

GIS BASED MODELLING FOR FOREST ROAD ALIGNMENTS, CULVERT PLACEMENTS AND LOGGING TRAIL DELINEATION

by

Nana Agyei Owusu Afriyie

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Supervisor: Paul Arp, PhD, Forestry and Environmental Management

Examining Board: Graham Forbes, PhD, Forestry and Environmental Management,
Chair
Charles Bourque, PhD, Forestry and Environmental Management
Dirk Jaeger, PhD, Forest Work Science, University of Göttingen

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ABSTRACT

Establishing stable forest road and trail networks requires proper trail and culvert placements. Past procedures involved manual surveying and hand digitizing road-stream crossings to estimate expected stream discharge for each location. This thesis reports on research-developed semi-automated ArcGIS/ArcMap tools to (i) align already digitized roads with DEM-recognized roadbeds, (ii) locate road-stream crossings and determine potential culvert locations and diameter, (iii) determine expected stream discharge and (iv) determine least-cost trail paths using DEM-generated cost rasters.

Results show that hand-digitized roads veered off DEM roadbeds, sometimes by 20 meters or more. Similarly, mapped culvert locations do not always align with actual road-stream crossings. Also, existing culverts tend to accommodate 50 mm/day but not necessarily 100 mm/day discharge events, thereby leading to washouts. This thesis explores and demonstrates how the developed tools combined with the 1-m resolution LiDAR-DEM coverage for New Brunswick can bring road, culvert, and trail locations into better hydro-topographic alignments.

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LIST OF SYMBOLS, NOMENCLATURE AND ABBREVIATIONS

Units

ha - Hectare, unit of area

m - Meter, unit of length

mm - Millimeters, unit of length

ppt - Precipitation excess

Geospatial Data

DEM - Digital Elevation Model

DSM - Digital Soil Mapping

GIS - Geographic Information System

GPS - Global Positioning System

LiDAR - Light Detection and Ranging

Soils and Watershed

BFW - Riverbank Full Width

DTW - Depth to Water

FA - Flow Accumulation or upstream flow contributing areas.

WAM - Wet Areas Mapping

RT_BFW - Riverbank Full Width Rating

RT_Slope - Slope Rating

RT_DTW - Depth to Water Rating

RT_FA - Flow Accumulation Rating

RT_Wetland - Wetland Rating

TPI - Topographic Position Index

Other Abbreviations

NB - New Brunswick

AOI - Area of Interest

DTI - Department of Transport and Infrastructure

CHAPTER ONE - GENERAL INTRODUCTION

1.1. Road Delineation and Culvert Prediction

The placement of roads, trails, road-stream crossings, culverts, cross drains, and bridges continues to be a challenging task involving multi-faceted management, engineering, economic and ecological considerations (Swift and Burns, 1999). This thesis provides background and examples focused on areas using and developing ArcGIS/ArcMap tools to delineate roads, road-stream crossings and associated upstream drainage while taking advantage of 1-m resolution LiDAR-generated digital elevation rasters (LiDAR: Light Detection and Ranging). The intent of doing this is directed at the forest watershed management context that deals with the layout of forest cut blocks and access roads intended for wood harvesting, forwarding, and site preparations. Matters of considerations deal with avoiding steep slopes, wet soils, wetlands, streams, water bodies, and areas intended for conservations or other purposes such as private or communal properties. In all of this, maintaining existing and constructing reliable forest roads is part of acceptable and sustainable forest management operations (Ramin, 2009).

Traditionally, existing roads and streams were digitized manually using locally available orthorectified surface images and elevation contours (Jenson & Domingue, 1984; Band, 1986). For road construction, this also involved time consuming on-the-ground surveying and GPS stream tracking (Angel, 2004; Seale et al. 2008). Currently, the presence of 1-m resolution LiDAR-DEM data has become a means for topographically, geomorphologically, and hydrologically evaluating the run and retention of surface water from high to low elevations across the landscape through wetlands, lakes, and rivers all the

way to the coasts (Quinn et al, 1991; Murphy et al, 2008; Ruopu et al, 2013). These evaluations also address detailed flood and depression mapping by areal extent, depth, and volume within the context of areas-wide storm and snowmelt events (Jensen, 1991; Wise, 2000). In this regard, New Brunswick, Nova Scotia, and Prince Edward Island have already acquired province-wide LIDAR and surface-image coverages, with open GeoNB data licenses available for New Brunswick involving bare-ground and full-feature elevations, canopy height, and building footprints (Connors, 2019).

While culvert sizing is specific to each road-stream crossing, forest management involves managing thousands of road-stream crossings with each requiring culvert-accommodating stream discharge rates as dictated by expected storm and snowmelt conditions and upstream drainage areas within and outside the specific forest management area. The most used methods for sizing of culverts are based on the Rational Method (Mulvany, 1851), where 100-year runoff events were determined by the formula:

$$Q = C I A,$$

with C as runoff coefficient, I is the uniform rate of rainfall intensity (inches/hour), and A is the upstream drainage area (Pomeroy et al., 2010; USGS, 2012). This method assumes rainfall, snowmelt, and run-off to be constant across upstream drainage areas. Other methods involved streamflow and/or rainfall data frequency analyses, with culverts sized specific flood recurrence intervals (McEnroe, 2007).

Floods that occur in Canada tend to be initiated by snowmelt and rainfall events (Loukas, et al. 2000), with spring flooding coupled with subsequent culvert washouts being most common. Protecting against these occurrences through larger culvert size

installation may not always be feasible because of the costs associated for doing so (Chatburn, 1921; Fragkakis et al., 2015). The overall goal, therefore, is to reliably recommend minimum culvert sizes for maximally expected discharge rates, and to note whether culverts that are already in place meet that recommendation for, e.g., recently encountered 50, 100 or even 200 mm/day discharge events.

1.2. Forest Road/Trail Suitability Modelling

Trail and road planning involves guiding trails and roads to meet user-specific objectives, whatever these may be. From a forest management perspective, this generally means lowering road and trail layout and construction costs while minimizing negative road and trail placement effects that would occur along crossing stream channels as well as wet and steep areas (Hellmund, 1993). For recreational trails, preferences are more oriented towards providing hiking and biking opportunities along, e.g., ridges, valleys, wetlands, streams, and shores (Xiang, 1996; Government of New Brunswick, 2022).

In this study, the emphasis is placed on designing and demonstrating a road and trail layout tool that would minimize road construction costs across streams as well as wet and steep areas. In this, the tool can be used to project alternative road and trail routes by keeping these routes as short as possible, and to take advantage of existing road and trail structures where warranted (Xiang, 1996; Kokkinidis, 2013; Effat and Hassan, 2020; Sari and Sen, 2020).

1.3. Thesis Objectives

To develop and demonstrate GIS-based tools:

1. to re-align roadbeds of existing hand-digitized road lines with LiDAR-DEM recognized road beds,
2. to optimize culvert locations and sizes across existing roads placements based on LiDAR-DEM quantified upstream stream discharge expectations,
3. to minimize overall construction and maintenance costs across forest areas of interest at 1 m resolution.

1.4. Hypotheses

1. Most suitable locations for road and culvert placements can be predicted using 1-m LiDAR-derived Dems.
2. Minimum discharge-accommodating culvert sizes in reference to maximum expected discharge events such as 50, 100 or 200 mm per day can be determined using 1-m LiDAR DEMs.
3. Cost-effective Forest logging roads can be automatically delineated using 1-m LiDAR DEMs.

1.5. Study Areas

This Thesis addresses 4 study areas, as shown in Figures 1.1-marked A, B, C and D. Closeups for these areas are respectively shown in Figures 1.2, 1.3, 1.4, 1.5, with further close-ups in Chapters 3, 4, 5 and 6.

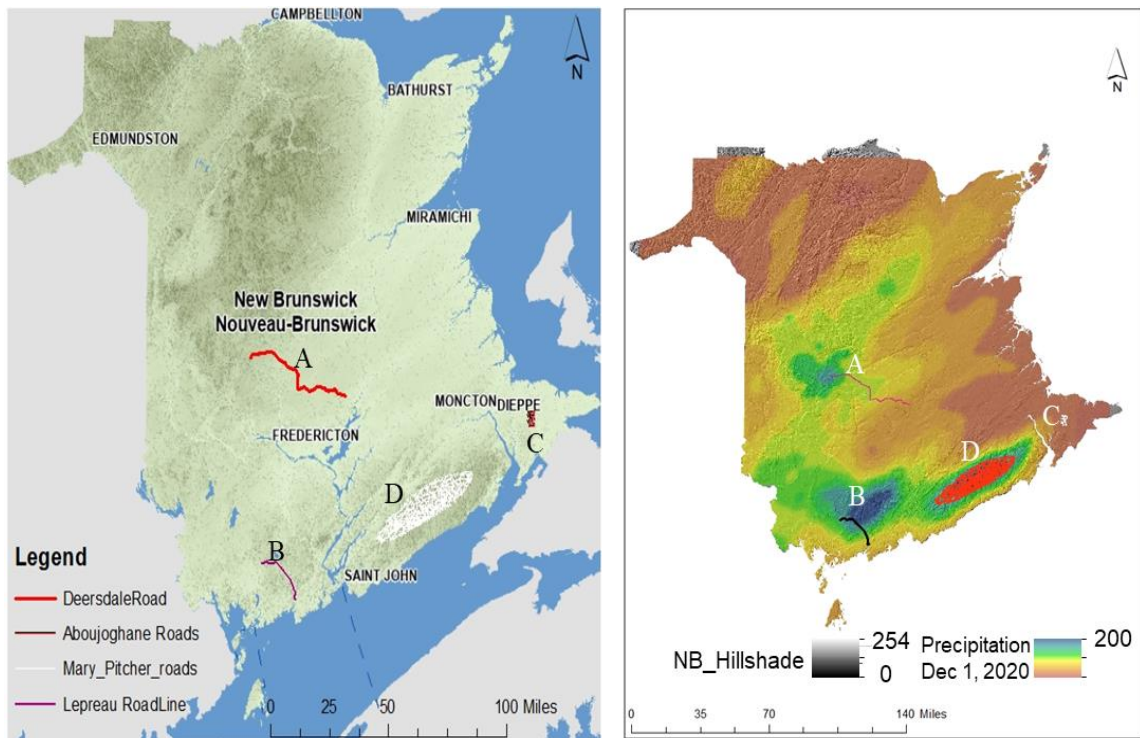


Figure 1.1. Locator map for the A, B, C, D Study Areas (left), with D done in part within the context of the December 1, 2020, precipitation event across New Brunswick (right).

Study area A (Figure 1.2) includes a 60-km long forest road that stretches from Deersdale to Duffy's Corner in central New Brunswick, Canada. This route serves as a forest harvest, supply, and service road, and needs information on road-stream crossing locations and related culvert placements and culvert sizing recommendations. It lies in part in York County to the west, and in Sunbury County to the east. The approximate coordinates stretch from 46.48° N, 66.06° W to 46.18° N, 66.03°W.

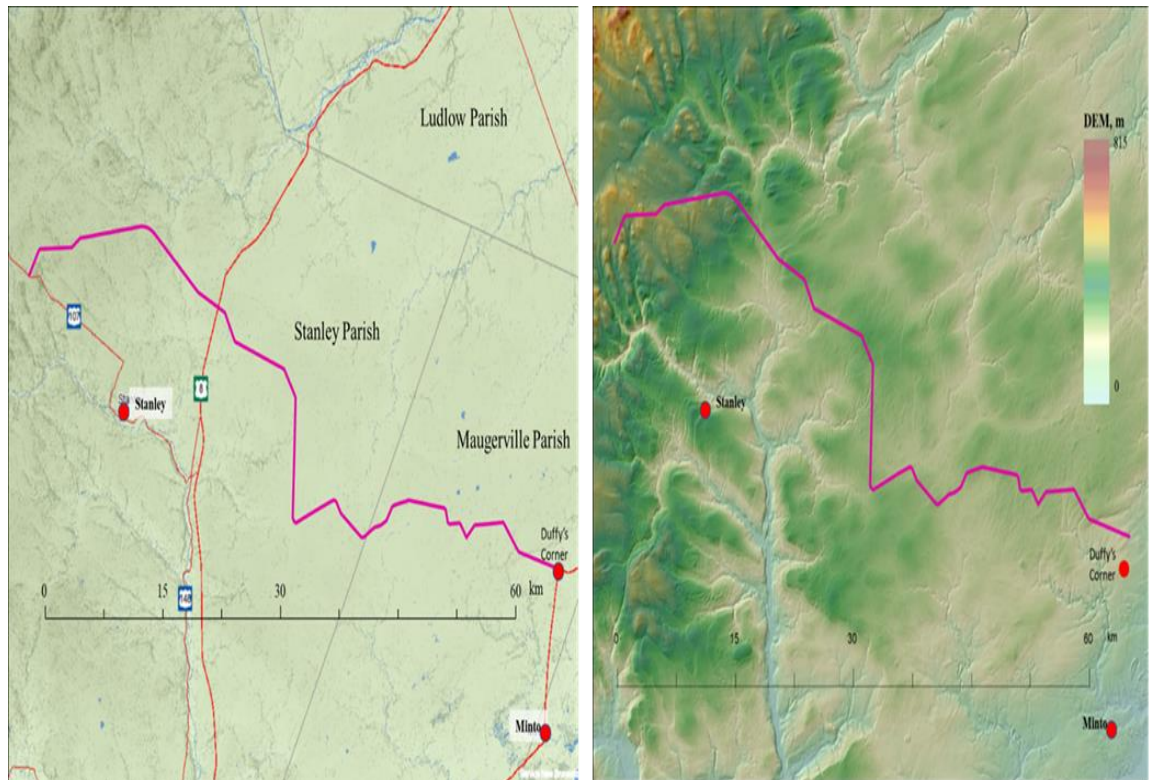


Figure 1.2. Locator map and hill-shaded DEM for Study area A, centered on an existing logging road needed to connect a forest management area to the west, northwest of Stanley (upper left corner) to the closest sawmill located in Chipman, east of Duffy’s Corner.

Study area B (Figure 1.3) is located northwest of Lepreau in southwestern New Brunswick, stretching from Saint John County in the east into Charlotte County in the northwest. The Road is 32 km long and runs within the Mink Brook and New River watersheds. The area is centered at 45.07° N, 66.45° W. This road also needs information on road-stream crossing locations within the context of actual culvert placements and culvert sizes.

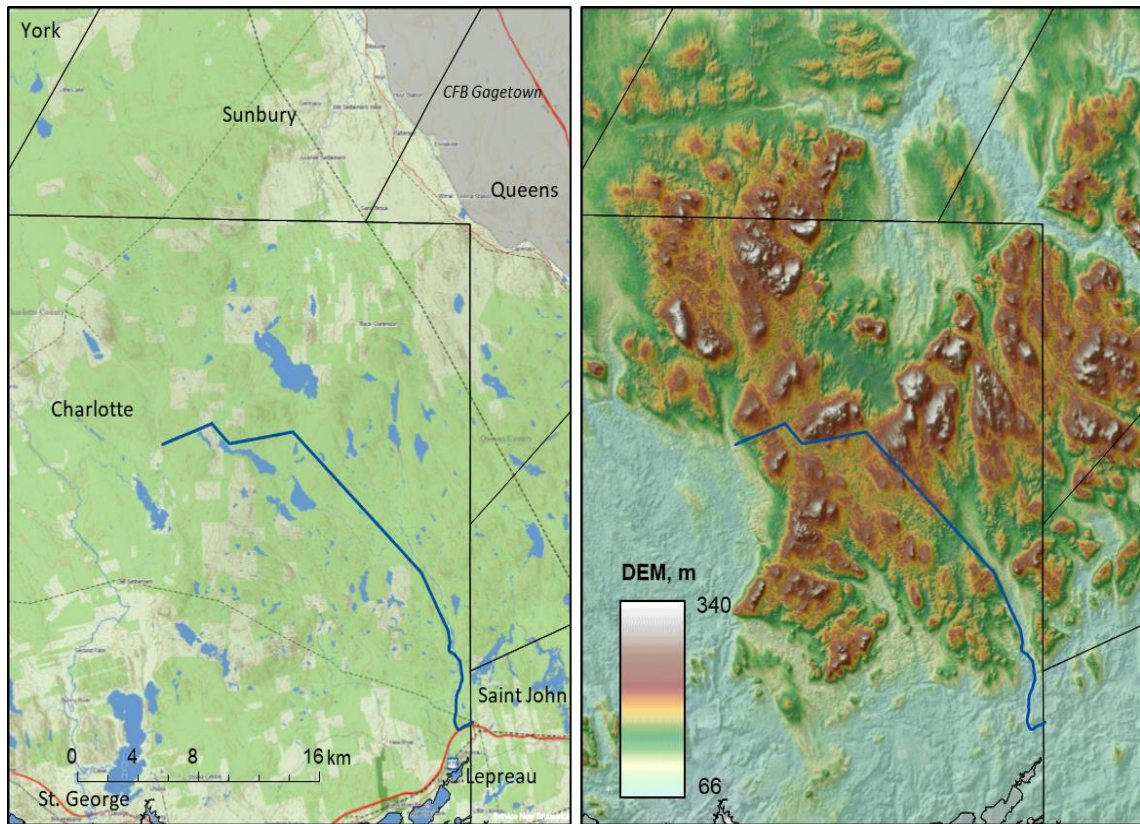


Figure 1.3. Locator map and hill-shaded DEM for B, centered on a proposed logging road needed to connect a forest management area centered on Pleasant Ridge (upper left corner) to the closest sawmill located at Lake Utopia near Point Lepreau in southwest New Brunswick (lower right corner).

Study area C (Figure 1.4) is centered on the forest road network connected with the Aboujagane road located within Westmorland County east of Moncton and north of Sackville, New Brunswick. This area is used to develop and to demonstrate the application of the road and trail selection tool.

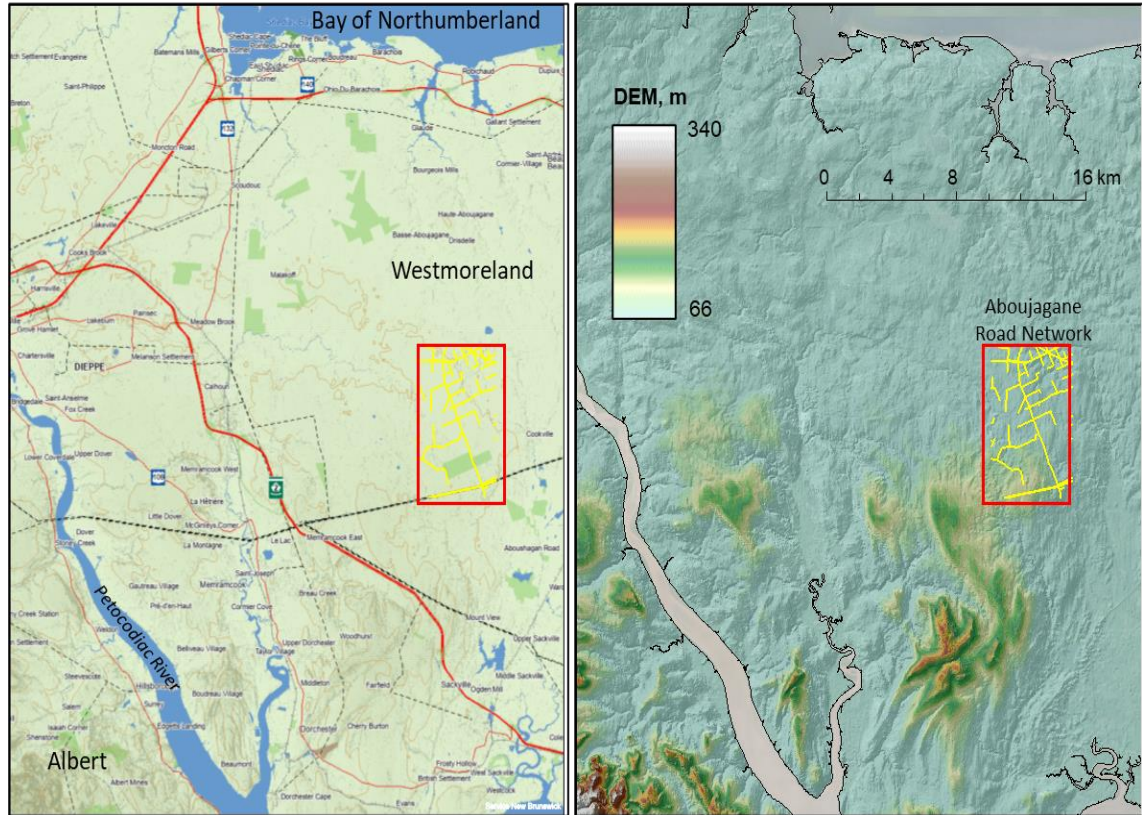


Figure 1.4. Locator map and hill-shaded DEM for Study Area C, centered on a section of the Aboujagane Road, used in this Thesis to show-case the Road and Trail Selection tool.

Study area D (Figure 1.5) is a network of roads located within Saint Martin's Parish and Saint Martin's Village, all located within the Saint John County in southeastern New Brunswick. This area, centered at 45.4296° N, 65.3530° W, corresponds to the area receiving the highest precipitation amounts during the December 1, 2020, storm event.

