Vulnerability of culvert to flooding

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Abstract: One of the most important steps in the conception of engineering structures such as culverts is the design flood estimation. Although, the estimation methods are really old, the laws requiring a methodology of application are relatively new. Many culverts of Quebec's road system were never subject to design flood figuring, which increases the risks during flooding events. Nevertheless, it can be expensive and time consuming for the Quebec Ministry of Transportation (MTQ) to perform a complete study for each culvert in order to identify which one will not be able to hold design flood. So, it is not possible for them to identify which one needs to be changed in priority. The goal of this research is to find a way to identify flood vulnerable culverts as a function of their drainage capacity. A high precision digital elevation model (DEM) adapted to flat landscapes was built. Topographic and hydrologic modifications induced by the road system were taken into consideration. The main variables needed to establish a relation for the estimation of the culvert diameter were identified but the watershed area was the only significant one. In fact, the results on the studied area suggest that the watershed area explains 67% of the culverts diameter. Culverts with a diameter under the estimated prediction interval were considered vulnerable to a flooding event.

Key words: GIS; Transport; Culvert; DEM; Flood; Watershed

Abbreviation list: ANUDEM: Australian National University Digital Elevation Model; BDTQ: Base de données topographiques du Québec; CBN1: Canadian Base Network of level 1; DEM: Digital Elevation Model; D8: Deterministic eight neighbour flow direction algorithm; ETM+: Enhanced Thematic Mapper Plus; FED3DC1: Federal 3-D Densification Network of level 1; GIS: Geographic Information System; IDW: Inverse Distance Weighting; MTQ: Quebec Ministry of Transportation; NDVI: Normalized Difference Vegetation Index; NTDB: National Topographic Data Base; PVBMC1: Primary Vertical Bench Marks of level 1; RMSE: Root Mean Square Error; TIN: Triangular Irregular Network

Introduction

A culvert is a small engineering structure, constructed under an embankment, with an opening smaller than 4.5 m (Transports Québec 1995). There are frequently used to allow a stream under a road, because they are cheaper to build than bridges (Johnson and Brown 2000). In order to do that, culverts must be able to drain water correctly, even during flooding periods.

While old culverts were not subject to dimensioning calculations, the diameter of new culverts is determined as a function of the design flood. This is a flood with a recurrence period of 50 years for highway culverts, 25 years for national road and 10 years for other roads (Transports Québec 1995). The flood discharge is influenced by physical characteristics of the watershed like watershed area, slope, length, percentage of forest area and the percentage of wetlands and lakes. The method used by the Quebec Ministry of Transportation (MTQ) to define the culvert's design flood is an empiric method which takes into consideration all of these characteristics (Ministère des transports 1994). However, according to some regional analysis made in Quebec and Canada (Assani et al. 2006; Assani et al. 2005; Belzile et al. 1997; Rousselle et al. 1990; Hoang and Tremblay 1976; Anctil et al. 1998), the watershed area is the most important variable as it explains 85 to 95% of the discharge variance.

Often, in the event of a flooding, culverts can not do their job, which can result in significant damages to the road and in the interruption of highway traffic flows (Beckers et al. 2002; Tung and Bao 1990). In addition to an increased risk for the road network users and road infrastructures (Tung and Bao 1990), an under-dimensioned culvert can decrease the stream channel stability, thereby harming the aquatic ecosystem (Beckers et al. 2002; Hotte and Quirion 2003; Johnson and Brown 2000; Molloy and Torresan 2001; Potvin 1997). It can be expensive and irksome for the MTQ to do a complete study of each culvert in order to identify which one are not big enough to hold the design flood. So, it's impossible for the MTQ to identify the most flooding vulnerable culverts, culverts that need to be replaced in priority.

In response to these problems, the main goal of this research was to find a method to identify flood vulnerable culvert as a function of their drainage capacity. A high precision digital elevation model (DEM) adapted to a flat landscape was build to compute a culvert's watershed delineation method which takes into consideration hydrologic and topographic modifications brought by the road network. This watershed definition allows us to highlight the different characteristics of the culvert's watershed, in order to identify which one is critical to estimate the culverts' diameter. A relation between the diameter of the culvert and the watershed area was established by a least square regression. As a result, we found that the culvert's watershed area explains 67% of the diameter of the culvert ($p \geq 0.05$).In order to identify culverts vulnerable to flooding, this research suggests a method that needs only a limited set of data: the culvert's diameter and the watershed area, to facilitate the work of MTQ.

Methodology

Studied culvert

Our study is about the culverts of regional and collector roads, two types of roadways with a design flood of a 10 years recurrence. The sample consists of 103 circular shaped culverts, located on specific roads of the *Direction territoriale de l'Ouest de la Montérégie* (Figure 1). These roads are located in the Châteauguay river watershed, on the Esturgeon river watershed, the Des Fèves river watershed and a small part of Des Anglais river watershed. These watersheds are farming lands, located in the St. Lawrence Lowlands physiographic region, a flat landscape area. Culverts were listed during the Spring and the Summer of 2007. A part of the census was done by the MTQ. Diameter for each culvert was measured and a GPS point was taken with a Garmin 76 GPS.

