channels, and barriers from avilable GeoNova Data sources.

2.2.2 Initial Hydro-enforcement and quality assurance benchmark

Before hydro-enforcing, an initial fill-difference was computed to construct Pools such that the levels of effort for each hydro-enforcement target accuracy level could be assessed (Figure 2.9). A histogram of the pool depths and pool area was also computed (Figure 2.10). The threshold values used for both pool depth and pool areas for three levels of accuracy/level of effort are reported in Table 6.

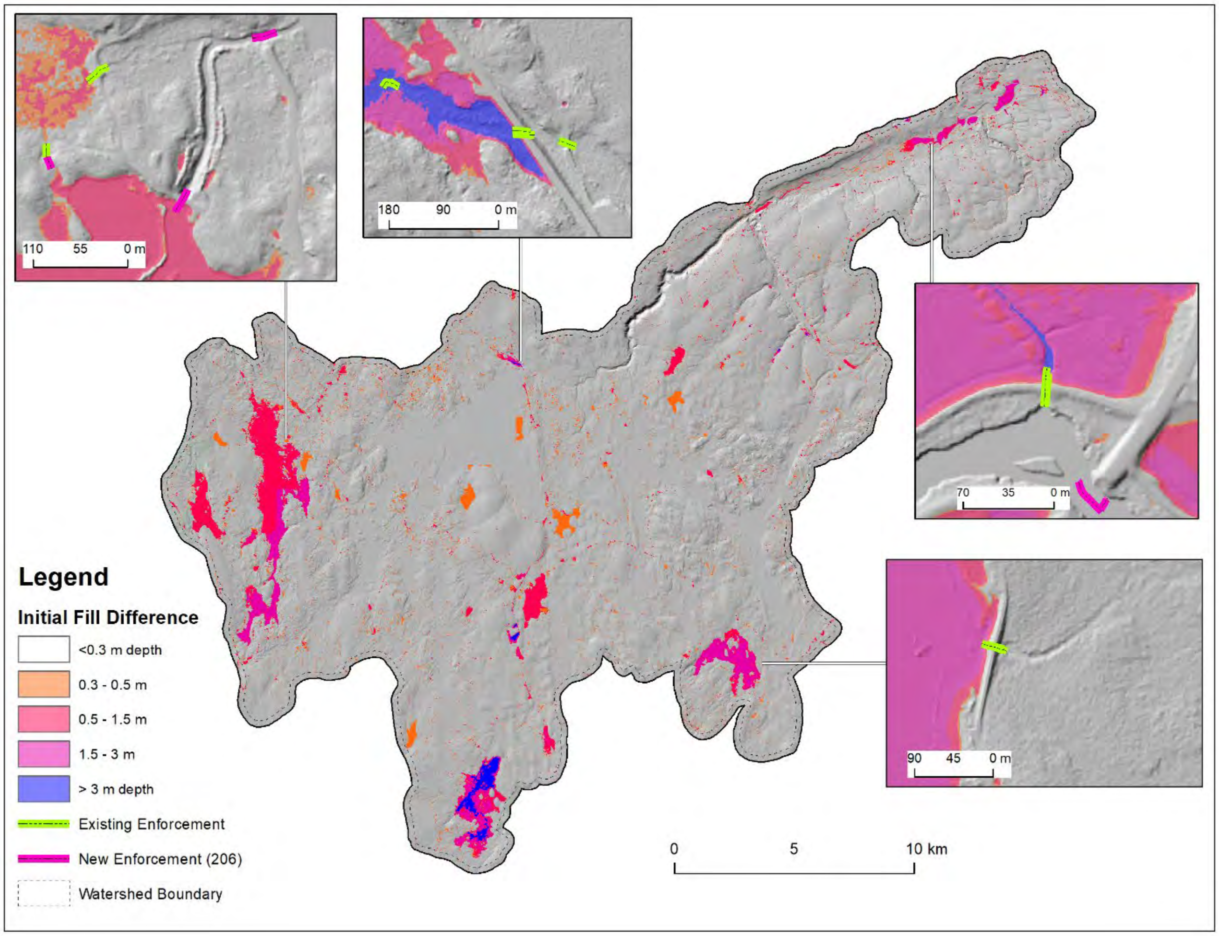
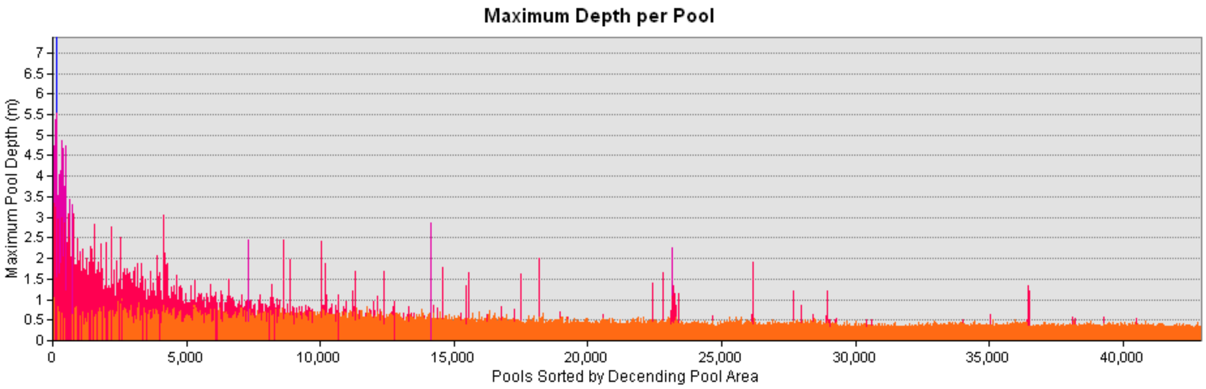


Figure 2.9 Initial Pools generated by filling sinks and calculating the differences between the resultant filled and original DEM. Pool depth is equal to Fill Difference. Green lines are existing enforcement features and red lines are new enforcement features.



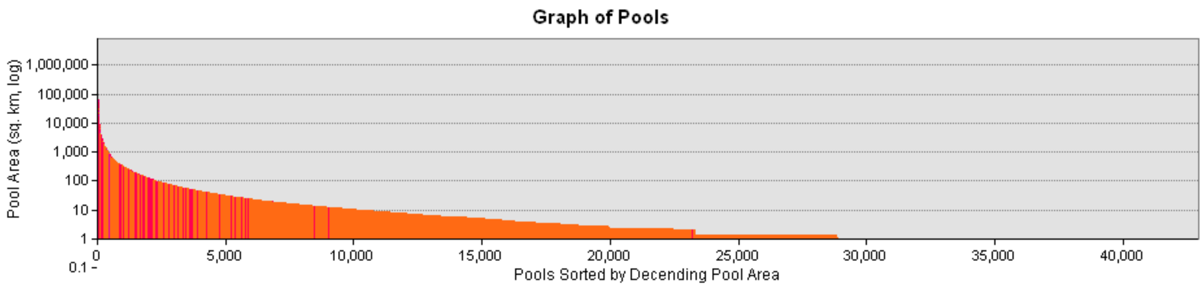


Figure 2.10 Distribution of Pools generated by fill difference with no enforcement imposed on watershed. Top graph shows the maximum depth per pool and lower graph shows the pool area.