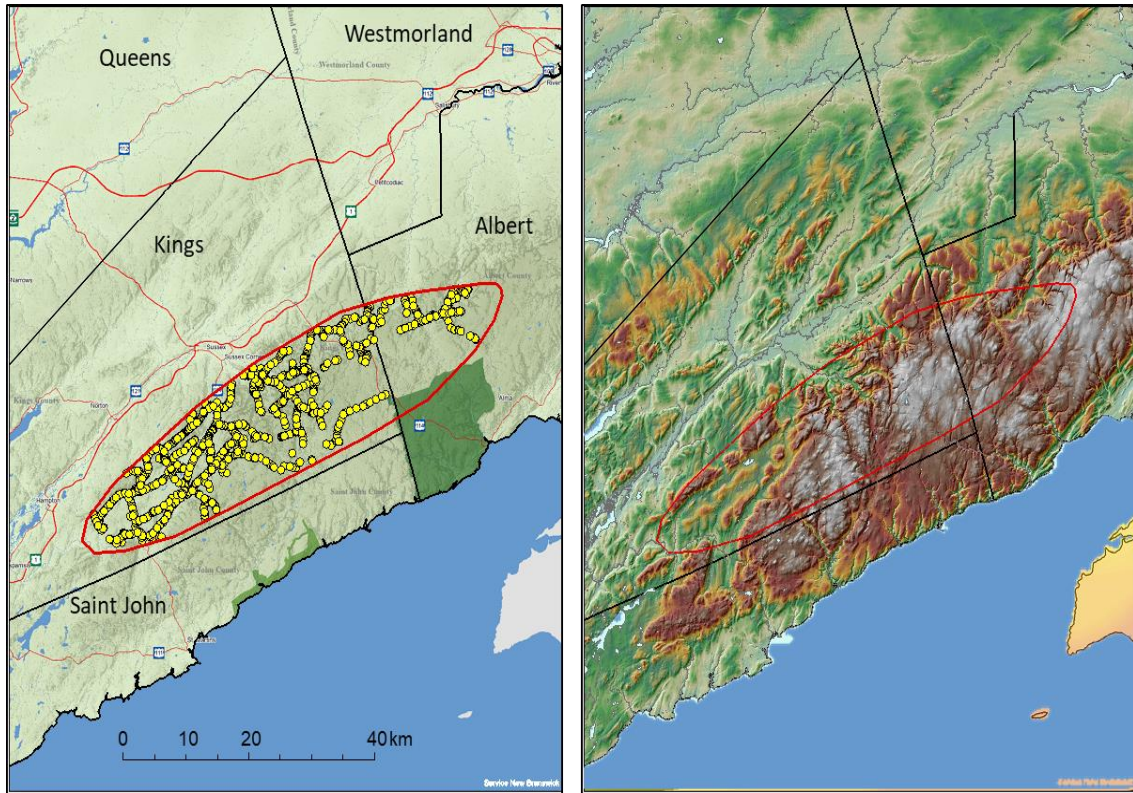


Figure 1.5. Locator map and hill-shaded DEM for Study Area D, centered on the areas that received the highest precipitation amounts during the December 1st, 2020, storm event.

1.6. Thesis Organization

Chapter 1 provides the overall thesis context.

Chapter 2 details the workflows used for generating the road and culvert delineation tools.

Chapter 3 and 4 demonstrates how the tools described in Chapter 2 are used for two road segment delineations in central New Brunswick, one 60 and one 32 km long.

Chapter 5 develops and demonstrates the layout for the road/trail layout tool and evaluates the same as for another road segment in New Brunswick, 10 km long.

Chapter 6 demonstrates the application of this study to a network of provincial and existing forest roads that experienced culvert washouts due to a major storm event in December 2020.

Chapter 7 summarizes the results achieved, explores matters of general and specific applications, and suggests areas for further research and related developments.

CHAPTER TWO: PROPOSED ROAD/CULVERT DELINEATION AND EVALUATION TOOLS

2.1. Introduction

The proposed road/culvert delineation and evaluation tools, intended to be used to evaluate existing road segments, are based on the premise that flow paths, flow directions and upstream flow contributing areas or flow accumulations can be modelled to favorable effect using high-resolution bare earth elevation data (Murphy et. al, 2008). To this end, already existing roads often need to be realigned to conform to DEM-recognizable roadbed locations. In addition, LiDAR generated DEMs with 1-m resolution need to be notched to ensure that DEM-generated flow paths are properly tracked and are crossing roads seamlessly and depression free. The crossings marked then become possible culvert and/or bridge locations. For culvert sizing purposes, potential discharge rates need to be estimated for each road-stream crossing based on upslope watershed areas and for, e.g., 50, 100 and/or 200 mm/day discharge events.

Figure 2.1 provides a 3-part workflow by which the proposed ArcGIS procedures can be used to improve the delineation and evaluation of existing road networks including culvert locations and sizes. For this work, study area must be specified, and the required shapefile and raster data layers need to be gathered and entered to the developing ArcGIS project and related area of interest. These layers refer to (i) the already existing road network prior to re-delineation, and (ii) the 1-m resolution bare-earth DEM showing the elevations from low to high and overlaid on the hill shaded DEM for direct visualization purposes. The resulting workflows are, as shown, organized in three parts.

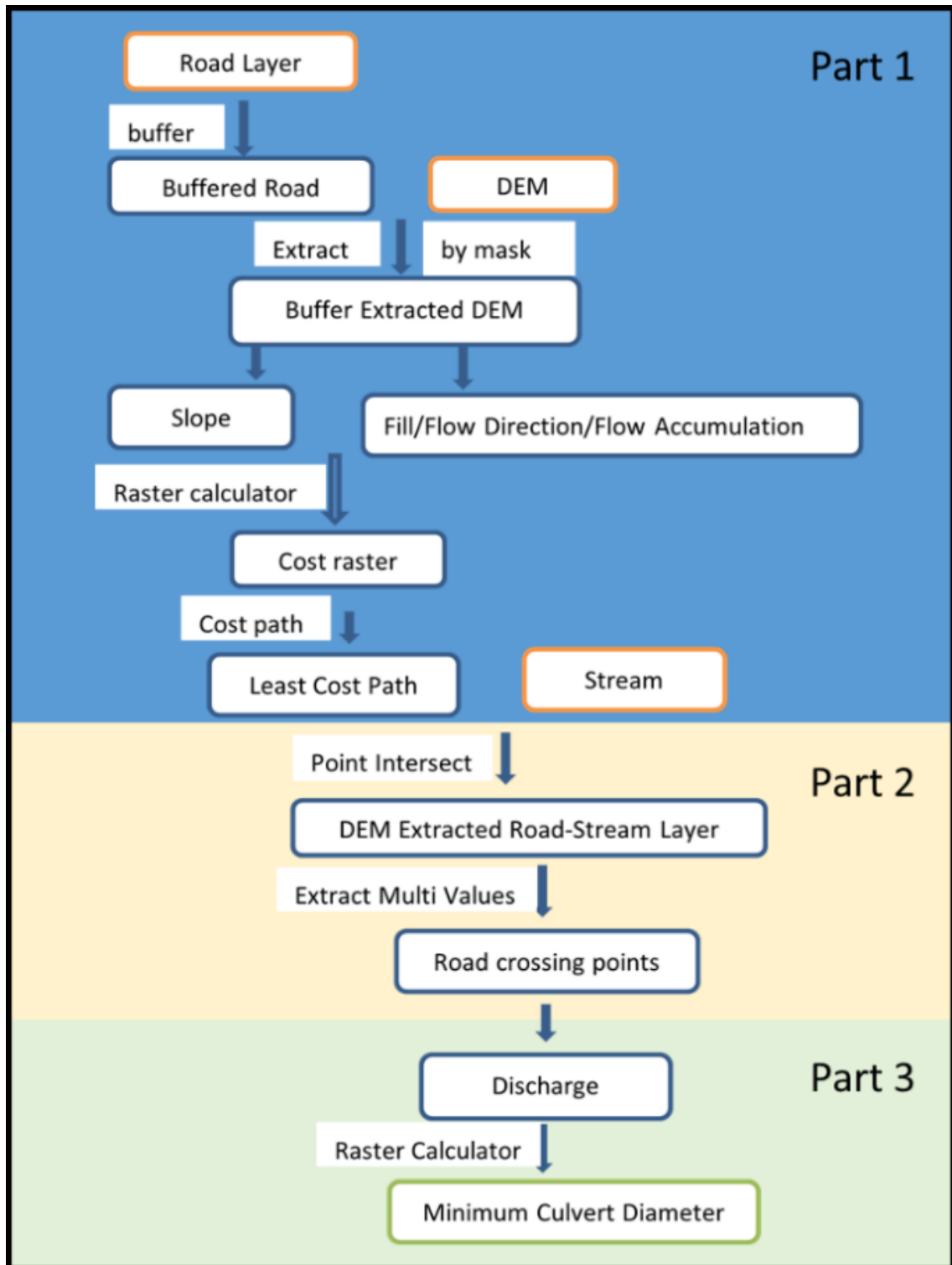


Figure 2.1. Simplified 3-part workflow of the ArcGIS model showing the steps to be followed. Inputs are in orange boxes, intermediate outputs in blue boxes and final output in green box.

Part 1 starts with the ArcGIS selection of an existing or suggested road segment with desired start and endpoints specified. The selected segment is then buffered, with its extent representing all the watershed areas that drain towards the selected road segment, as apparent from the 1-m hillshaded DEM. Once established, this buffer is used to extract the bare-earth elevation data across the buffered area. These 1-m resolution data within this area serves to derive:

1. The slope raster (Slope).
2. The depression filled DEM raster (FI).
3. The flow direction raster (FD).
4. The flow accumulation raster (FA).
5. The associated stream-channel network, derived from the flow accumulation raster through reclassification such that all FA cells $< 10,000$ or $< 40,000 \text{ m}^2$ (i.e., 1 or 4 hectares, respectively) become No Data and all cells with > 1 or 4 ha become 1.
6. The stream-to-feature process is then used to generate the hydro-network channel networks (Streams1ha, Streams4ha) with > 1 or 4 ha upslope flow accumulation areas (also called upslope discharge areas).

Part 2 uses the Part 1 developed Slope raster to generate the least-cost path between the beginning and the endpoint of the selected road segment. The least-cost path generally aligns itself with smooth roadbed elevations. The exception in this regard refers to, e.g., missing bridge connections that are removed as part of the LiDAR DEM provision process. Once reconnected, the re-delineated road is intersected by the buffer-established flow channel network based on all road-intersecting > 1 or > 4 ha upslope drainage areas.

In this way, the resulting intersection points become possible DEM-generated culvert/bridge locations.

Part 3 buffers each of the culvert/bridge location points to 10-m to extract the maximum flow accumulation number within each of these buffers. This is done using “Zonal Statistics.” The resulting maximum FA numbers serve to estimate maximum expected discharge rates at each road-stream location in m^3/second , based on incoming upslope discharge rates in terms of, say, 100 mm/day. The resulting discharge numbers are used to recommend minimum culvert diameter for each road-stream crossing point.

2.2. Workflow Details

Part 1. The workflow in Figure 2.1 requires the DEM, and the associated shapefiles for > 1 and >4 ha upstream flow accumulation channels, and the selected road segments as input. The selected road segments are buffered using the “Buffer” tool, to the extent that the already delineated road buffer covers the DEM-defined roadbed width three times. The “Dissolve” tool collects and dissolves all the buffered segments to become a single buffered road feature. The start and end of this feature is set to become flat rather than round. The resulting shapefile becomes the “Mask” for extracting the 1-m elevation data from the DEM. The DEM extracted, uses the “Fill” process to flatten the depressed areas (FI). The resulting raster becomes the input for the eight-cardinal-direction “Flow Direction, D8” process (FD), which, in turn, feeds into the “Flow Accumulation” (FA), and “Slope” tools (slope in percentage). This process for determining upslope flow contribution areas or FA is described in detail by Quinn et. al. (1991).

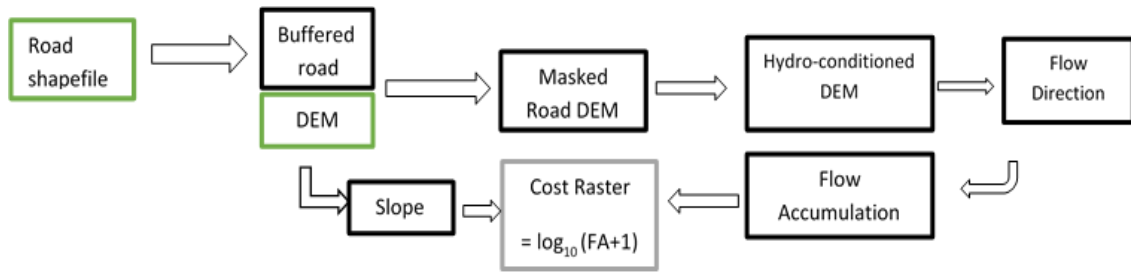


Figure 2.2. Part 1: workflow for the road delineation Tool.

The “FA” and “Slope” rasters determine the accumulating “FA” and “Slope” costs along the buffered road extent after all FA = 0 and Slope = 0 are adjusted to become 1 and 0.001, respectively using “Raster Calculator”. Doing so generates the cost for each cell across the entire extent including the FA = 0 and Slope = 0 cells as follows:

$$\text{Road delineation cost raster} = \log_{10}(FA+1) * 40 + (Slope + 0.001)\%$$

These “costs” increase more along steep upward and downward slopes ditches and road cuts but remain low along the crested roadbed centers.

The Road delineation cost raster provides the means to automatically track which cells remain on the DEM-captured roadbed. This tracking is accomplished by creating a shapefile for the start (A) point of the buffered road segment. This shapefile initiates the “Cost Distance” tool to run across the “Maximum Distance” extent of the $\log_{10}(FA+1) * 40 + (Slope + 0.001) \%$ cost raster. Doing so produces the “Cost Distance” and associated “Back Link” rasters, as needed for Part 2.

Part 2. The workflow chart in Figure 2.3 is used to create the “Start and End Points” A and B shapefile which is needed to initiate the “Least Cost Path” tool along the “Cost Distance” and associated “Back Link” rasters. The resulting one-cell path connects A to B.

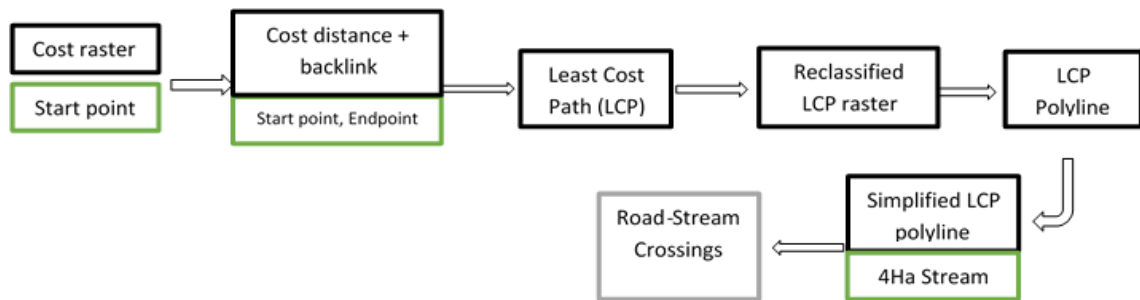


Figure 2.3. Part 2: workflow of the least-cost path and road-stream crossings tool.

This raster becomes the least cost path polyline (“LCP”) by:

1. Re-classifying all least cost cell values other than “No Data” into 1.
2. Converting the resulting raster into a line feature via the “Raster to Polyline” tool.
3. Further simplifying the resulting line using the “Simplify Line” tool, to remove inadvertent bends along and beyond the DEM-recognizable roadbed.

The simplified LCP line is subsequently point-intersected with the > 1 and > 4 ha flow channel layer to locate where the upstream flow channels cross the road. The resulting “Road-Stream Crossing Point” shapefile followed by 5-m buffering becomes the input layer for Part 3.

Part 3. The workflow chart in Figure 2.4 is used to determine the maximum FA number at each buffered road-stream crossing point. The “Extract Multi Values to Point” tool adds these values to the “Road-Stream Crossing” point shapefile. Using the “Create Field” tool creates two fields within this shapefile for discharge and recommended culvert diameter based on a set area-wide mm/day discharge event, such as 100 mm/day.

These calculations are done with the “Calculate Field” tool as follows:

$$\text{Discharge rate (Q)} = \frac{\text{FA} * \text{discharge} * 1000}{(24*60*60)}$$

This is followed by Manning's minimum culvert diameter formula (Manning, 1891), i.e.:

$$\text{Minimum Culvert Diameter CD (in mm)} = 2000 \left(\frac{(2^{2/3} \eta Q)}{\pi (\text{Slope})^{0.5}} \right)^{3/8}$$

with η as the culvert surface roughness, Q as even flow discharge rate in m³/sec, and Slope as culvert slope (drop / run), in percent.

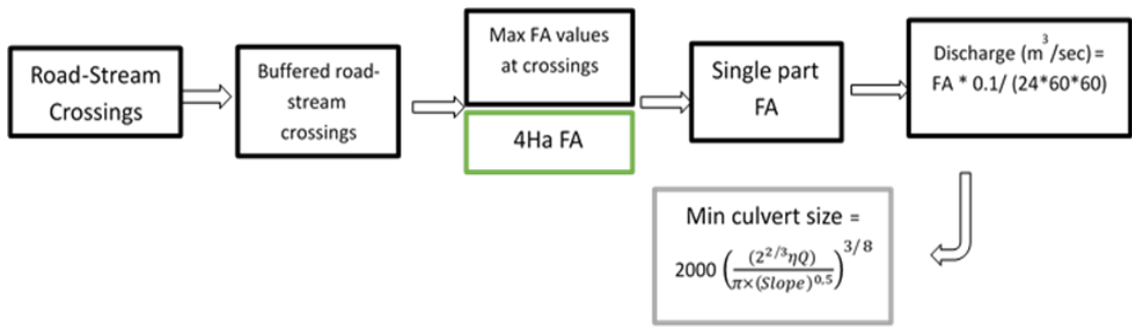


Figure 2.4. Part 3: workflow of the culvert sizing tool.

The above formula for Manning's culvert diameter can be obtained by equating Manning's formula for culvert discharge with expected watershed-generated discharge excess (D_{excess} , in mm/per day) as follows:

$$Q = A R_H^{2/3} \text{Slope}^{0.5} / \eta = \pi R^{3/8} \text{Slope}^{0.5} / (\eta 2^{2/3}) = \frac{\text{FA} * \text{discharge} * 1000}{(24*60*60)}$$

where

A is the cross-sectional area in m²,

$R_H = A / (2 \pi R)$ is the hydraulic radius in meters,

Slope is the culvert slope (drop/run) in percent, and

η is the culvert surface roughness coefficients, set at 0.022 for corrugate culverts, and

$$R = \left(\frac{2^{2/3} \eta Q}{\pi (\text{Slope})^{0.5}} \right)^{3/8}.$$

is the geometric radius in meters.

With this formulation, it is assumed that:

1. flow rates are even from the beginning to the end of each discharge event,
2. each precipitation event lasts longer than each discharge-affecting precipitation and snowmelt event,
3. each hydrometrically quantified discharge event, as represented by its hydrograph, rises towards peak flow before slowing down to background or base flow conditions.

To some extent, flow-discharge observations following single precipitation can be displayed in terms of standardized hydrographs (Gray, 1962; Zhu et al., 2019; Del Rio et al., 2020) such that:

1. flow rates are expressed in % of total discharge volume per event along the y axis, and
2. peak flow occurs in standardized time along the x-axis, so that time at peak flow equals 1.

By mathematical presentation, this hydrograph standardization as originally formulated by Gray (1962) tracks field-determined discharge rates Q in dimensionless form as follows:

$$Q_{t/P_R} = \frac{100 (\gamma')^q}{\Gamma(q)} e^{-\gamma' t/P_R} (t/P_R)^{q-1}$$

where

t is time (seconds),

P_R is peak time (seconds),

Q from t = 0.875 x P_R to 1.125 P_R is given in % by

$$Q_{t=P_R/P_R} = \frac{25 (\gamma')^q}{\Gamma(q)} e^{-\gamma'},$$

where

$$q = 1.445 + 0.873 \gamma',$$

$$\gamma' = 2.676 + 0.0139 P_R, \text{ and}$$

$$\frac{P_R}{\gamma'} = 9.77 \left(\frac{L}{S_c} \right)^{0.475}.$$

In addition, with

L = 1.40 A^{0.568} estimated as the mean upslope stream length in meters and

S_c = 1.62 L^{-0.663} estimated as the mean upslope stream slope in percent,

P_R can be determined from

$$P_R = \frac{2.676}{\frac{1}{P_R/\gamma'} - 0.0139}.$$

The means to estimate required minimum culvert sizes in terms of expected precipitation and snowmelt thresholds as specified above is facilitated through the STELLA modelling programme, with its workflow and script presented in Figure 2.5 and Table 2.1.

