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DEVELOPMENT OF DEM-BASED METHOD FOR MAPPING STREAM POWER DISTRIBUTION OF SOUTHERN ONTARIO STREAMS

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DEVELOPMENT OF DEM-BASED METHOD FOR MAPPING STREAM POWER DISTRIBUTION OF SOUTHERN ONTARIO STREAMS

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Abstract

Mapping of stream power along a stream system, a known determinant of channel form and dynamics, is a valuable component of geomorphic stream assessment procedures that, unlike current methods, is physically-based, time- and cost-effective, objective and repeatable. Continuous maps of stream power can be obtained by extracting channel slope from DEMs and combining them with a discharge-drainage area function. Using the case of Highland Creek, a highly urbanized basin in Scarborough Ontario for which extensive data and background information is available, it is shown that reliable and precise stream power maps can be obtained from the Ontario provincial DEM. Local stream power variation can be seen to match known features of the channel and both reach-scale and overall trends in stream power match those from a 1D computational model (HEC-RAS). Stream power maxima and minima also coincide with known areas of channel instability and deposition.

Keywords: stream power; Highland Creek; GIS; Ontario Provincial DEM v.2.0; mapping; stream assessment; fluvial geomorphology.

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Chapter 1: Introduction

Channel adjustment is a normal process in natural river systems, a result of constantly changing discharges and sediment loads. For example, river widening and incision is a common response to an increase in discharge. In urban areas these kinds of adjustments can occur as a result of urbanization-induced hydrological changes. The resulting changes in morphology and stream behaviour can result in expensive property loss and damage to infrastructure, which in turn perpetuate the negative feedback cycle of channel modifications and channel adjustments (Kondolf et al., 2003).

River management authorities must assess rivers in their jurisdiction in terms of the risk of erosion or channel stability in order, among other things, to audit the state of the watershed and plan stream restoration opportunities. A number of tools are available to conduct these types of assessments and the two most commonly used methods are hydraulic modeling and rapid in-field descriptive assessments. The first of these results in water surface elevation and shear stress data for cross-sections of the river at different flow conditions but is very data-, skill- and cost-intensive. In-field assessments on the other hand have poor repeatability and use apparent symptoms of stream instability but do not tie these to physical processes.

There is an opportunity and need for a rapid and objective approach to assessing the erosion potential and stability of stream systems at the scale of the reach and entire network. This would provide a reconnaissance level picture of the river system from the point of view of geomorphic activity and channel dynamics but use readily available data sources.

A possible basis for an objective assessment method is mapping stream power throughout the stream network. Stream power is a measure of potential energy exerted in a stream as water flows downhill and is an indicator of sediment transport potential in a system. It is a rate of doing work (Robert, 2003). When values are examined over an entire basin, the location of stream power maxima can be considered locations of rapid channel adjustment, maximum sediment transport rate and net erosion, while stream power minima would be locations of sediment accumulation (or deposition)(Jain et al.,

2006). While geomorphologists and researchers have recognized the value of stream power, little has been done to develop its use in stream channel assessment.

The remainder of this chapter consists of background information on channel engineering, stream power and using GIS for stream mapping. Chapter 2 consists of a description of the Highland Creek basin which will be used as a case for the development of DEM-derived stream power maps. Chapter 3 will take an in-depth look at the GIS processes involved in calculating stream power, specifically examining how to accurately calculate slope and discharge from the DEM. Chapter 4 presents the stream power results in map form and uses data available for Highland Creek to demonstrate different possible uses as well as to verify the results. Chapter 5 will compare the stream power maps to results from a full hydraulic analysis and one commonly-used stream assessment method.

1.1 Literature review

1.1.1 Fluvial geomorphology and channel assessment

Channel modification in modern-day cities was a responsibility first undertaken by engineers and focused on one simple goal: flood conveyance. The solution in most small streams was to modify and construct channels capable of routing water away from populated areas as quickly as possible (OMNR and Watershed Science Centre, 2002). Problems with this type of channel design became obvious in the late 20^{th} century: the cost of building and maintaining these artificial channels is high, they degrade or destroy stream habitat and the original problem is often propagated in the upstream and downstream reaches (Bellamy, 1994; Thorne, 1998; Downs and Gregory, 2004). There has been a realization that the success of channel management requires an understanding of the functional dynamics and connectivity of the channel hydrosystem and the notion of human dominance over nature has given way to a paradigm of sustainable management, a desire to work *with* instead of against the river (Downs and Gregory, 2004).

Urban areas are often a focus for channel modifications because of the changes in stream hydrology they experience, as well as the necessity for protection of infrastructure in and around the channels. In addition to this, stream corridors are increasingly viewed as natural amenities that should be managed for their inherent ecological value as

opposed to flood conveyance routes. The City of Toronto has noted that in their region, urbanization has led to an increase in stormwater runoff, flooding, erosion, destruction of habitat and reduced stream base flow (City of Toronto, 2006). As development continues, urbanization becomes an increasingly important problem for stream managers in southern Ontario and reliable assessment of stream stability, morphology and dynamics is an important element of this problem and in planning mitigation and restoration.

In 1986, the Supreme Court of Ontario ruled in favour of the Scarborough Golf and Country Club, property owner on Highland Creek in Scarborough, Ontario, and deemed the city responsible for property damage citing inappropriate upstream management (Lorant, 1994). This sets a precedent for municipalities that an investment in stream maintenance must be made one way or another. Concrete-lined channels require repair every 13 to 25 years at an estimated maintenance cost of $6.25/metre/year and a replacement cost of $1759/metre (OMNR and Watershed Science Centre, 2002). In contrast, a natural channel design can be defined as one which "seeks to establish sustainable, morphologically and hydraulically varied, yet dynamically stable fluvial systems that are capable of supporting healthy, biologically diverse aquatic systems" (Rhoads et al., 1999). A constructed 'natural channel' in an urban settings requires a capital cost of $550 per metre and a maintenance cost of $1.00/metre/year (OMNR and Watershed Science Centre, 2002).

Conferences such as the International Conference on Natural Channel Systems showcase the more recent trend towards interdisciplinary (engineering/ geomorphology/ biology) rehabilitation efforts and natural channel design. Engineers are still largely responsible for the design of rehabilitated channels, but a great deal of attention has been paid to the field of geomorphology and the perspectives that can be gained from that discipline.

Before natural channel designs can be considered, an understanding of the system must be acquired. In particular, the geomorphological perspective is important in terms of providing information and raising awareness of process dynamics and system connectivity as well as understanding landform complexity, positive-feedback, non-linear responses, event sequences, understanding of time-dependent processes and episodic change (Downs and Gregory, 2004). In short, it is the realization that water and sediment

must be managed together on a catchment scale. Although studies often focus on 'problem reaches', the controls (i.e. hydraulics and sediment transport processes) are determined by the channel network, and the network is a function of hydrology and sediment supply for the entire catchment (Downs and Priestnall, 2003). Accepting the river as a geomorphic system means acknowledging that it is a complex system and that a high level of training and experience is required to assess all the individual variables and to interpret their meaning.

Stream assessment has become a standard step in the process of channel design. Assessment can be defined as the process for identifying the likely consequences (to the biogeophysical as well as the anthropic environment) of implementing particular activities and for conveying this information in order to facilitate management decisions (Wathern, 1988). In other words, it should be an unbiased record of the state and function of a system on which design decisions can be based. Although a general definition of assessment can be agreed upon, by no means has a standard *method* of assessment been recognized. In order to assist in geomorphologically-based stream assessment, a number of documents have been published both by academics and government or proxy-government organizations.

The first type of stream assessment documents are 'adaptive management' strategies. In Ontario, such a document is produced by the Ministry of Natural Resources and the Watershed Science Centre (2002). The goal of adaptive management is to organize interdisciplinary cooperation and to use feedback loops throughout the stages of problem identification, assessment and remediation (Downs and Gregory, 2004). It is an 'active learning' approach that helps to deal with the complexity of a channel as a system. Very little information is provided about methodologies in such a document.

Another similar document published by the United States Federal Interagency Stream Restoration Working Group (1998), consists of a primer in geomorphology, hydrology, restoration and watershed management. Over its nine chapters, it thoroughly discusses a number of approaches, methods and techniques and considers how these can be applied, but does not focus on any particular attributes or methods. Discussion of data collection and analysis is thorough, or else refers to other more thorough and well known documents, but no single procedure is recommended. This document resembles an

introductory text in fluvial geomorphology with an emphasis on river management. A large number of issues are addressed, but the goal of the document is to educate and inform the reader about the issues involved with this new perspective on rivers. Although methods for collecting specific attributes (e.g. discharge) are discussed, the document does not provide a single assessment strategy or solution.

In terms of actual methods of stream assessment, three levels are recognized (Downs and Gregory, 2004). The first, and possibly most popular, is a 'catchment baseline inventory' and consists of a catchment-scale examination (mostly conducted in the field) of a number of different variables, leading to the classification of reaches based on what are considered standard forms of river morphology or process (Downs and Gregory, 2004). In such cases, quality assurance and consistent interpretations are very important and require intensive training in order to preserve repeatability. The appeal of these types of assessment lies in the fact that little to no pre-existing information on a basin or stream is required.

The types of documents published range from extremely detailed procedures to very short worksheets. In Canada, the British Columbia Ministry of Forests has published the 'Channel assessment procedure guidebook and field guidebook' (B.C. Ministry of Forests, 1996). The guidebook lists a series of measurements (bankfull width, channel depth, largest sediment particle and channel gradient) and calculations based on these measurements. From these, a channel type is chosen (ex.: riffle-pool, cascade-pool or step-pool, with further subcategories based on bed material and functionality of large woody debris). The channel is considered to be disturbed if it differs in form from the predicted channel type. A number of field indicators (e.g. sediment wedges, eroding banks, multiple channels or braids) determine whether the reach is aggrading or degrading. Based on this information, reaches are then rated as stable, aggraded or degraded.

An example of a worksheet-type inventory is in use in Ontario and is called the Rapid Geomorphic Assessment (RGA) (Ontario Ministry of the Environment, 1999). It consists of recording evidence of adjustment in channel form (i.e. aggradation, degradation, channel widening and planimetric form adjustments) to calculate a Stability Index Value. Depending on the score received, a reach can be classified as 'in

adjustment' (high score), 'transitional or stressed' or 'in regime' (low score). This type of inventory is known to be especially subjective and can yield very different results depending on the level of experience of the person conducting the assessment.

The River Styles Framework (Brierley and Fryirs, 2005) is an example of an academic response to the demand from managers of a simple, direct, coherent method or approach to river assessment. It is extremely detailed (a 400-page book) but results, just like the others, in the geomorphic *description* and classification of a catchment based on field typing and diagnosis.

The Rosgen Classification Method (Rosgen, 1996) is likely the most popularized river classification scheme in existence and is also one of the more detailed 'catchment baseline inventory' assessment methods. Classifications are based primarily on stream form, valley form and sediment type, as illustrated in Figure 1.1. The type of stream identified from the classification procedure dictates the channel design. The method has been widely adopted by agencies in the United States, partly because basic training can be accomplished in a one-week training course with no previous background. It now forms part of the Watershed Assessment of River Stability and Sediment Supply (WARSSS) methodology of the U.S. Environmental Protection Agency. However, the small amount of training in this method cannot replace the insight of fully trained geomorphologists (Kondolf et al., 2003).

There have been a number of published criticisms of the Rosgen method, and at least two of these (Juracek and Fitzpatrick, 2003; Simon et al., 2007) conclude that the method should only be used as a communication tool to describe channel form and not as a basis for predicting channel instability or equilibrium morphologies. To the extent that all catchment baseline inventories seek to simplify and categorize, these criticisms must be extended to the entire category of inventory-type assessments. All are very dependent on highly-skilled practitioners and are based on non-quantitative or semi-quantitative classifications; geomorphic *descriptions* only.

The second type of stream assessment methodology is a catchment historical analysis. This type of analysis relies on the examination of any and all historical data available for a particular basin. This includes, but is not limited to, old maps, flow records, aerial photographs, narrative accounts and floodplain stratigraphy. All data

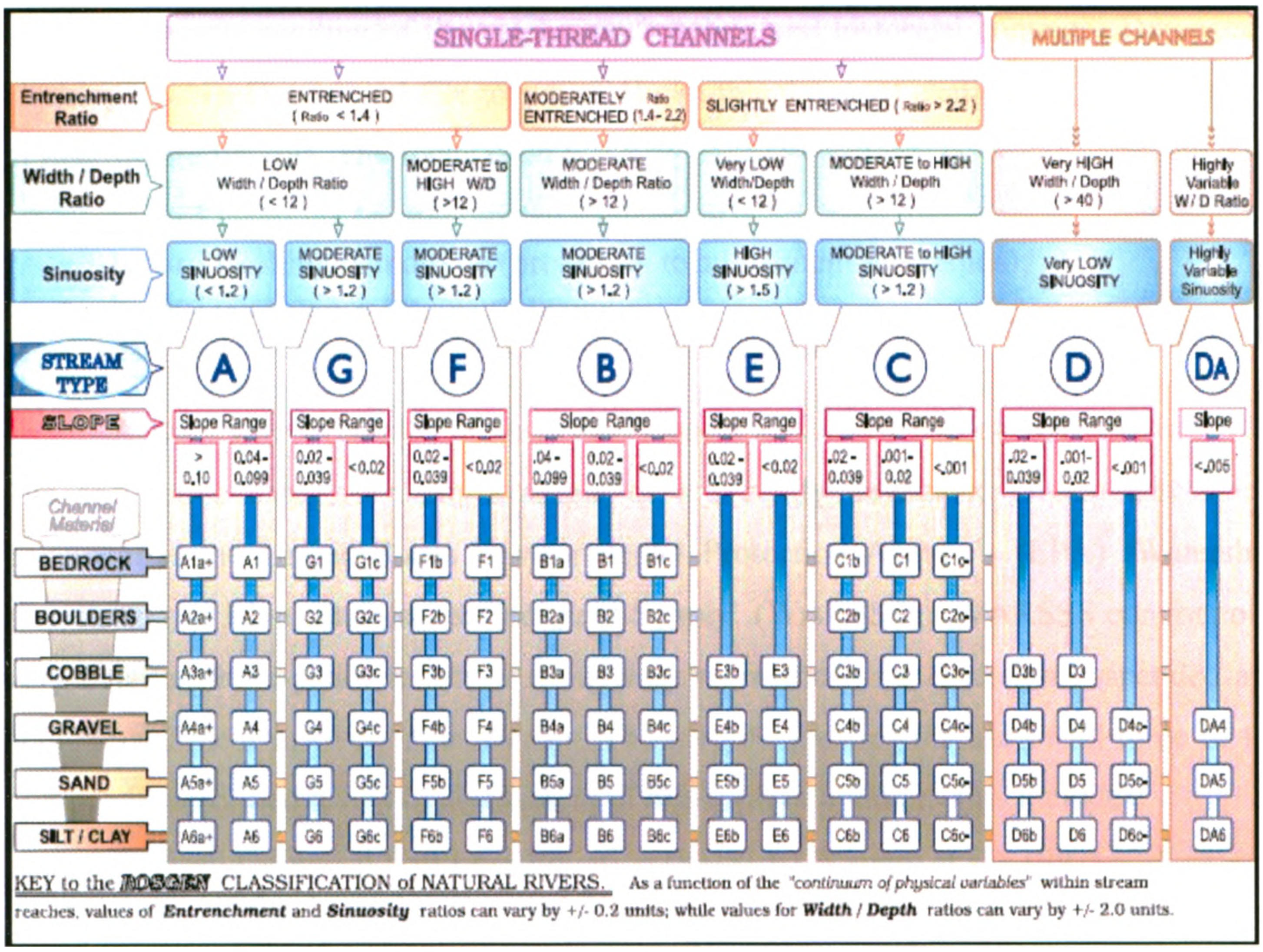


Figure 1.1 Rosgen classification of natural rivers.
http://www.epa.gov/watertrain/stream_class/25solo.htm

should be examined, regardless, but also cognizant, of possible limitations. Different methods of organizing the information include watershed analysis (Montgomery et al., 1995), cumulative impacts analysis (Reid and McCammon, 1993), fluvial audits (Sear et al., 1995) and sediment budgets (e.g. Reid and Dunne, 1996). The benefit of this method is the emphasis on active processes and channel changes providing a context and understanding of the current state of the river and the events leading to it.The obvious drawback, however, is that it is limited to streams and basins where there *is* historical data available and in southern Ontario this information may be very limited. Furthermore, the historical assessment makes no quantitative analysis of the current morphology and processes or future events and may not take into account the effects of events such as rapid land-use change to which the stream may still be adjusting.