The number of pools for an initial hydro-enforcement, *Enforcements* (such as culverts lines) were burned into elevation models directly. Channels including rivers and lake spines were burned into the DEM only where intersecting barriers including roads and dams were within 25 m to reduce the enforcement impact of the poorly referenced channel vectors.

Table 6. The Minimum/Mid-level/High accuracy thresholds for the initial DEM fill-depth and area assessments used for each level of accuracy.

	Gaspereau Watershed Case Study		
	Minimum Accuracy	Mid-level Accuracy	High Accuracy
Pool Depth Checks	50	295	5629
Pool Area Checks	71	412	3697

Additiona analysis was conducted to intersect the channel features (streams) with the barrier features (roads) to form a set of points that may represent culverts or bridges (Figure 2.11).

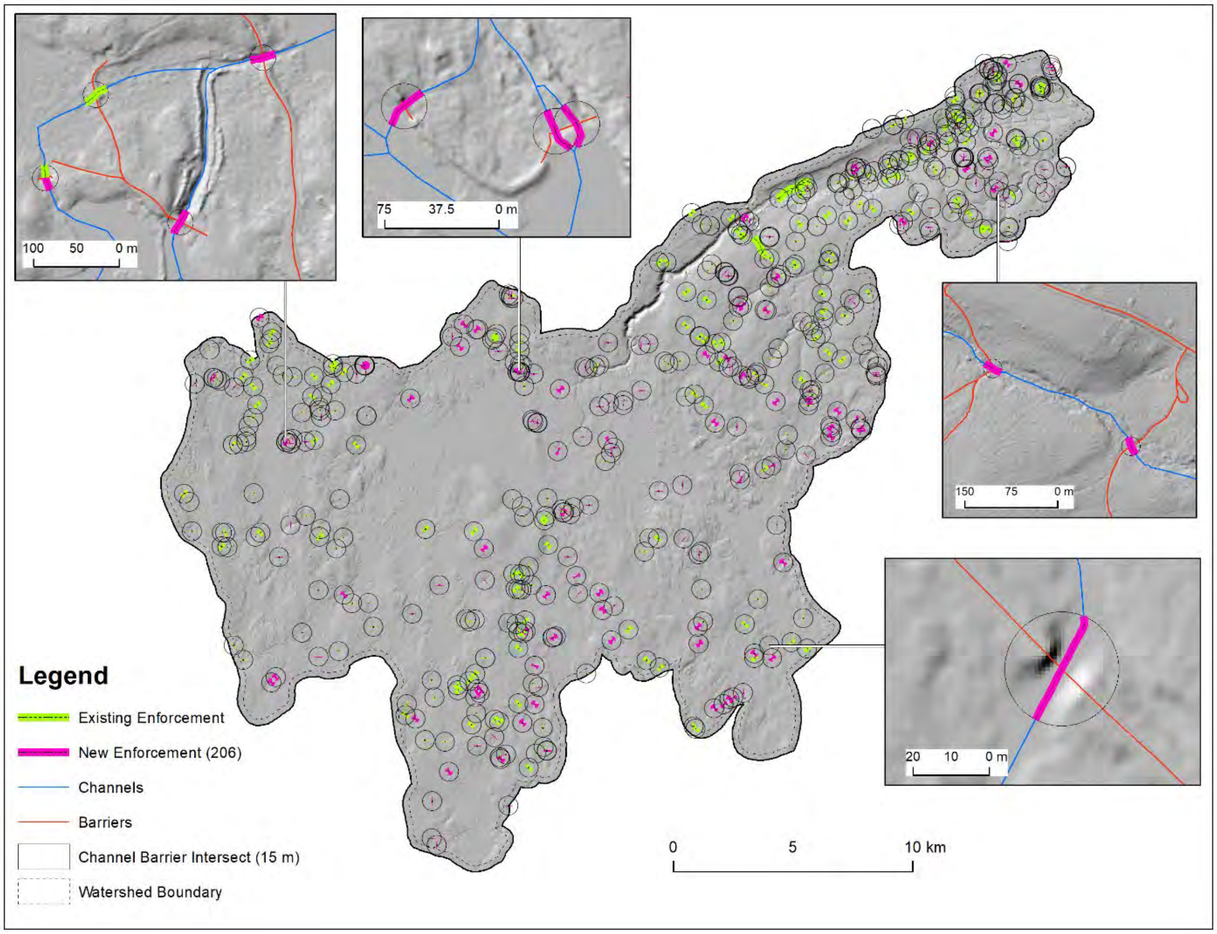


Figure 2.11 Output of points from tool generating additional enforcements from where the channel layer intersects the barrier layer.

After the initial sink filling and intersecting of channels with barriers, an initial hydro-enforcement was completed using these linear features to modify the DEM (Figure 2.12).