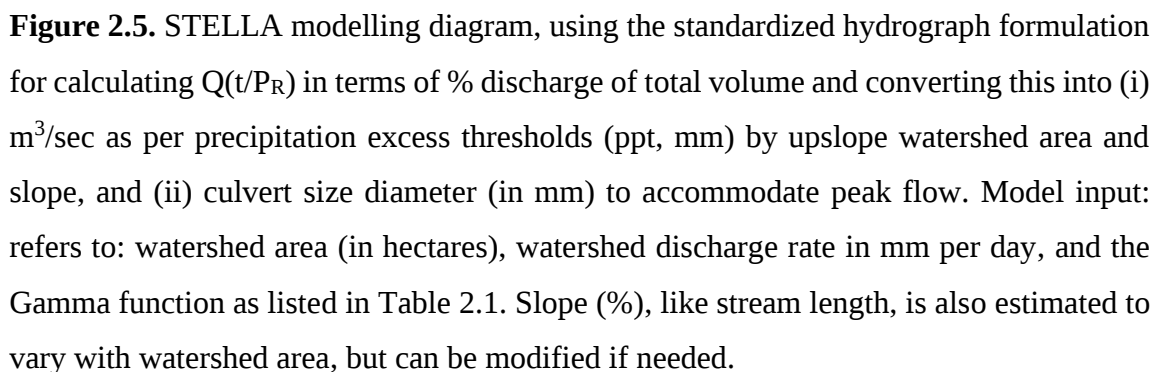


Table 2.1. Stella model equation details for estimating even flow and peak flow of discharge according to the standardized hydrograph formulation by Gray (1962) by varying watershed area, slope, and set precipitation rate (mm per day). Also included: required culvert size for even and peak flow discharge based on Manning's formula.

```

Cumulative_discharge_%(t) = Cumulative_discharge_%(t - dt) + (Discharge_%) * dt
INIT Cumulative_discharge_% = 0
Culvert_diameter_mm = 2000 * (2^0.5 * Surface_roughness * Peak_flow_m3_sec
/3.14/Culvert_slope^0.5)^(3/8)
Culvert_slope = 0.015
Days_of_flow = Peakttime_in_days*3.8
Even_flow_cfs = Cubic_feet/(Days_of_flow*24*60*60)
Even_flow_m3_sec = Volume_m3/Days_of_flow/24/60/60
Gamma_function = exp((q-.5)*LOGN(q)-q+0.5*logn(pi*2)+1/(12*q)
-1/(360*q^3)+1/(1260*q^5-1/(1680*q^7)))
HydroQ% = q_prime^q/Gamma_function*exp(-q_prime*time)*time^(q-1)*100
Lslope = Main_stream_length/Slope^0.5
Main_stream_length = 1.4*(Watershed_area_km2/1.60934^2)^0.568
Peak_to_even_flow_ratio = Peak_cfs/Even_flow_cfs
Peak_cfs = PeakQ%*Cubic_feet_per_second/100
Peak_flow_m3_sec = Peak_cfs*0.028
Peak_gamma = 9.77*Lslope^0.4750
Peak_time_adjustment = 12*1.6
Peak_time_seconds = Peak_time_units*60*Peak_time_adjustment
Peak_time_units = 2.676/(1/Peak_gamma-0.0139)
Peakflow_mm_day = Peak_flow_m3_sec*Peak_time_seconds*0.25*1000
/(Watershed_area_km2*10^6)
PeakQ% = q_prime^q/Gamma_function*exp(-q_prime)*25
Peakttime_in_days = Peak_time_seconds/24/60/60
ppt_mm = 108*8/11/2.4
q = (1.445+q_prime*0.873)
q_prime = Peak_time_units/Peak_gamma
Slope = 1.62*Main_stream_length^(-0.663)
Surface_roughness = 0.022
Volume_m3 = ppt_mm/1000*Watershed_area_km2*10^6
Watershed_area_km2 = 27

```

Table 2.2. (below) shows how the standardized hydrograph formulation varies by:

1. Upslope Flow Accumulation (or watershed area) in terms of Peak Time (P_R in minutes),
2. Number of Peak Time Durations (in terms of P_R units), and
3. Peak Discharge Rates Q (t/P_R) in % of total event discharge volume V .

According to the Table 2.2 results, standardized peak flow discharge tends to be about three times higher than assumed even-flow discharge across estimated hydrograph duration. Hence, according to Manning's formula, the minimum required culvert diameter needed to accommodate peak discharge rates associated with, e.g., 50, 100 or 200 mm/day discharge events per day needs to be adjusted to:

$$CD \text{ (mm)} = 2000 \left(\frac{2^{2/3} \eta 3 Q}{\pi (\text{Slope})^{0.5}} \right)^{3/8}.$$

Table 2.2. Standardized hydrograph calculations for peak flow time (P_R , minutes), peak flow discharge ($Q_{(t=P_R)}$ in % of total flow volume), flow duration (expressed in P_R units), and peak-to-even flow ratio.

Watershed Area km ²	log10 (Area) x	Dimensionless Peak Time Durations			Peak Time	Peak Discharge	Even Flow units per 0.25 Peak Time	Even Flow	Peak / Even Flow Ratio
		Modelled y	Regressed y vs.x	Absolute Difference	minutes	%		%	
0.01	-2	4.34	0.00	1.73	4.0	15.7	17.4	5.8	2.73
0.1	-1	4.28	4.25	0.79	9.4	16.0	17.1	5.8	2.73
1	0	4.1	4.16	1.49	22.9	16.6	16.4	6.1	2.72
10	1	3.7	3.80	2.73	61.9	18.3	14.8	6.8	2.71
25	1.40	3.4	3.48	2.22	98.4	19.8	13.6	7.4	2.69
50	1.70	3.14	3.13	0.34	147.1	21.6	12.6	8.0	2.71
75	1.88	2.92	2.89	1.12	194.1	23.1	11.7	8.6	2.70
100	2.00	2.76	2.70	2.16	241.7	24.6	11.0	9.1	2.72
120	2.08	2.6	2.58	0.90	292.5	26.0	10.4	9.6	2.71
150	2.18	2.48	2.42	2.38	348.2	27.5	9.9	10.1	2.73
175	2.24	2.38	2.31	2.87	410.2	30.0	9.5	10.5	2.86
200	2.30	2.24	2.22	1.07	480.7	30.6	9.0	11.2	2.74
225	2.35	2.14	2.13	0.40	562.1	32.2	8.6	11.7	2.76
250	2.40	2.04	2.06	0.77	657.9	34.0	8.2	12.3	2.77
275	2.44	1.94	1.99	2.44	772.8	35.9	7.8	12.9	2.78
325	2.51	1.86	1.87	0.46	1,091.7	40.2	7.4	13.4	2.99
350	2.54	1.76	1.82	3.20	1,323.7	42.7	7.0	14.2	3.00
400	2.60	1.68	1.72	2.57	2,097.3	48.2	6.7	14.9	3.24

This standardized hydrograph formulation would, in principle, not be applicable when multiple precipitation and snowmelt events occur in quick succession during the same storm. The resulting flow patterns will likely be spiked, but these spikes would diminish with increasing upslope watershed area because the run-off flows would merge with increasing upslope areas provided that overall precipitation rates remain the same across the increasing areas. For small upslope watershed areas, individual runoff bursts could be short and frequent over the course of a day, but these bursts could still result into a single discharge peak across the larger watershed area.

Another point to note is that the above formulation for $Q_{(t/P_R)}$ becomes more symmetrical about its peak with increasing upslope watershed area and storm durations, thereby approaching a Gaussian distribution curve (Figure 2.6).

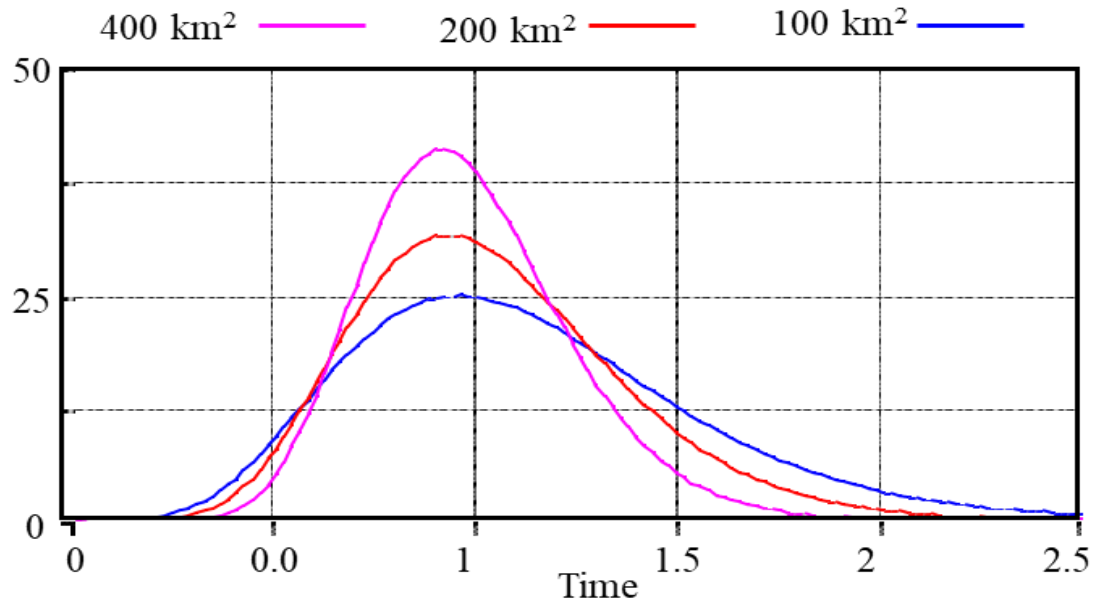


Figure 2.6. Display of $Q(\text{Time}/P_R)$ in % of total discharge volume per storm event as the upslope discharge area increases from 100 to 200 and 400 km^2 . Note that the Q as function of Time/P_R narrows in duration and becomes increasingly symmetrical towards peak discharge. Also, note that peak flow occurrence as modelled shifts to slightly lower than when calculated when $P_R = 2.676 / [1/(P_R/\gamma') - 0.139] = 1$.

CHAPTER THREE: ROAD-STREAM DELINEATION, DEERSDALE ROAD (STUDY AREA A)

3.1. Introduction

This chapter applies road delineation, flow accumulation network and culvert evaluation tools described in Chapter 2 to Study Area A, known as Duffy's Corner Road. This road, a dedicated forest logging route, is part of the existing provincial road network, with its eastern portion constructed recently. The objectives for this chapter refer to the following:

1. To contrast the original-versus the tool-generated roadbed delineation through visual and quantitative means.
2. To evaluate the Study Area A hydro-network channel network in relation to the DEM-located road-stream crossings based on applying two contrasting flow direction and flow accumulation algorithms using:
 - (i) the study-area DEM resampled and filled at 10-m resolution, and
 - (ii) The 1-m DEM of the study area subjected to continuous flow algorithm in ArcGIS Pro.
3. To compare and evaluate the road-stream crossing outputs generated, with both in contrast with the road-stream crossing points associated with
 - (i) GeoNB's hydro-network data layer for streams, and
 - (ii) the existing culvert inventory data along the selected road segment.

3.2. Methods

Input data layers used for this case study refer to the provincial 1-m resolution DEM, and the existing Road and Basemap Enhanced Image layers (all obtained from GeoNB Data Catalogue) and associated culvert specification layers (obtained from J.D. Irving Ltd.). The selected road segment was overlaid on the hill-shaded 1-m DEM and its resampled 10-m resolution version. This overlay was visually inspected to determine the extent to which the already delineated road required either visual and/or automated DEM re-alignments. By application of the Part 1 and Part 2 procedures in Chapter 2, visual and/or automated re-alignment was needed across several instances, especially along the eastern part of the selected road segment. Figure 3.1 highlights the Deersdale road segment overlaid on the 1-m hill-shaded DEM and the provincial road network.



Figure 3.1. Selected road segment (red line) overlaid on the local road network (white lines) and the 1-m hill-shaded DEM of Study Area A.

The 1 and 10-m resolution DEMs were used to derive the DEM flow channel patterns across Study Area A. These were visualized with the following upslope flow accumulation thresholds: > 1, > 4, > 10, > 40, > 100, and > 400 ha, and to contrast the

channels derived with the GeoNB derived hydro-network where the upslope flow accumulation threshold would vary with each first order stream.

Potential culvert and bridge locations were determined along the 60 km road segment by intersecting each of the flow channels generated with this road. Doing so produced the number of un-notched road-stream crossings for the 1 and 10-m resolution DEM and the GeoNB derived hydro-network lines. These numbers were subsequently refined by notching the 1 and 10-m DEMs by:

1. DEM-generated depressions above the roads, produced by subtracting the original DEM elevations from the filled DEM elevation.
2. Prolonged ditch-mitigated flow diversions along the road.
3. Readily transparent culvert and bridge installations as per image and the hill-shaded 1-m resolution DEM.

The finalized number of road-stream crossings were evaluated in terms of potential 100 mm per day stream discharge based on the maximum flow accumulation at these locations. The resulting discharge rates (m^3/sec) were used to estimate the minimum culvert diameters that would be required to accommodate these flow rates. The information generated was tabulated and compared with the culvert size specifications within the provincial road-stream crossing data layer.

3.3. Results

Road Delineation: Scanning the selected road segment from its beginning to end revealed that the road consisted of two parts: the western section was part of the established provincial road network, while the eastern part was recently upgraded. The existing western road delineation coincided entirely with the hill-shaded DEM roadbed projection. Along the eastern part, there were 25 locations where the road delineation was marginal at best and/or deviated from the hill-shaded DEM roadbed projection. Examples of these deviations are shown in Figures 3.2 and 3.3. While these deviations could easily be corrected through manual editing, it was instructive to observe how the automated road delineation tool of Chapter 2 would perform along the entire road segment.



Figure 3.2. An example where the original road delineation veers off the elevated roadbed and falls into ditches along the road.

Generally, this delineation worked well except where the actual and the DEM-recognizable roadbed displayed irregularities, thereby requiring manual adjustments. Such irregularities occurred where the roadbed on bridges had been removed as part of the LiDAR DEM provision process.



Figure 3.3. Two additional examples of where the original road delineation fails. Top: road line gap. Bottom: road line follows a ditch next to the road.

Additional care needed to be taken in terms of simplifying the tool-generated road line by adjusting the bend and line simplification thresholds. Setting these too small would

not generate straight and smooth road segments as desired, conversely, setting these to high would lead to unacceptable roadbed deviations, especially along road intersections. Examples of original roadbed delineation deviations are illustrated in Figures 3.2 and 3.3 showing select overlays of the original (blue line) and the finalized DEM-re-aligned (red line) roadbed delineations within the DEM hill-shaded 10-m wide road buffer on the latest GeoNB surface imagery.

Flow channel networks: The two DEMs and the GeoNB hydro-network channel networks were used to determine the locations of road-stream crossing points, and related upslope flow accumulation areas. The resulting networks, as presented in Figure 3.4, differed in the following ways:

1. The D8 fill, flow-direction and flow accumulation algorithm using the smoothed 10-m DEM generated increasing road-stream crossing numbers with decreasing upslope flow accumulations areas. In contrast, the ArcGIS Pro algorithm for continuous flow direction and accumulation using the unsmoothed 1-m DEM leveled off with decreasing upslope flow-accumulations areas (Figure 3.5, Table 3.1).
2. The 10-m D8 algorithm followed the hill-shade recognizable flow paths quite closely but road-stream crossing locations had lower precision than what was attained with the 1-m ArcGIS Pro algorithm. This decreased flow-path precision led to frequent road-mitigated depressions and related ditch diversions, thereby decreasing the overall number of road-stream crossings across the mapping extent, and especially so when flow-accumulation areas above the roads drop below 20 ha (Table 3.1). At and above

this threshold, road-stream crossings tend to occur in valley bottoms where the roadbed elevations are lower than the surrounding elevations.

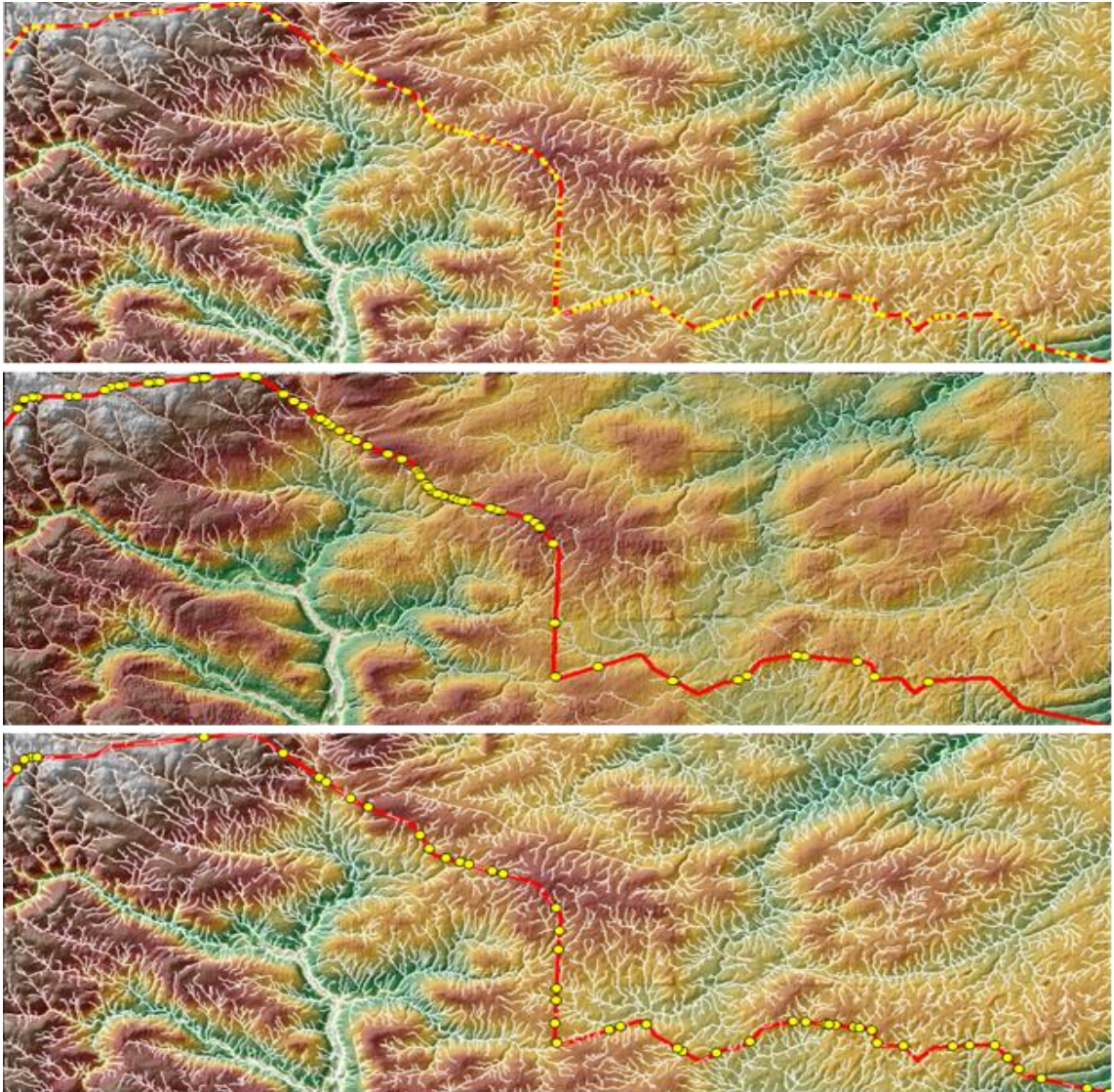


Figure 3.4. Study Area A with selected road segment (redline) overlaid by road-stream crossing locations (yellow dots) obtained by: (i) visual inspection of the 1-m hill-shaded DEM (top), (ii) placement of officially registered culvert locations (middle), and (iii) intersecting GeoNB's hydro-network channel network with the selected road segment (bottom). Also shown in white lines: the 1-m DEM derived flow channel network with >10 ha upslope flow accumulation areas (top and bottom), and GeoNB's hydro-network channel network (middle).

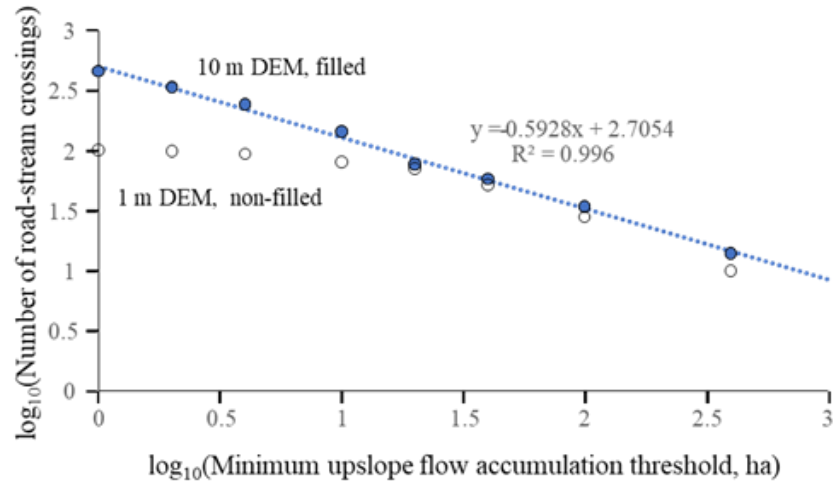


Figure 3.5. Number of Road-Stream crossings versus minimum upslope flow-accumulation threshold (ha), for the road-stream crossings along the Deersdale road segment in Study Area A, based on the 1 and 10-m DEM derivations (log10 vs. log10 plot, open versus filled points, respectively).

Table 3.1. Number of road-stream crossings generated using the filled and continuous (non-filled) flow direction and flow accumulation algorithms with varying minimum upslope flow-accumulation thresholds.

Minimum upslope flow accumulation area, ha	Number of road-stream crossings	
	DEM Resolution	
	10-m	1-m
	Depression- Filled Flow	Continuous Flow
400	14	10
100	34	28
40	58	52
20	77	71
10	144	80
4	243	94
1	461	102
GeoNB hydro network road-stream crossings: 49		
Visually derived road-stream crossings from the		
hill-shaded 1 m resolution DEM: 149		

Only 49 road-stream crossings were generated by intersecting the GeoNB's stream network with the selected road segment (Table 3.1, Figure 3.5). In comparison, the provincial culvert inventory listed 87 locations along the selected road segment. Visually inspecting the filled 10-m DEM and non-filled 1-m DEM with their DEM-derived flow channels located 149 road-stream crossings, i.e., about 3 times higher than the number produced by intersecting GeoNB's hydro-network channel network along the selected road segment (Table 3.1). In practice, locations with small culvert sizes are easily overlooked especially when overgrown or submerged with ditch-filled water.

Checking the locations of the provincial culvert locations with the visual DEM-suggested road-stream crossing revealed variations in nearest-neighbour distance from 0 to 200 m as plotted in Figure 3.6. About 84 and 90% of these distances fell within 40 and 80 m, respectively. These differences are likely due to GPS location errors.