Definition of watershed using DEM

The geographic information system (GIS) ArcGIS (Environmental Systems Research Institute) was used to delineate the culverts' watershed with DEM. These were made with 1:20 000 contour lines from the *Base de données topographiques du Québec* (BDTQ). The spot height from this database, from the National Topographic Data Base (NTDB), from the geodetic monument of the Canadian Base Network of level 1 (CBN1), from the Primary Vertical Bench Marks of level 1 (PVBMC1) and from the Federal 3-D Densification Network of level 1 (FED3DC1) allowed us to increase the precision of the DEM.

Spatial interpolation methods of Inverse Distance Weighting (IDW), Simple Kriging, Ordinary Kriging, Universal Kriging, Triangular Irregular Network (TIN) and "Topo to raster" were tested to find which one was able to give the best DEM for the studied area. DEM were generated with a resolution of 5 meters, which can end up generating huge data files. To be able to use all of the interpolation method, the area under scrutiny was divided into four sections. Comparisons between all of the methods were made on only one section, the Des Anglais river. The topography being similar for the four areas, there are not many differences in the interpolation results for the four sections. The root mean squared error (RMSE) obtained by a set of sample points against elevation estimation was compared for all the DEM with variance analysis and T tests made using SYSTAT 12 (Systat Software Inc). Even if the RMSE is the most widely used error measure (Weng 2002), the flow accumulation matrix also helped to identify the best method depicting flows on the territory.

To use stream network during the DEM creation, a stream burning method was applied to the DEM in order to obtain a more realistic flow accumulation matrix (Turcotte et al. 2000; Kenny and Matthews 2005). The stream network was burned by 6 meters in the DEM. Thereafter, a buffer of ten meters was generated with a Euclidean distance. We used a 3 pixels by 3 pixels filter to smooth the stream's edges.

The presence of roads in flat landscapes modifies the drainage via the topographical modifications brought to the landscape (Duke et al. 2003; Duke 2004; Duke et al. 2005). To take into consideration the transport network while defining watersheds, a one meter increase of the DEM was applied on the location of each road and highway (with the exception of streets). Then, depressions in the DEM were filled. The deterministic eight neighbour flow direction algorithm (D8) was used to get the flow direction matrix. Introduced by O'Callaghan and Mark in 1984 (Tarboton 1997), this algorithm was chosen because it is one of the most widely used, so it is available easily in the ArcGIS software. The creation of the flow direction matrix gave the flow direction accumulation matrix. This allows placing culvert on the closest pixel with the biggest accumulation. The culverts were considered as outlets, and the watershed of each one were delineate. Areas and slopes were calculated for each watershed. Slopes were given by the use of the DEM percentage slope map. The mean of the slope was calculated for each watershed.

Landsat image supervised classification

The Geomatica software (PCI Geomatica) was used for the spectral values classification of the June 8, 2001 satellite image by Enhanced Thematic Mapper Plus (ETM+) sensor of Landsat 7. Table 1 contains spectral bands of this image. To avoid topographic influence on the sensor values, bands ratio were computed. A threshold allowed distributing values for a better discrimination. Table 2 contains the spectral bands and the bands ratio used during the classification. A Normalized Difference Vegetation Index (NDVI) was used. This is frequently used and known to be efficient for the quantification of vegetation biomass (Goward et al. 1985), primary production (Boelman et al. 2003) and for land uses changes (Tucker 1979).

The satellite image classification was supervised. The Maximum Likelihood algorithm was chosen for the classification. Covers identified by the classification are: borders, water, wetlands, urban high density (urban HD), urban low density (urban), forests, low vegetation and farming. After completing the land uses classification, percentage of land uses of each culvert watershed were computed.

Relation between culvert diameter and watershed area

The relation between culvert diameter and watershed area, land uses and slope was determined by multiple regressions performed with the help of SYSTAT 12 (Systat Software Inc). The stream length, a characteristic with an important impact on the discharge, was not considered, because stream which are feeding culverts are often seasonal and hard to identify. After getting the regression's coefficients, a confidence interval and a prediction interval were computed. The prediction interval allows identifying culverts with a diameter that is not proportional to their watershed area.

Results

Census of culvert

The culvert census of the studied area regional and collector roads gave us a sample of 103 culverts. Culvert diameters are ranging from 30 to 300 cm, with a mean of 91 cm, median of 60 cm and a standard deviation of 52.7 cm (Figure 2). Culverts were used as outlet during the watershed definition. The delineation was done with a DEM generated by a spatial interpolation method.