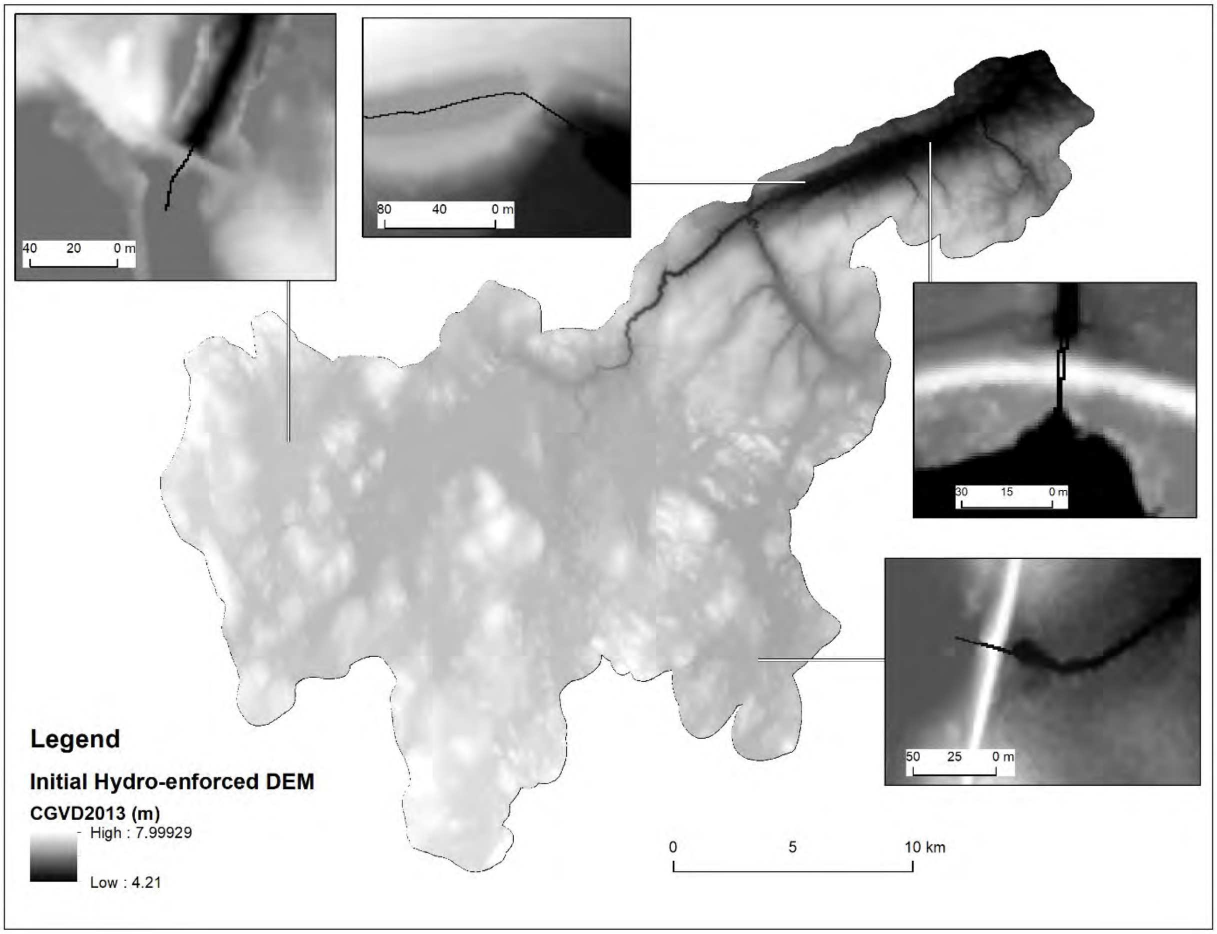


Figure 2.12 Initial hydro-enforcement of lidar DEM generated directly from NSHN data including channels around barrier intersections.

An initial baseline hydrologic model was computed from the hydro-conditioned DEM, resulting in an initial *Stream* network (Figure 2.13). In the figure below the streams were generated from the flow accumulation model. The stream locations are very accurate, except around large lakes as is the case for Gaspereau

Lake where, near the center of the map where the streams have a very linear fishbone pattern as result of the flat lake surface.

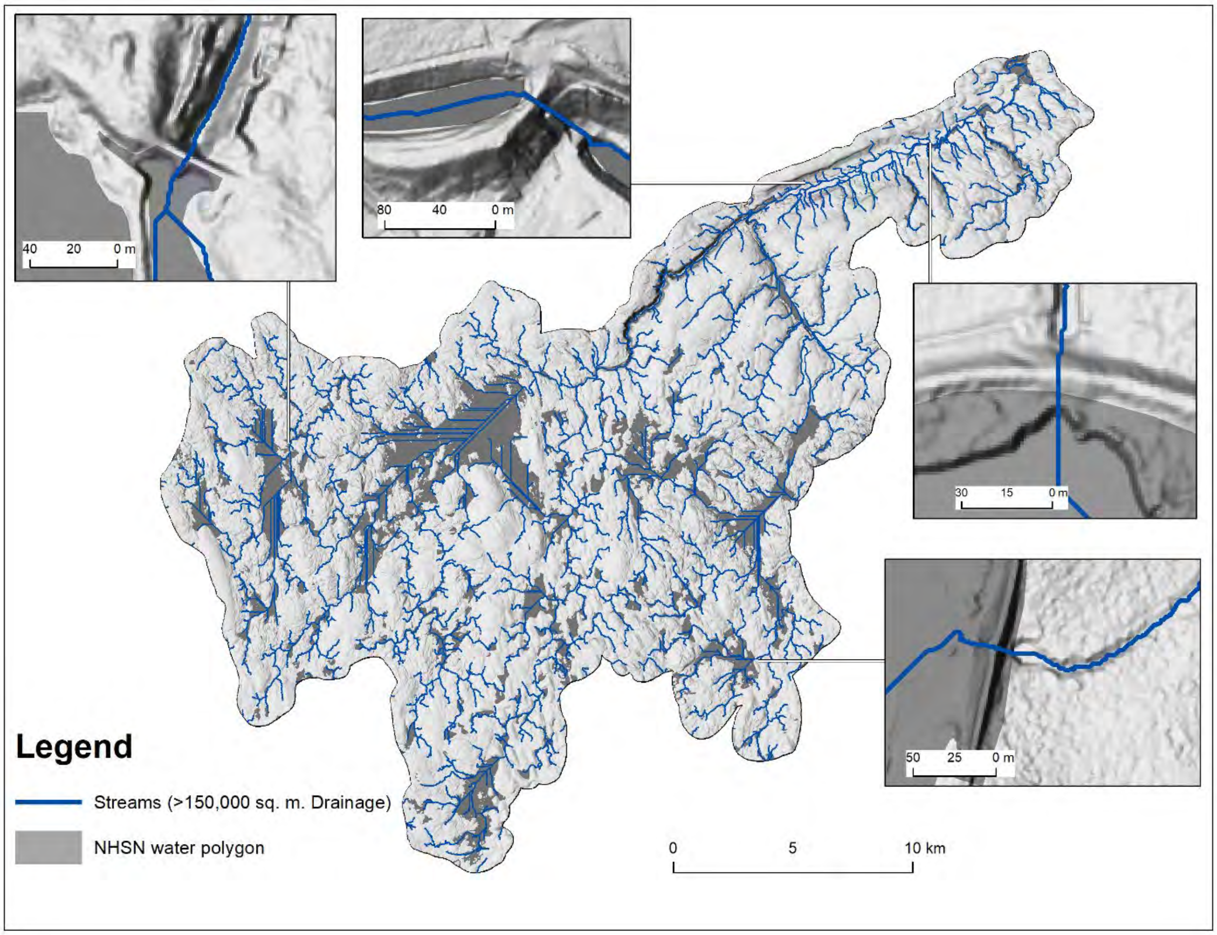


Figure 2.13 Initial stream generated from a standard hydrologic analysis conducted on the hydro-enforced DEM.

Barriers were intersected with the initial derived stream network to compute *Overtops* which form an additional basis for the accuracy assessment (Figure 2.14). Accuracy assessments are linked to the drainage area threshold for the derived streams: Minimum > 150,000 sq. m; Mid-level >50,000 sq. m; and High accuracy > 10,000 sq. m.