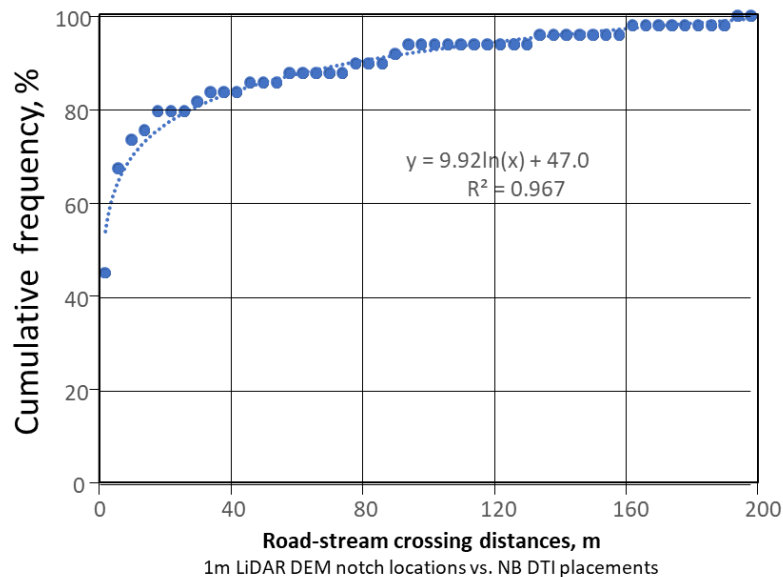


Figure 3.6. Distance variations between the 1-m DEM notched locations and the DTI culvert placements locations versus cumulative occurrence of these road-stream crossings.

Culvert Diameters, Reported and Estimated: Even flow and peak flow rates and related minimum culvert diameters required to withstand storm events leading to 100 mm per day discharge were estimated for the 10-m DEM generated road-stream crossings based on upslope flow accumulation areas. Flow rates and culvert diameters were expressed in terms of m^3/sec and mm, respectively. Figure 3.7 presents the diameter comparisons between these results when adjusted for culvert slope (i.e., 0.5, 1 and 2 %) and the corresponding reported values in the form of the 1:1 line.

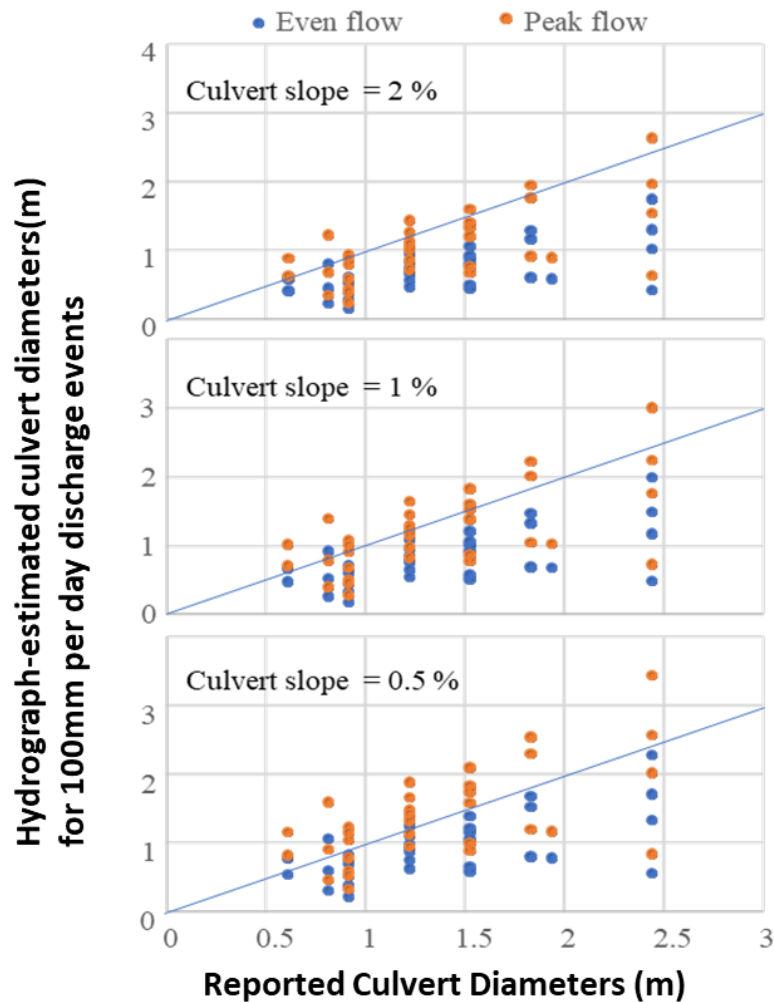


Figure 3.7. Estimated minimum culvert diameters based on the 10-m DEM flow accumulation algorithms as applied to the values reported for the provincially registered culvert locations, presented by the 1:1 line.

As shown, the estimated diameters for even flow tend to be below the reported values regardless of varying culvert slopes from 0.5 to 2%. Some of the estimated peak flow values, however, exceed the 1:1 line as culvert slope decreases from 2 to 0.5%. Generally, the slope = 0.5% specification allows for unrestricted fish passage (Feurich, 2012). Repeating these calculations for storm events with 50 mm per day discharge led to peak flow diameter specifications that do not exceed the reported values for the most part, i.e., like the 2 % slope generated values in Figure 3.7.

Figure 3.8. shows how maximum flow velocities through culverts vary during storm discharge events with 50 and 100 mm/day by hydrograph and reported diameter specifications. This is done within the context that fish generally do not overcome flow velocities > 1.2 m/sec (Watercourse and Wetland Alteration Technical Guidelines, 2012). As shown, and as expected, the range of even- and peak flow velocities < 1.2 m is much wider during 50 than for the 100 mm/day discharge events.

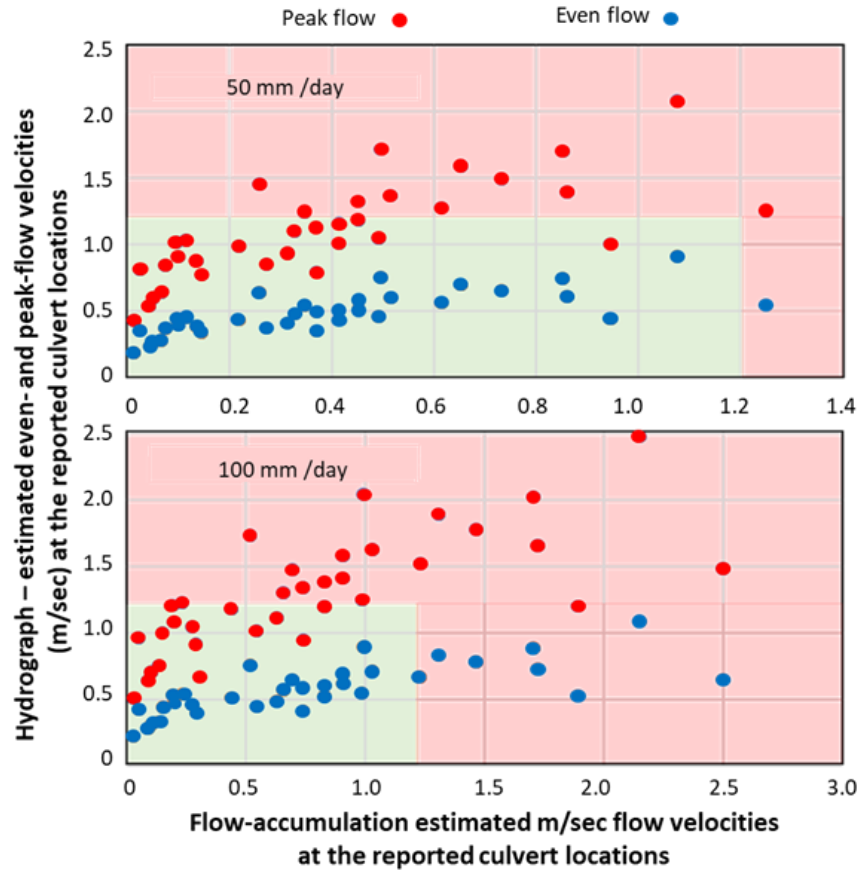


Figure 3.8. Maximum flow velocities = $R^{2/3} \text{ Slope}^{0.5} / \text{Culvert Roughness}$ as per reported and hydrograph-evaluated culvert diameters for 50 (top) and 100 (bottom) mm/day discharge in comparison with the > 1.2 m/sec fish passage limit. R: Culvert Radius; Slope= 0.005 for ensuring fish passage (Slope % = 0.5%); Culvert Roughness = 0.022.

Figure 3.9. provides two examples about the reported (black) and the 10-m DEM (yellow) derived road-stream crossing locations with > 1 ha upslope flow-accumulation areas. These are labelled by reported and minimum hydrograph-expected culvert diameters (in m), respectively. As seen, there are more yellow than black dots, including reported road-stream crossing locations with no culvert diameter specifications. This is possibly due to (i) underreporting, and/or (ii) intended ditch diversion of converging flow channels

towards lower elevation locations. The 0-labelled black dots mark reported cross drain locations.

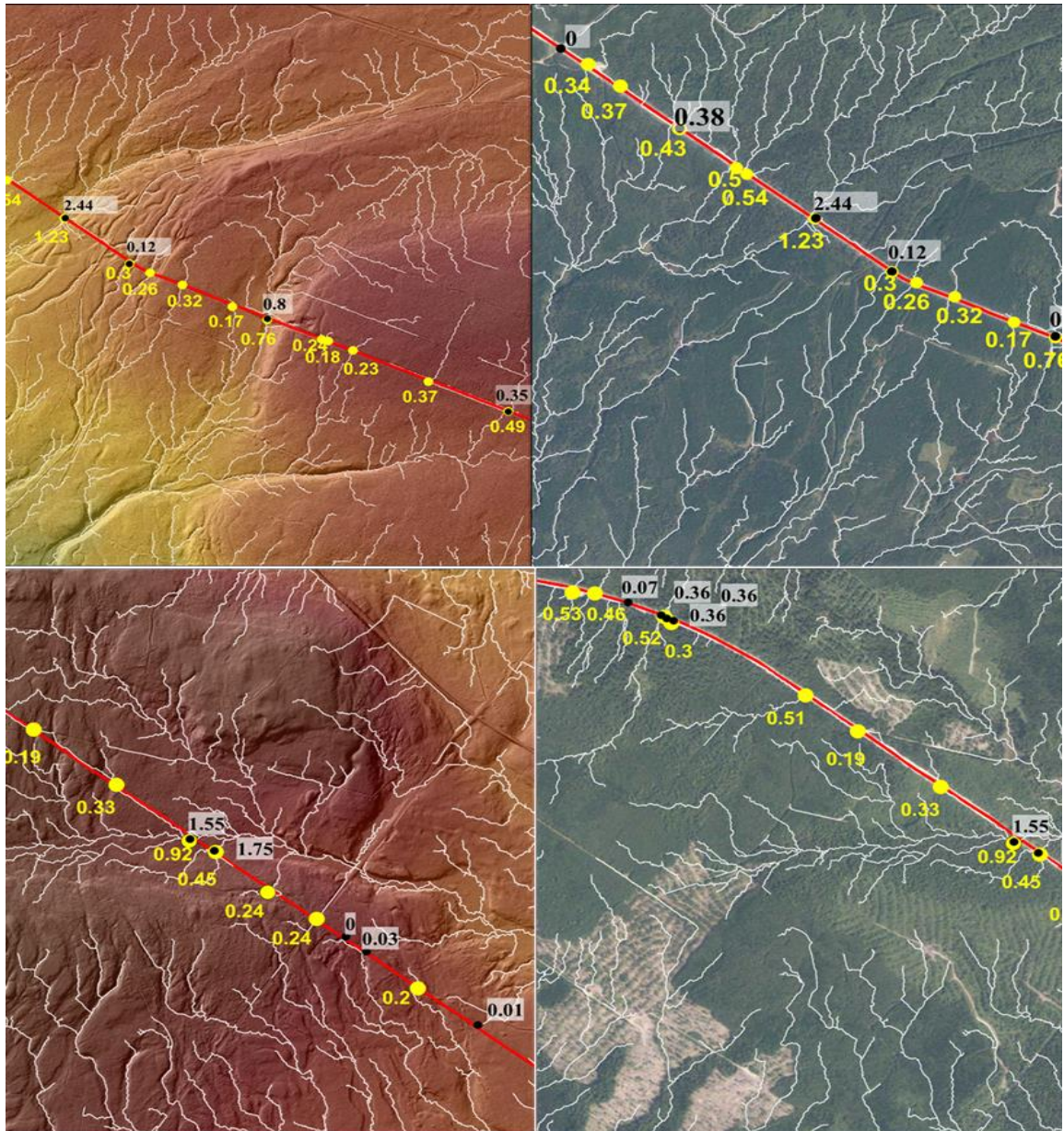


Figure 3.9. Reported (black) and 10-m-derived (yellow) road-stream crossing locations, with labels for reported and DEM-estimated minimum culvert diameter (m) to accommodate 100 mm/day discharge events, on hill-shaded 1-m DEM (left) and GeoNB imagery (right).

CHAPTER FOUR: ROAD-STREAM DELINEATION, LEPREAU ROAD (STUDY AREA B)

4.1. Introduction

This chapter applies the road delineation, flow accumulation network and culvert evaluation tools of Chapter 2 to Study Area B. The 32 km long road is needed to connect a forest management area centered on Pleasant Ridge to the sawmill located at Lake Utopia near Point Lepreau in southwest New Brunswick.

Like Chapter 3, the objectives for this chapter refer to the following:

1. To contrast the original versus the tool-generated roadbed delineation through visual and quantitative means.
2. To evaluate the Study Area B hydro-network channel network in relation to the DEM-located road-stream crossings based on applying two contrasting flow direction and flow accumulation algorithms (i) the study area DEM resampled and filled at 10-m resolution, and (ii) the study area as subjected to the ArcGIS Pro continuous flow algorithm.
3. To compare and evaluate the road-stream crossing outputs so generated, with both in contrast with the road-stream crossing points associated with (i) GeoNB's hydro-network channel data layer for streams, and (ii) existing culvert inventory data along the selected road segment.



Figure 4.1. Selected road segment (red line) overlaid on the local road network (white lines) and the 1-m hill-shaded DEM of the Study area B.

4.2. Methods

Like the procedure in Chapter 3, the 1 and 10-m resolution DEMs were used to derive the DEM flow channel patterns across Study Area B. These were visualized with the following upslope flow accumulation thresholds: > 1 , > 4 , > 10 , > 40 , > 100 , and > 400 ha, and contrasted with the GeoNB derived hydro-network. Potential culvert and bridge locations were determined along the road segment by intersecting each of the flow channels generated with this road.

4.3. Results

Road Delineation: Scanning the approximately 32km road segment from its beginning to end revealed that the road was continuous, and part of the established provincial road network, and it coincided entirely with the hill-shaded DEM roadbed projection. Although the data of the road layer coincided with the elevated roadbed for majority of the road, there were a few portions that veered off into ditches. Examples of these deviations are shown in Figures 4.2 and 4.3.



Figure 4.2. An example where the original road delineation veers off the elevated roadbed and falls into a ditch at an intersection along the road.



— Existing Lepreau RoadLine — DEM delineated Roadline

Figure 4.3. An example where the original road delineation veers off the elevated roadbed and falls into a ditch for about 200 m.

4.3.1. Flow Channel Network.

As in Chapter 3., the 1- and 10-m DEM-derived and GeoNB-provided flow networks were used to determine the locations number of road-stream crossing points along the selected road segment, as presented in Figure 4.4. The number of road-stream crossing points obtained differed as follows:

1. The D8 fill, flow-direction and flow accumulation algorithm using the smoothed 10-m DEM generated increasing road-stream crossing numbers with decreasing upslope flow-accumulations areas (Figure 4.5). In contrast, the ArcGIS Pro algorithm for continuous flow direction and flow accumulation using the unsmoothed 1-m DEM leveled off with decreasing upslope flow-accumulations areas (Figure 4.5).
2. The 10-m D8 algorithm followed the hill-shade recognizable flow paths quite closely but road-stream crossing locations had lower precision than what was attained with the 1-m ArcGIS Pro algorithm. This increased flow-path precision led to frequent road-mitigated depressions and related ditch diversions, thereby decreasing the overall number of road-stream crossings across the mapping extent, and especially so when flow-accumulation areas above the roads dropped below 20 ha (Table 4.1). At and above this threshold, road-stream crossings tended to occur in valley bottoms where the roadbed elevations are lower than the surrounding elevations.

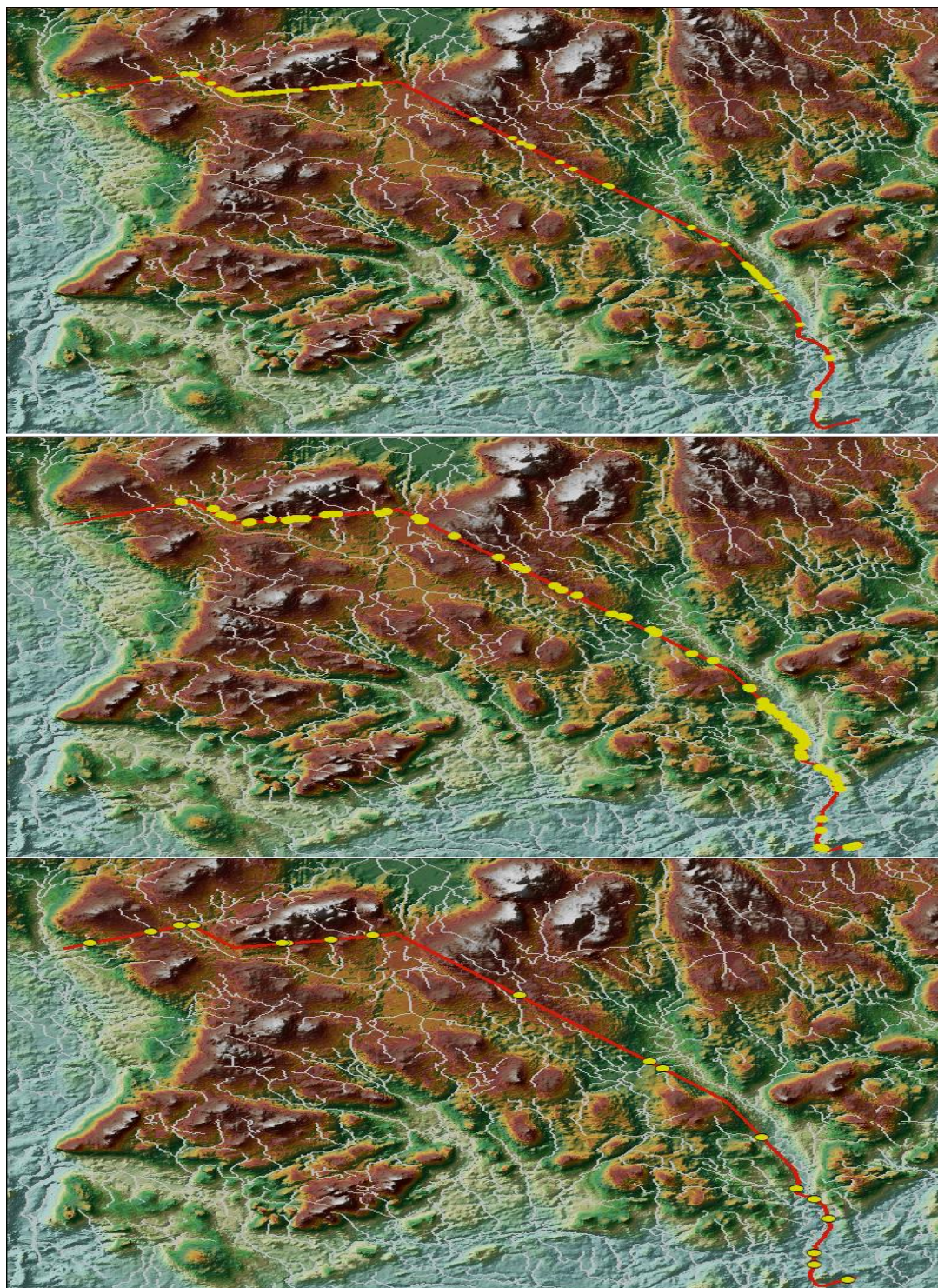


Figure 4.4. Study Area B with selected road segment (redline) overlaid by (i) 1-m DEM derived >10 ha streams and (ii) road-stream crossing locations (yellow dots) obtained by: (a) visual inspection (top), (b) officially registered culvert locations (middle), and (c) intersecting GeoNB's hydro-network channel with the selected road segment (bottom).

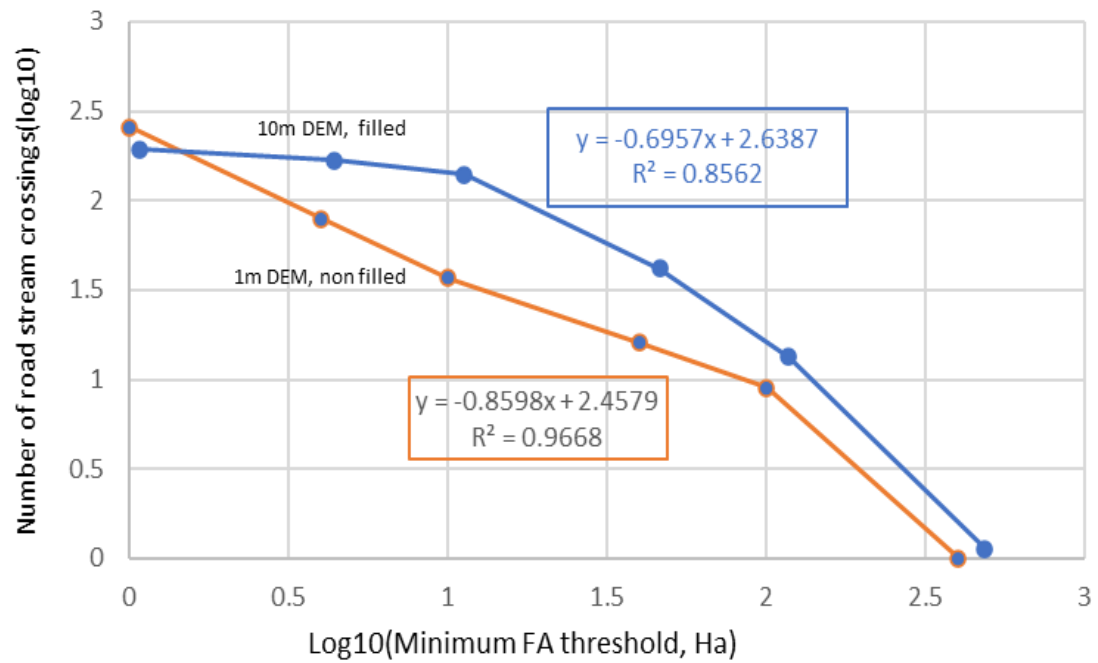


Figure 4.5. Number of road-stream crossings versus minimum upslope flow-accumulation threshold (ha), for the road-stream crossings along the Lepreau Road segment, based on the 1 and 10-m DEM derivations, open versus filled points, respectively

Table 4.1. Number of road-stream crossings generated using the filled and non-filled (continuous) flow direction and flow accumulation algorithms with varying minimum upslope flow-accumulation thresholds.