Efficiency comparison between different spatial interpolation methods

The results of each interpolation method are shown in figure 3. To compare each method, a sample of spot height and geodetic monument (55 elevation points) were selected randomly to generate the RMSE. The Topo to raster method gave the lowest RMSE. Although the variance analysis shows that RMSE were significantly different ($p \geq 0.05$), the difference in RMSE between Topo to raster and the two other best methods (TIN and Simple kriging) weren't significant ($p \geq 0.05$). In order to select the best method, the quality of the accumulation matrix was compared for each interpolation method. The Strahler order was established for all the streams in order to detect errors in the matrix (circled on figure 3). The Topo to raster, a method based on ANUDEM (Australian National University Digital Elevation Model) (Hutchinson et Dowling 1991), was the only one able to depict correctly stream flows. This method allowed us to generate a hydrologically realistic DEM with the drainage enforcement of an oriented hydrologic network. Topo to raster was the interpolation method chosen to delineate watersheds.

Definition of culverts' watershed using DEM

Culverts' watershed obtained by increasing by one meter the transport network location was compared with culvert watershed given by a DEM without an increase of elevation (Figure 4). In most cases, watersheds given by the increase of one meter were more realistic. So, watersheds were delineated with that method. The size of the watersheds ranged from 132 m^2 to 5.14 km^2 (Figure 5a). The mean of the area was

0.58 km², with a median of 0.04 km² and a standard deviation of 1.19 km². The slope of the watershed was quite low (Figure 5b). In fact, the range was between 0.38% to 9.68%, with a mean of 2.32%, a median of 1.55% and a standard deviation of 2.08%.

Landsat image supervised classification

The efficiency of the Landsat image supervised classification was 96.37% for the training sites. Table 3 shows the confusion matrix of the different covers. Borders, water and forests were easy to differentiate (100%). It was harder to differentiate urban high density (91.3%) and urban low density covers (90.8%). The percentages of land uses for each watershed were evaluated. Minimum, maximum, mean, median and standard deviation for each land uses are shown in table 4. These data, watershed area and slope were useful to find a relation to determine diameter of culvert.

Influence of different variables on the culvert diameter

A least square regression, with diameter as dependant variable, was performed. The watershed area, slope of the watershed, percentage covered by lakes and wetlands, percentage covered by vegetation, percentage in urbanized area and percentage in farming lands were considered as independent variables. Notwithstanding, only the watershed area was kept as a significant variable ($p \geq 0.05$). We obtained a coefficient of determination (R^2) of 0.665. Figure 6 shows the relation between culvert diameter and the watershed area. The prediction interval was chosen for the identification of vulnerable culverts. The lower limit of the interval is the limit under which a culvert is considered under dimensioned ($p \geq 0.05$). Only one culvert in the sample was found to be under this limit (circled with a star on the figure 4).

Discussion

The main goal of this study was to create a method for identifying culverts vulnerable to flooding as a function of the drainage capacity. This is currently hard to realize with the MTQ dimensioning method. The suggested method begins with a delineation of the watershed based on a DEM created by spatial interpolation. The DEM generated with Topo to raster were well adapted to the flat landscape of the studied area with the use of hydrology and the transport network. The stream burning of a hydrologically oriented network gave good result, as in the work of Kenny and Matthews (2005). The RMSE values was 2.07m, witch is lower than the contour lines error. The addition of a road network to the DEM gave a more realistic watershed definition. Those results are in line with the results obtained by Duke et al. (2003, 2005). Only a few watersheds were not really realistic, because the presence of farm fields, where drainage trench, modified the topography, just like the transport network (Duke et al. 2005). Taking into consideration that topographical modification needs a lot of data, which can increase the complexity of the watershed delineation. Increasing the DEM basic data precision with a method like LIDAR can be a realistic approach to have a better precision for the watershed delineation (Murphy et al. 2008).

For the relevant dimensioning variables, only the watershed area was identified by the linear regression as statistically significant. However, the rejection of the slope variable can be explained by the lack of spatial variability in the studied area. Indeed, the area is located in a really flat landscape, and the highest mean slope was only 9.68%. It is possible that a higher variability could show the slope's influence.

Results suggest that watershed area explain 67% of the culverts' diameters. This relation between area and the culvert's diameter is weaker than the other relation between area and discharge described in other researches (Assani et al. 2006; Assani et al. 2005; Belzile et al. 1997; Rousselle et al. 1990; Hoang and Tremblay 1976; Anctil et al. 1998). However, the sample includes culverts from different years of construction and nothing showed that they were dimensioned correctly. A sample containing only recent culverts could probably allow us to obtain a higher coefficient of correlation.