Channel dynamics, or 'geomorphological dynamics assessments' are the third type of stream assessment (Downs and Gregory, 2004). These types of assessment

incorporate "specific, reach-level, analyses of the dynamics of channel processes and follows an understanding of the catchment baseline and historical context" (Downs and Gregory, 2004). Downs and Gregory (2004) call this the most challenging level in terms of making predictions. The focus is on :

- hazard locations (contemporary adjustment);
- hazard likelihood and type (proximity to adjustment thresholds);
- hazard persistence (recovery potential);
- hazard magnitude (predicting incremental adjustment).

A few other examples of assessment documents exist that do not necessarily fit into the above categories. An example of a recently developed stream assessment document is the United States Environmental Protection Agency's (EPA) 'Watershed Assessment of River Stability & Sediment Supply' (WARSSS)[1]. WARSSS consists of a very detailed three-phase technical framework of methods for assessing suspended and bedload sediment in rivers and streams. The method features the use of all three of the previously described levels of assessment in one form or another. This includes:

- Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997)
- Bank erosion hazard index (BEHI) and near-bank stress (NBS) (Rosgen, 1996)
- sediment rating curves
- Rosgen Stream Classification System (Rosgen, 1996)
- channel evolution (based on Rosgen Classification)
- stability assessment
- reference reach characteristics

In particular, the stability assessment uses a series of worksheets to collect information on stream characteristics such as 'flow regime', 'debris content' and also involves the calculation of a large number of dimensionless ratios. The method relies heavily on the classification of streams and the original Rosgen Classification Method (Rosgen, 1996) to determine sensitivity to disturbance, sediment supply, bank erosion potential and the controlling influence of vegetation. Although the WARSSS system requires collection of data in the field, the data that is collected only characterizes conditions in the stream at the exact time it was collected and contributes only to the categorization of the streams as per the Rosgen Classification Method.

[1] This document consists of a "technical tools website" available at http://www.epa.gov/warsss/index.htm

The United States Army Corps of Engineers (USACE) have long made available a suite of hydrologic and hydraulic modeling programs at no cost. The hydraulic modeling program 'HEC-RAS' (Hydraulic Engineering Center – River Analysis System) is a one-dimensional computational hydrodynamic model of flow in the channel. It requires cross-section elevations and flow rates as input and returns water surface elevation and a large number of other hydraulic variables at each defined cross-section. Among these, it generates a shear stress value and a power per unit wetted area and also has the capability of modeling sediment transport. The data input is very intensive and the model set-up and interpretation requires a large amount of training, but the model *could* be used as a stability assessment tool. This is rarely done and instead it is often used simply to predict flood levels and ensure that new developments do not change flood conveyance in a significant manner.

Although there are a number of documents available to educate the river management authority (e.g. conservation authority) about the role of geomorphology in stream restoration, there are very few well-defined tools that use physical parameters to quantify the potential for channel stability or instability in a basin-wide context. Classification methods in particular can cause problems because stream types can vary considerably from one geographic area to the next. Form-based methods do not address the magnitude, frequency of duration of channel processes and channel behaviour because they examine the channel only for a moment in time (Simon et al., 2007). In fact, there is no evidence that any of the described documents or methods, other than the RGA, are in use in Ontario.

Approaches that rely on quantifying the driving and resisting forces are better suited to stability assessment as the physics of erosion, transport and deposition are the same regardless of the stream type or geographic setting (Simon et al., 2007). Doyle et al. (2000) demonstrate that purely quantitative assessment methods, aiming to define the sediment flux in a reach or basin using measures of shear stress or stream power, were significantly better at predicting channel stability and instability. However, complete hydrologic and hydraulic modeling of a catchment is time-consuming and expensive and may not be justified.

The end goal of assessment methods is to facilitate decisions for river training and stabilization. Thorne (1998) states that in such cases, rivers "should retain a planform and hydrologic geomorphology that mimic as many morphological features and periodicities of a natural self-formed channel as possible" (p.28). This of course assumes that there are standard morphological features and periodicities to replicate. Trends in channel evolution are unsteady, non-uniform and complex and river form cannot always be easily typified.

There is a need, especially in urbanizing basins in southern Ontario where hydro-geomorphic impacts and infrastructure risk are greatest, for an initial assessment method that is at once objective, accessible and reliable. This thesis proposes that a stream-power analysis using GIS tools provides an assessment method that fits this objective. This method would fall into the third category defined by Downs and Gregory (2004), a geomorphological dynamics assessment. The use of GIS greatly simplifies the task by automating data collection and hazard location calculations. Stream power (or a surrogate) may be calculated from topographic data alone or supplemented by a discharge-drainage area relationship, giving a method that can be used without the need for detailed information on channel morphology and flows.

1.1.2 Stream power

The term 'stream power' is used to refer to the general concept of the expenditure of potential energy over time in a channel as water travels downstream (Rhoads, 1987). The literature is inconsistent in its use of formulae and nomenclature, but the conventions in terminology proposed by Rhoads (1987) are outlined in Table 1 and will be those used in this thesis. From the table, ρ is the density of water (ML^{-3}), g is the acceleration of gravity (LT^{-2}), Q is discharge (L^3T^{-1}), S is the slope of the channel bed (LL^{-1}), X is the length of the reach (L), R is the hydraulic radius (L) and V is the mean velocity (LT^{-1}).

There are three important types of energy in a system of flowing water: potential, kinetic and thermal. However, only potential and kinetic energy can perform mechanical work which is defined as overcoming internal friction, friction at the channel boundary, eroding the channel boundary and transporting sediment load (Knighton, 1998).

Table 1.1 Standardized stream power nomenclature.

Eq. No.	Term	Symbol	Functional Form	Definitional Form	SI Derived Units	SI Base Units
Eq. 1	Total Stream Power	ρ	ρgQSX	Power of a defined reach of a stream channel	Watts	kg m^2 s^{-3}
Eq. 2	Cross-sectional Stream Power	Ω	ρgQS	Power per unit length of a defined reach	Watts/m	kg m s^{-3}
Eq. 3	Mean Stream Power	ω	ρgRVS	Power per unit wetted area of a defined reach	Watts/m^2	kg s^{-3}
Eq. 4	Unit Stream Power	vs	VS	Power per unit weight of water	Watts/ Newton	m s^{-1}

(modified from Rhoads (1987)*, his Table 2)*

Bagnold (1966) originally used stream power as an indicator of the ability of the stream to transport sediment and as the hydraulic component of his bedload transport function. A major focus in the past 15 years has been to use stream power for the modeling of incision in bedrock channels (ex. Seidl and Dietrich, 1992; Anderson, 1994; Howard et al., 1994; Tucker and Slingerland, 1994; Willett, 1999). Stream power has been shown to be a good predictor of variables such as channel pattern (Graf, 1983; Lawler, 1992; Magilligan, 1992; Lecce, 1997; Knighton, 1999) and channel mobility thresholds (Bull, 1979; Baker and Costa, 1987; Magilligan, 1992; Lapointe et al., 1998; Wohl, 2000). Magilligan (1992) suggests that stream power is a better estimator of work done in a channel than the discharge magnitude/ frequency concept originally described by Wolman and Miller (1960) because it can include variables in addition to discharge, such as gradient and shear stress. Although stream power has been acknowledged as a potentially unifying theme for characterizing catchment and channel behaviour (Downs and Gregory, 2004), little has been published on its direct application in the fields of stream assessment and management.

When attempting to predict the course of channel adjustment, there are a number of questions to address: channel susceptibility to adjustment, the direction of response,

the rate of response and the extent of response (Knighton, 1998). The method proposed here will focus on using stream power to identify locations of channel susceptibility as well as the direction of response. Although there has been work done on the theoretical distribution of stream power through a fluvial system (e.g. Knighton, 1999), finer-scale evaluations reveal that predicted curves based on simplified theory for alluvial channels do not apply in most cases (e.g. Magilligan, 1992; Knighton, 1999; Jain et al., 2006), especially if the streams have atypical long profiles or flow through more than one geologic unit. This means that there is no *a priori* theory for general prediction of locations of stream power maxima or channel instability along a river system; stream power distribution must be assessed on a case by case basis.

Baxter (2001) examined the possibility of using stream power as a surrogate for channel stability. This thesis takes his analysis one step further by integrating it into a Geographic Information System (GIS) and mapping the results.

GIS is an important tool for hydrologic and geomorphic assessment. It is also very useful for communication with non-specialist audiences (Kondolf et al., 2003). Many models, described in section 1.1.1, are advocated by academic and governmental groups, but all are very complex and data-intensive, leaving a great deal of room for parameter adjustment and range of output. Kondolf et al. (2003) argue that models must be simple and adapted to local cases. GIS-based analysis of catchments and stream networks uses a standard set of algorithms to analyse individual cases along with a unique dataset for each river. It is increasingly used in assessment and prediction of stream network characteristics and physical habitat. For example, Benda et al. (2007) demonstrate the use of a GIS in developing a regional scale terrain database that supports watershed science and resources management, automates watershed analyses and improves tools for interpreting watershed-level controls on aquatic systems.

1.1.3 GIS for stream mapping

This thesis adopts a GIS-based approach to map the distribution of stream power throughout a stream network, as part of a physical assessment method. Although the final product requires the use of more advanced analyses discussed in the body of the thesis, the initial steps require the mapping of the stream network and watershed boundaries

from the DEM. These methods are well-developed and this section will briefly review the literature on stream network mapping and catchment delineation using a Digital Elevation Model (DEM).

Digital Elevation Models (DEM) are a representation of the earth's surface in grid form. GIS programs classify DEMs as a 'raster' type of information and have the capability of performing numerous raster or grid type algorithms. Contour data can also be visualized in a GIS, but this is considered 'vector' type data. The contour lines carry information representing elevation, but the space between the lines does not carry any value. In a raster, every portion of the image carries information. In order to model stream power continuously over the landscape, calculations are more easily carried out using raster type data.

Many GIS programs now exist that incorporate hydrologic modeling algorithms [ESRI ArcGIS with Spatial Analyst, Terrain Analysis System (TAS), TauDEM]. Most of these use raster DEMs as a surface over which flow can be theoretically routed. The details of algorithms for doing this have been debated extensively (ex. O'Callaghan and Mark, 1984; Jenson and Domingue, 1988; Garbrecht and Martz, 2000; Wilson and Gallant, 2000). In general, the steps followed to create a flow network and catchment from a DEM are:

1. In order to facilitate hydrologic modeling in a GIS, the DEM can have the location of the stream etched into its surface in a process known as **Stream Burning**. This means that the elevations corresponding to the location of the stream are systematically altered using one of a number of existing algorithms to ensure correct stream delineation (*see* Hutchinson, 1989; Hellweger, 1996; Hutchinson, 2004). The changes are usually minor but are necessary for allowing theoretical flow from the basin edge to the mouth. DEM products as available to the general public (ex.: Ontario Provincial DEM v.2) often have stream locations incorporated into the interpolation process when they are created, in which case this step does not have to be performed by the end-user.
2. The presence of pits in the DEM may prevent the algorithm from directing flow down-slope. These can consist of single- or multi-cell locations of elevation minima that stop flow. Although some of them may be real, as in the case of lakes or ponds,

the method of directing flow across the DEM does not permit their existence. A number of different algorithms exist to deal with pits in a process commonly referred to as **Filling** (Jenson and Domingue, 1988; Martz and Garbrecht, 1998; Rieger, 1998; Planchon and Darboux, 2002; Lindsay and Creed, 2005).

3. When the surface has been prepared using the above steps, the **Flow Direction** algorithm is applied. This consists of assigning a direction code to each cell that signifies in what direction (to which cell) water would flow. It is computed on a cell by cell basis, but can be calculated a number of different ways to address such issues as divergent or braided flow, or divergent flow on hillslopes and convergent flow in valleys, etc. (O'Callaghan and Mark, 1984; Garbrecht and Martz, 1997; Tarboton, 1997; Garbrecht and Martz, 2000; Wilson and Gallant, 2000). The most basic form is known as the D8 algorithm, where flow can move from a centre cell in eight possible directions (N, S, E, W, NE, SE, NW, SW; i.e. the adjacent cells) and is allocated to the direction of greatest drop in elevation between cells to form a channel that is one cell wide.
4. **Flow Accumulation** is calculated based on the flow direction image. The number of consecutive cells flowing into one another is added so that areas of convergent flow, and streams, have increasingly high flow accumulation values in the downstream direction. In a watershed, the cell at the mouth of the basin will have a value corresponding to the total number of cells in that basin.
5. **Drainage Area** can be approximated using a discharge to area relationship and the flow accumulation image. By applying such a relationship, drainage area values are converted to a discharge.
6. **Streams** can then be delineated using flow accumulation values as thresholds. Although the actual threshold value will vary depending on the DEM cell size, the climate and the gradient of the region, examination of the flow accumulation image will reveal a threshold value above which the location of streams can be verified, often using blue-line streams from topographic maps. Applying this threshold to the image produces a binary stream image (i.e. in-stream values or streams *above* a determined threshold area are assigned a value of 1, a value of 0 is assigned to all those below that value).

The result is of a series of images that together define the stream network and catchments in that area. These images form the basis for the stream power calculation. The more advanced steps required to complete the stream power calculation will be discussed in Chapter 3.

1.1.4 GIS mapping of stream power: Background and methods

The method of stream power mapping developed in this thesis is based on calculating cross-sectional stream power (Eq. 2, Table 1.1) for both geomorphological and practical reasons. There is evidence in recent literature that mean stream power (Eq. 3, Table 1.1) and cross-sectional stream power, despite having different absolute values, share very similar patterns (Lecce, 1997; Haschenburger and Church, 1998; Knighton, 1999; Bledsoe and Watson, 2001). This is especially true if hydraulic geometry relationships have been used to approximate the variables in the stream power equation (Finlayson et al., 2002; Reinfelds et al., 2004). If the goal is an assessment of relative values of stream power along the channel, either of the two types of stream power would be suitable. Bledsoe and Watson (2001) are in favor of an equation that omits width and depth in urbanized channels since these may have already adjusted to the hydrological impact of urbanization. Haschenburger and Church (1998) also state that width should only be used if true field values can be measured and incorporated and this requires more background data analysis such as measuring channel widths from aerial photographs or field survey. Therefore, the simpler data requirements for cross-sectional stream power provide an additional advantage.

Fonstad (2003) was the first to suggest that displaying the stream power values on a *map* may be extremely important in revealing patterns on a basin-scale. He calculated stream power at discrete cross-sections and displayed the results on a map of the basin. The recent advances in GIS have enabled the relatively fast extraction of topographic data and created the possibility of calculating *continuous* stream power values across an *entire* basin at small increments of channel length. A few examples of GIS stream power extraction have been published for the continental scale (Finlayson et al., 2002; Finlayson and Montgomery, 2003), in midsize (1000 – 5000 km^2) catchments (Reinfelds et al., 2004; Jain et al., 2006), and at the small (< 200 km^2) catchment scale (Worthy, 2005).

Highland Creek catchment is comparable in scale to those studied by Worthy (2005). In terms of DEM resolution, cell sizes from largest to smallest are:

- 853 metres (Finlayson et al., 2002)
- 30, 90 and 900 metres (Finlayson and Montgomery, 2003)
- 25 metres (Reinfelds et al., 2004; Jain et al., 2006)
- 1, 5 and 10 metres (LiDAR derived) (Worthy, 2005).

The Ontario Provincial DEM v.2 is composed of 10 by 10 metre cells.

Finlayson et al. (2002) calculated an erosion index based on area/discharge relationships, precipitation data and bedrock incision rate models. They examined the relative potential for erosion in Himalayan basins as well as the distribution of these values and their coincidence or not with accepted beliefs about Himalayan erosion patterns. Finlayson and Montgomery (2003) examined the effects of DEM grid resolution on slope, drainage area, stream length and stream power. They found that decreasing resolution (from 30 m cells to 900 m cells) decreased all the above variables except drainage area which was found to increase with decreasing cell resolution.

Jain et al. (2006) focused on different ways of calculating channel long profiles and on the catchment scale distribution of stream power compared to theory (Knighton (1999). Reinfelds et al. (2004) compared cross-sectional stream power to mean stream power and examined the longitudinal profile differences to identify zones of potential sediment transport discontinuity. The width variable in their calculations of mean stream power was obtained using a discharge-based hydraulic geometry relationship. In addition, they compared the slope values extracted from the DEM to those from field surveys for a 20 km reach and a 4 km reach of the rivers being studies and concluded that the DEM slopes were "reasonably accurate" (Reinfelds et al., 2004, p.408).