Minimum upslope flow accumulation area, ha	Number of road-stream crossings	
	DEM Resolution	
	10-m	1-m
	Depression- Filled Flow	Continuous Flow
400	3	1
100	23	9
40	59	16
20	71	25
10	160	37
4	185	85
1	258	209
GeoNB Hydro network road-stream crossings: 18 Visually derived road-stream crossings from the hill-shaded 1 m resolution DEM: 155		

By intersecting the official NB hydro-network stream layers from GeoNB with the Lepreau road, only eighteen road-stream crossings were generated. (Figure 4.4). In comparison, the provincial culvert inventory from Department of Transport and Infrastructure (DTI) listed 99 locations along the Lepreau Road, mostly directly on the road or within its 10-m road buffer. Intersecting the road with the 10-m DEM aligned 4 ha stream network produced 185 points. Inspecting all these points in terms of practical road-stream crossing potential involving small ditch diversions to connect closely spaced locations reduced this number to 155.

4.3.2. Culvert Diameters, Reported and Estimated

Shown in Figure 4.6 are actual with 100 mm/day accommodating culvert diameters, overlaid on the surface image and the hill-shaded DEM, with the former generally wider than the latter.

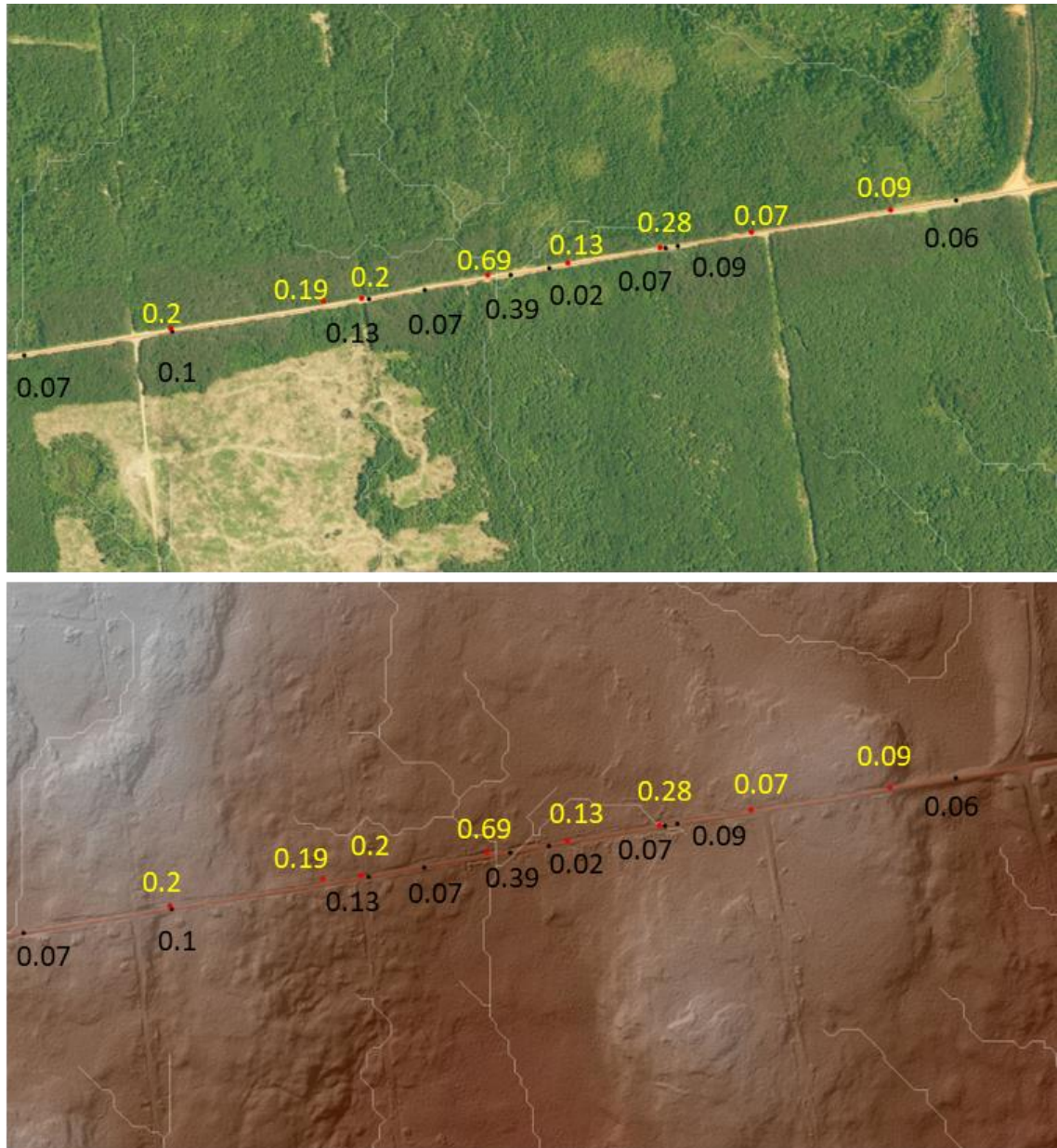


Figure 4.6. Reported (black) and 10-m-derived (yellow) road-stream crossing locations, with labels for reported and DEM-estimated minimum culvert diameter (m) to

accommodate 100 mm/day discharge events, on hill-shaded 1-m DEM (down) and GeoNB imagery (top).

4.4. Discussion (Chapter 3 and 4)

The complexity and density of road and trail networks across New Brunswick, as exemplified by the above study areas in Figure 3.1 and 4.1, represents a challenging task to generate a road-intercepted stream network that is hydrologically seamless, i.e., creates no above-road water-retaining depressions. As demonstrated for the 60 km and 32 km long selected road segments, specific tasks remain with:

1. obtaining precise roadbed delineations and locating where streams are crossing roads naturally and/or are limited by engineered structures,
2. ascertaining how LiDAR-DEMs can be modified to emulate hydrologically seamless road-stream crossings through automated road notching across entire road and trail network,
3. comparing actual versus DEM-estimated stream discharge expectations for specific storm events,
4. making detailed observations along roads with roadbed and culvert failures.

Some of these discrepancies as identified in Figures 3.2 to 3.8 and 4.2 to 4.6 illustrate the following:

1. The quality of already existing road delineations varies along road segments but can be further improved either by hand-tracking the course of roadbeds across hill-shaded DEMs original, or through automated GIS-based tracing along smooth roadbed surfaces.

2. The changes in number of potential road-stream crossings with varying upslope flow accumulation thresholds, as generated through emulating hydrological flow networks using (i) existing flow lines (such as the GeoNB streamlines), or (ii) LiDAR DEMs at 1 m or at 10 m resampled resolution versus the un-notched 10-m and notched 1-m DEM derivations,
3. While similar to some extent, there remain unexplained differences between the reported versus the DEM-derived culvert locations and sizes.

The above results obtained suggests that further work needs to be done to ensure that:

1. Road lines coincide with DEM-revealed roadbed centerlines across the entire road network.
2. DEM-derived road-stream crossings are seamlessly connected across each road. Care is required in doing so in terms of (i) also tracking stream braiding (not available by way of the D8 flow-accumulation algorithm), and (ii) ascertaining upslope flow initiation points for best management practices and regulatory ephemeral and permanent hydro-network channels definition purposes.
3. More work needs to be done to rigorously compare the DEM-located hydrograph-suggested culvert sizes with actual culvert sizes, as further influenced by culver construction, roadbed condition, and incoming discharge rates during major storm events.

CHAPTER FIVE: ROAD AND TRAIL SELECTION TOOL, STUDY AREA C (ABOUJAGANE ROAD)

5.1. Introduction

Construction and maintenance of forest roads and trails to facilitate various forest operations are challenging and costly (Walbridge, 1997; Swift and Burns, 1999). This Chapter presents a road and trail selection tool that can be used to rate existing as well as planned trails by layout suitability, desirability, usability, and potential costs. According to Coleman (1981), good trail suitability indicators refer to soil conditions, slope, and pre-existing trail locations. In the proposed model, cost rating refers to crossing slopes, streams and rivers, and wet areas that would be subject to temporary and/or permanent wetness and flooding. The rated costs are set to increase with increasing slope, soil wetness, and streambank and riverbank width. Areas covered by wetlands, lakes and other areas with no access permission are avoided altogether. Hence, straight roads and trails along flat and dry areas with no wetlands, streams and rivers are most desirable and would carry the least costs (Olive and Marion, 2009; MA DCR, 2012; Kokkinidis, 2013). Cost thresholds implying similar costs refer to (i) slopes =10%, (ii) wet soils with 1-m seasonal to temporary depth to water (DTW), and (iii) streams with upslope flow accumulation areas exceeding 4 ha.

The application of the tool is demonstrated for a section of the Aboujagane Road, east of Moncton NB (Figure 5.1). In part, this road segment serves as forest logging road and as access to a few homes and cottages along its southern end. Inspecting the Google Earth imagery revealed about forty-five poor to extremely poor road conditions mostly along the northern portion of this road segment (Figure 5.2). These conditions refer to (i)

non-passable wetland-induced roadbed flooding, (ii) partial to complete wet roadbeds leading to ruts and braiding due to flow channelling along the road, and (iii) instances of partial to complete road washout (Figure 5.3). All of these conditions occur where the 1-m LiDAR DEM applied Wet-Areas Mapping process suggests potential instances of road flooding, flow channeling, rutting, and washout (Figure 5.4).

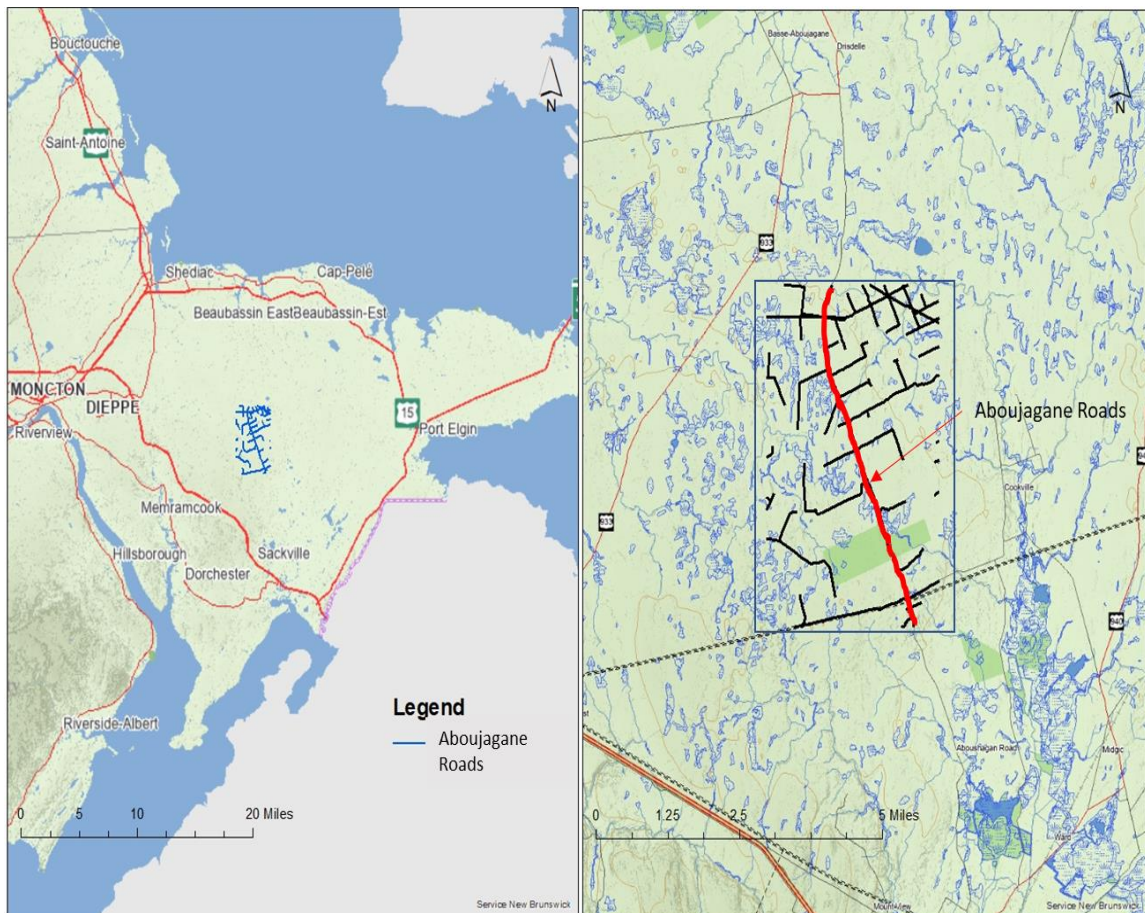


Figure 5.1. Locator map for the Aboujagane road segment (red line) and selected area of interest including 1-m DEM-delineated roads (black lines) east of Moncton in New Brunswick.

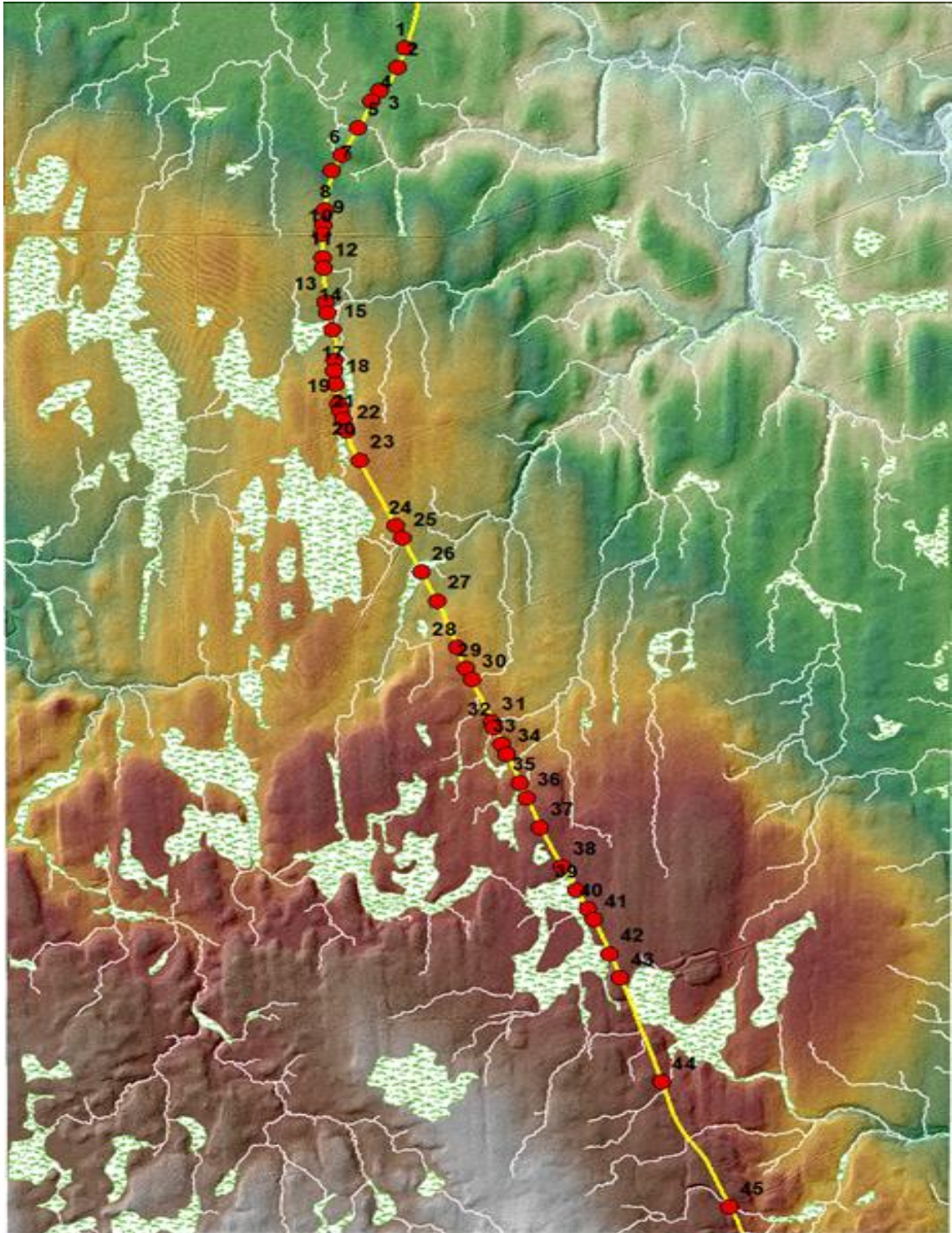


Figure 5.2. Selected Aboujagane road segment with locations that incur road flooding, water pooling, rutting, braiding and/or washouts, overlaid on the hill-shaded 1-m DEM (left) and the Google Earth Imagery (right, dated May 2017).



Figure 5.3. Road deterioration examples along the Aboujagane road segment: hydro-network channel induced flooding at Locations 29 and 30 (top); wetland-induced flooding at Location 26 coupled with channel-induced water flow along the road at Location 25. LiDAR-derived flow channels: white lines; depressions: blue polygons.



Figure 5.4. Road deterioration examples along the Aboujagane road segment: road braiding with partial culvert exposure and flooding at Location 31, and flow-induced road flooding at Location 32 (top); flow-induced road flooding at Location 32 LiDAR-derived flow channels: white lines; flow induced road narrowing at Location 45 (bottom). LiDAR-derived flow channels: white lines; depressions: blue polygons.

5.2. Objectives

The objectives of this Chapter refer to:

1. Determining the least cost path of the area of interest depicted in Figure 5.2 based on separate and combined road and trail layout constraints pertaining to slope, DTW, stream bank widths, and wetland avoidance.
2. Comparing the accumulated cost ratings of the least cost path generated with the accruing cost ratings along the existing road segment.

5.3. Methods: Workflow

The workflow of the road and trail selection tool is presented in Figure 5.5. This workflow starts with selecting 1-m DEM of the study area and using that DEM to determine slope, flow directions (FD), flow accumulations, (FA), flow channel networks or streams, starting with 4, 1 and 0.1 ha as minimum upslope flow accumulation to develop the DEM-implied DTW pattern. Each least cost path determined is subsequently cost profiled along the length of the path, using 0.5 m point intervals.

5.3.1 Simplified Workflow of Road and Trail Suitability tool

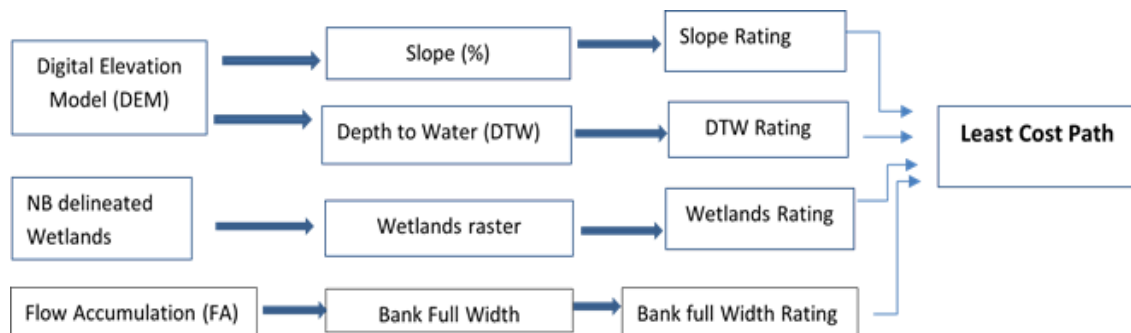


Figure 5.5. Workflow of the road and trail selection tool.

5.3.2. Cost Rasters

The cost rating process is enabled by converting Slope, DTW and FA into additive cost rasters where the lowest cost for each raster is set at 1 but increases exponentially towards 1000, or is set to 1000(No Access) as follows:

1. Wetlands and lakes are classified as No Access zones.
2. Slope rating, i.e., $RT_Slope\% = [(\exp(0.1 \text{ Slope}) - 1)]^3$ (Figure 5.6).

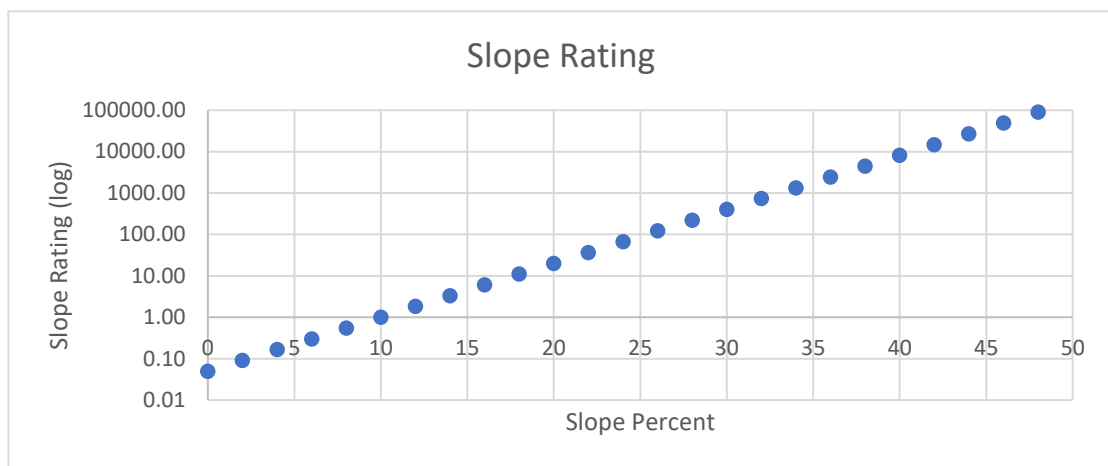


Figure 5.6. Slope% cost rating in relation to increasing Slope%.