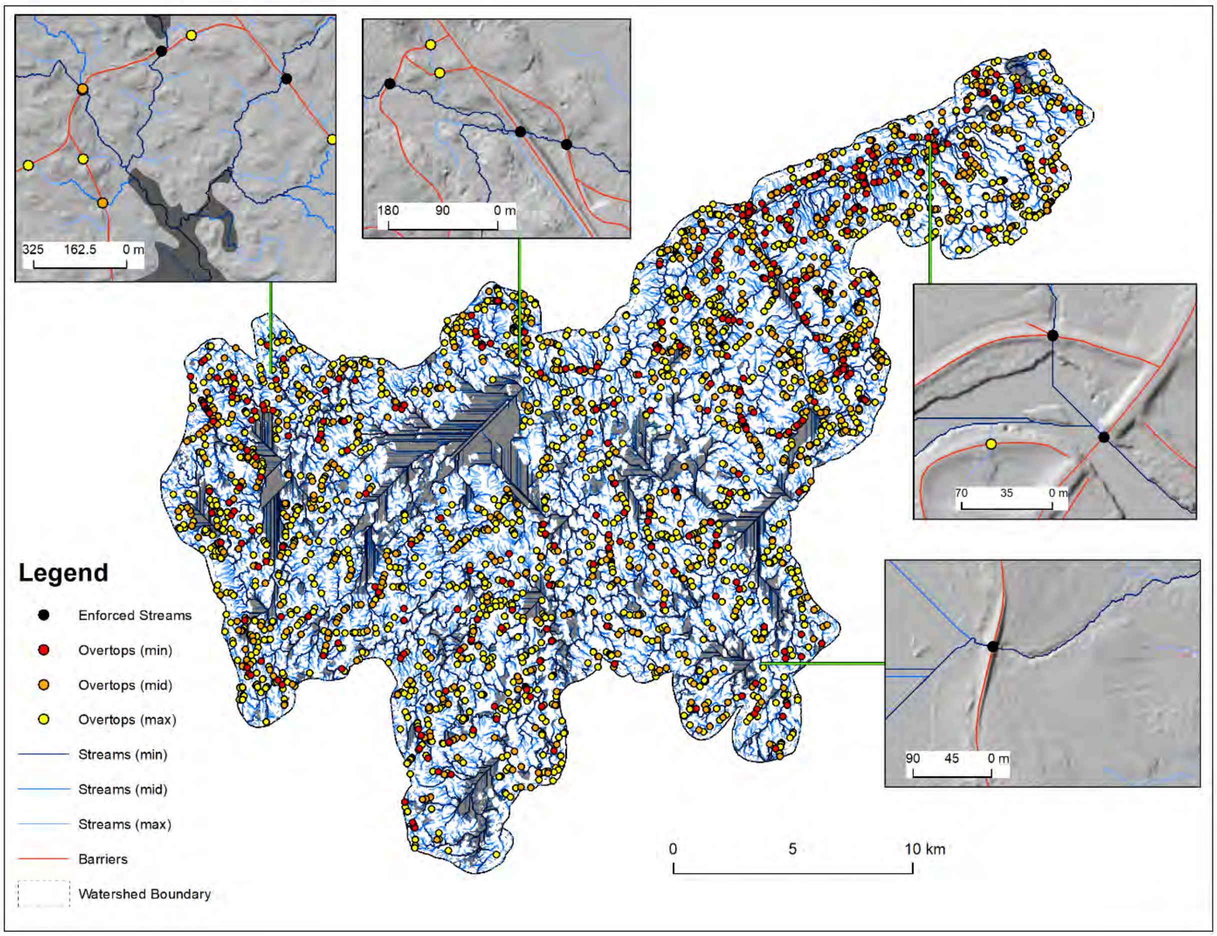


Figure 2.14 Initial overtops(points) for the Gaspereau watershed. The stream network derived from standard hydrological analysis including initial hydro-enforcement from available provincial data. Overtops are defined where intersects are >30 m from enforcement lines.

A procedure for completing hydro-enforcement for each of the described accuracy levels was conducted so that the following observed occurrences were accounted for based on the previously defined thresholds of hydro-enforcement accuracy levels:

Table 7. Min/Mid/High accuracy thresholds for initial stream-road overtop locations (i.e. the number of overtop points). Enforcement at each location should be ensured correct to achieve a given accuracy level.

	Minimum Accuracy	Mid-level Accuracy	High Accuracy
Overtop Checks	307	932	2875
Initial Enforced Streams	386	468	569

2.2.3 Minimum Accuracy Hydro-Enforcement

To facilitate a minimum accuracy hydro-enforcement, locations indicated by the various minimum accuracy measures including pools of a given depth, pools of a given area, and stream-road overtop locations representing a given drainage area, were manually inspected to ensure accuracy. Additional manually digitized enforcements were included as required based on the visual inspection. Once satisfactory, the culvert/bridge feature was burned into the DEM, sinks filled, and the hydrological modelling steps were recomputed. This resulted in a minimum accuracy hydro-enforced DEM and stream network..

2.2.4 Mid-level Accuracy Hydro-Enforcement

Building on the results from the minimum accuracy procedures described above, the mid-level accuracy hydro-enforcement was conducted by inspecting and including additional enforcement vectors automatically generated with the custom hydro-enforcement tool *Nearest Lower* (Section 1.8.3.1). These new enforcements were incorporated and once again the procedure to burn, fill, and produce a hydrological model were recomputed resulting in a mid-level accurate hydro-enforced DEM and a mid-level accuracy stream network.

2.2.5 High Accuracy Hydro-Enforcement

Following the mid-level analysis, a maximum level hydro-enforcement was computed by feeding the above mid-level hydro-enforced DEM to the WhiteboxTools Breach Depressions Least Cost Function (Section 1.8.2.2). Table 8 highlights the parameters used in the WhiteboxTools Breach Depressions function. After significant computational time, approximately 5.5 hours, the resulting hydro-conditioned DEM was used in a hydrological analysis that resulted in a high accuracy stream network.

Table 8. Breach Depressions Least Cost function settings applied to generate high-accuracy hydro-enforcement DEM

Maximum search distance (cells	50
Maximum Breach Cost (z units)	250
Minimize breach distances	enabled
Fill unbreeched depressions	enabled

3 Results

Each of the hydro-enforcement accuracy levels resulted in a hydro-enforced DEM with 1 m spatial resolution and an accompanying stream network poly-line feature. All steam features were finally generated with a flow accumulation threshold of >50,000 sq. m. which is a typical accepted value for first order streams (Knighton, 2014). The different level of effort or accuracy level of the derived stream network were displayed and can be compared (Figure 3.1). When examining this figure, at the coarse scale all vectors are roughly coincident indicating all methods produced comparable results. However, at the more detailed scale, suitable differences can be observed between the different accuracy level streams (Figure 3.1). Also Figure 3.1 shows the difference in location between the provincial NSHN channels (dashed black lines) with all the lidar derived stream vectors, regardless of the level of effort/accuracy in the hydro-enforcement.