Worthy (2005) compared LiDAR-derived DEMs of different resolution (cell sizes of 1, 5 and 10 metres) to examine the effects on modeling. He found that overall patterns at all scales were very similar, with differences in the absolute stream power maxima and minima.

In all of these examples, continuous values of stream power were extracted from the GIS analysis and presented in bi-variate graphs of stream power versus distance, rather than in the GIS. A technical step in this thesis is to display the calculated stream power values *in* the GIS in map form.

The variables that must be extracted by analysis of the DEM in order to calculate cross-section stream power are discharge at a chosen reference return interval (*Q*) and slope (*S*). Discharge can be estimated at any point in the stream network using a discharge to area relationship which typically has the form:

$$Q=cA_d^x \qquad (Eq.\ 5)$$

where A_d is drainage area in square kilometres and c and x are empirical coefficients. Where a flow accumulation image has been created for a DEM, the value of each cell corresponds to the number of cells draining into it. Multiplying this value by the area of each cell results in a drainage area, which can, in turn, be multiplied by the region-specific empirical coefficients c and x from Equation 5 in order to give a discharge in cubic metres per second. Finlayson and Montgomery (2003) show that in rain shadow zones and basins that cross climatic zones it is more appropriate to use a precipitation-weighted cumulative area to estimate runoff. Where there is adequate discharge to drainage area type data, basin-specific relationships can also be calculated.

Slope can be measured in a number of different ways. The method for calculating slope that is a component of most GIS programs is known as the kernel method. This is the method used by Worthy (2005) and consists of passing a three cell by three cell window or kernel across the landscape. Depending on the algorithm used by the GIS, the slope is calculated for the middle cell in this kernel by measuring the average rise over run for all eight cells surrounding it or for the steepest rise over run out of the eight possible values. Many articles have been published on the accuracy of these different types of slope calculation over the whole landscape (*see* Jones, 1998), but this method does not appropriately address the issue of calculating the slope of the stream channel. For example, large slopes are often assigned to in-stream cells with high banks, even though the actual channel slope is not especially large (Wobus et al., 2006). In order to get an accurate channel-bed slope, as is required for the stream power calculation, the flow direction in the landscape must be considered.

There are a number of algorithms for calculating slope according to the steepest drop in elevation from the middle cell of an array. For example, the 'Maximum Downward Slope' function in the program TAS (Terrain Analysis System) and the 'Drop Raster' option in the Flow Accumulation algorithm in ArcGIS calculate slope on a cell by

cell basis in a downstream direction. However, the distance over which each slope value is measured is very small compared to the overall length of stream, and the resulting slopes are extremely variable (Wobus et al., 2006).

Reinfelds et al. (2004) resolve this problem by employing a vertical slice approach to slope extraction. A *constant change in elevation* is chosen that is equal to the original contour interval of the maps from which the DEM was extracted. This constant rise is divided by the distance over which that change in elevation occurs. In effect, it is the vertical slice method that is being employed when slope is measured manually from a topographic map. This method has the benefit of eliminating any interpolation errors in the DEM by using only elevation values that are known to exist on the original contour map. The disadvantage is that slope values are not continuous, i.e. there is no variation in the slope value for locations between contour lines. In addition, DEMs are increasingly derived photogrammetrically rather than from contours. In these cases, using the vertical slice slope does not eliminate any interpolation errors and, especially in low gradient areas, results in very few slope measurements.

Jain et al. (2006) compared three different methods of calculating slope: curve fitting, theoretical models based on hydraulic relationships and long profile smoothing. The long-profile smoothing method they used is called the horizontal slice method. In this case, changes in elevation are measured over *constant distances*. This method produces a slope value for each cell. Jain et al. (2006) found that the curve fitting and hydraulic relationships methods of calculating slope did predict broad-scale patterns in stream power distribution, but the long-profile smoothing produced results with higher resolution that could be used to study reach-scale channel processes. Although there was large local-scale variability, Jain et al. (2006) felt that changes in slope and discharge throughout the system effectively explained those variations. In addition, they made the argument that since stream power is an expression of energy expenditure per unit *length*, slope should be measured using a constant length instead of a constant elevation difference.

Of the methods of extracting slope that were described here, only the kernel method can be performed *in* the GIS. The other methods require the extraction of in-channel elevation values to a spreadsheet program. As a result, in the previously

published examples of GIS-extracted stream power values, final stream power distributions are all shown in bi-variate graphs of stream power versus distance. The stream power values have not been returned to the GIS to be displayed on a map of the basin. There is one known example of continuous cross-sectional stream power values mapped using a GIS (Finlayson et al., 2002), but the mapped values of stream power were calculated using the kernel method for slope instead of one of the more appropriate stream long-profile methods.

There are also two automated GIS toolkits that perform a number of watershed analyses. NetMap (Benda et al., 2007) uses DEMs along with precipitation and streamflow data to perform a number of watershed analyses. A number of maps are created; among these are sediment supply and erosion potential maps. The SciMap Framework (http://www.scimap.org.uk, *Oct. 19, 2008*) uses connectivity in a basin to model diffuse pollution risk. As part of the model, a stream power map is also created. These maps are more generalized than those that will be presented here, but are a good example of where a stream power analysis could fit within an assessment/mapping process.

1.2 Objectives

It is the objective of this thesis to develop and test a method by which maps of cross-sectional stream power can be created for basins in southern Ontario using the case of Highland Creek, a highly urbanized basin. The thesis will build on and refine previous GIS-based analyses of stream power and examine the practicality based on data sources available for southern Ontario streams and watersheds. The maps will enable spatial analysis of the stream power distribution along a stream and compare the results against the location of stable and unstable reaches based on independent assessments (by Conservation Authority and consultants) and the history of channel changes following major floods and urbanization in Highland Creek.

Chapter 2: Case study background

The primary focus of this thesis is to develop a method for mapping stream power in a GIS. This will be done using a basin in southern Ontario as a case study. The purpose of this chapter is to introduce the case of Highland Creek.

Highland Creek was chosen as a case for two major reasons:

1. Highland Creek has undergone extreme changes to its flow regime, especially peak flows, following rapid urbanization in the 1960s and 1970s, which have caused chronic and extreme erosion, geomorphic change and channel instability which has damaged infrastructure and lead to substantial intervention and channel engineering – it is a classic example of a stream system in need of geomorphic assessment.
2. As a consequence of its recent history there has been extensive investigation of aspects of the hydrology, hydraulics and geomorphology of Highland Creek along with various studies for engineering, natural channel design and restoration. This provides abundant background information and data on the creek that are useful in this thesis and are not available in other cases. These include existing RGA assessments and HEC-RAS analyses for the basin, a calibrated hydrological runoff model, current work on historical changes of channel pattern and width that will reveal those reaches that have been most sensitive to changes in stream-flow, and background mapping of channel and bank materials and of grade control and bank protection engineering. This information allows comparison of the stream power mapping with hydraulic predictions (HEC-RAS model) and correlation of areas of known widening and straightening with the stream power map and with unstable reaches identified by RGA.

In this way, Highland Creek provides a case in which the stream power values can be validated and their predictive value assessed, and in which there is known geomorphic response and ongoing problems related to channel adjustment and stability. It is a situation typical of the kind of real stream assessment problems that exist and one in

which sufficient background data and analysis exist to test the stream power mapping and prediction.

2.1 Location

Highland Creek is located in what was formerly the City of Scarborough, and is now almost entirely within the City of Toronto, with a small area at the head of the basin in the Town of Markham (Fig.2.1). It is in the jurisdiction of the Toronto Region Conservation Authority (TRCA). The total population as of 1999 in the Highland Creek watershed was approximately 357,673 (TRCA and City of Toronto, 1999).

The creek flows roughly northwest to southeast from an elevation of about 210 metres above sea level into Lake Ontario at approximately 75 m.a.s.l., and drains an area of just over 100 km^2. Figure 2.2 is a map of major roads in the basin, and Figure 2.3 is a map of the branch names commonly in use by the Toronto Region Conservation Authority. Both will be used throughout the thesis to help refer to specific reaches or locations along Highland Creek.

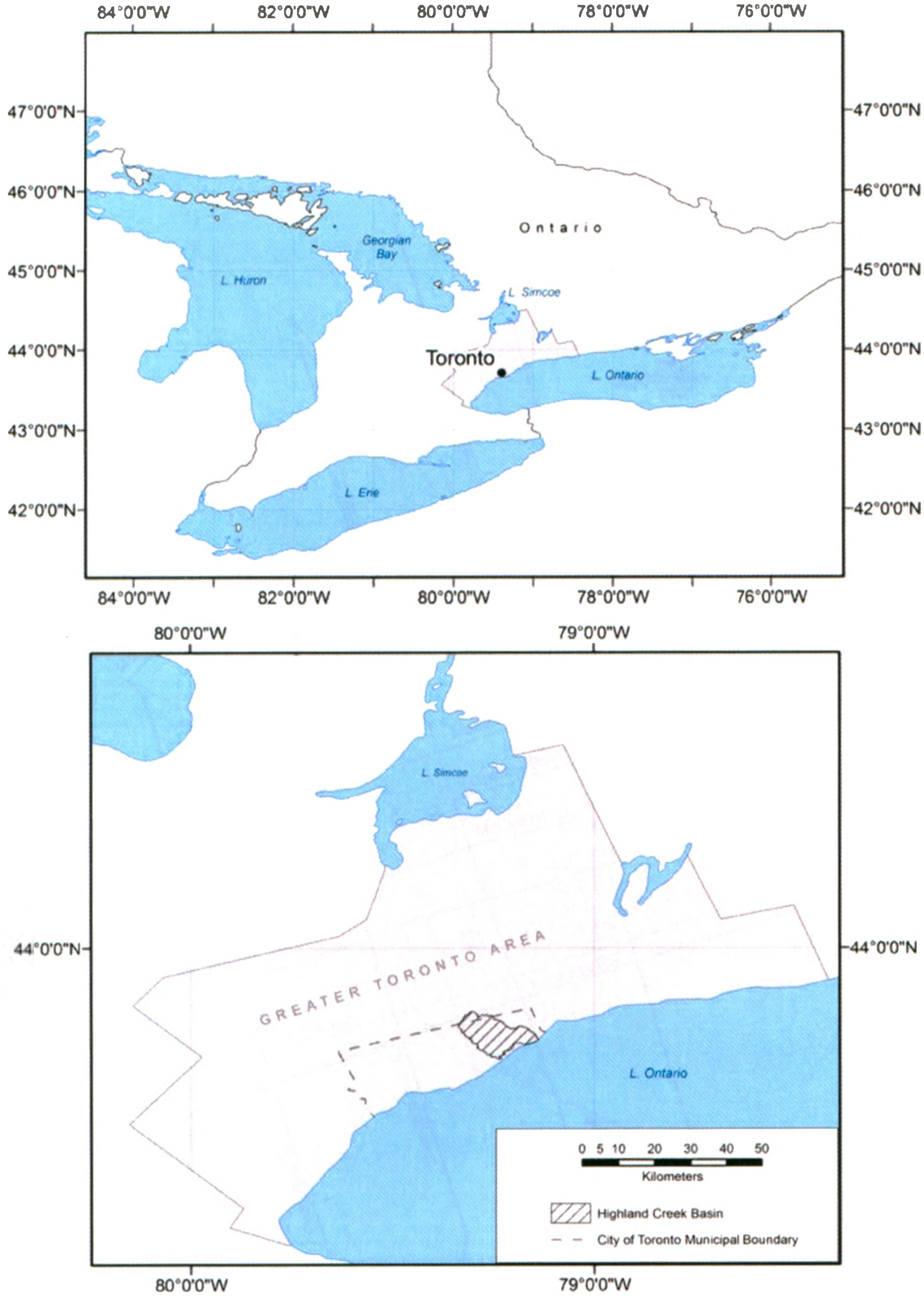


Figure 2.1 Location of study area.
(Above) Map of southern Ontario highlighting location of the city of Toronto;
(Below) Close-up of the Greater Toronto Area highlighting the location of the Highland Creek basin and the City of Toronto municipal boundary.

Figure 2.2 Transportation network of the Highland Creek watershed. *The WSC gauge (02HC013) is also shown upstream of the Morningside Ave. bridge. Road network taken from the Ontario Fundamental Dataset (2002).*

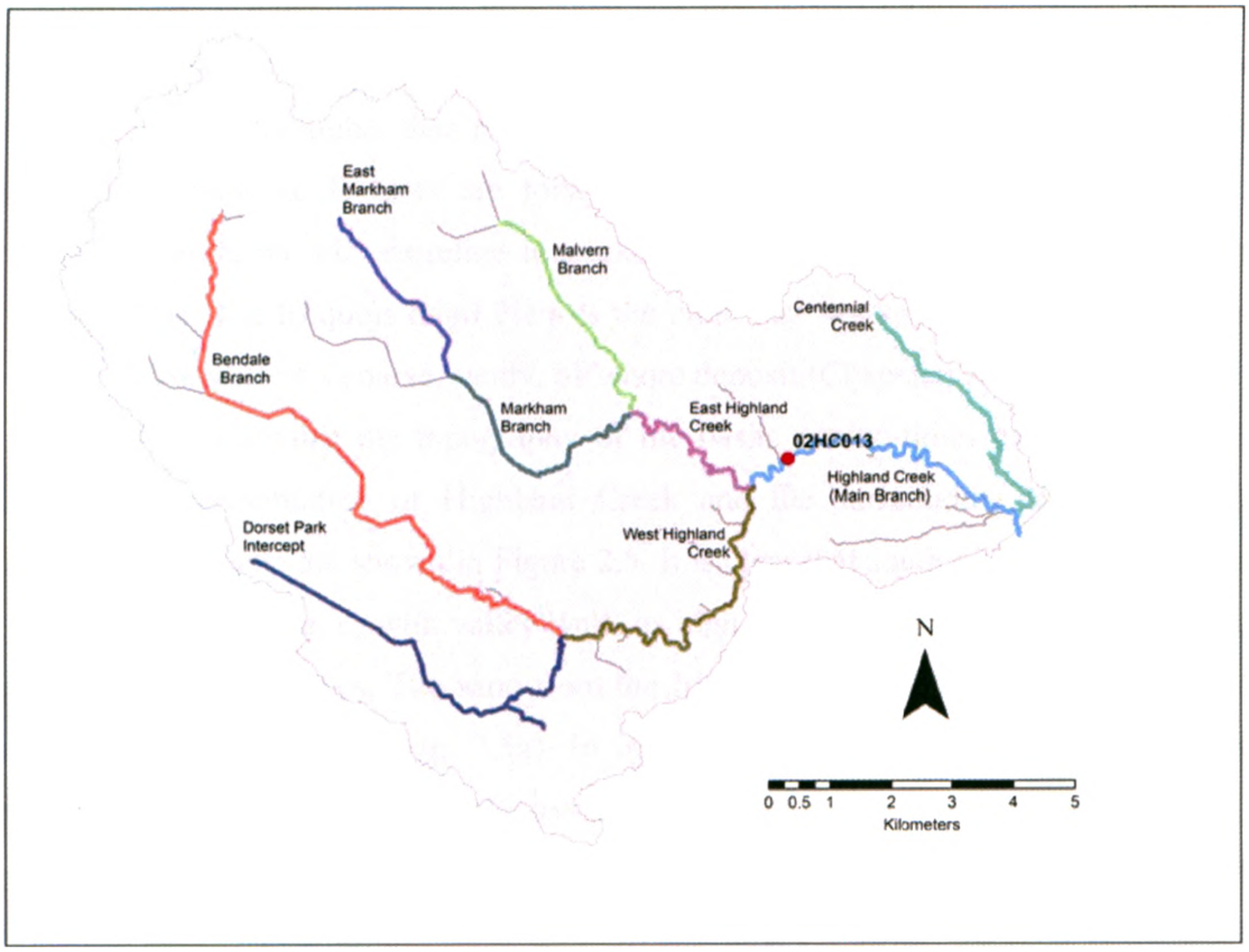


Fig. 2.3 Conventional branch names for Highland Creek.

2.2 Physiography

The basin of Highland Creek is divided into two major physiographic regions: the South Slope and the Iroquois Sand Plain (Chapman and Putnam, 1973) (Fig. 2.4). The South Slope is the southern slope of the Oak Ridges Moraine, an inter-lobate moraine that runs approximately parallel to the north shore of Lake Ontario. In the area of the Highland Creek basin, there are approximately 30 km from the lakeshore to the southern edge of the moraine (Chapman and Putnam, 1973). In this region, the stratigraphy is composed, from stratigraphically highest to lowest, of Halton Till, Northern (or Newmarket) Till and Thorncliffe formation silts and sands (Boyce and Eyles, 2000). The till is variable in nature, but is composed mostly of overconsolidated clays interspersed with clasts of varying size and lithology (Boyce and Eyles, 2000).