To identify flooding vulnerable culverts, this research suggests the use of the culvert position in comparison to the lower prediction threshold in figure 6 as a vulnerability measure. So, all the culverts located under this lower boundary computed with a confidence level of 95% will be considered as under dimensioned, and therefore vulnerable. It is worth pointing out that the studied culvert located beyond this threshold (circle with a star on figure 6) has a diameter of 180 cm and is located on road 209 in the city of Saint-Rémi. The state of this culvert is bad. Some facts can explain this bad state. It could be caused by a natural worsening, or an accelerated worsening caused by an absence of dimensioning figure.

In this research, regional and collector roads were the only one to be studied, in order to compare culverts with the same design flood. It will be important to repeat the experience on highways and national roads to obtain the regressions models necessary for the identification of vulnerable culverts on these roads. Furthermore, a sampling on areas with more topography is essential for the validation of slope effect on the culverts' diameters.

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Tables

Table 1: Satellite image spectral bands of ETM+ sensor by Landsat-7

Name of the spectral band	Wave acquired	Wavelength acquired (μm)
ETM 1	Visible Blue-green	0,450 to 0,515
ETM 2	Visible Green	0,525 to 0,605
ETM 3	Visible Red	0,630 to 0,690
ETM 4	Near Infrared	0,750 to 0,900
ETM 5	Mid-Infrared 1	1,550 to 1,750
ETM 7	Mid-Infrared 2	2,090 to 2,350

Table 2: Parameters used for the spectral values of the satellite image

Bands and bands ratio of the classification
Blue-Green
Green
Green/ Blue-Green
Near Infrared / Blue-Green
Mid-Infrared 1/ Red
Mid-Infrared 2/ Blue-Green
Mid-Infrared 2/ Near Infrared
Mid-Infrared 2/ Mid-Infrared 1
NDVI

Table 3: LANDSAT Image supervised classification confusion matrix for the training sites

Class	# of pixel	Border	Water	Wetland	Urban HD	Urban	Forest	Low Vegetation	Farming
Border	2840	**100%**	0%	0%	0%	0%	0%	0%	0%
Water	463	0%	**100%**	0%	0%	0%	0%	0%	0%
Wetland	1085	0%	0%	**98%**	0%	0,2%	0,6%	1,3%	0%
Urban HD	243	0%	0%	0%	**91,3%**	3,3%	0%	0,4%	4,9%
Urban	509	0%	0%	0%	4.1%	**90.8%**	0,2%	4,9%	0%
Forest	82	0%	0%	0%	0%	0%	**100%**	0%	0%
Low Vegetation	365	0%	0%	0%	0%	2,7%	0%	**96,2%**	1,1%
Farming	3323	0%	0%	0%	4,8%	0,2%	0%	0,4%	**94,7%**

Table 4: Descriptive Statistics of land uses percentage for culvert watershed

Statistics	Water	Wetland	Urban HD	Urban	Forest	Low vegetation	Farming
Minimum	0	0	0	0	0	0	0
Maximum	0,7	71,43	100	100	61,57	100	100
Mean	0,009	2,93	8,22	15,17	13,49	33,88	27,3
Median	0	0	1,15	2,5	1,7	30,16	13,48
Standard deviation	0,07	9,33	18,62	28,86	17,83	28,66	17,83