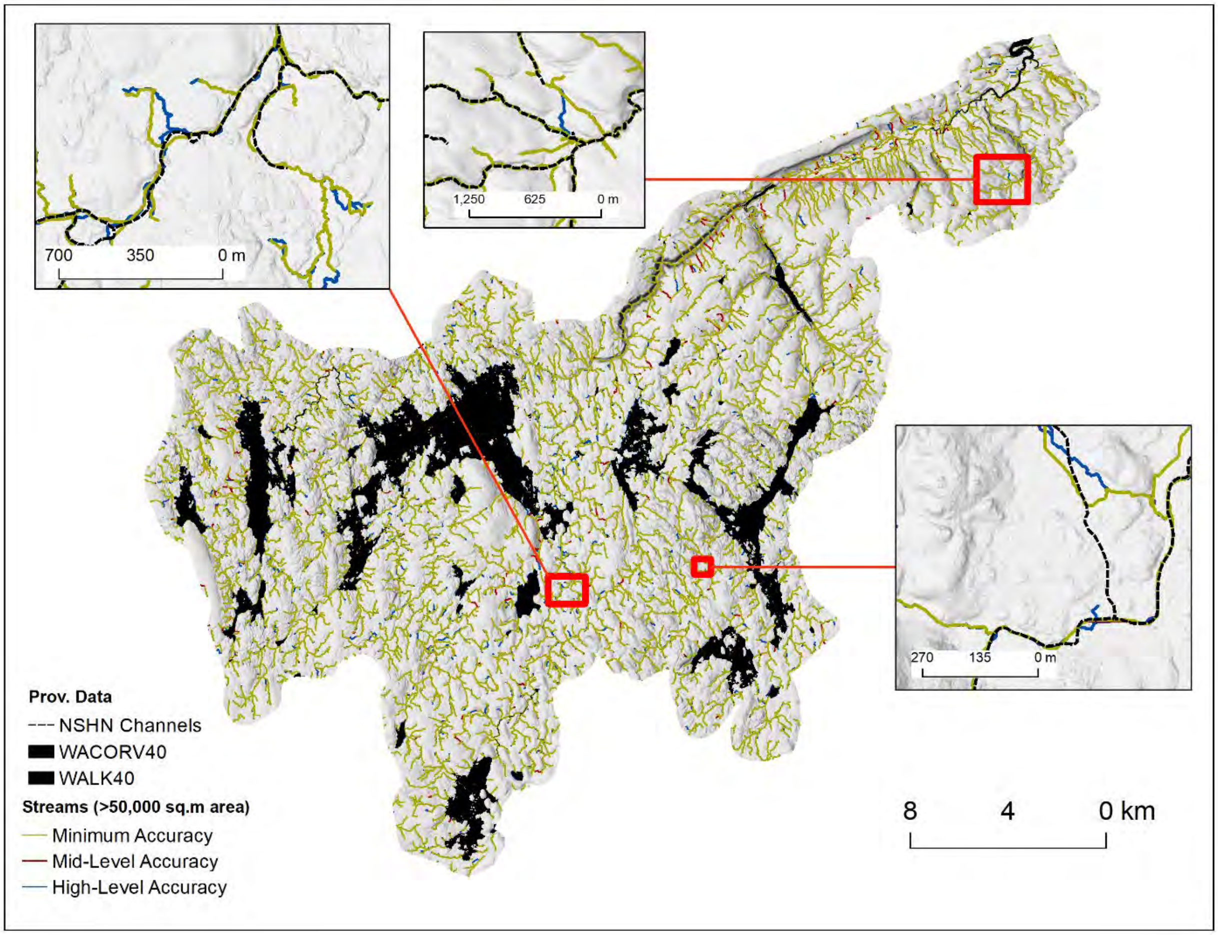


Figure 3.1 Full stream networks generated for Min/Mid/High accuracy hydro-enforcement methods (yellow/red/blue lines respectively). Lake features (NSHN) are masked to de-emphasize discrepancies of the streams in flattened areas.

It is apparent based on the results that each of the lidar derived stream network products provides a significant increase in accuracy when compared to the stream networks in the Nova Scotia Hydrographic Network (NSHN) (Figure 3.1). This is especially apparent in areas of dense tree cover, since the NSHN network was interpretation from aerial photograph and the stream locations were probably obstructed resulting in the stream vectors in these areas having a higher locational uncertainty compared to the streams derived from the lidar DEM.

Additionally, one can simply increase the accumulation threshold value to generate denser stream networks as required. This is important in the case of mapping ephemeral streams that may not flow year-round. Furthermore, the resulting lidar DEM derived streams follow a consistent downslope trend along the terrain which may be of great use for certain analysis including fish habitat or fluvial flood analysis.

Users should be cautioned however, that experience has shown that the length of the derived streams from this method of using a lidar-DEM are typically longer than that of the NSHN streams. This is a result of the meandering path the derived stream obtains from the flow accumulation grid for wider streams. The resultant zig-zag pattern for the derived streams when plotted as a longitudinal profile is artificially longer than the more simplified streams features from the NSHN.

3.1 Minimum Accurate Hydro Enforced DEM

The minimum accuracy lidar-DEM derived stream network and related hydro-enforced DEM provides a great deal of improvement over the NSHN data with a minimal effort (Figure 3.2). The minimal processing time and relatively small number of enforcement features indicated by the quality assurance threshold, present this option as a very practical first step whereas further higher accuracy enforcement routines can exhibit diminishing returns.

Table 9 shows the processing workflow in ArcGIS involved in producing the minimum accuracy or level of effort hydro-enforced DEM and associated derived stream network. The table reports the effort involved with respect to processing time for the Gaspereau watershed, consisting of an area of 559 sq.km., and then that time is extrapolated to estimate the effort to process the entire province based on an area of 55,284 sq.km.

Table 9. The general processing workflow and time required for minimum accuracy DEM hydro-enforcement based existing provincial data and minimal user input.

Software	Processing Stage	Processing Time	
		Study Area (~559 sq. km.)	Province-Wide (~55,284 sq.km)
ArcGIS	Mosaic lidar DEM tiles Compile Provincial Data (enforcements)	4 Hours	*392 hours
	Initial hydro-analysis (pools, overtops)	40 min	65 hours
	Manual Enforcing (low)	3 hours	294 hours
	Hydro-analysis (Enforced, low)	50 min	81.7 hours
	Total	**8.5 Hours**	**833 Hours**