Iroquois is the name of the proglacial lake that existed approximately 12,000 years B.P. in what is now the Lake Ontario basin (Muller and Prest, 1985). Iroquois water levels were 40 metres higher than present day Lake Ontario (Muller and Prest, 1985), and the Iroquois shoreline features are today visible inshore from Lake Ontario. In the Scarborough area, the old shoreline is marked by bluffs or gravel bars (Chapman and Putnam, 1973). The Iroquois Sand Plain is the plain that lies below the ancient Iroquois shoreline. It consists of a coarse, sandy, off-shore deposit (Chapman and Putnam, 1973).

To help visualize the topography of the basin, a nine-times exaggerated three-dimensional representation of Highland Creek and the surrounding area along with photos from the basin are shown in Figure 2.5. It is clear that south of Hwy 401 the creek is entrenched (Fig. 2.5a, c) with valley walls as high as 35 metres near the confluence of the east and west branches. The sand from the Iroquois Sand Plain is also visible in the banks near the confluence (Fig. 2.5a). In most reaches, the channel bed of Highland Creek is either clay (till and glacio-lacustrine material), coarse gravel or boulders (often a thin layer over clay), fine gravel with bars, or engineered / armoured (Fig. 2.5b). In the entrenched sections, valley widths range from 200 to 350 metres. The river is much less entrenched north of the 401 and consultants report that 100% of the banks have been hardened along these tributaries (Aquafor Beech Limited, 2007) (Fig. 2.5d). The channel conforms to what has been increasingly referred to in the literature as a semi-alluvial channel (Ashmore and Church, 2001). 'Semi-alluvial' refers to streams that have a relatively thin veneer of alluvium (e.g., gravels) on top of a non-alluvial, but relatively erodible base, and limited floodplain development (Foster, 1998; Foster and Ashmore, 1999). They are typically incised into glacial deposits or highly erodible bedrock. The long profiles of Highland Creek and its major tributaries are shown in Figure 2.6. The long profiles, except for Centennial Creek, are slightly convex in the upstream portion of the watershed and slightly concave for the lower portion with maximum gradient in the middle of the basin. This is closer to what a non-alluvial bedrock stream might look like and illustrates one of the differences between semi-alluvial streams and the classic alluvial types, which would normally have a concave profile throughout.

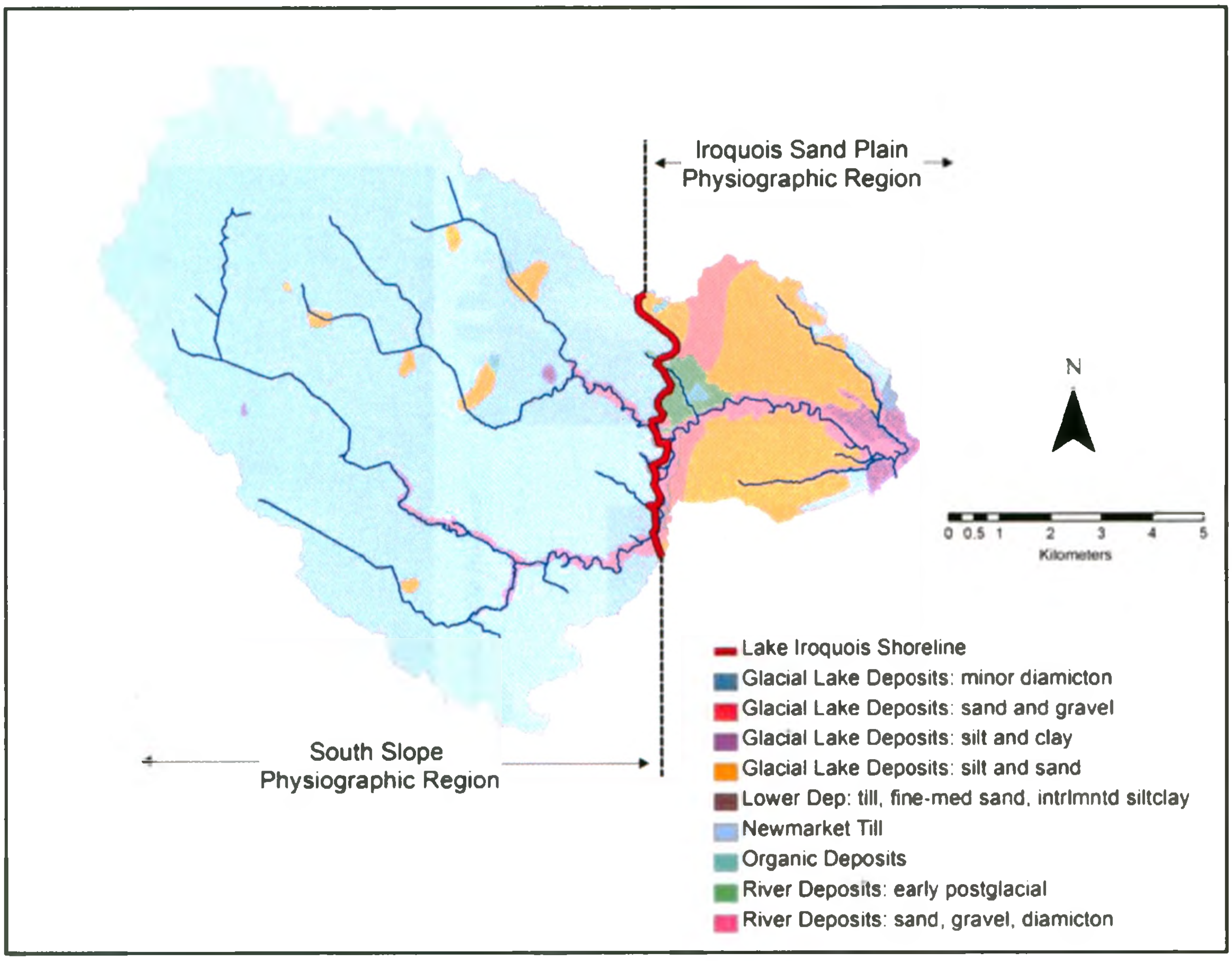


Figure 2.4 Physiographic regions and surficial geology of the Highland Creek basin. *The red line marks the location of the ancient Iroquois shoreline. The area upstream is known as the 'South Slope' region, and the area downstream of the shoreline as the 'Iroquois Sand Plain'.* (Chapman and Putnam, 1973; Toronto Region Conservation Authority and City of Toronto, 1999; Sharpe et al., 2001)

Three-dimensional exaggeration of the relief in the Highland Creek basin, letters correspond to the location of photos shown below.

a) Sandy banks of the Iroquois Sand Plain

d) Trapezoidal cement-lined: grass or gabion channels

b) Large boulder deposit, 'urban debris', cohesive banks

c) High valley walls with exposed glacial deposits and cohesive banks (right bank)

Figure 2.5 DEM and photos characterizing Highland Creek. *DEM in top left corner is a 9-times exaggeration of Provincial DEM v.2 (OMNR, 2005) (photos a, b, c by M. Ferencevic, photo d by P. Ashmore)*

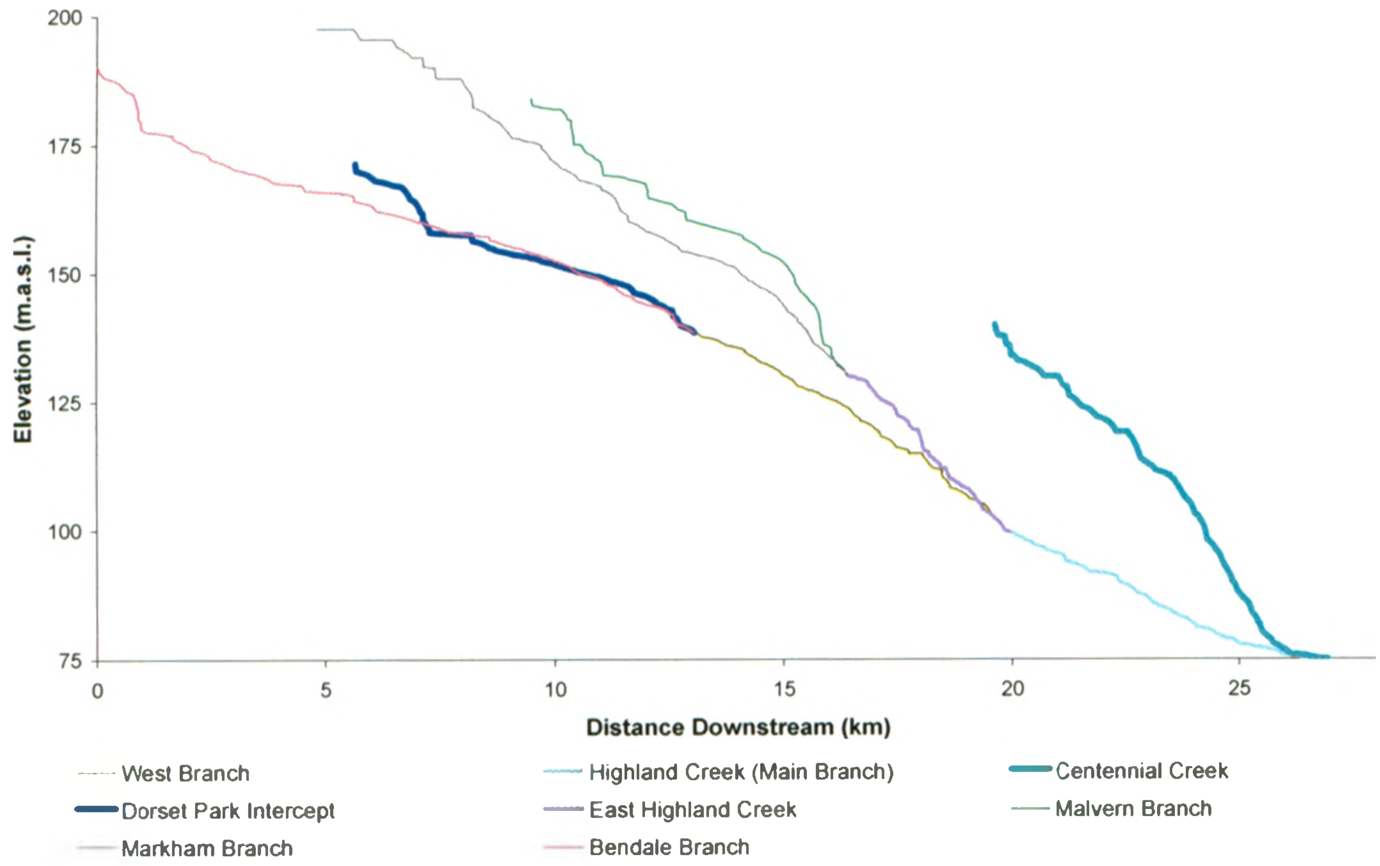


Figure 2.6 Long profiles of Highland Creek and its major tributaries.
(see figure 2.3 for map of branch names)

2.3 Urbanization

Over the last half-century, the basin of Highland Creek has urbanized rapidly such that in 1996 85.11% of the basin area was 'settled and developed' according to the Ontario Land Cover Database (OMNR, 1996) (Fig. 2.7). Development spread up the watershed starting near Lake Ontario in the 1950's and 1960's and moved north of the 401 in the 1970s and 1980s. Figure 2.8a shows the progression of development since 1900 and Figure 2.8b shows the mixture of commercial, industrial, institutional and residential land uses. Open areas are focused on the valley corridor and consist of parks, wooded areas, golf courses and cemeteries (TRCA and City of Toronto, 1999). The presence of some of these 'green' areas is the result of a de-urbanization effort by the city and the Toronto Region Conservation Authority for the purpose of flood regulation after Hurricane Hazel.

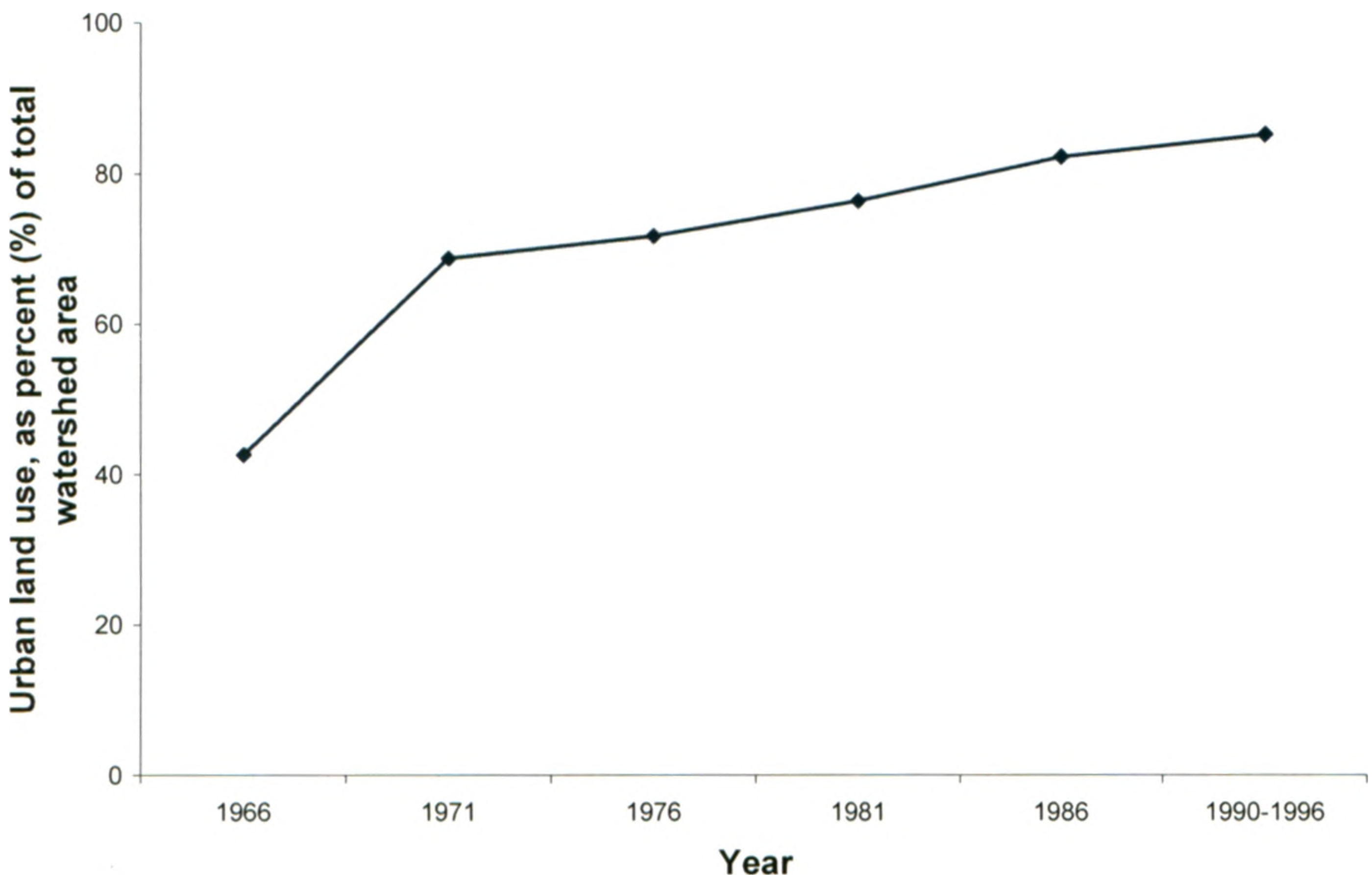


Figure 2.7 Progression of urbanization in Highland Creek basin.
Source: Canadian Land Use Monitoring Program Data (Government of Canada, 1966-1986) and Ontario Land Cover Database (OMNR, 1996).

Fieldwork done as part of geomorphic investigations for the City of Toronto reveals that 100% of the banks upstream of Highway 401 and 50% of the bank length downstream from the highway have been hardened (Aquafor Beech Limited (ABL), 2007). Hardening refers to an engineered structure of some kind being put into place in the bank and in this case includes the presence of armourstone, concrete, cribwall, gabion baskets, geo-grids, rip rap and round stone. Bellamy (1994) reported that of the original 100 km of channel, only 4 km "remain in a natural to near-natural state" (p.121). The river is also crossed in a multitude of locations by rail, road and foot bridges and there are over 90 in-stream structures such as mill dams and weirs that are considered barriers to the movement of fish (Fig. 2.9). These in-stream structures are geomorphologically significant in that they cause abrupt changes in slope in the channel. The sanitary sewer lines for the area run underground along the valley floor of Highland Creek, often passing under the creek itself and in some cases, although originally covered, are now exposed in the channel due to bed incision (Fig. 2.10).