3. DTW rating, i.e., $RT_DTW = [7.38906 \exp(-0.002 \text{ DTW})]^4$ (Figure 5.7).

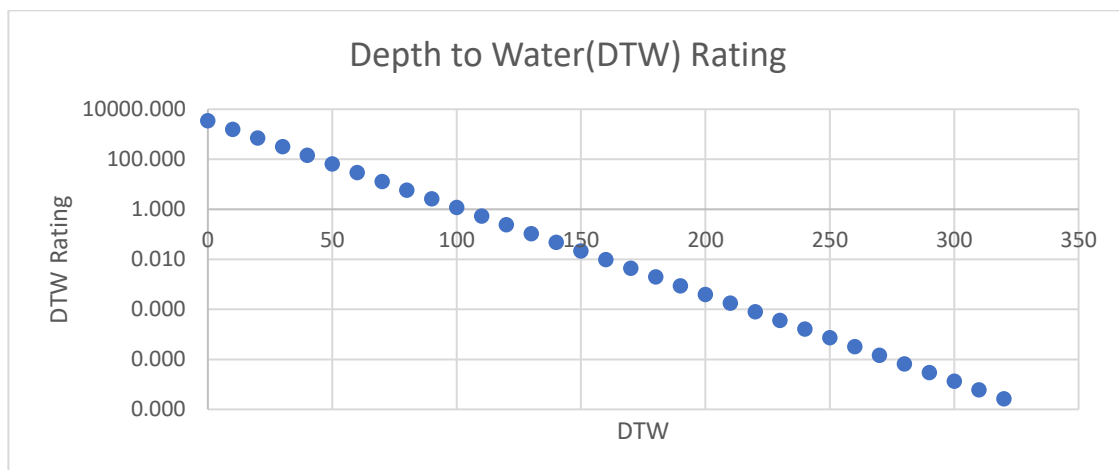


Figure 5.7. DTW cost rating in relation to increasing DTW, in cm.

4. Streambank full width rating: RT_BFW is set equal to 1 when outside three times the bank-full stream zone and to 1000 when inside this zone. In principle, BFW is defined as the distance from the ordinary high-water mark from one stream bank to the other, as evidenced by visible signs of stream flow such as water marks, stream-carried deposits of sediments and debris (Vianello and D'Agostino, 2007). According to Mulvihill et al. (2009), BFW can be approximated along each channel by setting, $BFW = 0.5557 \cdot FA^{0.401}$, with FA in hectares and BFW in meters.

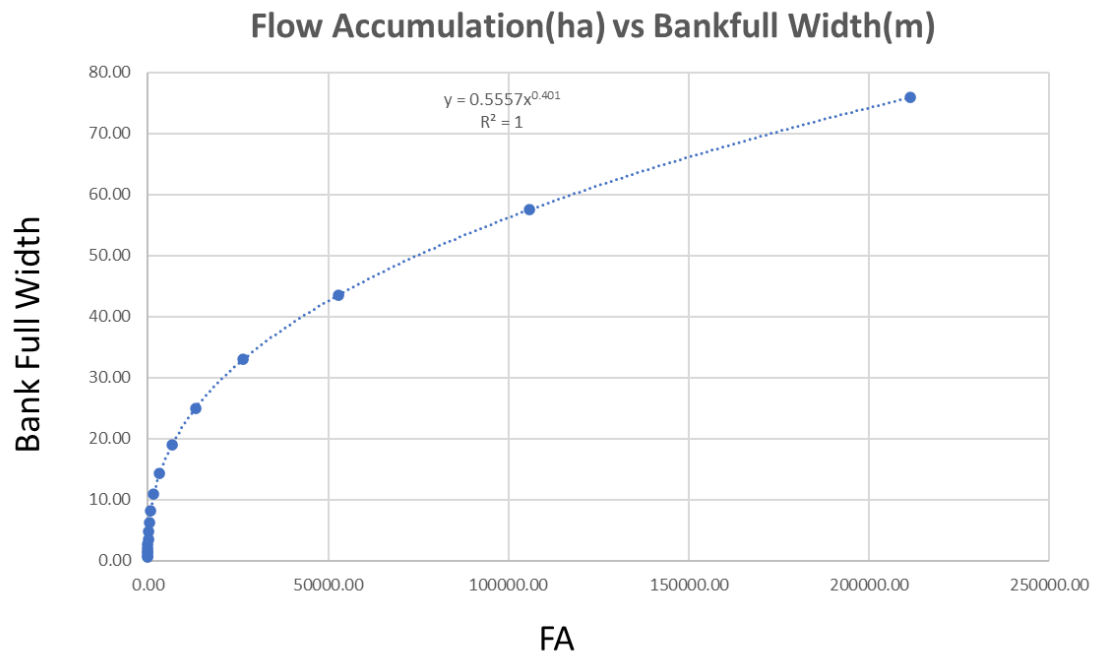


Figure 5.8. Bank full width in meters in relation to increasing flow accumulation areas FA along flow channels, in hectares.

The cost ratings generated are listed in Table 5.1 and are subsequently applied to the DTW, Slope, FA, wetland, lakes, and flow channel rasters.

5.3.3. Generating Least-Cost Paths

The pixel-quantified Slope, DTW, FA and Bank Full Width cost rasters are used (i) individually and (ii) in additive combinations to determine the least cost paths along any trail that would connect any desired start point with any desired end point within the area of interest. This can be done using the Raster Calculator and Least Cost Path tools in ArcMap and/or ArcGIS Pro. Doing this is similar to the cost-path delineation process by Kokkinidis (2013), which involved combining threshold-categorized rather than combining continuously increasing cost rasters, as described above.

Table 5.1. Cost ratings for increasing Slope% (RT_Slope), Depth to water (RT_DTW), and Bank full width (RT_BFW).

FA(ha)	RT_BFW	Slope(%)	RT_Slope	DTW(cm)	RT_DTW
1.29	0.62	0	0.05	0	3501.28
2.58	0.81	1	0.07	10	1573.23
6.45	1.17	2	0.09	20	706.90
12.9	1.55	3	0.12	30	317.63
25.8	2.05	4	0.17	40	142.72
51.6	2.70	5	0.22	50	64.13
103.2	3.57	6	0.30	60	28.81
206.4	4.71	7	0.41	70	12.95
412.8	6.22	8	0.55	80	5.82
825.6	8.21	9	0.74	90	2.61
1651.2	10.84	10	1.00	100	1.17
3302.4	14.32	11	1.35	110	0.53
6604.8	18.91	12	1.82	120	0.24
13209.6	24.96	13	2.46	130	0.11
26419.2	32.96	14	3.32	140	0.05
52838.4	43.53	15	4.48	150	0.02
105676.8	57.47	16	6.05	160	0.01
211353.6	75.89	17	8.17	170	0.00

5.4. Results and Discussion

The resulting tool-selected least-cost road layouts using only one cost raster type while zero costing the existing Aboujagane road segment are displayed in Figure 5.9. By road length, the accumulated costs along this road rank as follows: $RT_{Slope} < RT_{wetland} < RT_{FA} < RT_{DTW}$. The results of combining several and all of rasters into single cost rasters are shown in Figures 5.9, 5.10 and 5.11.

The cumulative costs along the least cost paths shown in Figures 5.11 are displayed in Figure 5.12 and 5.13 and Table 5.2. These costs tend to be least along the existing roadbeds when RT_{Slope} is either the only cost contributor or is part of the cost raster combinations that do not involve RT_{DTW} . This reflects the fact that slopes are, by design, smooth and least variable along the direction of existing roads (Pope,1914). Adding RT_{DTW} to the least cost evaluations overrides the slope costs by considerable margins thereby leading to least cost paths that differ significantly from the Aboujagane road segments in length and as follows:

1. By turning south with RT_{DTW} as the only cost raster.
2. By turning east and then south when the RT_{DTW} and RT_{FA} cost rasters are combined.
3. By following a more central northwestern to southeastern path when the RT_{DTW} , RT_{FA} and $RT_{Wetland}$ cost rasters are combined.

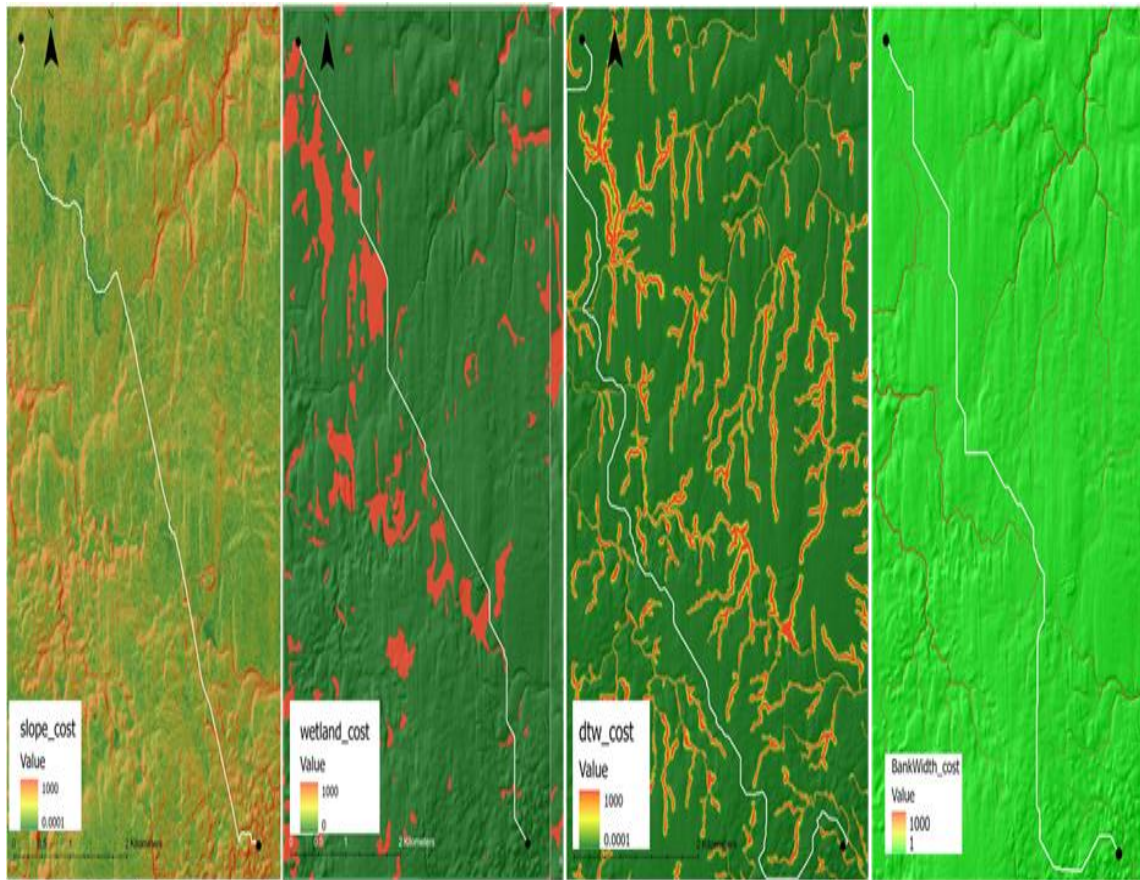


Figure 5.9. Least single-raster cost paths (white lines) across the Aboujagane area of interest with a northwestern start point and southeastern end point overlaid on the red - yellow - green traffic-coloured RT_Slope, RT_Wetland, _RT_DTW, and RT_FA cost rasters, shown from left to right. The least-cost path for RT_Slope remains generally straight because Slope% mostly remains < 10 % along this path.

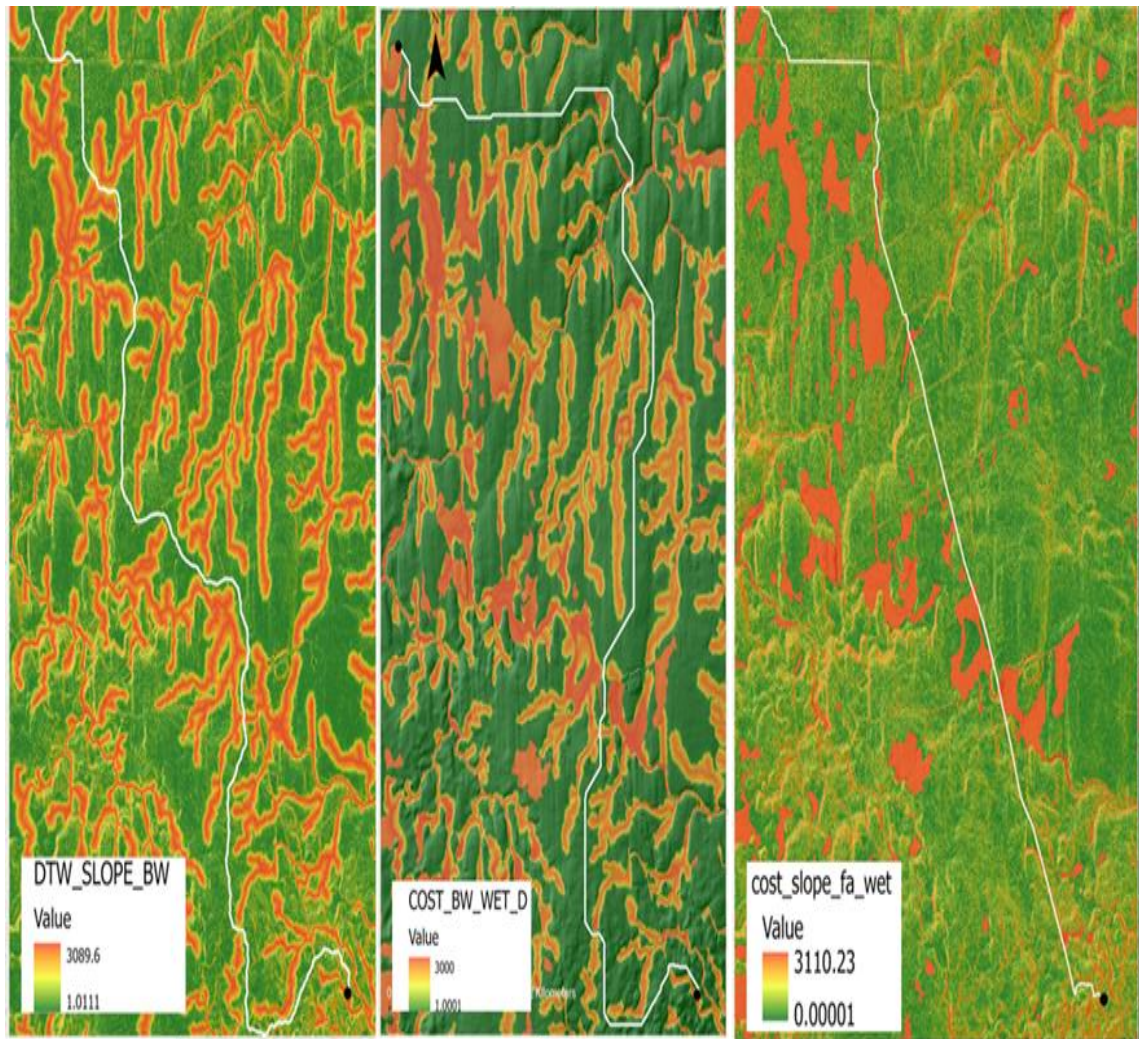


Figure 5.10. Least double or triple cost-raster paths (white lines) across the Aboujagane area of interest with a northwestern start point and a southeastern endpoint overlaid on the following traffic-coloured cost-raster combinations (red - yellow - green): RT_Slope, RT_DTW and RT_BFW (left), RT_BFW, RT_Wetland, RT_DTW (middle), RT_Slope, RT_FA, RT_Wetland (right). Note: wet = Wetlands.

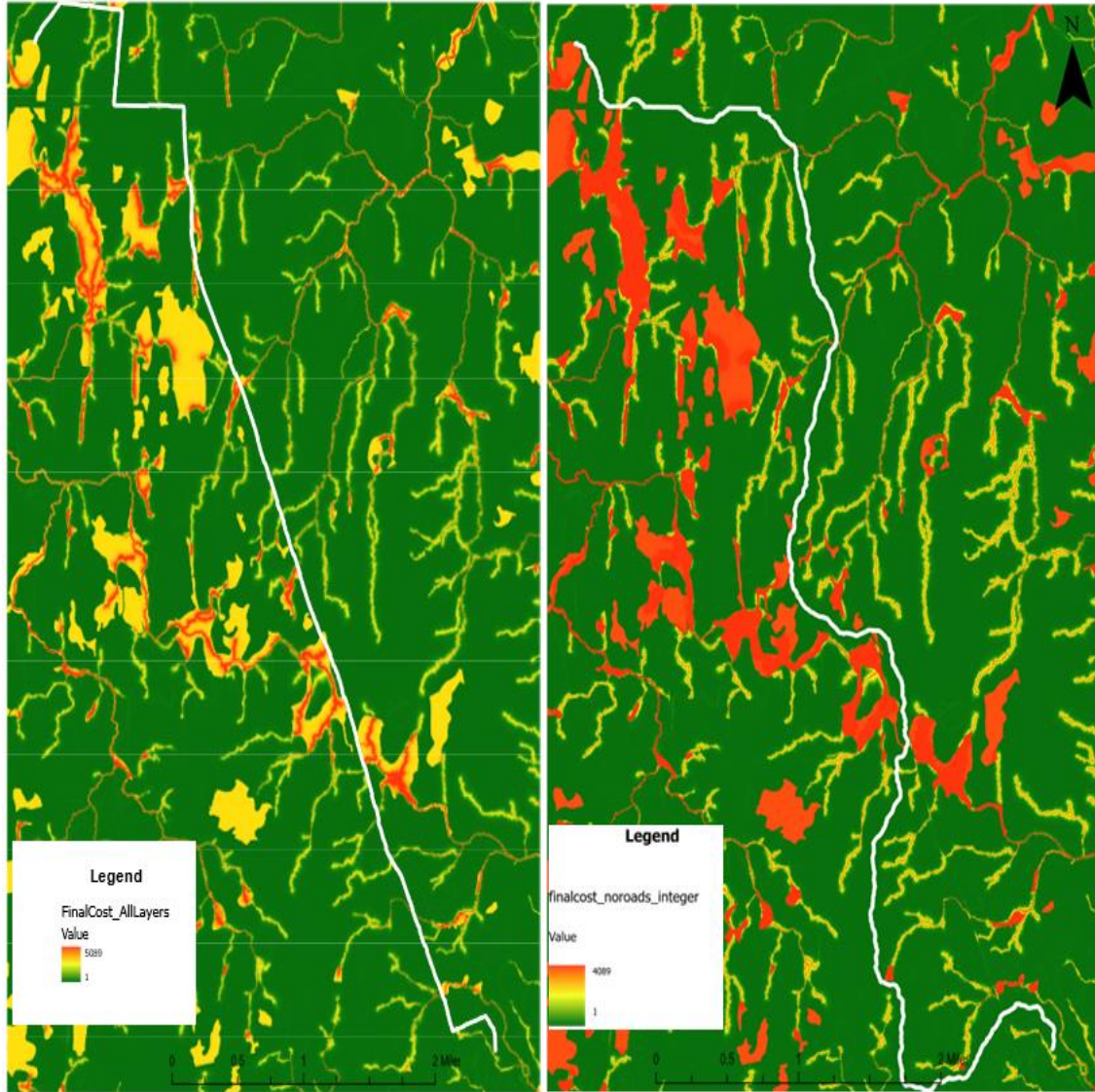


Figure 5.11. Combined least-cost paths (white lines) across the Aboujagane area of interest with a northwestern start point and southeastern endpoint using the traffic-coloured (red - yellow - green) RT_Slope, RT_DTW, RT_BFW, RT_Wetland cost raster combinations with (left) and without (right) RT_Roads. Note: RT_Road = 1 on road, and = 1000 everywhere else.

The 0.5-m point-evaluated costs for the finalized cost paths in Figure 5.11 are statistically and graphically profiled in Table 5.2 and in Figures 5.12 and 5.13. In total, the shorter but straighter trail contains 22,017 profile points whereas the longer and curved

trail contains 27,862 points. This amounts to a 26.5% gain in length. In comparison, the cumulative costs along these paths dropped, respectively, from 3,598,468.5 for the shorter path to 134,337.2 for the longer path, i.e., dropped by a factor of 26.7. Accordingly, the accumulated costs as rated for the shorter path exceed the rated costs for the longer least cost path by 2.5 orders of magnitude. The extent that this could actually be the case is reflected by the poor road conditions along the 11 km Aboujagane stretch, as illustrated in Figures 5.1 to 5.4. Actual costs that would make this road passable again refer to:

1. placing or replacing all culverts at the DEM located road-stream crossings, done in a systematic way to direct water away from accumulating and/or flowing next to the road,
2. elevating the roadbed where needed to avoid future flooding from adjacent wetlands and elsewhere.

In so doing, Figure 5.2 could be used as a road and trail planning guide. For example, the preferred cost path would only require 4 instead of 22 culvert installations, as listed in Table 5.3, where the location-specific upslope flow accumulations and recommended culverts diameters for a 100 mm per day discharge event are also presented.

Table 5.2 Statistical 0.5 m point-profile evaluation of the least-cost paths in Figure 5.11.