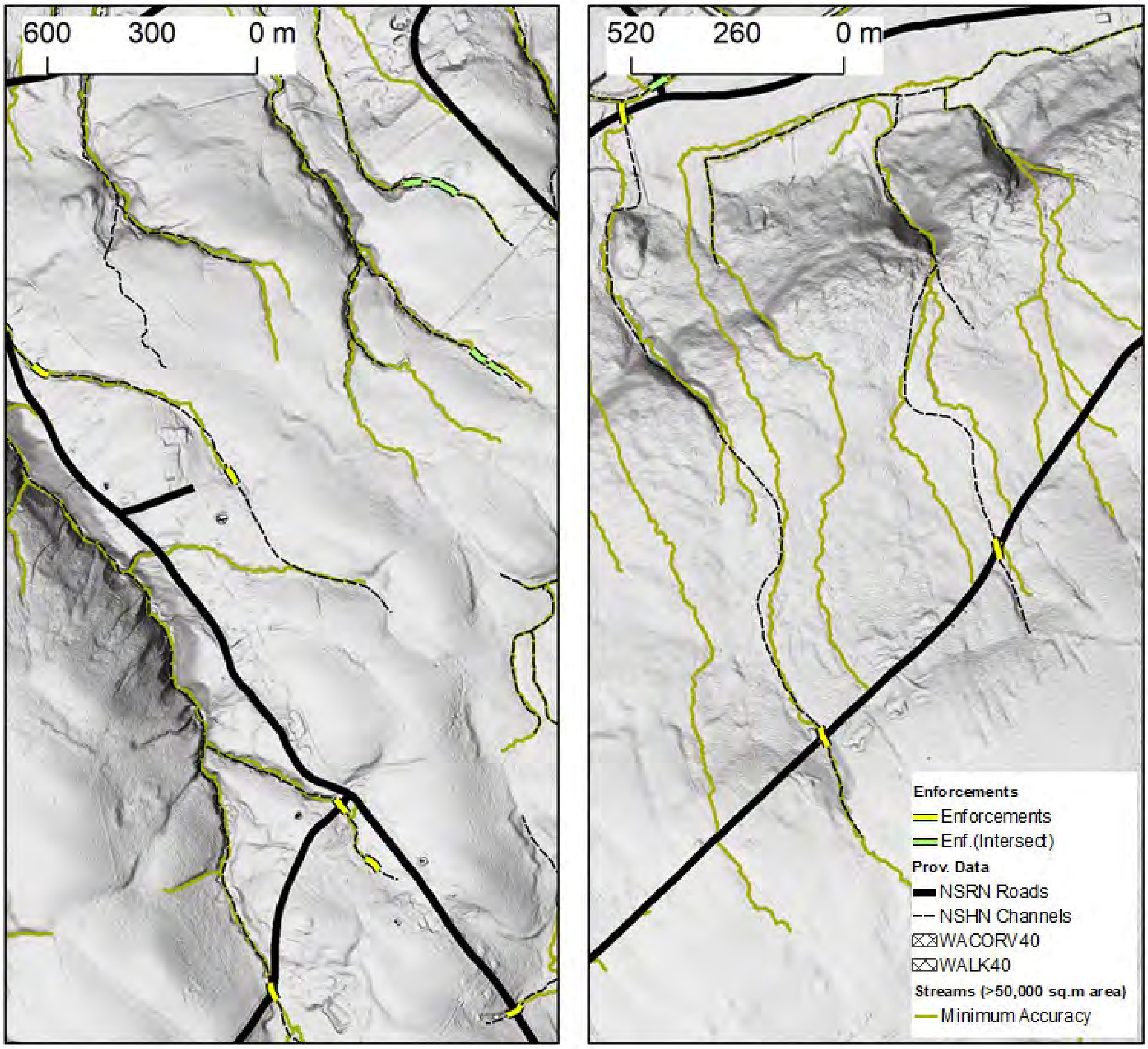


Figure 3.2 Comparison of the minimum accuracy hydro-enforced stream vector (yellow) to existing NSHN channel vector (dashed black). Roads (thick black) with enforcement locations (thick yellow).

3.2 Mid-Level Accurate Hydro Enforced DEM

The mid-level accuracy results show an overall subtle improvement at the scale of the greater watershed compared to the minimum accuracy level hydro-enforcement results (Figure 3.3). However, looking in more detail it is apparent that in many cases the additional enforcements generated by the *Nearest Lower* tool do provide a significant improvement in many areas near road-road intersections where major ditches terminate at unmapped crossroad culvert (Figure 3.3). The processing time of the Nearest Lower tool is very quick and the assessed level of effort for conducting the quality assurance for the Mid-level accuracy is attributed to a user spending the time to inspect the data thoroughly. As a result of the Mid-level accuracy processing, there are more overtops and pools included which thus should be visually examined for correctness. However, as the *Nearest Lower* concept is improved and re-implemented, less time can be attributed to quality assuring this level making the Mid-level effort more cost effective. It is important to note that for this analysis many poorly delineated autogenerated enforcement features were passed to the hydro-enforcement stage to facilitate processing which resulted in only a few errors. Note that very small incorrect enforcement lines can have a very minimal effect on the resulting stream vector delineated because a very small amount of flow area will accumulate for an incorrectly placed enforcement feature.

Table 10 shows the processing workflow in ArcGIS involved at producing the Mid-level accuracy or level of effort hydro-enforced DEM and associated derived stream network. The table reports the effort involved with respect to processing time for the Gaspereau watershed, consisting of an area of 559 sq.km., and then that time is extrapolated to estimate the effort to process the entire province based on an area of 55,284 sq.km.

Table 10. The general processing workflow and time required for mid-level accuracy DEM hydro-enforcement based on semi-automated enforcement/culvert detection.

Software	Processing Stage	Processing Time	
		Study Area (~559 sq. km.)	Province-Wide (~55,284 sq.km)
ArcGIS	Mosaic lidar DEM tiles Compile Provincial Data (enforcements)	4 Hours	*392 hours
	Initial hydro-analysis (pools, overtops)	40 min	65 hours
	Manual Enforcing (low)	3 hours	294 hours
	Hydro-analysis (Enforced, low)	50 min	81.7 hours
	Semi-automated Enforcing (mid)	6 hours	588 Hours
	Hydro-analysis (Enforced, mid)	50 min	81.7 hours
	Total	**15.3 Hours**	**1502 Hours**