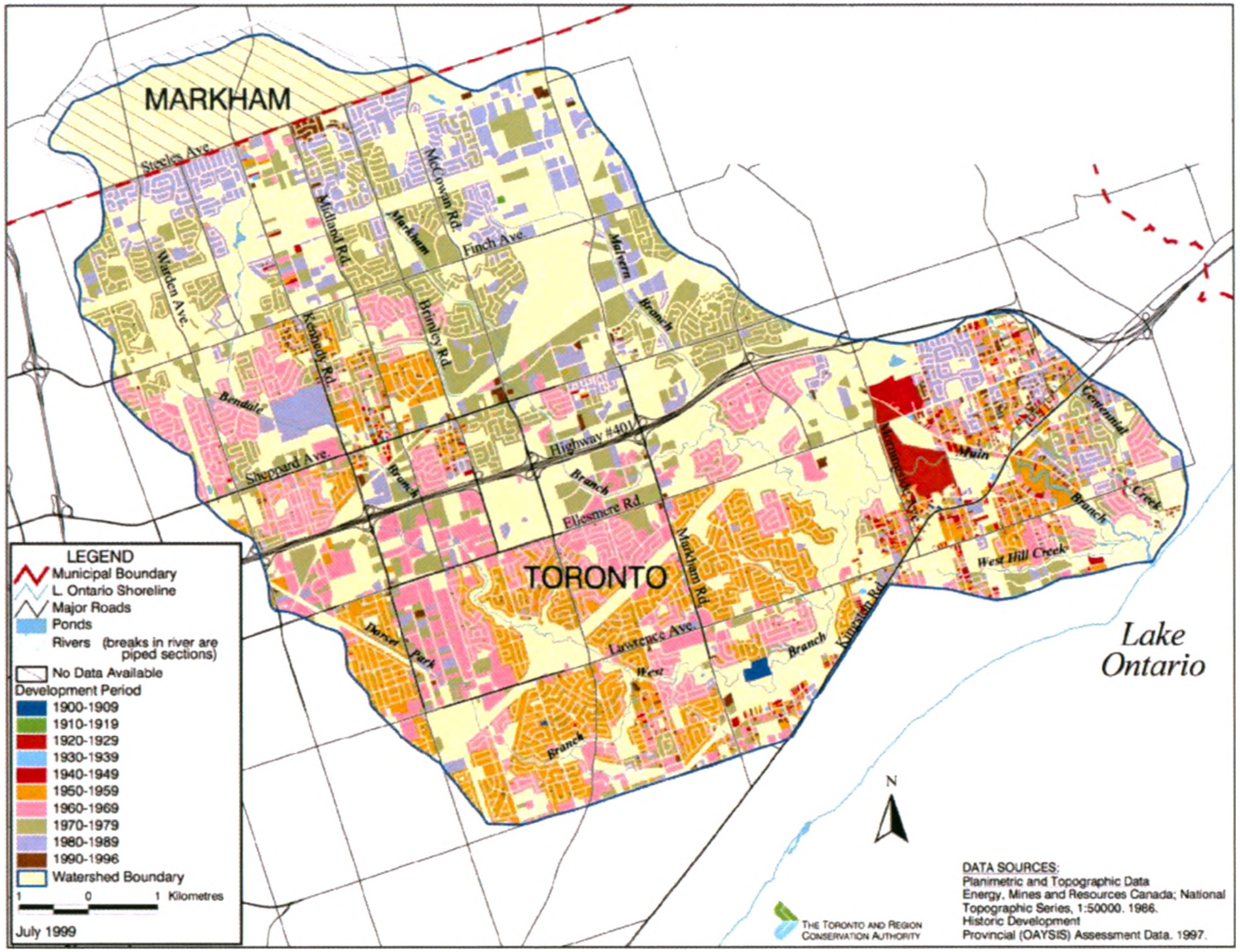


Figure 2.8a Historical development of the Highland Creek watershed.
Taken from TRCA and City of Toronto (1999), their 'Map 5'.

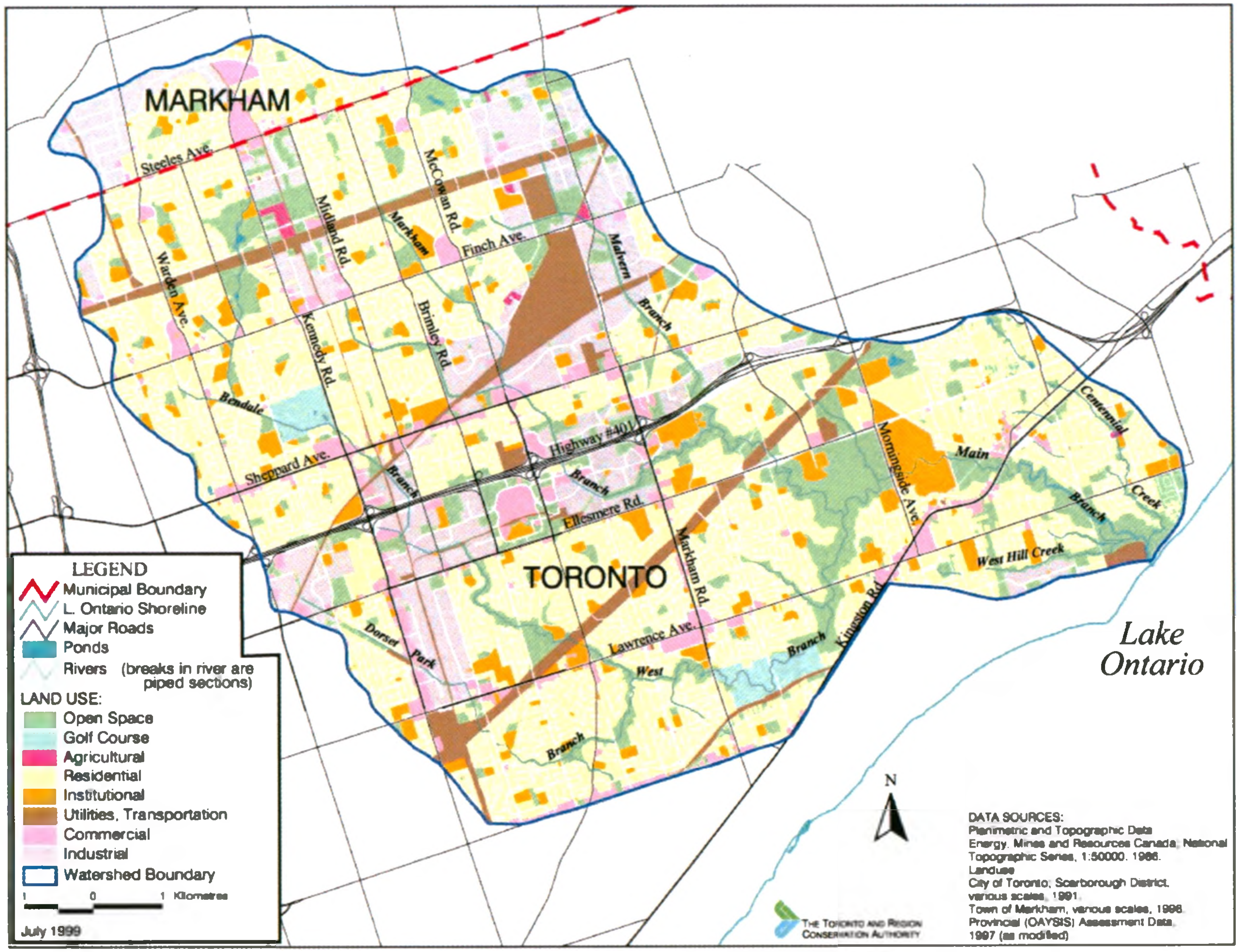


Figure 2.8b Landuse in the Highland Creek watershed.
Taken from Toronto Region Conservation Authority and City of Toronto (1999), their 'Map 7'.

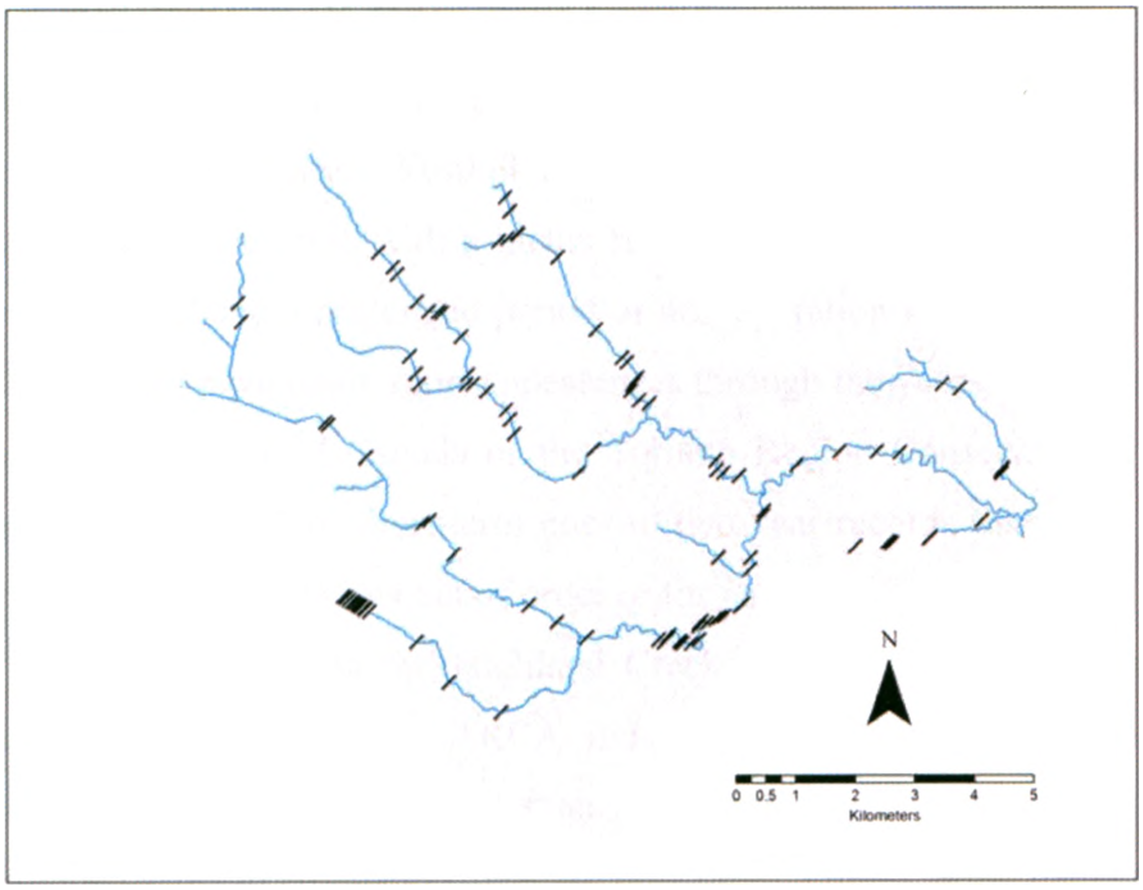


Figure 2.9 In-stream barriers of Highland Creek.
The location of in-stream barriers was collected for the purpose of evaluating fish habitat but can serve, in the case of a geomorphic investigation, to highlight engineered areas and areas with high slopes. (Toronto Region Conservation Authority and City of Toronto, 1999)

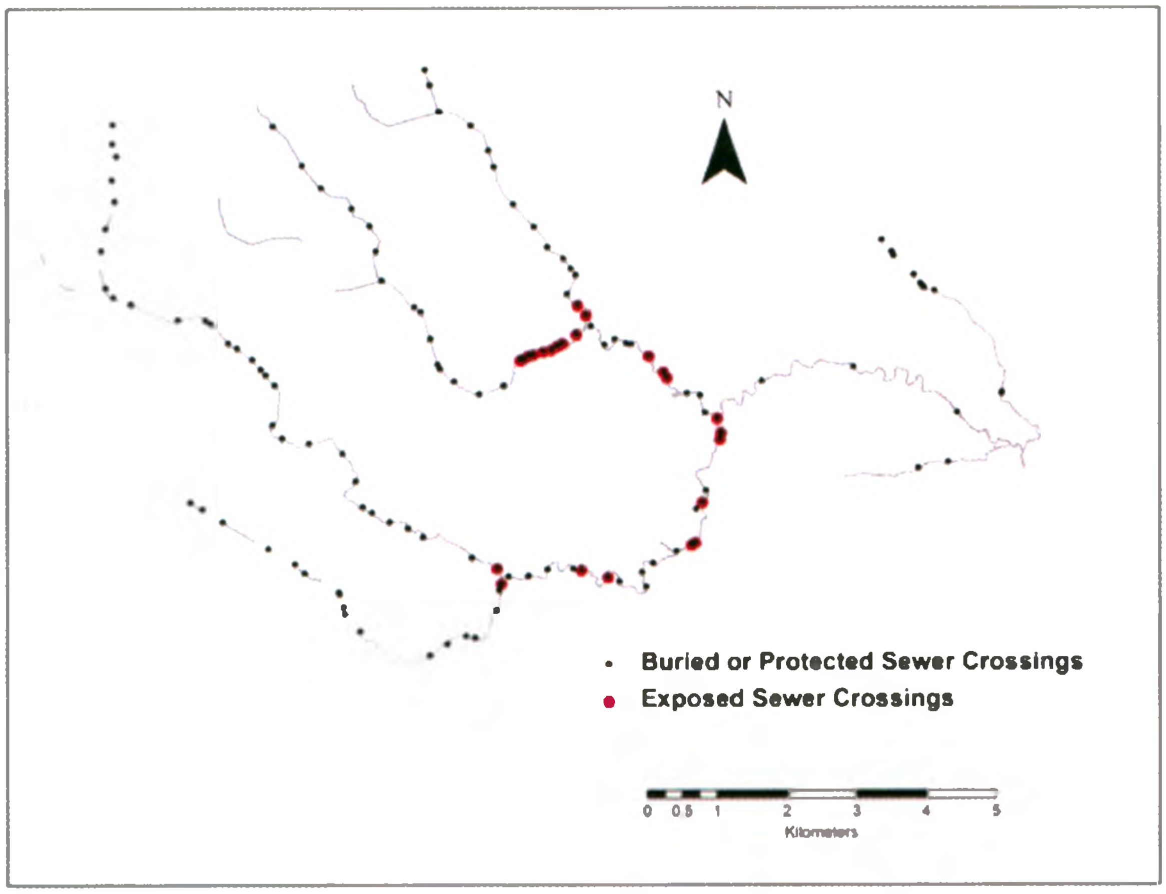


Figure 2.10 Locations of sewer crossings in Highland Creek. *(Aquafor Beech Ltd., 2007)*

2.4 Hydrology of Highland Creek

The Water Survey of Canada operates a stream-gauge on Highland Creek (02HC013, "Highland Creek near Westhill". See location on Figure 1.2). The gauge has been operational since 1956 with a hiatus from January 1974 to July 1975, January 1988 to January 1989 and a prolonged period of non-operation from 1998 to 2005. A number of other gauges have made short appearances through the years and were operated by either the Water Survey of Canada or the Toronto Region Conservation Authority. None of these have more than short-term one- to two-year records that seem to have been used while the main gauge was out of order or for particular studies.

Urbanization in the Highland Creek basin has caused a change in runoff and streamflow hydrology. The TRCA and City of Toronto (1999) report that since 1969, mean annual flows have more than doubled (Fig. 2.11). O'Neil (2008) reports that extreme events in Highland Creek are now up to 5 times larger than pre-urban conditions and comparable rural watersheds, and the seasonality of discharge has almost disappeared and been replaced by numerous large flashy floods that occur throughout the year. The compilation of annual hydrographs in Figure 2.12 illustrates this last point.