Trail cost statistics	Rated Trail Costs	
	Figure 5.12	Figure 5.13
Cost Points	22,017.0	27,862.0
Mean Cost	163.4	4.8
Median Cost	6.1	1.0
Least Cost	1.0	1.0
Max. Cost	2,061.0	1,899.8
Sum	3,598,468.5	134,337.2

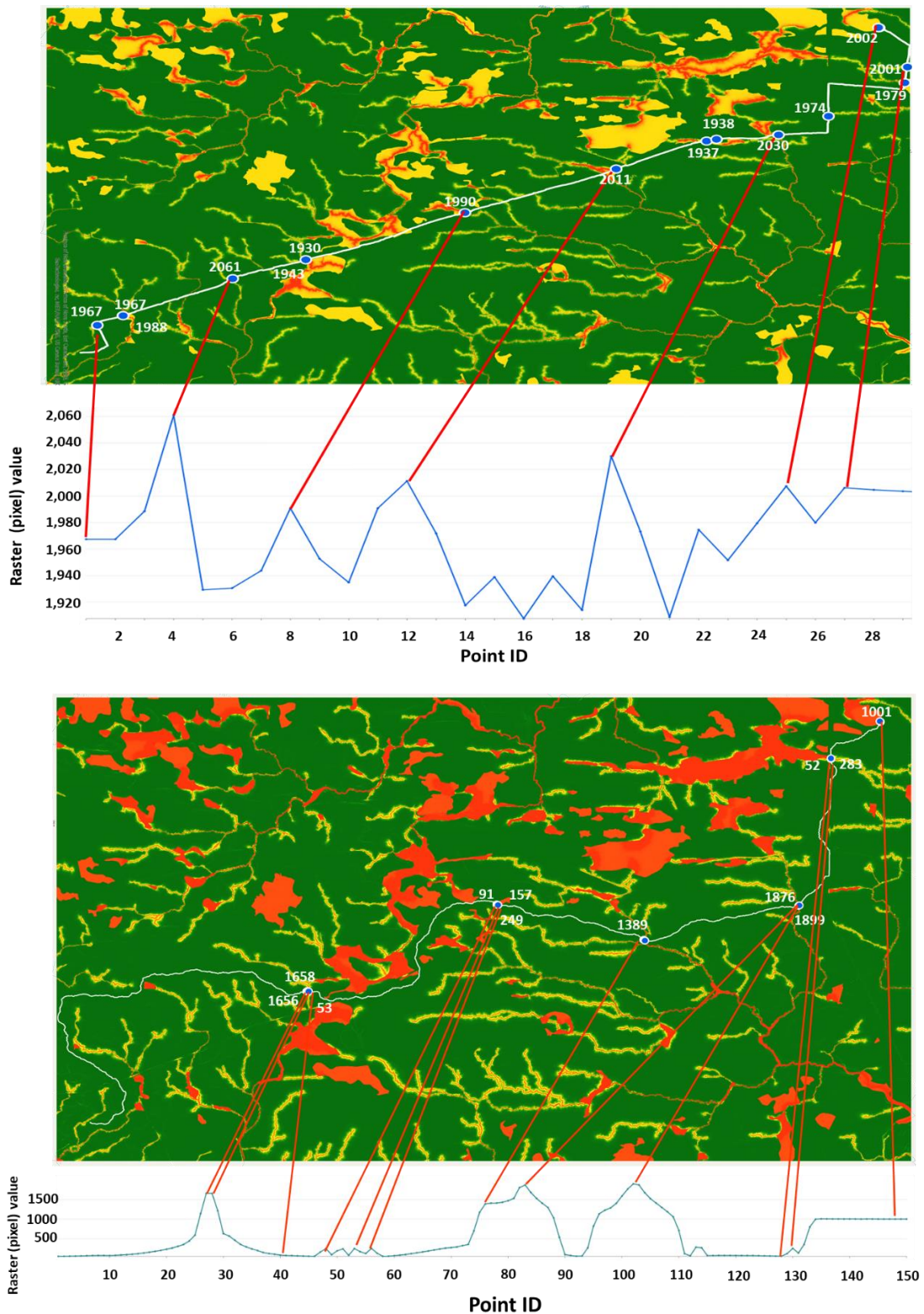


Figure 5.12. Graphs showing the cost profile along the equally spaced points (0.5-m intervals) i. with preference along the existing trail (top), and ii. Without the existing

Table 5.3. Culvert installation requirements for existing and preferred trails.

Existing Trail			Preferred Trail		
Culvert number	Flow Accumulation ha	Culvert Diameter m	Culvert number	Flow Accumulation ha	Culvert Diameter m
1	4.9	0.5	1.0	148.7	1.8
2	63.2	1.3	2.0	0.8	0.3
3	45.2	1.2	3.0	4.5	0.5
4	19.7	0.9	4.0	5.8	0.5
5	25.4	1.0	5.0	129.6	1.8
6	20.2	0.9	Sum	289.4	4.9
7	5.5	0.5			
8	21.2	0.9			
9	14.3	0.8			
10	13.4	0.7			
11	105.2	1.6			
12	33.2	1.1			
13	33.0	1.1			
14	12.6	0.7			
15	12.7	0.7			
16	16.1	0.8			
17	41.9	1.1			
18	45.0	1.2			
19	8.8	0.6			
20	31.1	1.0			
21	6.4	0.6			
22	0.8	0.3			
Sum	579.8	19.5			

CHAPTER SIX: ROAD NETWORK INVENTORY RESPONSE TO A MAJOR RAINSTORM, STUDY AREA D

6.1. Introduction.

On December 1, 2020, New Brunswick was subjected to a major storm event amounting up to 180 mm of rain received within a 24-hour period as presented in Figure 6.1. Maximum deposition rates occurred along the southeastern highlands, and in Central New Brunswick. Several road washouts were reported for these areas. The objective of this Chapter is to analyze and report on bridge and culvert locations along provincial and forest road networks within the affected areas, with focus on Study Area D. Of special interest are the differences between actual and estimated culvert diameters to accommodate peak flows for:

1. this storm event, and
2. storm events with discharge rates of 100 mm per day.

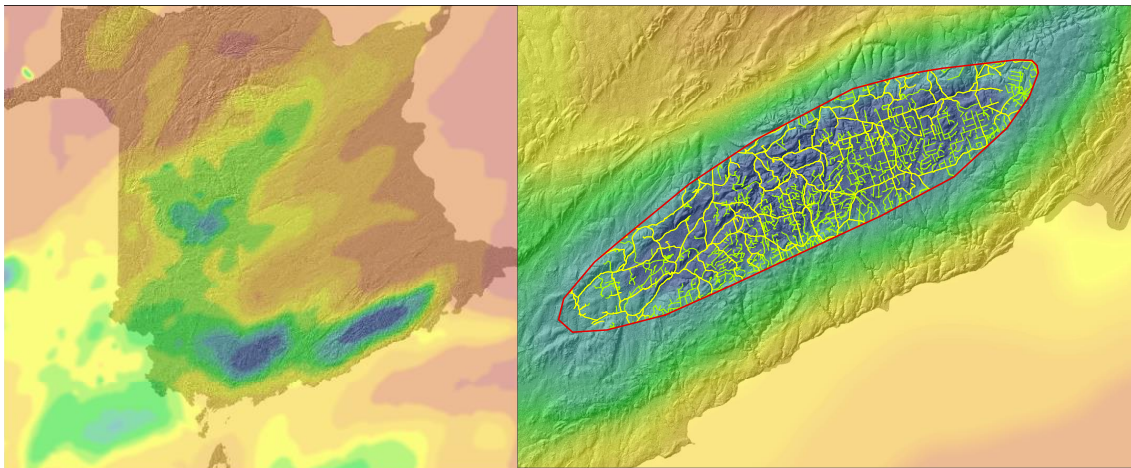


Figure 6.1. New Brunswick map showing the precipitation event recorded on December 1, 2020 (left) with a section in southern New Brunswick highlighting a network of roads where washouts were recorded along some roads.

These calculations are based on the Manning Equation for corrugated culverts, with a roughness coefficient of 0.22 and a fish-accommodating culvert-elevation drop at 0.5%.

6.2. Methods

Study Area D contains 1168 road-stream crossings along its 493.2 km provincial road network, including 51 bridges. In addition, there are 999.5 km of unpaved forest roads with 900 road-stream crossings. Culvert size specifications were generally available for the provincial road network, but only for select locations along the forest roads.

The 1-m LiDAR DEM for the study area was used to develop the following raster data layers: filled DEM, flow direction, flow accumulation, the stream network with upslope flow accumulations > 1 ha, and depression polygons > 0.25 cm deep. The stream network was intersected with the road and forest road layer to locate all road-stream crossings and where needed, to notch the DEM raster accordingly. Once the locations were ascertained through visual inspection, the work proceeded by determining the corresponding minimum culvert diameters that would accommodate these discharge rates for (a) the December 1, 2020, storm event and (b) for a 100 mm per day storm event in general. The details for these Manning-based culvert size estimations including time to and discharge rates at peak flow are presented in Chapter 2. The results generated for the provincial and select forest road-stream crossings were compared with the reported culvert diameters.

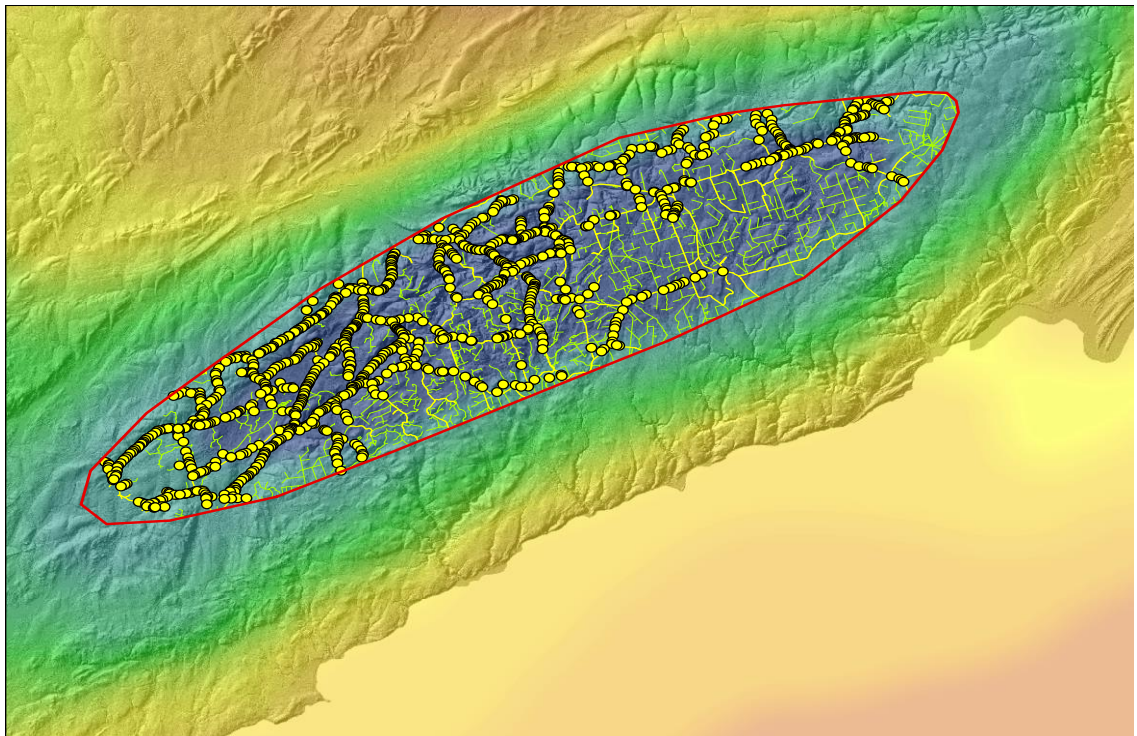
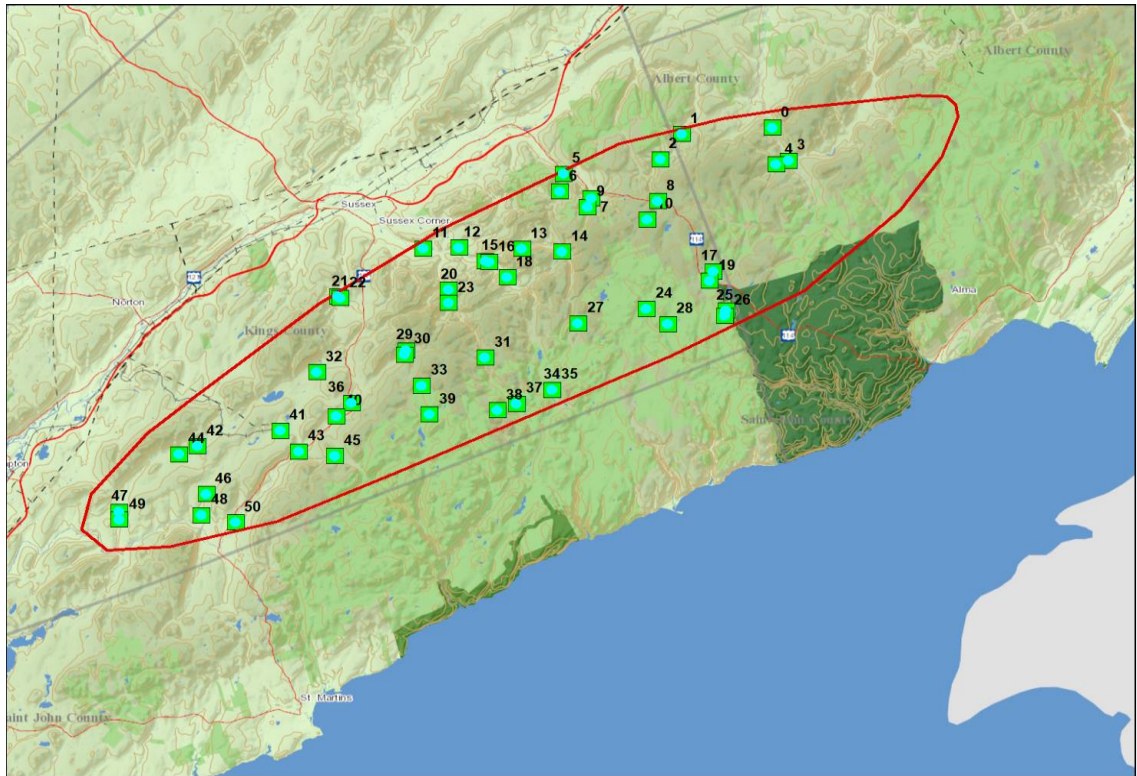


Figure 6.2. Locator maps showing the road-stream networks and culverts in the study area. Numbered culverts in the top image represent culverts that were assessed for this chapter of the study.

6.3. Results

Listed in Table 6.1 are the upslope flow-accumulation areas for the bridge locations of the provincial road network in Study Area D. These are used to estimate:

1. the mean precipitation rates per upslope area in mm/day for the December 1, 2020, storm event,
2. subsequent expected discharge rates in m³/sec, and
3. related peak flow culvert sizes along the bridge locations of the provincial road network in Study Area D.

These diameters ranged from 1.3 to 10.8 m. Actual culvert diameters ranged from 0.3 to 2.4 m. There were only four bridge locations with suggested culvert diameters < 2.4 m.

Listed in Table 6.2 are the locations with reported culvert size along storm-surveyed forest roads, pertaining to December 1, 2020. Also listed are the estimated 100 mm/day discharge rates and corresponding Manning-calculated culvert diameters for each location and associated upslope flow-accumulation areas (or drainage areas). Storm-affected road sections are displayed in Figure 6.3 for the Clearwater and Funny Corner Brook locations and for the area next to Camp 62.

Table 6.1. Bridge locations in Study Area D, with upslope flow-accumulation areas, associated mean precipitation rates in mm/day and subsequent expected discharge rates in m³/sec, and related peak flow culvert size specifications.

ID	FA, ha	Ppt, mm	Discharge, m3/sec	Min.peakflow culvert size, m	ID	FA, ha	Ppt, mm	Discharge, m3/sec	Min.peakflow culvert size, m
0	2851	146	48.2	6.4	26	53	155	0.9	1.5
1	2197	139	35.5	5.7	27	336	200	7.8	3.3
2	977	161	18.2	4.5	28	362	175	7.3	3.2
3	1269	187	27.4	5.2	29	230	200	5.3	2.8
4	617	190	13.6	4	30	903	200	20.9	4.7
5	341	135	5.3	2.8	31	176	200	4.1	2.6
6	51	151	0.9	1.4	32	807	193	18	4.5
7	253	175	5.1	2.8	33	458	200	10.6	3.7
8	1766	200	40.9	6.1	34	2987	140	48.3	6.5
9	192	182	4.1	2.5	35	2987	140	48.3	6.5
10	1369	200	31.7	5.5	36	2833	200	65.6	7.2
11	13393	150	232	11.6	37	1708	144	28.4	5.3
12	7975	170	156.5	10	38	115	148	2	1.9
13	2824	198	64.8	7.2	39	442	179	9.2	3.5
14	1998	200	46.3	6.3	40	3672	200	85	8
15	7509	195	169.6	10.3	41	929	200	21.5	4.8
16	3867	197	88.3	8.1	42	573	156	10.4	3.6
17	1490	200	34.5	5.7	43	7490	192	166.5	10.3
18	3295	200	76.3	7.7	44	1167	145	19.6	4.6
19	1421	198	32.5	5.6	45	1412	177	28.9	5.3
20	2704	200	62.6	7.1	46	311	145	5.2	2.8
21	265	141	4.3	2.6	47	1082	140	17.5	4.4
22	1832	144	30.5	5.4	48	562	140	9.1	3.5
23	2187	200	50.6	6.6	49	1274	140	20.6	4.7
24	980	198	22.5	4.8	50	1754	140	28.4	5.3
25	35	159	0.7	1.3					

Table 6.2. Surveyed road-stream crossing locations, upstream flow-accumulation areas, and related discharge expectations pertaining to the December 1, 2020, storm event: actual versus 100 mm/day accommodating culvert diameters.

Road System		Culverts in place		Upslope drainage area, ha	Average discharge, 100 mm/day	Minimum required culvert diam., mm,		Max. discharge for culverts in place, m3/sec	Culvert size comparison, actual/needed	
		Description	mm		m3/sec	Average daily	Peak flow		Average	Peak flow
Hayward Brook		4ft	1,219	741	8.58	2,235	3,374	1.70	0.55	0.36
Camp 62 road		36" *	914	189	2.18	1,338	2,020	0.79	0.68	0.45
Clearwater Brook		6ft**	1,829	16,757	193.94	7,197	10,866	5.02	0.25	0.17
Stewart Brook		2 - 5fters***	1,524	935	10.82	2,439	3,682	3.09	0.62	0.41
Funny Corner		4ft	1,219	1,552	17.96	2,949	4,452	1.70	0.41	0.27
Markamville Road		30"	762	84	0.98	989	1,494	0.49	0.77	0.51
Shepody Road		30"	762	40	0.46	748	1,130	0.49	1.02	0.67
Shepody Road		30"	762	21	0.24	587	886	0.49	1.30	0.86
Shepody Road		24"	610	56	0.65	850	1,284	0.27	0.72	0.47
Mary Pitcher		72"	1,829	455	5.27	1,862	2,811	5.02	0.98	0.65
								Average	0.73	0.48
DOT			600	18	0.21	554	837	0.26	1.08	0.72
DOT			750	33	0.38	696	1,051	0.47	1.08	0.71
DOT			900	18	0.20	550	830	0.76	1.64	1.08
DOT			750	4	0.05	324	489	0.47	2.31	1.53
DOT			1,500	27	0.32	648	979	2.96	2.31	1.53
DOT			600	41	0.47	754	1,139	0.26	0.80	0.53
DOT			600	24	0.28	621	938	0.26	0.97	0.64
Mary Pitcher			762	25	0.28	623	941	0.49	1.22	0.81
Mary Pitcher		30	762	23	0.26	606	915	0.49	1.26	0.83
DOT			450	9	0.11	433	653	0.12	1.04	0.69
								Average	1.37	0.91



Figure 6.3. Road and stream conditions resulting from the December 1, 2020, event downstream from Camp 62 (top), and along the roads across Funny Corner (middle) and Clearwater Brook (bottom).

Figures 6.4 and 6.5 provide examples of how the reported and estimated culvert diameters relate to their DEM-generated topographic positions along the Mary Pitcher and Dicks Lake roads. For Mary Pitcher Road, locations show where a culvert was installed at a saddle point location, to ensure that water could flow one way or the other underneath the road, depending on changing water levels on either side of the road. At this location, the upslope flow accumulations indicate a near-zero culvert diameter requirement. The installation, however, placed a culvert with a 1219 mm diameter to protect against potential flood occurrences on either side of the road.