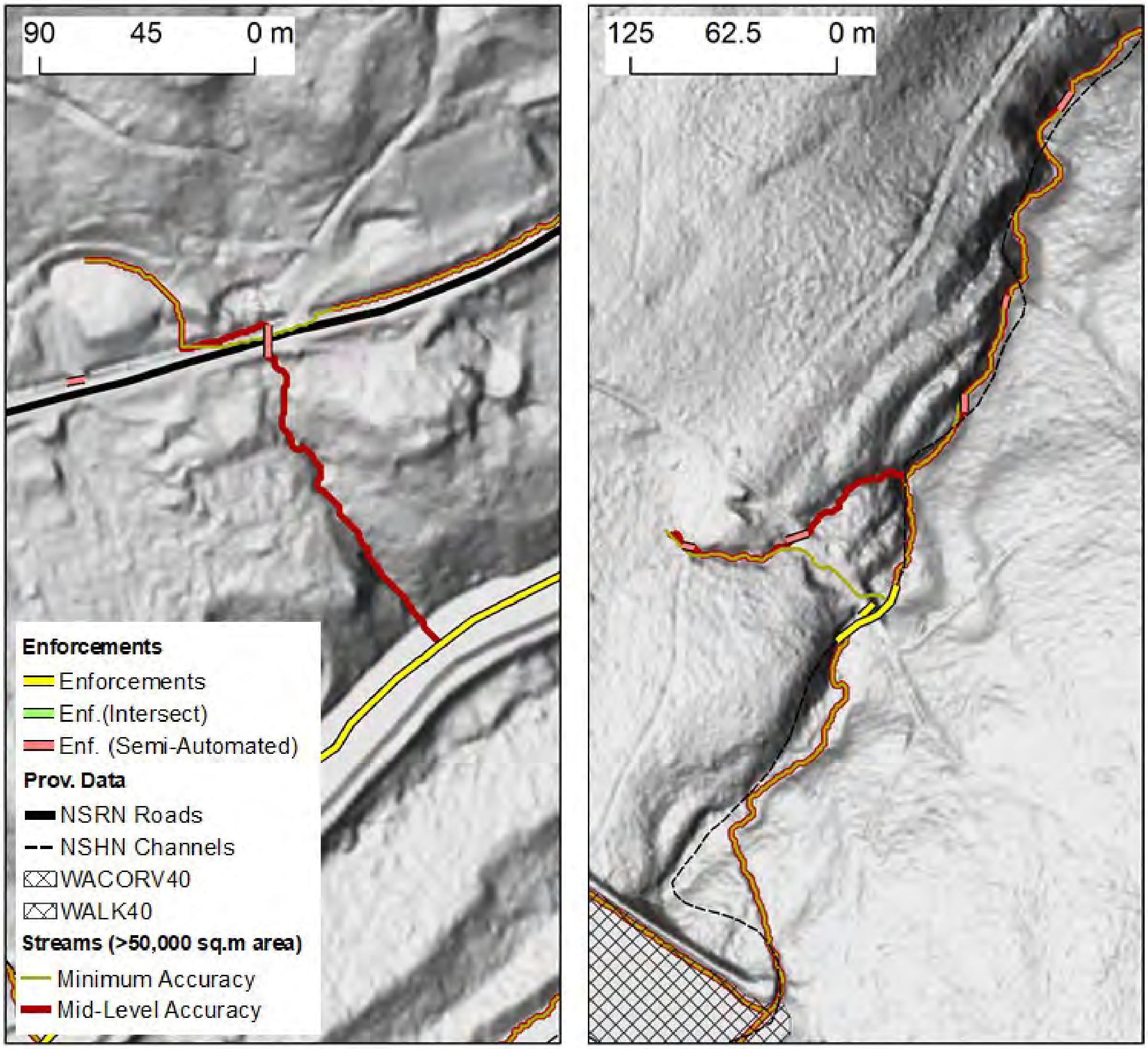


Figure 3.3 The Mid-level accuracy hydro-enforced DEM and derived stream (red) captures a greater level of detail than the minimum accuracy derived stream (yellow) by including additional culvert enforcements not represented in the NSHN or NSTDB datasets.

3.3 Highly Accurate Hydro-Enforced DEM

The High accuracy hydro-enforcement results for this case study were unsatisfactory in general. To facilitate approximating the level of effort required for this task the typical parameters were used for the WhiteboxTools breach function. In some tests, for example, in the case of the 1-meter Gaspereau watershed DEM, this tool can take as much as 12 hours to complete a single run on a large computer image processing server allocating as much as 50 Gb of RAM at a time. Furthermore, the process was unstable and terminated on many test runs. As a result, we did not conduct an exhaustive set of tests on varying the parameters associated with Breach Depression Least Cost Function. The tool, however, is certainly capable of generating highly accurate hydro-enforcement results if conditions and settings are correct. Figure 3.4 shows the differences in derived stream locations between the Mid-level and High level of accuracy. The main differences were observed for streams on gentle slopes or along ditches (Figure 3.4).

Table 11 shows the processing workflow in ArcGIS involved at producing the High level accuracy or level of effort hydro-enforced DEM and associated derived stream network. The table reports the effort involved with respect to processing time for the Gaspereau watershed, consisting of an area of 559 sq.km., and then that time is extrapolated to estimate the effort to process the entire province based on an area of 55,284 sq.km. The table also shows the difference in processing time using WhiteboxTools compared to ArcGIS.

Table 11. The general processing workflow and time required for High level accuracy DEM hydro-enforcement based on WhiteBoxTools Breach Depressions Least-Cost analysis.

Software	Processing Stage	Processing Time	
		Study Area (~559 sq. km.)	Province-Wide (~55,284 sq.km)
ArcGIS	Mosaic lidar DEM tiles Compile Provincial Data (enforcements)	4 Hours	*392 hours
	Initial hydro-analysis (pools, overtops)	40 min	65 hours
	Manual Enforcing (low)	3 hours	294 hours
	Hydro-analysis (Enforced, low)	50 min	81.7 hours
	Semi-automated Enforcing (mid)	6 hours	588 Hours
	Hydro-analysis (Enforced, mid)	50 min	81.7 hours
Whitebox Tools	Breach Depression Least-Cost	5.5 hours	539 hours
ArcGis	Semi-automated Enforcing (high)	8 hours	784 Hours
	Hydro-analysis (Enforced, high)	50 min	81.7 hours
	Total	**26.7 Hours**	**2906.4 Hours**

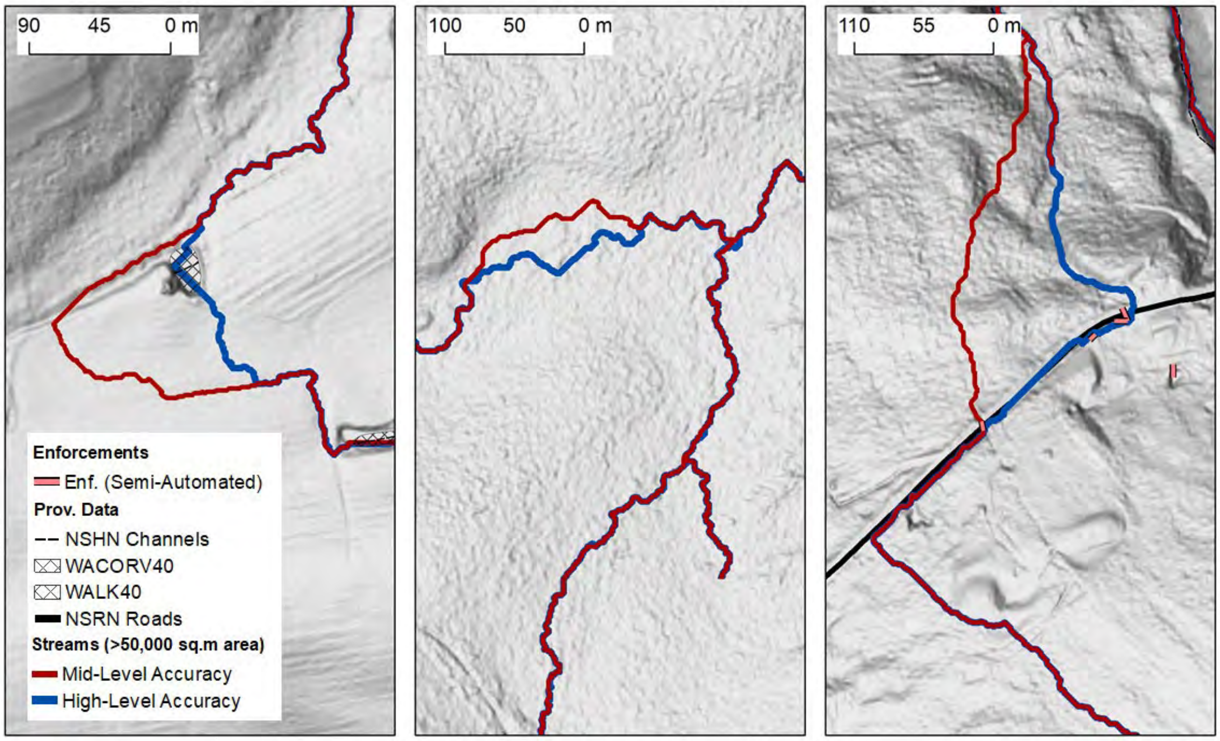


Figure 3.4 Comparison of Mid-level streams (red) and High-level accuracy hydro-enforcement derived streams (blue). There is an apparent diminishing return of improvement restricted mostly to subtle sloping areas.