Table of figures

Figure 1: Studied culverts
Source: BDTQ, MTQ, NTDB

Figure 2: Diameters of culverts distribution

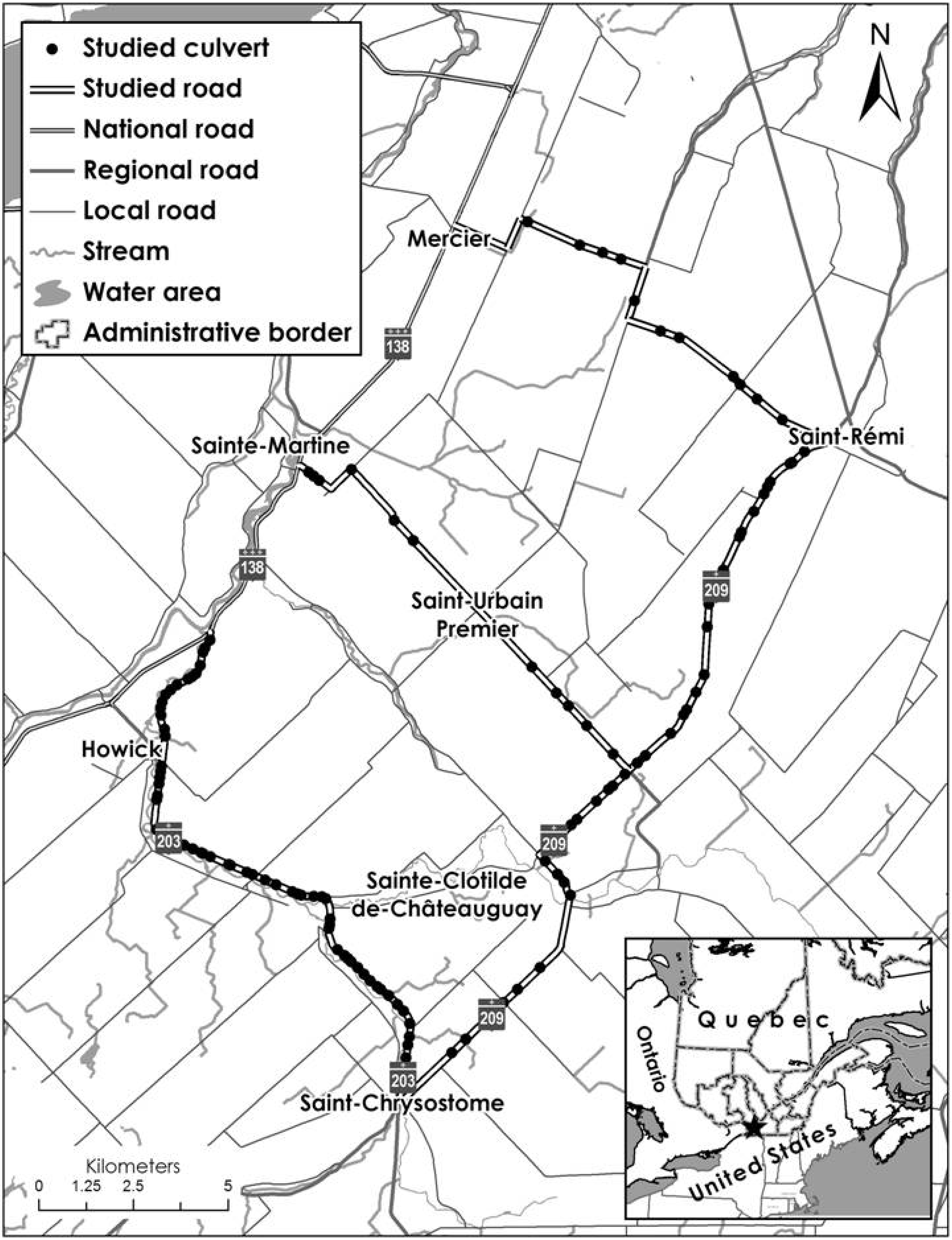
Figure 3: Comparison of the flow accumulation matrix for different spatial interpolation methods. The hydrologic network given by the accumulation matrix is given for each DEM. Errors in the stream network are circled in white.
Source: BDTQ, NTDB

Figure 4: Delineation of culverts watershed. Watersheds in squared were delineate with a DEM modified by an increase of 1 meter for road location. Watersheds in grey were delineated with a standard DEM.
Source: BDTQ, MTQ, NTDB

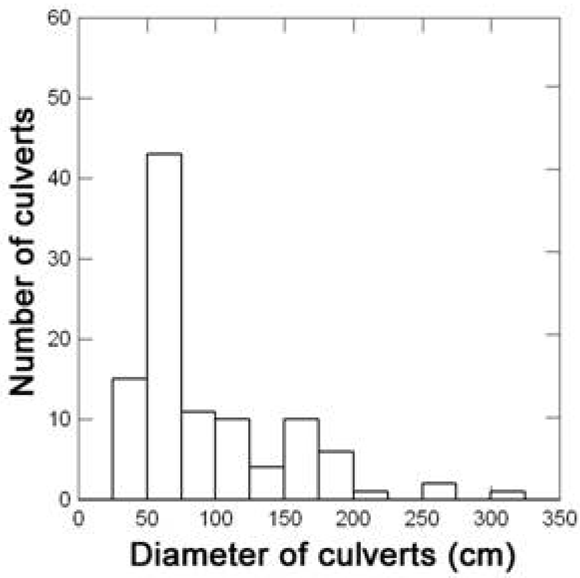
Figure 5: Distribution of a) watersheds area and the b) mean slope of the watersheds

Figure 6: Linear regression between the diameter of a culvert and his watershed area. Each dot symbolizes a culvert of the study. The culvert circle with a star is vulnerable to flooding.