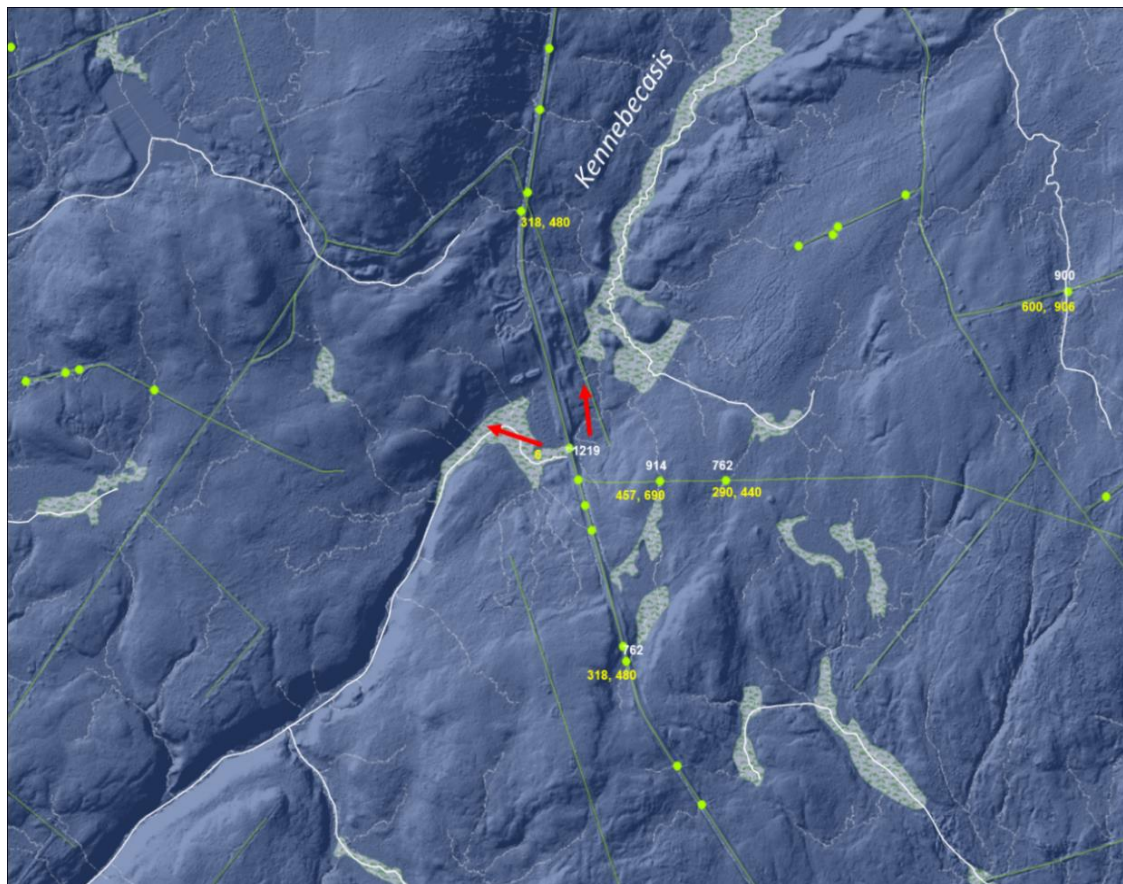


Figure 6.4. Culvert installation across a saddle point along the Mary Pitcher Road. Green dots: installed culverts. White numbers: Culvert diameter (mm), JDI specified. Yellow numbers: DEM-derived, culvert diameter (mm), 100 mm/day estimates for even and peak flow. Peak flow = 1.51 x Even flow.

At Dicks Lake, there were two culvert installation locations: one would be sufficient to protect the road against 100 mm/day discharge storm event at peak flow (culvert size = 762 mm), while the other would only protect against even flow conditions (culvert size = 1524 mm).

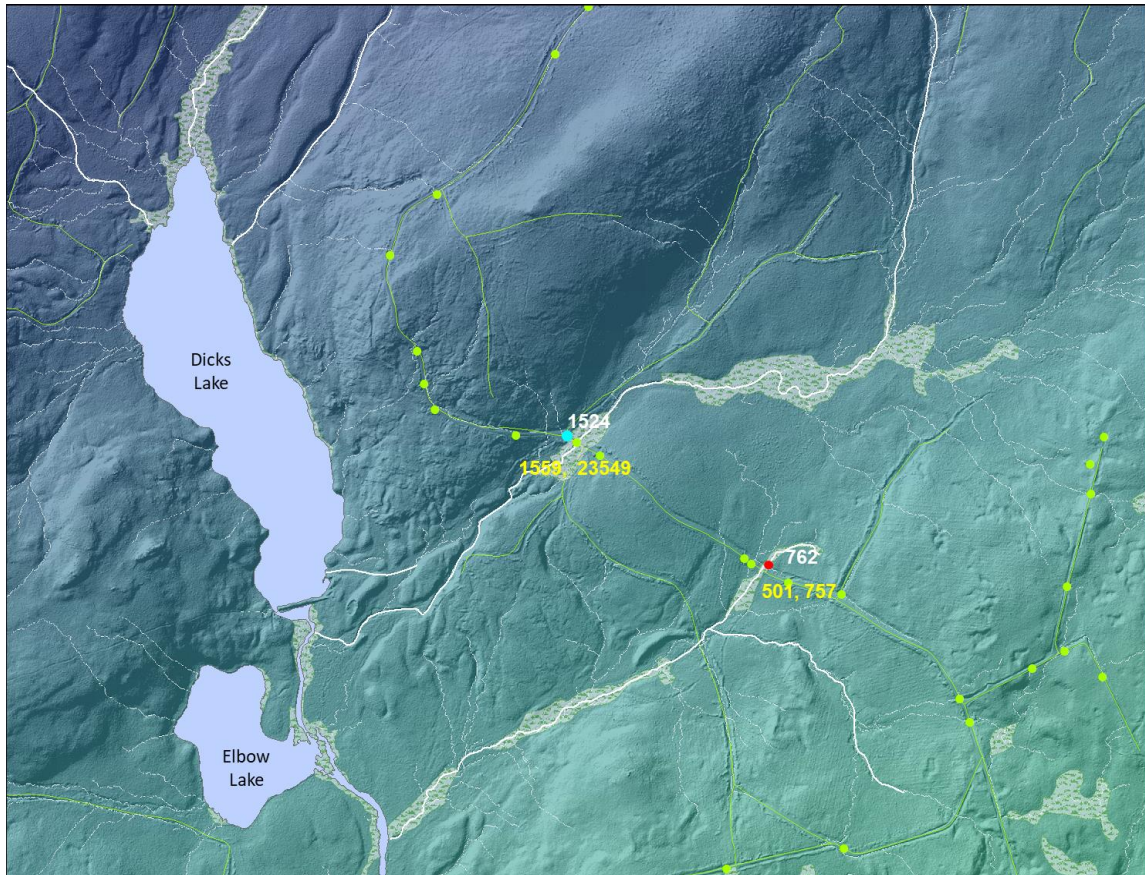


Figure 6.5. Culvert installation across Dicks Lake Road. Green dots: installed culverts. White numbers: Culvert diameter (mm), JDI specified. Yellow numbers: DEM-derived culvert diameters, mm, estimated for 100 mm/day even and peak flow. Peak flow = 1.51 x Even flow.

Table 6.3 provides an additional list of actual versus Manning-estimated culvert diameters to accommodate the corresponding December 1, 2020, inferred upslope flow-accumulation discharge rates at forty-five forest road locations. Of these, fifteen of the culverts installed were likely undersized for the December 1, 2020, event, leading to road

flooding with possible washout consequences. In addition, 11 culverts would possibly be undersized as well, by limited upstream ditch flooding and accompanying whirlpool flow (Figure 6.6).

Table 6.3. Actual versus estimated culvert diameters to accommodate upslope flow-accumulation discharge at select forest road locations, as occurred on December 1, 2020.

FID	Location	Culvert size, mm	Material	Upslope FA, ha	Precipitation, Dec.1, 2020, mm	Discharge, m3/sec	Min.culvert size, mm	Culvert size ratio	Undersized for peak flow?	
814	Mary Pitcher	1524	Galv	22.2	153.5	0.394	1063	0.70	no	1
241	Dobson Trail	762	Plastic	54.3	177.3	1.114	1569	2.06	yes	2
727	Mary Pitcher	762	Galv	283.5	198.9	6.528	3046	4.00	yes	3
239	Dobson Trail	1219	Plastic	103.4	178.2	2.133	2003	1.64	yes	4
257		1219	Plastic	120.1	200.0	2.781	2212	1.81	yes	5
423	SHEP	1219	Plastic	113.8	200.0	2.634	2167	1.78	yes	6
214	Dobson Trail	1219	Plastic	100.0	176.1	2.039	1969	1.62	yes	7
453	Fundy Connector	1219	Plastic	105.0	197.5	2.400	2093	1.72	yes	8
443	North Shepody	900	Plastic	81.8	200.0	1.894	1915	2.13	yes	9
795	Dicks Lake	762	Plastic	10.7	195.5	0.243	887	1.16	possibly	10
412	Grassy Lake	762	Plastic	12.1	179.2	0.250	896	1.18	possibly	11
102	Collier Mountain	762	Plastic	12.9	182.1	0.272	925	1.21	possibly	12
772	Mary Pitcher	762	Plastic	2.2	184.9	0.048	482	0.63	no	13
683		914	Plastic	10.5	200.0	0.243	886	0.97	no	14
759	Mary Pitcher	762	Plastic	24.2	191.3	0.536	1193	1.57	yes	15
833	Dicks Lake	610	Plastic	13.1	182.0	0.277	931	1.53	yes	16
331	North Shepody	900	Plastic	36.9	200.0	0.855	1421	1.58	yes	17
294		762	Plastic	2.7	200.0	0.063	535	0.70	no	18
162	Dobson Trail	762	Plastic	17.4	173.1	0.349	1016	1.33	yes	19
827	Mary Pitcher	762	Plastic	180.8	145.3	3.042	2288	3.00	yes	20
776	Shepody	914	Plastic	20.4	148.4	0.350	1017	1.11	no	21
401	SHEP	914	Plastic	4.5	200.0	0.105	646	0.71	no	22
372	SHEP	914	Plastic	4.4	200.0	0.102	640	0.70	no	23
821	Dicks Lake	610	Plastic	3.2	186.4	0.069	554	0.91	no	24
362	SHEP	914	Plastic	4.1	200.0	0.095	623	0.68	no	25
444	Fundy Connector	914	Plastic	41.0	200.0	0.949	1478	1.62	yes	26
431	Fundy Connector	762	Plastic	10.4	200.0	0.241	884	1.16	possibly	27
420	SHEP	762	Plastic	10.4	200.0	0.241	884	1.16	possibly	28
448	Fundy Connector	762	Plastic	8.8	200.0	0.203	828	1.09	possibly	29
447	Fundy Connector	762	Plastic	9.4	200.0	0.217	850	1.12	possibly	30
639	Shepherd	762	Plastic	6.5	160.5	0.121	683	0.90	no	31
557	Fundy Connector	762	Plastic	6.6	176.0	0.135	711	0.93	no	32
449	Fundy Connector	762	Plastic	7.9	200.0	0.183	797	1.05	possibly	33
303	Fundy Connector	762	Plastic	150.6	200.0	3.487	2408	3.16	no	34
305	Fundy Connector	762	Plastic	22.8	200.0	0.527	1185	1.56	yes	35
320	Fundy Connector	400	Galv	24.6	200.0	0.569	1220	3.05	no	36
378	Fundy Connector	762	Plastic	41.9	200.0	0.970	1490	1.96	yes	37
355	SHEP	762	Plastic	13.7	200.0	0.317	980	1.29	possibly	38
158	Fundy Connector	762	Plastic	10.8	200.0	0.251	897	1.18	possibly	39
407	SHEP	914	Plastic	22.7	200.0	0.525	1184	1.30	possibly	40
349	Fundy Connector	1219	Plastic	4.1	200.0	0.095	623	0.51	no	41
								Sum:	0	

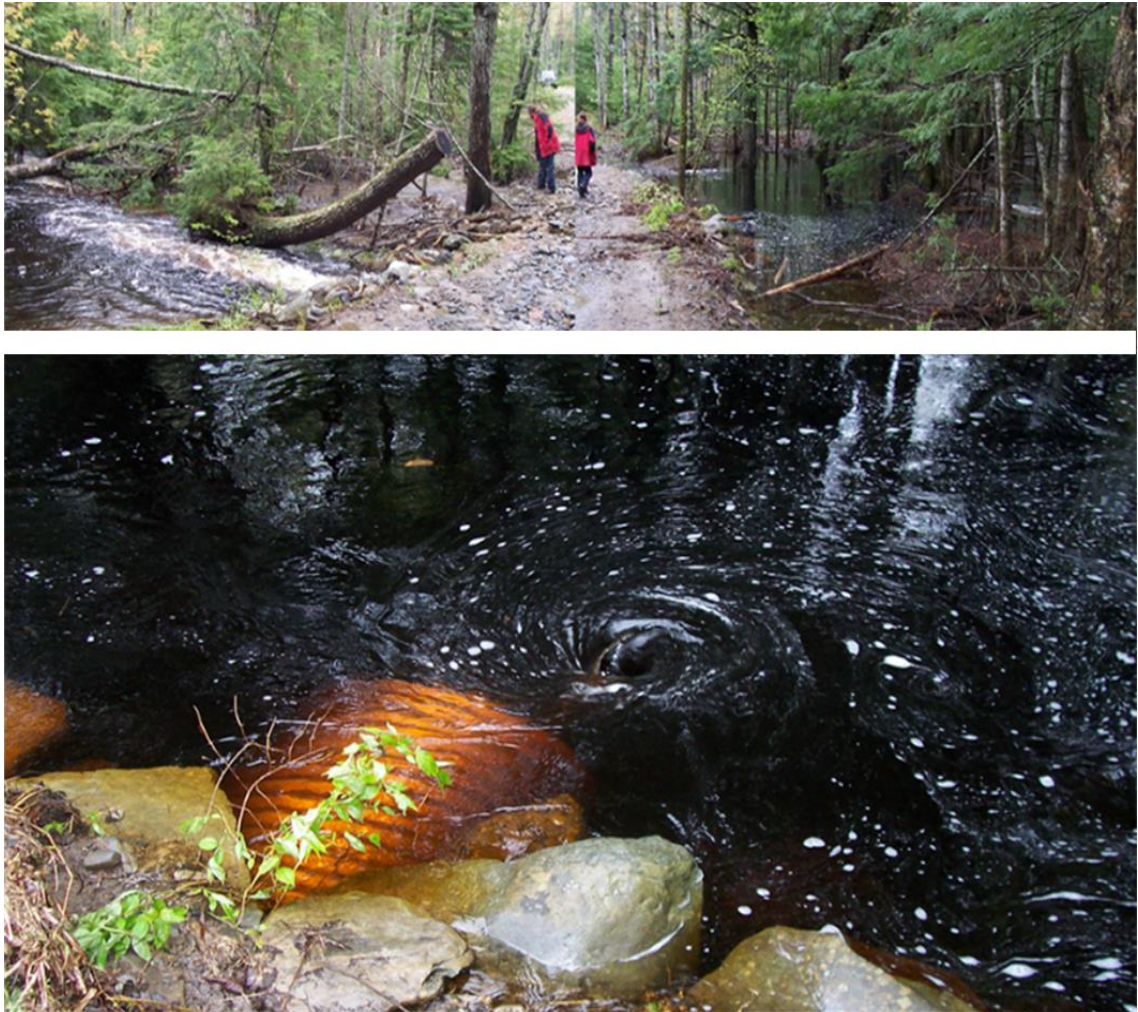


Figure 6.6. Example of a culvert-induced whirlpool inducing flow conditions (bottom) due to above-road ditch-limited flooding (top).

6.4. Discussion

The procedures for estimating discharge-affected recommendations for minimum culvert size outlined in Chapter 2 for the December 1, 2020, event, and for storm events not exceeding 100 mm or precipitation per day appear to be in reasonable agreement with observed road conditions, at least where surveyed and reported. Whether or not the daily discharge patterns as hydrometrically observed compare with standardized hydrograph

expectations relate to doing further work. At this stage, it can be reported that the standardized hydrograph model (Gray, 1962) presented in Chapter 2 can be adjusted to the hydrometrically captured hydrograph at Catamaran Brook in response to the Hurricane Bob event on August 20, 1991 (Figure 6.7, Caissie et al. 1996). Adjusting the standardized hydrograph to this event suggested that:

1. peak flow occurred within 1.4 days following the beginning of the storm,
2. storm-expected run-off and seepage discharge would amount to 33 mm instead of 108 mm of storm-induced precipitation.
3. This being so, calculated and recorded peak flow rate would amount to $6.2 \text{ m}^3/\text{sec}$, while the hydrograph flow would last for 5.2 days.

Reducing the discharge-causing flow rate from 108 to 33 mm is related to the timing of the storm event. As shown in Figure 6.7, actual discharge rates prior to August 20 were near zero. This means that the upslope soils of the Catamaran Brook basin can easily absorb and retain the storm-induced rain for the most part. The exception would occur along the upslope-limited recharge zones where the soil is generally shallow. This leads, in part, to surface runoff and to seepage-causing infiltration. This infiltration would also lead to seepage gradually percolating towards the stream through the underlying glacier-cracked rock formations.

In contrast to the August 20, 1991, event, most of the incoming precipitation on December 1, 2020, would directly discharge into the streams. At this time, i.e., at the end of the generally wet fall conditions, upland and lowland soils would be nearly to fully saturated, with very low water-absorbing water capacity remaining.

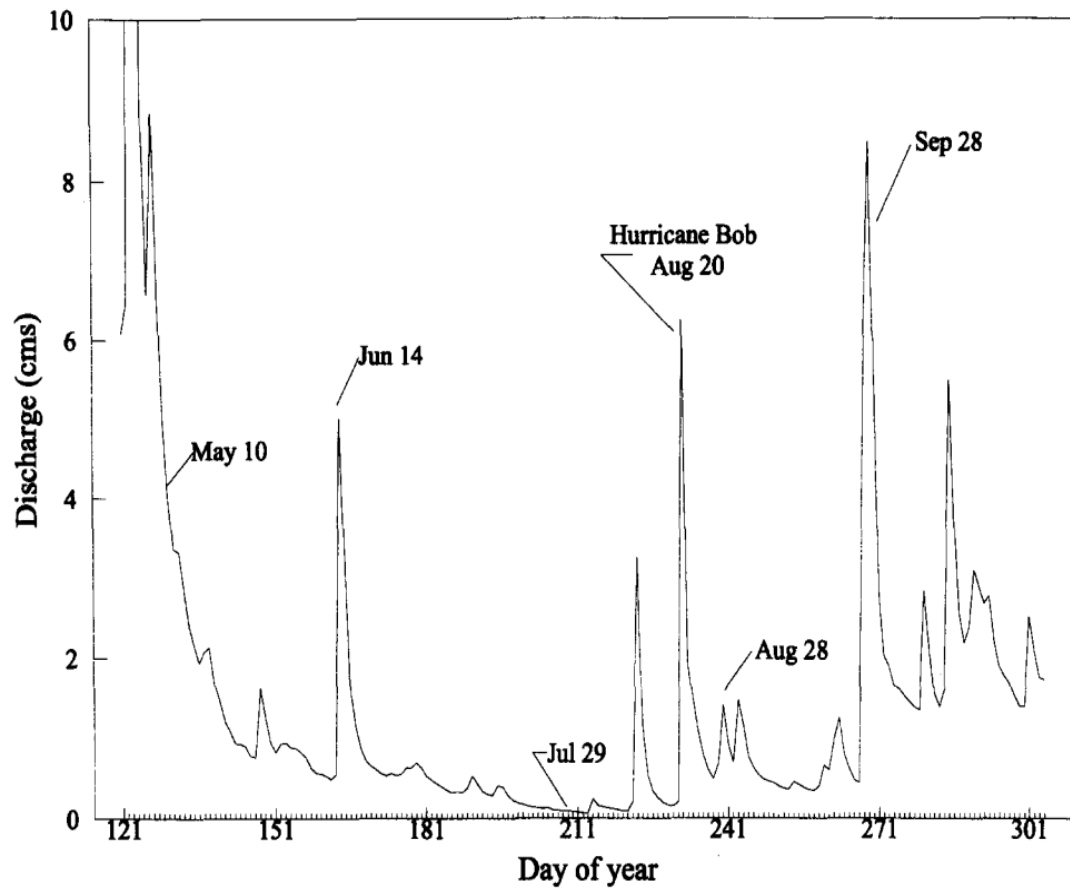


Figure 6.7. Daily discharge hydrographs at Catamaran Brook centered on the Hurricane Bob event, recorded on August 20, 1991 (Caissie et al. 1996).

CHAPTER SEVEN: SUMMARY, RECOMMENDATIONS AND APPLICATIONS

This thesis describes how LiDAR derived Digital Elevation Models can be used to delineate (Chapter 2) and evaluate existing forest roads (Chapters 3 and 4), suggest the layout for additional roads and trails in New Brunswick (Chapter 5), and with special focus on road-stream crossings as affected by a storm event (Chapter 6). The procedures needed to do this by way of operable and transferrable workflows are highlighted as follows:

1. Align hand-digitized roads with 1 and 10-m resolution LiDAR derived DEM's to make sure the roads stay on the elevated roadbed (Chapter 2).
2. Use the 4 and 1ha stream layers to determine locations where roads cross streams to predict possible culvert locations (Chapter 3 and 4).
3. Determine uniform and peak flow of discharge at each predicted culvert location and use that to calculate minimum culvert sizes (Chapter 3 and 4).
4. Generate individual costs for parameters that affect the road and trail network (Chapter 5).
5. Produce an overall suitability map using each rated individual cost to determine ideal trail locations.
6. Determine least-cost path for road and trail networks (Chapter 5).
7. Assess extent of existing culverts to accommodate storm-generated discharge rates (Chapter 6).

The procedures developed are of practical value in terms of:

1. Highlighting vulnerabilities in existing infrastructure.
2. Identifying culvert locations and size for new and existing roads and repair of existing culverts.
3. Facilitating culvert and road inventorying and monitoring in reference to flood and storm occurrences.
4. Determining new trail locations or reconstructing/repairing existing ones.

It is expected that these procedures can be applied to any elevation layers with at least 1-m resolution. In so doing, more can and needs to be done to evaluate local outcomes from operationally and scientifically important points of view. This would involve:

1. Enhancing the thesis-applied methodology towards a hydrologically seamless flow channel and depth-to-water representation across New Brunswick and elsewhere. This would include the thesis-formulated way for assessing minimum required culvert size based on selected storm-induced discharge thresholds.
2. Extending the process of automating LiDAR-DEM delineation from single roads to road networks.
3. Conducting hydrometric verification work to determine the extent to which the proposed standard hydrograph methodology applies to capture hourly stream

discharge in New Brunswick, and in relation to the more recent hydrograph standardization efforts (Chapter 2).

4. Automatically evaluating forest road conditions by classifying satellite images and LiDAR-DEM generated data layers pertaining to road braiding, softening, flooding and washouts, whether incurred gradually or following major storm events.
5. Further generalizing the road and trail-layout methodology through addressing additional layout preferences and restriction.

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CURRICULUM VITAE

Candidate's full name: Nana Agyei Owusu Afriyie

Universities attended:

University of New Brunswick

Master of Environmental Management

2019-2020

Kwame Nkrumah University of Science and Technology

Bachelor of Science Natural Resource Management

2011-2015