The breaching system does tend to generate many small breaches in some instances (Figure 3.4). The resultant breached DEM may contain areas of multiple breaches and the hydrological analysis will select the breach with the highest flow accumulation. As a result, it is advised that the breached DEM not be used directly as a hydro-enforced DEM product but instead the resulting high quality stream vector be used to double back and hydro-enforce the DEM to minimize the effect of over-breaching. Conversely, if integrating this approach more closely with the user-guided system of the Mid-level accuracy, it maybe practical to restrict the search radius of the breach function to provide a final smooth enforcing on an otherwise High accuracy hydro-enforced DEM.

4 Discussion

This project provides a great deal of insight into the general concepts and challenges associated with hydro-enforcement, as well forms a general benchmark method and estimate for the various levels of effort involved. However, it would be naive not to consider various additional difficulties possible when expanding the analysis province wide. AGRG researchers have had experience conducting High level accuracy hydro-enforcement analysis across watersheds withing Nova Scotia. For example, deriving catchment basins for storm water infrastructure across Halifax Regional Municipality (HRM) has shown the affect of varied geophysical characteristics of the landscape relevant to this approach. Specifically in the case of HRM, steep and frequently undulating landforms can present a larger quantity of pools. When considering the number of pools detected as a measure of accuracy, as proposed in this study, this approach may become more laborious in this type of geography. Furthermore, significantly built-up areas such as the suburban environment of scattered throughout HRM may have as many as 300 to 500 small driveway culverts per sq. km. which collectively may begin to from a significant role in combined drainage area mapping. Typically, these features may be missed or incorrectly handled by automated hydro-enforcement techniques. In the Gaspereau watershed, only a small number of driveway culverts were encountered, and they were generally observed to have a small impact on the flow accumulation analysis.

Another significant consideration when expanding this analysis to the province is the overall quality of the known infrastructure data as well as the lidar data. It should be noted that the quality of the Nova Scotia Hydrographic Network data was remarkably high, although some discrepancies were observed in the stream locations compared to lidar derived stream in forested areas. Small defects were observed in the lidar elevation data including inconsistent tidal and river water heights, some tinning artifacts, and some faintly visible tile boundaries. These artifacts did not significantly affect the results in this case but may be more impactful in a province wide analysis and requiring additional processing.

4.1 Provincial Wide Cost Assessment

Based on the experiences and best estimated and recorded time completing this case study, the following is a summary of the approximate time and costs to complete a province wide hydro-enforcement analysis. This assessment assumes that the lidar data needs to be compiled individually for similarly sized processing areas to the Gaspereau watershed and a similar procedure is maintained as outlined in this report (Table 12).

Table 12. Summary of recorded and estimated time required for each hydro-enforcement accuracy level for Gaspereau and the entire province.

	Processing Time	
	Study Area (~559 sq. km.)	Province-Wide (~55,284 sq.km)
Minimum Accuracy Hydro-Enforcement	8.5 Hours	833 Hours
Mid-Level Accuracy Hydro-Enforcement	15.3 Hours	1502 Hours
High Accuracy Hydro-Enforcement	26.7 Hours	2906.4 Hours

4.2 Proposed Provincial Hydro-enforcement Workflow

The following is a general outline and guide proposing a best practice method to conduct hydro-enforcement of the provincial lidar data collection:

1) Compile the existing lidar data into a continuous and most up to date 1 meter resolution DEM. This should include an effort to check and resolve any outstanding hydro-flattening issues, tile boundary, or other artefacts.
2) Subdivide the continuous and clean 1-meter DEM into similarly sized processing units. These sub-DEMs should encompass, extend beyond, and overlap across some significant hydrological boundary (watersheds) with a buffered minimum distance of 250 meters. The NSHN basin polygons seem to be an ideal dividing boundary.
3) For each sub-DEM, compute an initial *Pool* area and depth analysis as outlined in this report to gauge the approximate level of effort and accuracy assessment metrics for quality assurance.
4) For each sub-DEM watershed area buffered 250 meters, follow the general procedure outlined in the methods of this report compiling best available provincial data from the NSHN (streams, dykes, etc.) and the NSTB (roads, culverts) completing a complete set of *channels*, *barriers*, and *enforcement*s.
   a) *Channels* should include NSHN feature codes WACA59, WACORV59, WADI50, WADM59, WAFI50, WAFU59, WALK59, WARS59, WARV50, WARV55, WARV56, WARV59, WARVSP50.
   b) *Barriers* should include NSHN feature codes WADM50, WADYL0, WADYR0, WARS20 and all road features from NSTDB .
   c) *Enforcements* should include NSHN feature codes WARV56, WAFU59 and RRCL50 (NSTDB).
5) Using these data, conduct an initial hydro-enforcement followed by the standard hydrological analysis and *Overtop* calculation.

6) Conduct a level of hydro-enforcement as outlined in this report between the levels of Minimum and Mid-level accuracy through a combination of user generated enforcement lines and autogenerated enforcement lines from the Nearest Lower technique.
7) Fulfill the Min-Mid accuracy level by assessing the validity of locations for *Pool* depth, *Pool* area, and *Overtop* location metrics.
8) Optionally, conduct a restricted Breach Depressions Least Cost analysis to improve the quality assured hydro-enforced DEM results to achieve the High-level accuracy.

4.3 Considerations for provincial Data

For a Minimum and Mid-level accuracy hydro-enforcement workflow, the data provided by the province in this case study area were reasonably good. It maybe beneficial to ensure data in the Nova Scotia Hydrographic Network are coded by some indication if they are underground features. If these features were sufficiently accurate, they could be used as enforcement features for updated lidar DEM hydro-enforcement directly. It is certainly sensible to consider amalgamating the 'additional' enforcement features generated from provincial data in the methods of this report directly as the intersection of a water channel and barrier features (i.e. where roads intersect streams).

The distribution and complexity of infrastructure which affect the flow calculation from the lidar DEM varies greatly throughout the province. The predominantly naturally preserved watersheds may have a minimum of such features requiring any enforcement and significantly built-up areas such as the suburban environment of Halifax Regional Municipality (HRM) may have a very large number of enforcements that need to be considered such as driveway culverts. None of the accuracy metrics attempted in this report specifically targeted driveway culverts. The described ditch detection methods, Section 1.8.3.2, can be further explored to facilitate a higher accuracy hydro-enforcement product. Also, certain deep learning tools maybe soon be practical for detecting culverts directly from their shape in a DEM and should be considered for future attempts as the science related to this improves (Arge, 2019).

It should also be considered weather hydro-enforced DEMs are practical to store or simply if the resulting steam vectors from the analysis should be stored instead that can be used to update the NSHN layers with an accuracy associated with the lidar.

It is the experience of AGRG that several external groups including municipal water utilities do maintain and have a desire for high quality ditch, culvert, and hydrological layers. It maybe in the best of interest of these groups and the province to collaborate on a system to better map and maintain these data.

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