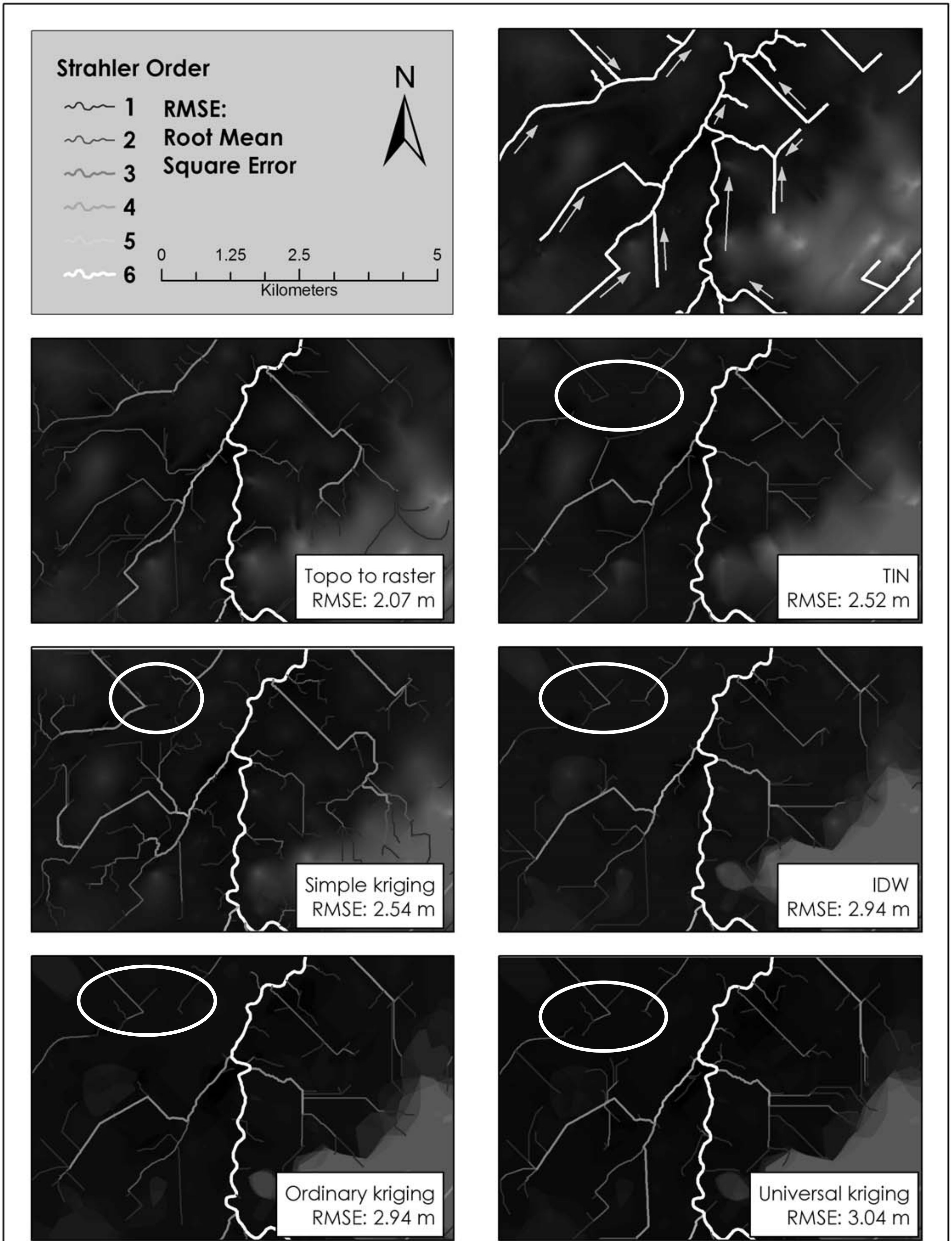
Figures



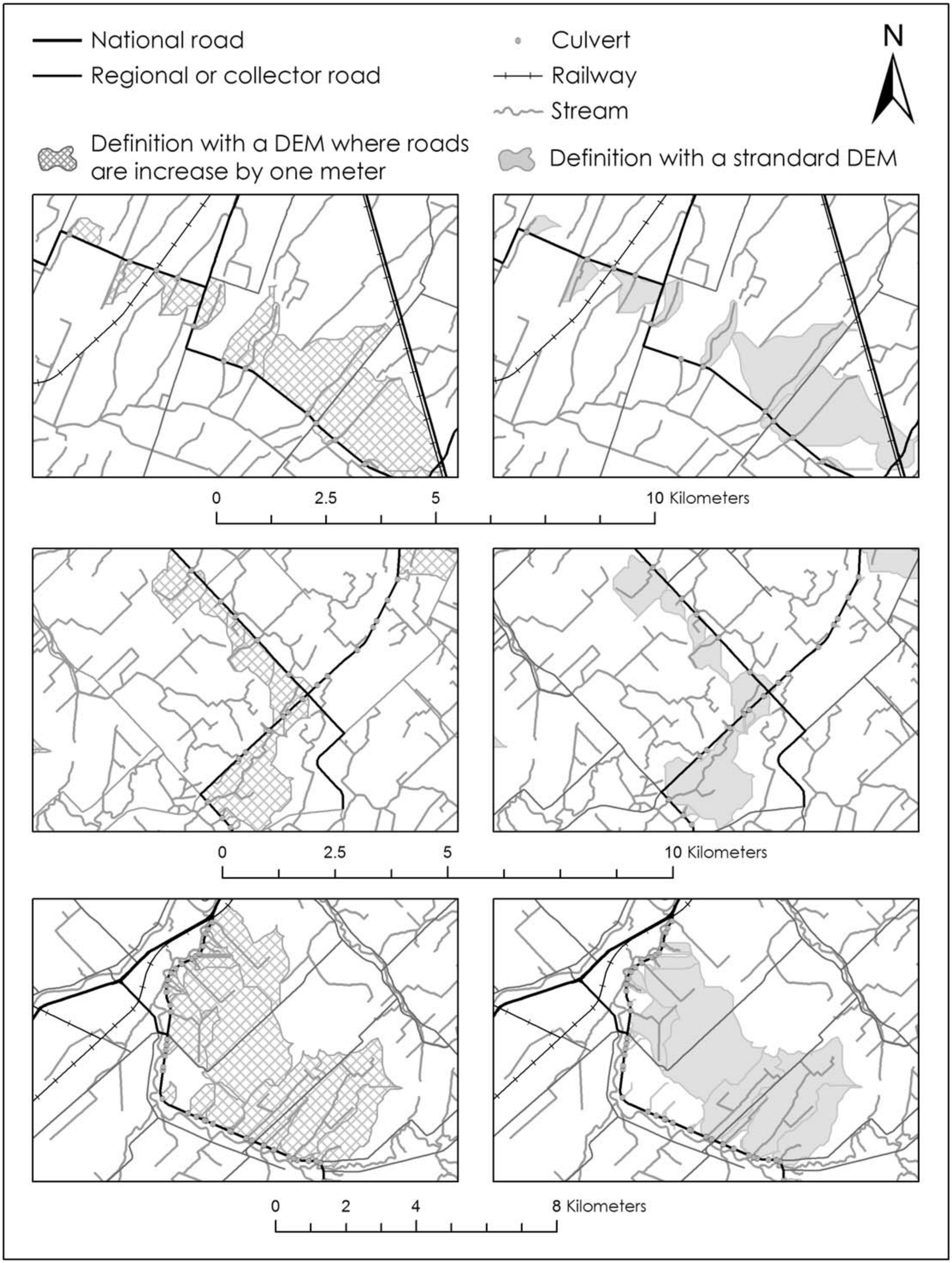
Studied culvert
Studied road
National road
Regional road
Local road
Stream
Water area
Administrative border
N
Mercier
138
Sainte-Martine
Saint-Rémi
138
Saint-Urbain
Premier