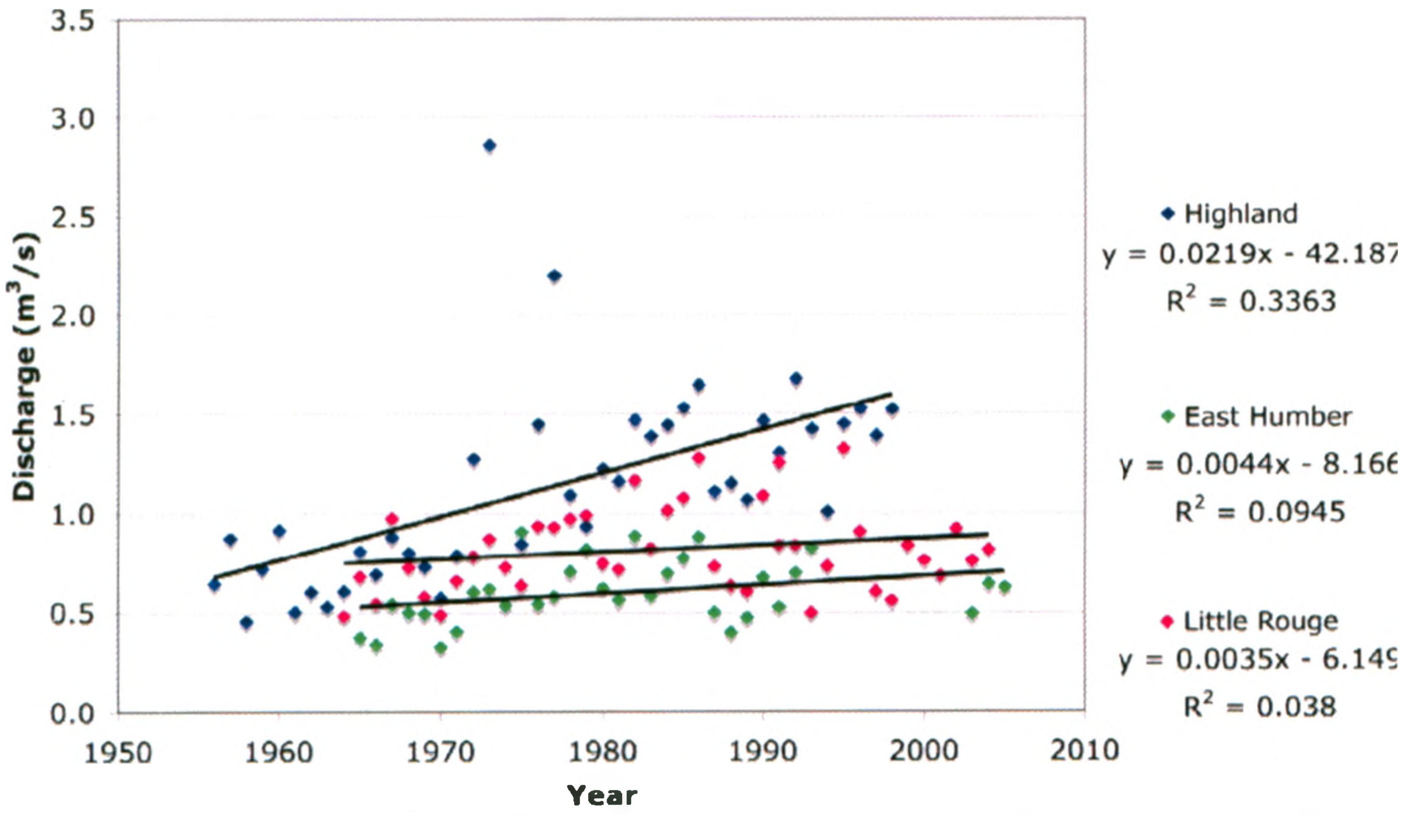


Figure 2.11 Mean annual discharges for Highland Creek, East Humber and Little Rouge Rivers. *Trendlines show the increase in mean annual discharges for Highland Creek over time and compared to adjacent rural watercourses (East Humber and Little Rouge).* (taken from O'Neil (2008), her Fig. 3.1)

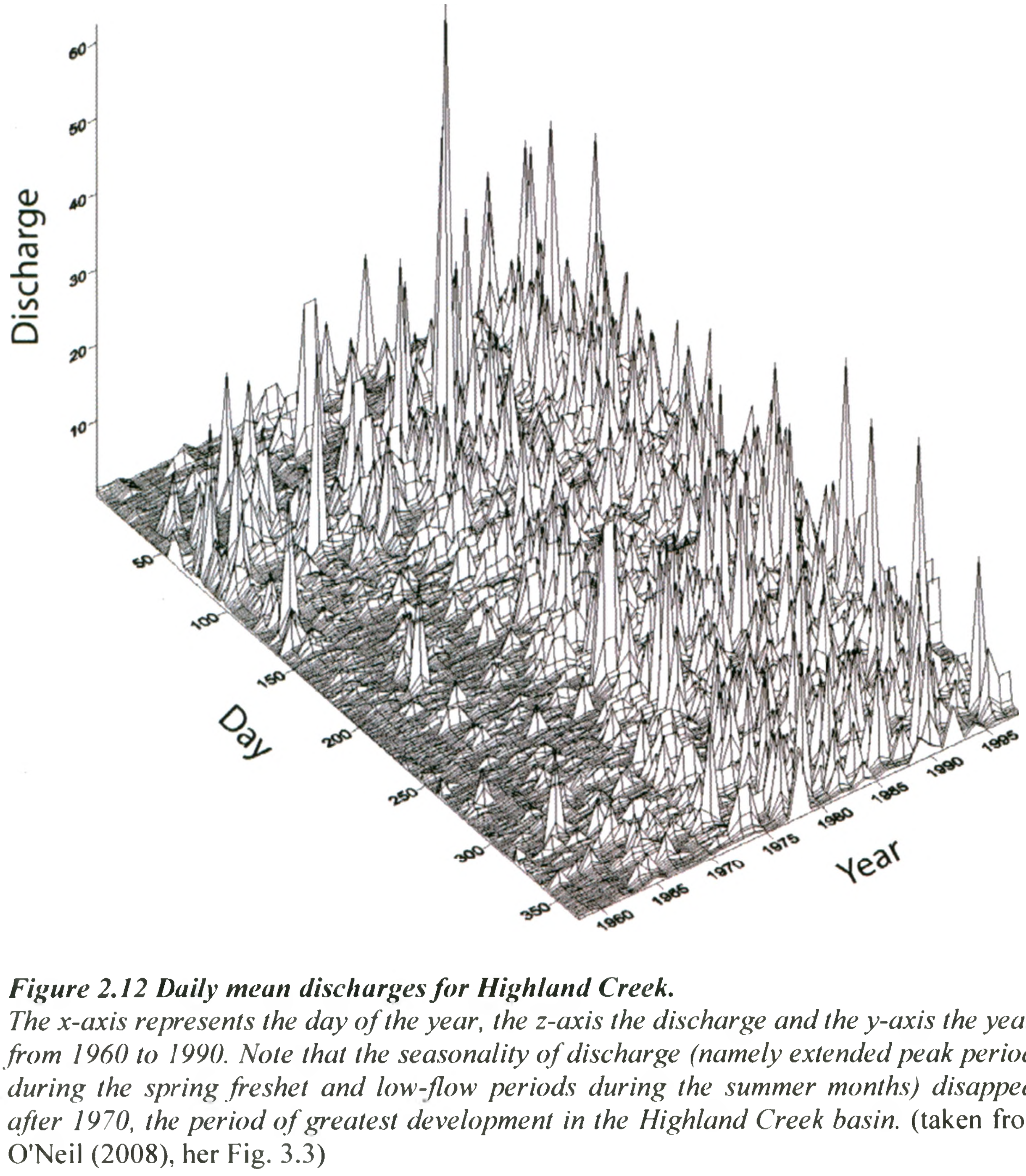


Figure 2.12 Daily mean discharges for Highland Creek.
The x-axis represents the day of the year, the z-axis the discharge and the y-axis the years from 1960 to 1990. Note that the seasonality of discharge (namely extended peak periods during the spring freshet and low-flow periods during the summer months) disappear after 1970, the period of greatest development in the Highland Creek basin. (taken from O'Neil (2008), her Fig. 3.3)

A large precipitation event occurred on August 19th, 2005 that exceeded the 100-year return period depth at the City of Toronto gauge (TRCA, 2006). Figure 2.13 illustrates the magnitude of the flood (estimated from a calibrated runoff model) as experienced on the east portion of Highland Creek and compared to other rivers in the Toronto Region. Clearly, urbanization has caused Highland Creek to behave differently from other rivers in the region, even those that are substantially urbanized.

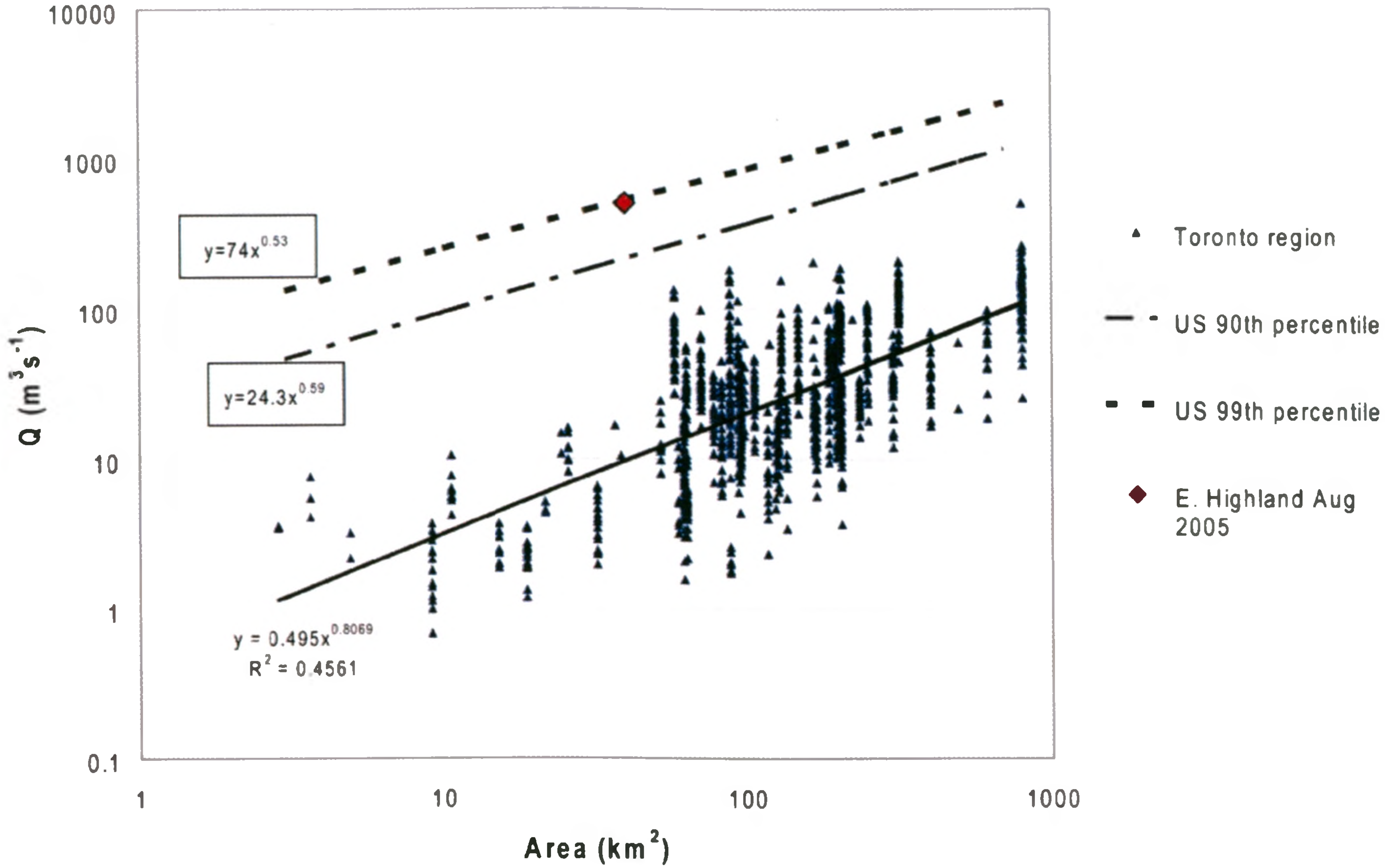


Figure 2.13 Instantaneous maximum discharge (Q) vs. drainage area for Highland Creek, the Toronto Region and top US floods. *From Ashmore and McDonald (2006). The US 90th and 99th percentile lines plotted by Ashmore and McDonald are taken from O'Connor and Costa (2004) and refer to the top 10% of annual peaks recorded at 14,815 USGS stream gauging stations in the United States and Puerto Rico.*

2.5 Degradation

The urbanization of Highland Creek has led to a number of direct and indirect changes in morphology. As urbanization progressed to the upper portions of the watershed in the late 1960s and 1970s, those portions of the creek were channelized (see Fig. 2.5d). This only intensified the downstream effects of changes in hydrology typical of urbanized environments that include fast runoff rates. The lower portion of the creek in the Iroquois Sand Plain is particularly sensitive to changes in hydrology and is experiencing rapid adjustment, as shown in Figure 2.14, in the form of widening, deepening and a disconnection of the low flow channel from its floodplain (TRCA and City of Toronto, 1999).

Figure 2.14 Example of channel degradation.
Reach between Morningside Ave. and Old Kingston Rd. (photo by M. Ferencevic)

Changes in morphology have also been occurring in the more resistant South Slope region of the watershed. The Markham Branch, immediately west of Markham Rd. has seen an increase in channel depths from 1.1 m -1.3 m in 1971 to 2.0 m -3.5 m in 1994 (Bellamy, 1994). The Scarborough Golf and Country Club, located on the West Branch, between Markham Rd. and the intersection of Lawrence Ave. and Kingston Rd., won a lawsuit in the late 1980s against the City of Toronto to recover the cost of property loss, infrastructure damage and bank reinforcements caused by erosion (Lorant, 1994). The 'State of the Watershed Report' (TRCA and City of Toronto, 1999) undertook as part of the project to identify sites of erosion that endanger infrastructure and private property (Figure 2.15). A total of 46 sites were identified, a large number of which are in the Iroquois Sand Plain physiographic region. The storm of August 2005 also caused substantial erosion, especially on the East Branch south of Ellesmere Rd. where a major

reconstruction project, involving the reburial of sanitary sewer lines damaged in the flood and substantial channel construction, has only recently been completed (Fig. 2.16). The channel incision, as well as the presence of rock ramp control structures and bank hardening, that are so common in Highland Creek all indicate issues related to erosion and channel stability. Highland Creek is therefore a good candidate for testing stream power mapping and a location in which it might be usefully applied in the short term.

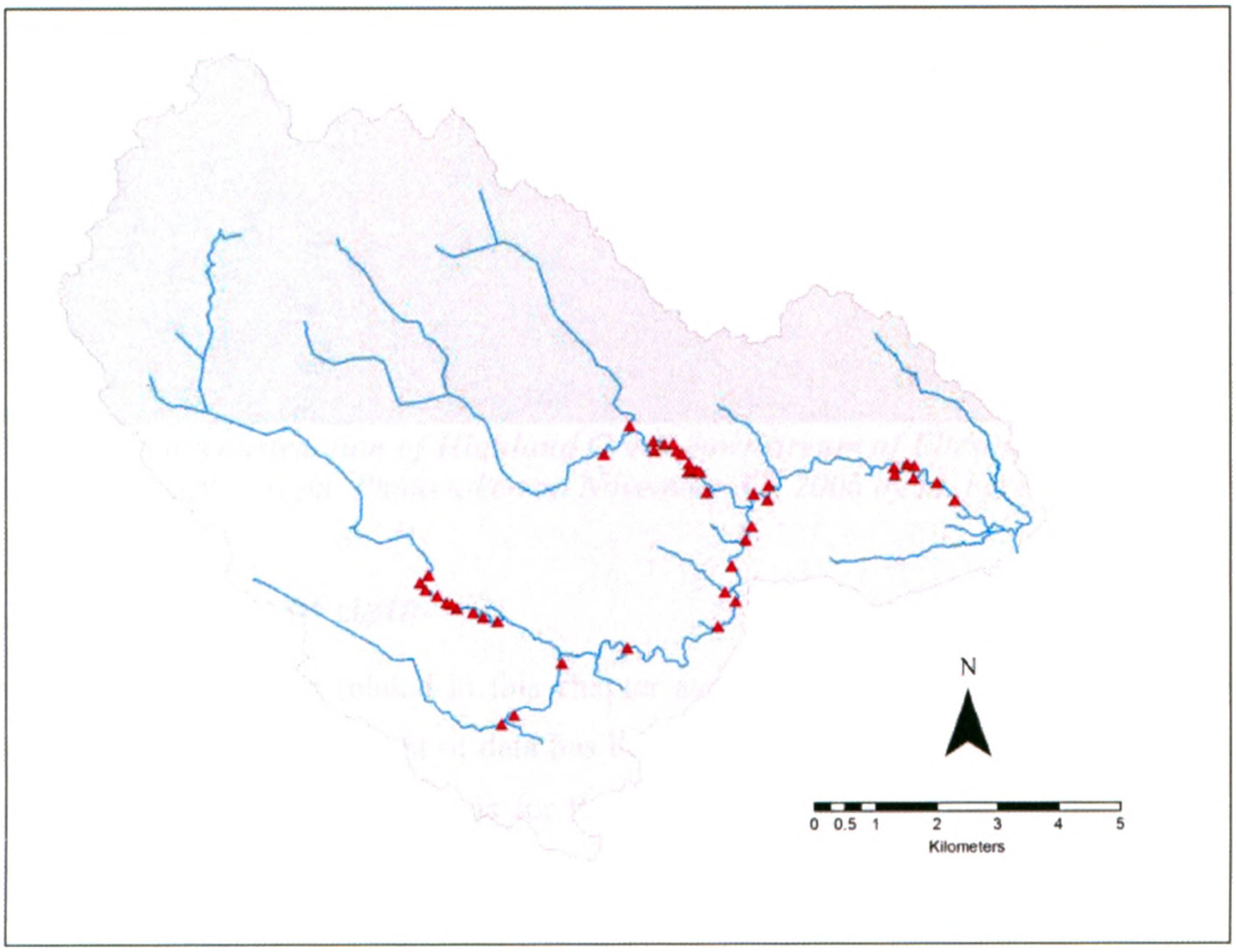


Figure 2.15 Sites of erosion in Highland Creek.
Erosion Sites in the Highland Creek Watershed as of 1999 (Toronto Region Conservation Authoirty & City of Toronto, 1999). These sites were identified prior to the August 2005 flood.