209
Howick
203
209
Sainte-Clotilde
de-Châteauguay
209
203
Saint-Chrysostome
Kilometers
0
1.25
2.5
5
Quebec
Ontario
United States

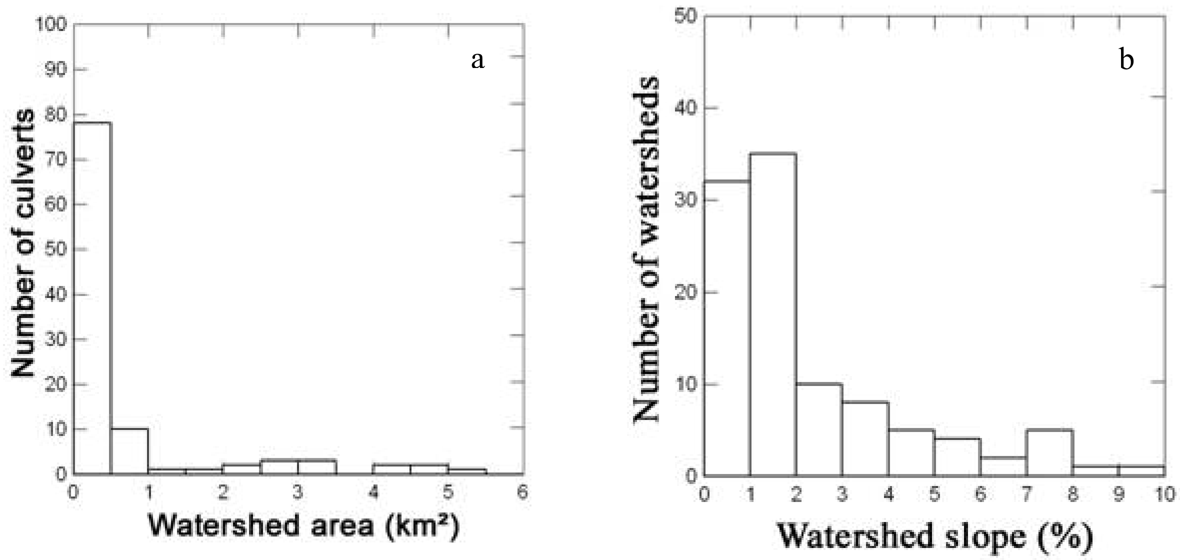


Number of culverts
60
50
40
30
20
10
0
0
50
100
150
200
250
300
350
Diameter of culverts (cm)