Figure 2.16 Reconstruction of Highland Creek downstream of Ellesmere Rd. bridge. *Flow is from left to right. Photo taken on November 3rd, 2006 by M. Ferencevic.*

2.6 Availability of data

Due to the information related in this chapter as well as the chronic erosion occurring along the river, a large amount of data has been collected on Highland Creek and is very valuable with respect to this thesis for the validation and cross-referencing of the GIS analysis and results. Of particular use are:

- Hydrologic model (OTTHYMO) (ABL, 2004)
- Hydraulic model (HEC-RAS) completed in 2007 (from TRCA)
- Surveys of specific reaches and geomorphic assessments (Parish Geomorphic, 2003)
- 1-m contour maps (Regional Municipality of York, 2001)
- Air photography of Highland Creek post-August 2005 flood (XEOS Imaging Inc., 2005)

Hydrologic model (OTTHYMO)

The consulting company Aquafor Beech Limited (ABL) was contracted in 2004 by the city of Toronto to complete an update of a hydrologic model for Highland Creek. ABL used the single event hydrologic modelling program 'Visual OTTHYMO' to complete

this analysis and specific details of the model parameters can be found in the final report (ABL, 2004). To summarize, the steps used to calibrate the model are:

1. Comparison of streamflow data from three streamflow gauges within the Highland Creek watershed;
2. Verification of the model using seven rainfall-runoff events as recorded at nearby rain gauges, distributed over the Highland Creek watershed using Thiessen Polygons;
3. Derivation of 'observed' runoff hydrographs from streamflow gauge data and comparison to the simulated runoff hydrographs;
4. Adjustment of CN* parameters to minimize differences between observed and simulated runoff volumes; (CN* refers to 'curve numbers' used in rainfall-runoff models that characterize the minimum infiltration capacity of different soil types (Dingman, 2002))
5. Derivation of a relationship between the CN* adjustments and recorded precipitation in days preceding the storm in order to predict CN* adjustments using a 10-day antecedent precipitation index for each storm.

The output from the presults of the model is return interval (RI) discharges for 27 locations in the basin and based on maximum instantaneous discharges (*Greg Frew, ABL, pers. comm., Oct. 16th, 2008*). These represent the 2, 5, 10, 25, 50, 100-year and Regulatory Storm floods. In this region, the Regulatory Storm is based on Hurricane Hazel, and is considered larger than the 100-year RI flood. It will be referred to as the Regulatory discharge in this thesis.

Hydraulic model (HEC-RAS)

A 1-D hydraulic model for Highland Creek was completed in January 2007 by an engineering firm for the City of Toronto and Toronto Region Conservation Authority. The USACE Hydraulic Engineering Center's 'River Analysis System' (or HEC-RAS) was used. The HEC-RAS model computes water surface elevations at each cross-section. The inputs required for the model are 'Geometric data' (cross-section information including elevation and energy loss coefficients) and 'Steady flow data' (flow regime, boundary conditions and peak discharge information). A total of 910 cross-sections were extracted from 2002 1-metre contour data. The minimum distance between cross-sections is 0.69 metres, the maximum distance is 306 metres and the average distance is 73 metres. The connectivity of the model and the cross-sections are illustrated in Figure

2.17. The previously-discussed OTTHYMO hydrologic model was used to input discharge information for Highland Creek .

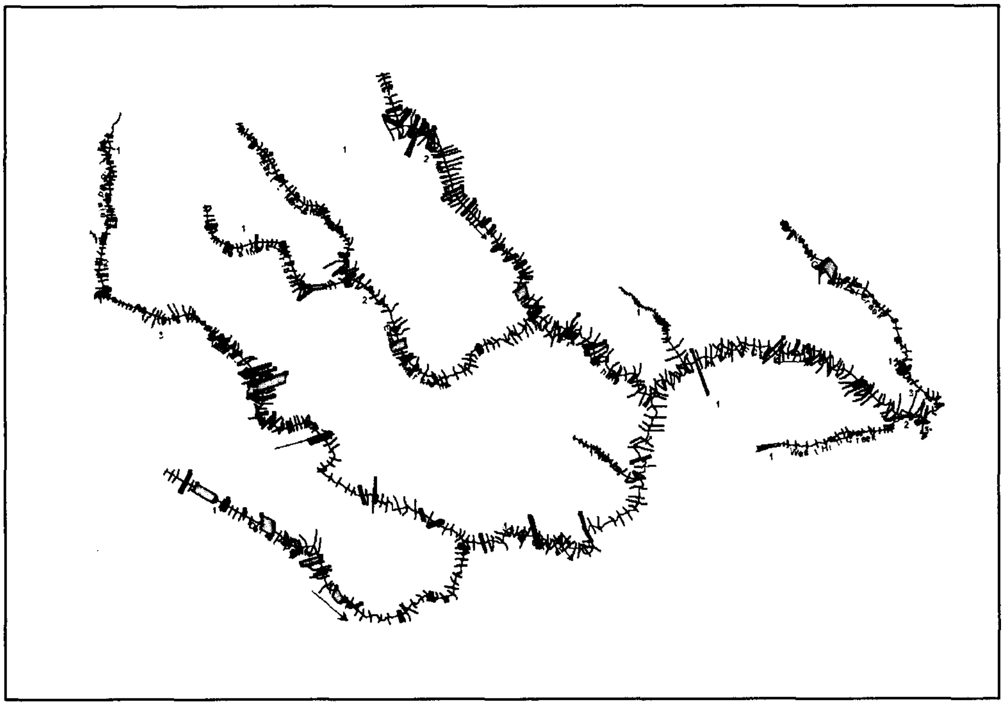


Figure 2.17 HEC-RAS cross-sections along Highland Creek.

Surveys

As part of the Regional Monitoring Program commissioned by the Toronto Region Conservation Authority, eighteen reaches along Highland Creek were surveyed in 2002 (Parish Geomorphic, 2003). The report states only that 'a level' was used to measure the long profile of the channel bed as well as the channel morphology along an arbitrary datum. The final data sheets include elevations for the thalweg, water level and left and right 'bankfull depth'. The measured reaches vary in length but average 430 metres.

Rapid Geomorphic Assessments

The Rapid Geomorphic Assessment (RGA) uses a number of indicators identified in the field to calculate a reach stability index. Some of these indicators include the presence or absence of exposed tree roots, siltation in pools, or exposed bridge footings. A sample field checklist used in an RGA is provided in Appendix A. The Toronto Region Conservation Authority commissioned a consulting company to set up a number of

monitoring sites on streams in the Greater Toronto Area, seven of which were on Highland Creek (Parish Geomorphic, 2003). In 2002, RGAs were conducted in order to evaluate the stability of these reaches. A map of the RGA-assessed reaches and the RGA results will be compared to a stream power map in order to evaluate any similarities.

Digital topographic maps: 1-m contour interval

The 2002 1-metre contour map (Regional Municipality of York, 2001) for Highland Creek was generated by the OMNR using 2002 orthophoto stereopairs and vector mapping (WRIP et al., 2007). In this comparison, elevations were extracted from the 1-metre contour line maps by matching each contour line that crosses Highland Creek with the downstream distance of the GIS stream. The fine resolution of this product will allow for a good assessment of DEM-extracted elevations for the channel bed.

Airphotos of Highland Creek post 2005 flood

As of the time of writing, post flood airphotos for Highland Creek were only available for the East Branch between the creek's intersection with Ellesmere Rd. and the confluence with the West Branch (XEOS Imaging Inc., 2005). The flood in question is discussed in more detail in section 2.4. These photos are compared to pre-flood photos of the same location to show the significant channel changes that resulted from the high flow event and the correspondence to locations identified in the stream power analysis.

2.7 Problems specific to urbanized basins

The method being developed in this thesis should be applicable to all types and sizes of stream. However, streams in urbanized basins present issues that merit discussion, and the case of Highland Creek presents an opportunity to explore these issues. In particular, flow routing and discharge approximation and their effects on the GIS analysis are examined here.

Flow routing and drainage areas

In urbanized watersheds, small tributaries and overland flow are often routed through storm sewers. Compared to the GIS hydrological model that is based entirely on topography, this can cause differences in the location of inputs to the system. Because

flow is unlikely to be directed against the general slope of the landscape, the overall final pattern is not likely to be very different. In the case of the Ontario Provincial DEM v.2, the location of the actual stream on the DEM has been verified and is correct. What is likely to be affected by the sewering of flow are the boundaries of drainage areas. For Highland Creek, there is a map of the entire Highland Creek watershed that appears to have been corrected for sewersheds on its boundaries (ABL, 2004). The map is reproduced below (Fig. 2.18) but ABL has stated that the edges were likely digitized from non-digital data and for this reason could not be integrated with the DEM (pers. comm. ABL, Nov. 2006).

The DEM-derived watershed has a very similar boundary to the actual one, the only major difference is that the actual watershed omits an area of about 1.6 km^2 north of Hwy 401 near Centennial Creek. The city of Toronto derives watershed areas from a GIS-database (the specifications of which are unknown) and reports that Highland Creek's drainage area is 106 km^2, while the OMNR DEM drainage area is 102 km^2. This is a small difference in area, that can be accounted for in a number of ways. First is the reconstructed boundary at Hwy 401, second is the result of the rounding in area that must occur when drainage area is calculated from a DEM using cells measuring 10 metres by 10 metres. The remaining 'missing' area is likely the result of artificial cutoffs on the edge of the drainage basin that have been caused by routing flow underground into sewers. Therefore, in the case of Highland Creek, the changes in watershed boundary and total area due to urban development do not appear significant.

Discharge approximation

As discussed in Chapter 2, the hydrology of Highland Creek has been significantly altered by urbanization. In GIS hydrologic modeling, rural areas can use a discharge to area relationship with confidence. However, it has been demonstrated that urbanization has significantly altered the hydrology of Highland Creek to the point that it is no longer similar to its rural neighbours (O'Neil, 2008). The hydrologic model completed for Highland Creek and described in section 2.6 serves as the basis for a basin-specific discharge to area relationship. Although this works well for this case, future work on urban basins will require better methods of estimating discharge.

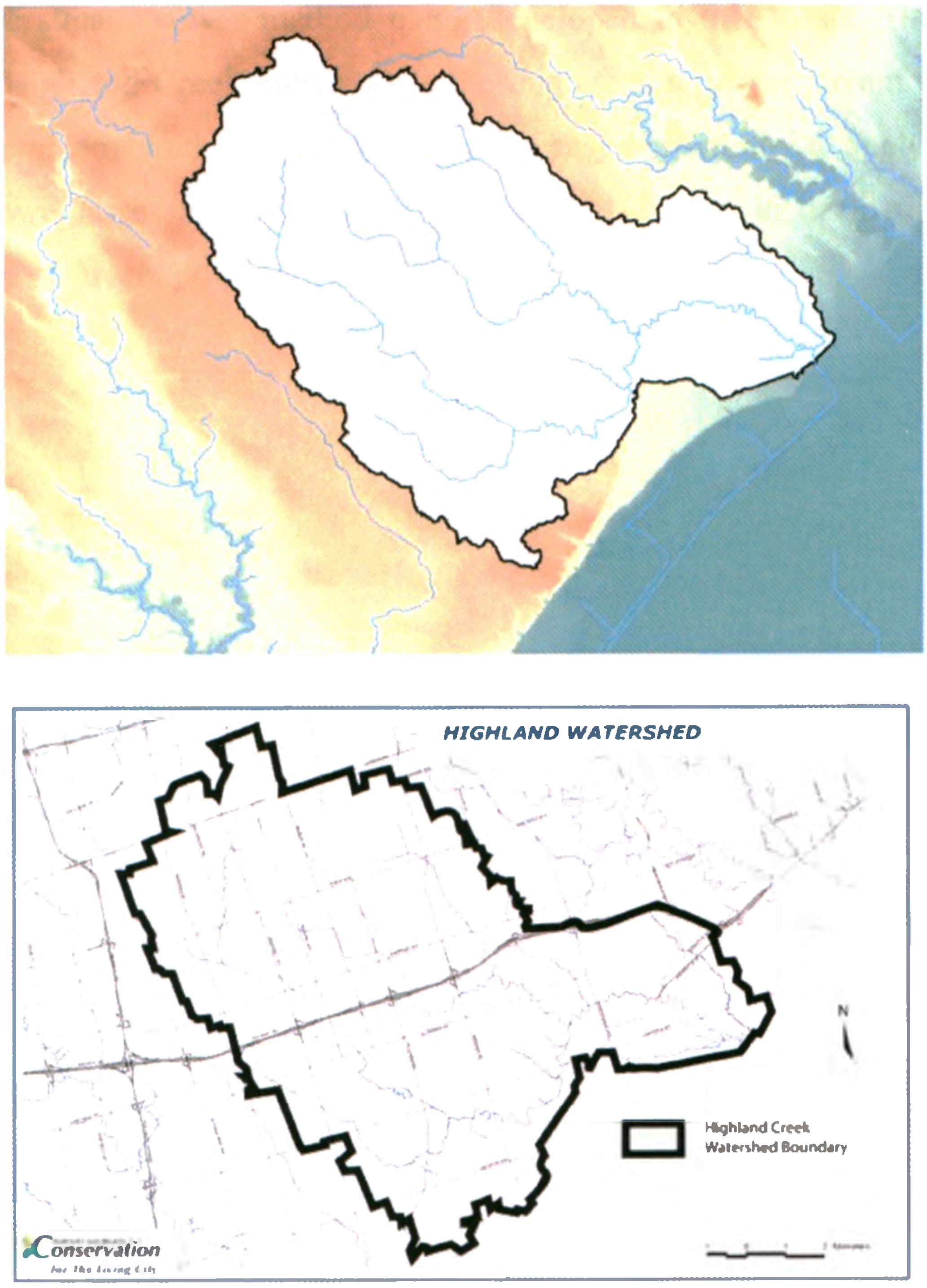


Figure 2.18 Map of Highland Creek watershed from DEM (above) and corrected for sewersheds (below). *Notethat where the watershed has been topographically derived, the boundary is jagged and rough. Where the drainage network has been corrected for stormwater drainage through sewers, the boundary edges are straight.*

Highland Creek, although an extreme case of urbanization, presents an excellent example for testing the stream power method being developed in this thesis. The data that is available for Highland Creek allows for a thorough testing of the stream power results. The stability problems in the river also present an easy opportunity to apply the results of the stream power assessment. The next chapter will discuss in detail the method for creating a map of stream power.

Chapter 3:
Developing a method for mapping stream power

The focus of this thesis is to develop a method through which stream power values can be extracted using GIS. The data sources used will be described, followed by a discussion of analysis issues relating specifically to the extraction of stream power and the data for southern Ontario. Figure 3.1 is a flowchart of the GIS analysis that summarizes the steps required to extract stream power values. The numbers in the diagram refer to the corresponding sections in the text.