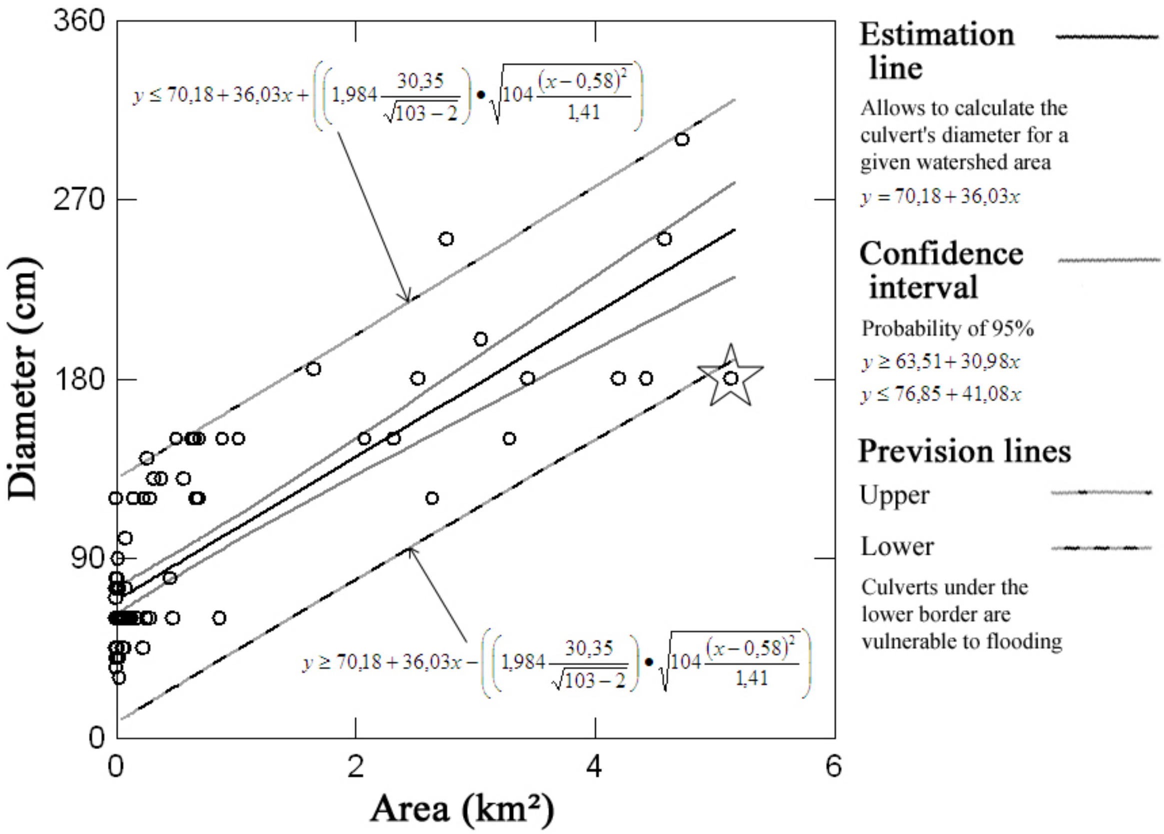


Strahler Order
1
2
3
4
5
6
RMSE:
Root Mean
Square Error
N
0
1.25
2.5
5
Kilometers
Topo to raster
RMSE: 2.07 m
TIN
RMSE: 2.52 m
Simple kriging
RMSE: 2.54 m
IDW
RMSE: 2.94 m
Ordinary kriging
RMSE: 2.94 m
Universal kriging
RMSE: 3.04 m


National road
Regional or collector road
Culvert
Railway
Stream
N
Definition with a DEM where roads are increase by one meter
Definition with a strandard DEM
0
2.5
5
10 Kilometers
0
2.5
5
10 Kilometers
0
2
4
8 Kilometers



a
Number of culverts
Watershed area (km²)
0
10
20
30
40
50
60
70
80
90
100
1
2
3
4
5
6
b
Number of watersheds
Watershed slope (%)
7
8
9


Diameter (cm)
Area (km²)
360
270
180
90
0
0
2
4
6
$y \le 70{,}18 + 36{,}03x + \left(\left(1{,}984 \frac{30{,}35}{\sqrt{103-2}}\right) \bullet \sqrt{104 \frac{(x-0{,}58)^2}{1{,}41}}\right)$
$y \ge 70{,}18 + 36{,}03x - \left(\left(1{,}984 \frac{30{,}35}{\sqrt{103-2}}\right) \bullet \sqrt{104 \frac{(x-0{,}58)^2}{1{,}41}}\right)$
Estimation line
Allows to calculate the culvert's diameter for a given watershed area
$y = 70{,}18 + 36{,}03x$
Confidence interval
Probability of 95%
$y \ge 63{,}51 + 30{,}98x$
$y \le 76{,}85 + 41{,}08x$
Prevision lines
Upper
Lower
Culverts under the lower border are vulnerable to flooding