Summary of GIS analysis

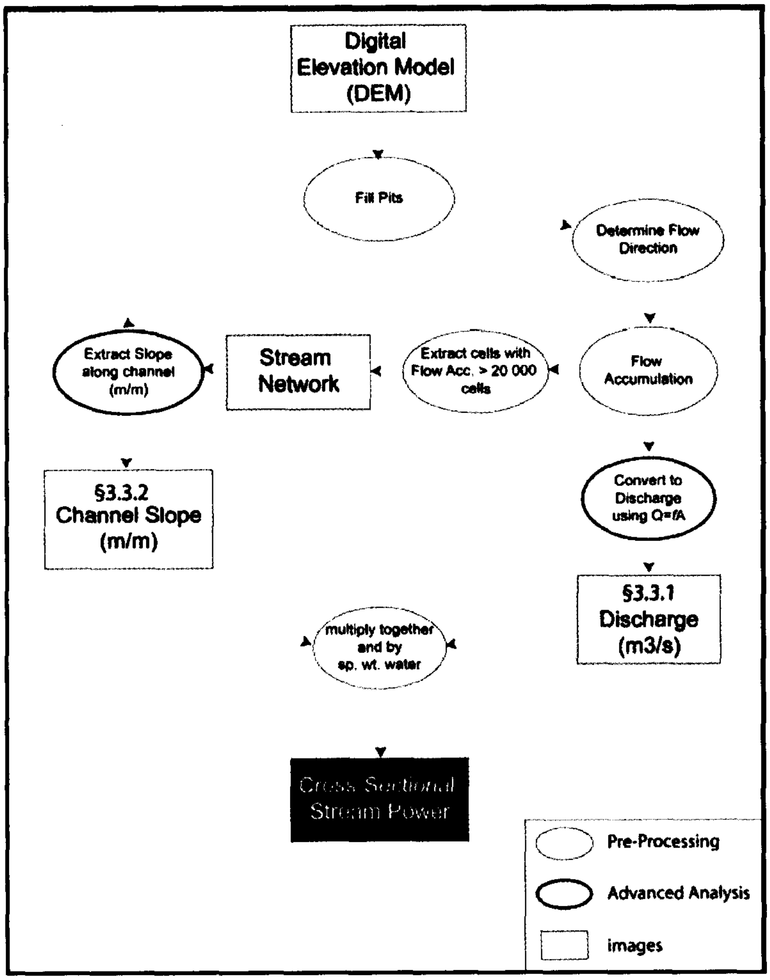


Figure 3.1 GIS flowchart.
Summary of steps required for GIS extraction of stream power.

3.1 Data sources for analysis

3.1.1 Provincial digital elevation model

The provincial topographic digital elevation model (DEM) for southern Ontario is composed of 10 metre by 10 metre cells with elevation values representing the ground surface. The root mean square error for the elevations in the DEM is 1.436 metres (OMNR, 2002). The data used for this research consists of version 2.0.0 of the DEM (OMNR, 2005), and is itself based on a number of different data sources, as illustrated in Figure 3.2.

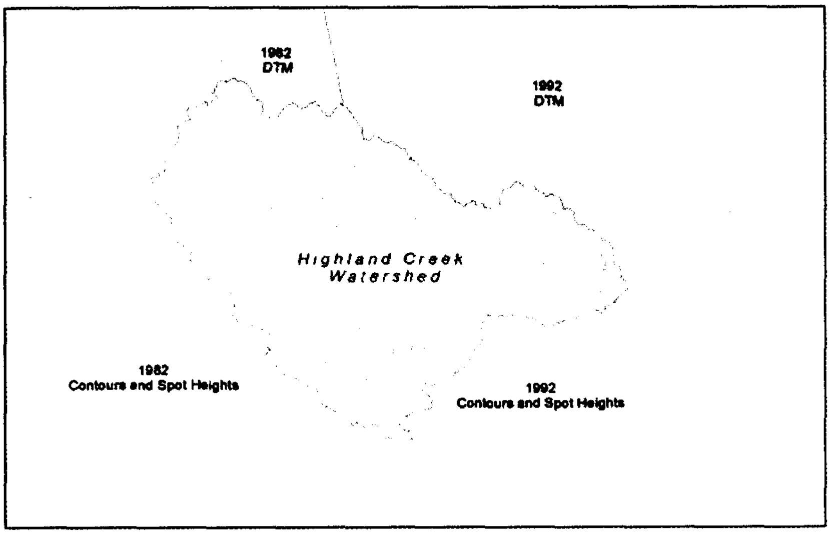


Figure 3.2 Data sources used for the interpolation of the Provincial DEM v.2.0. (OMNR, 2005)

Elevation data for the light blue areas of Figure 3.2 was interpolated from contour lines and spot heights from the Ontario Base Map (OBM) series, while the dark blue areas were interpolated from OBM digital terrain model (DTM) elevation points. The light blue areas have original elevation values concentrated along lines of equal elevation with no elevation values in between, while the DTM consists of a grid-like pattern of elevation values that were systematically extracted at regular intervals. The elevation data was compiled and processed as illustrated in Figure 3.3 in order to interpolate values for the whole surface.

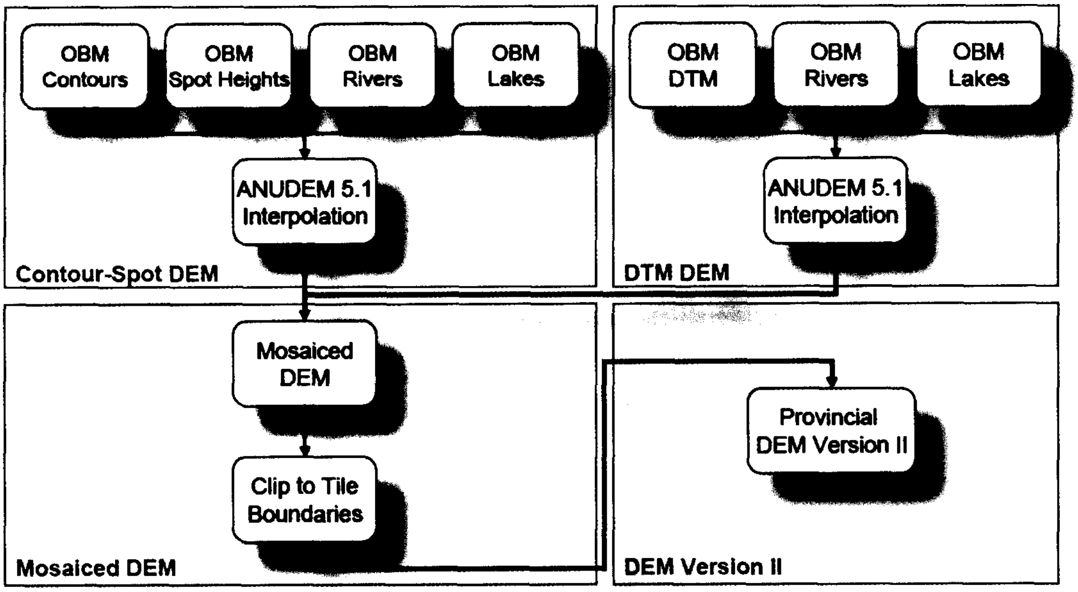


Figure 3.3 Flowchart for data processing of Provincial DEM v.2.0. *(OMNR, 2006)*

The elevation data was further processed by the Ontario Ministry of Natural Resources in order to eliminate known errors. Post-processing includes:

- Stripe removal (stripes being an artifact of the grid-like pattern in which DTM elevation points were extracted);
- Contour edits (to ensure that data were being extracted from connected lines of constant elevation);
- Spot height filtering (original OBM spot heights were often accidentally captured for buildings);
- Lake elevation assignment (to avoid false elevation values over lake surfaces);
- Constructing a geometric waterflow network.

The program ANUDEM that was used for interpolation allows for stream enforcement of the landscape using the above-mentioned geometric waterflow network (OMNR, 2006). The result is that the DEM elevations account for the location and the direction of flow in hydrological networks. This alteration of the DEM is an important and necessary step for hydrologic analysis (*see Chapter 1, section 1.1.3, 'stream burning'*), but comes at a cost. Figure 3.4 illustrates the difference in long profiles of the west and main branch of Highland Creek extracted from the un-enforced and the enforced DEM.

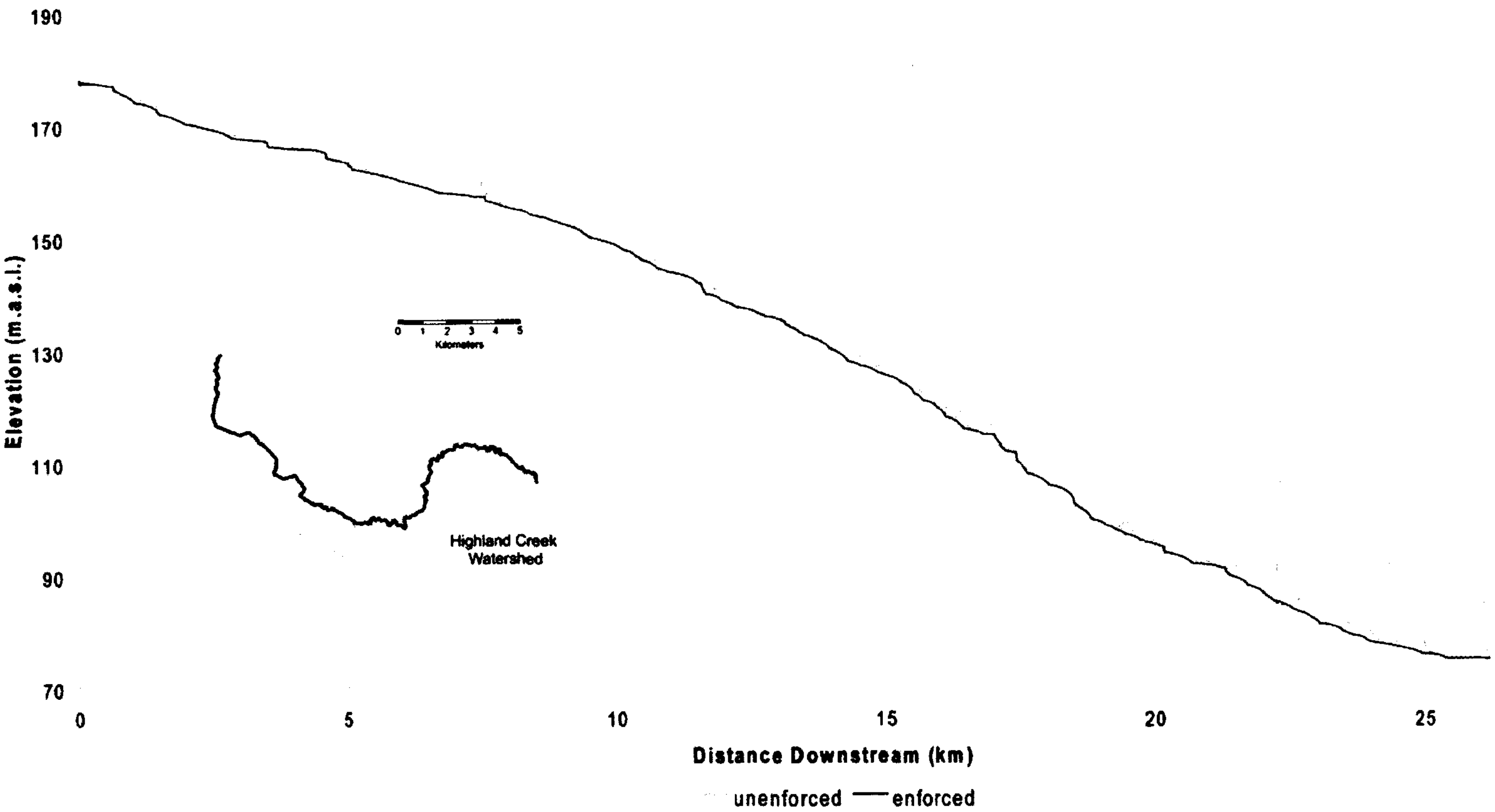


Figure 3.4 Comparison between enforced and unenforced DEM.
These long profiles were extracted from the unenforced DEM (grey) and the hydrologically enforced DEM as it is delivered by the OMNR (black).

The peaks that are so obvious in the un-enforced DEM are a good example of the type of artifacts that often result from the interpolation of elevation contour lines and spot heights. Figure 3.5 illustrates the coincidence of these peaks with the location of road and train bridges crossing the river (*see Fig, 2.2 for map of transportation network in Highland Creek*). Not all road crossings have a coincident peak on the long profile. In these cases, the previously described post-processing has 'caught' the errors of non-earth-surface elevation points and removed them from the interpolation data set. Those roads and bridges that have not been removed are also visible on the DEM (Fig. 3.6).

The peaks in the unprocessed long profile would prevent flow from moving to the mouth of the river. The 'corrected' long profile does allow for upstream to downstream flow, and is a very close approximation of the true long profile, but neither the processed or the unprocessed are composed entirely of true surface elevations.

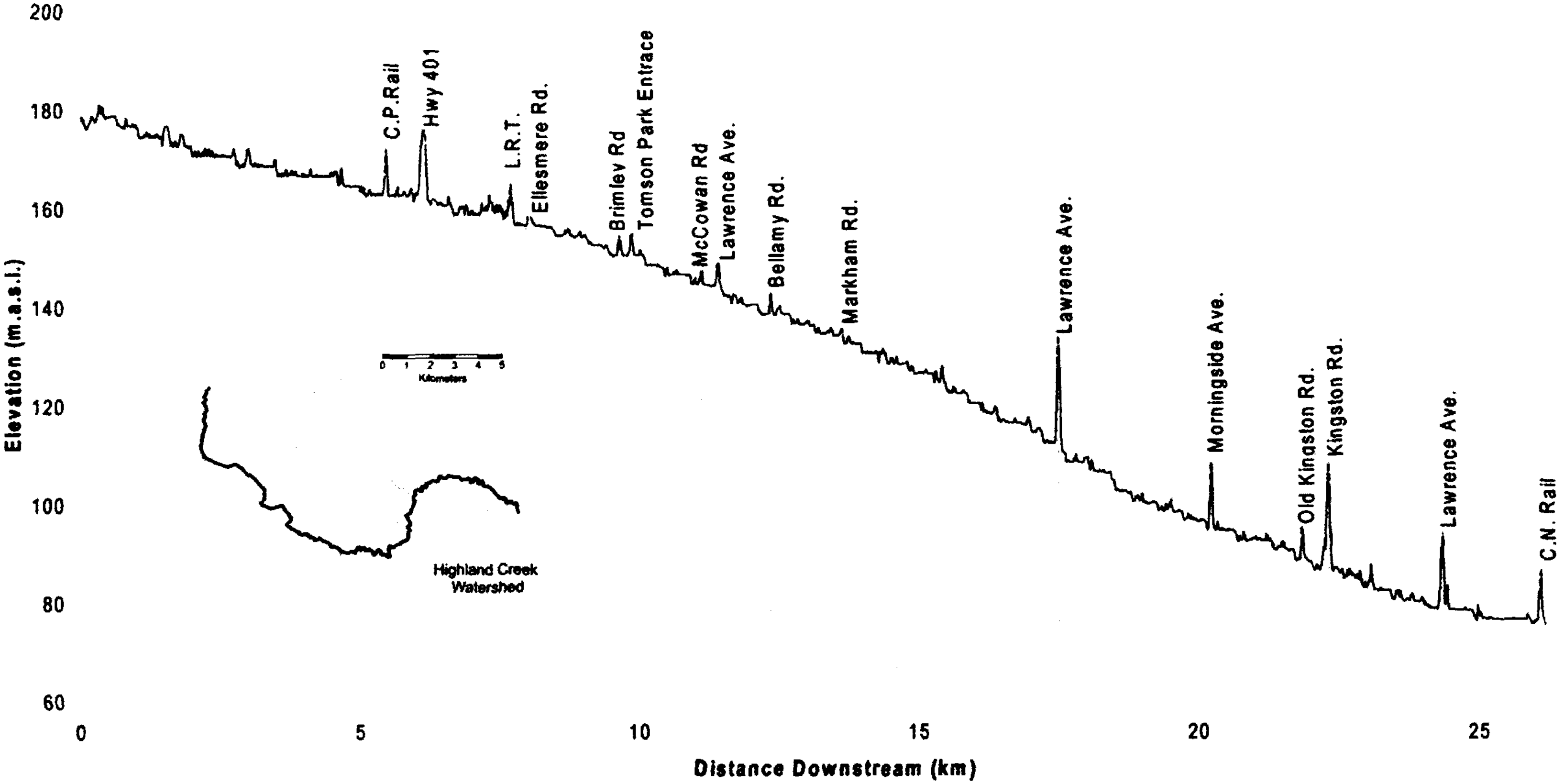


Figure 3.5 Identification of the peaks in the long profile of the unenforced Provincial DEM v.2.0.
Peaks in the long profile for the westernmost branch of Highland Creek coincide with the location of road crossings or bridges. See Figure 2.2 for map of transportation network in the Highland Creek watershed.

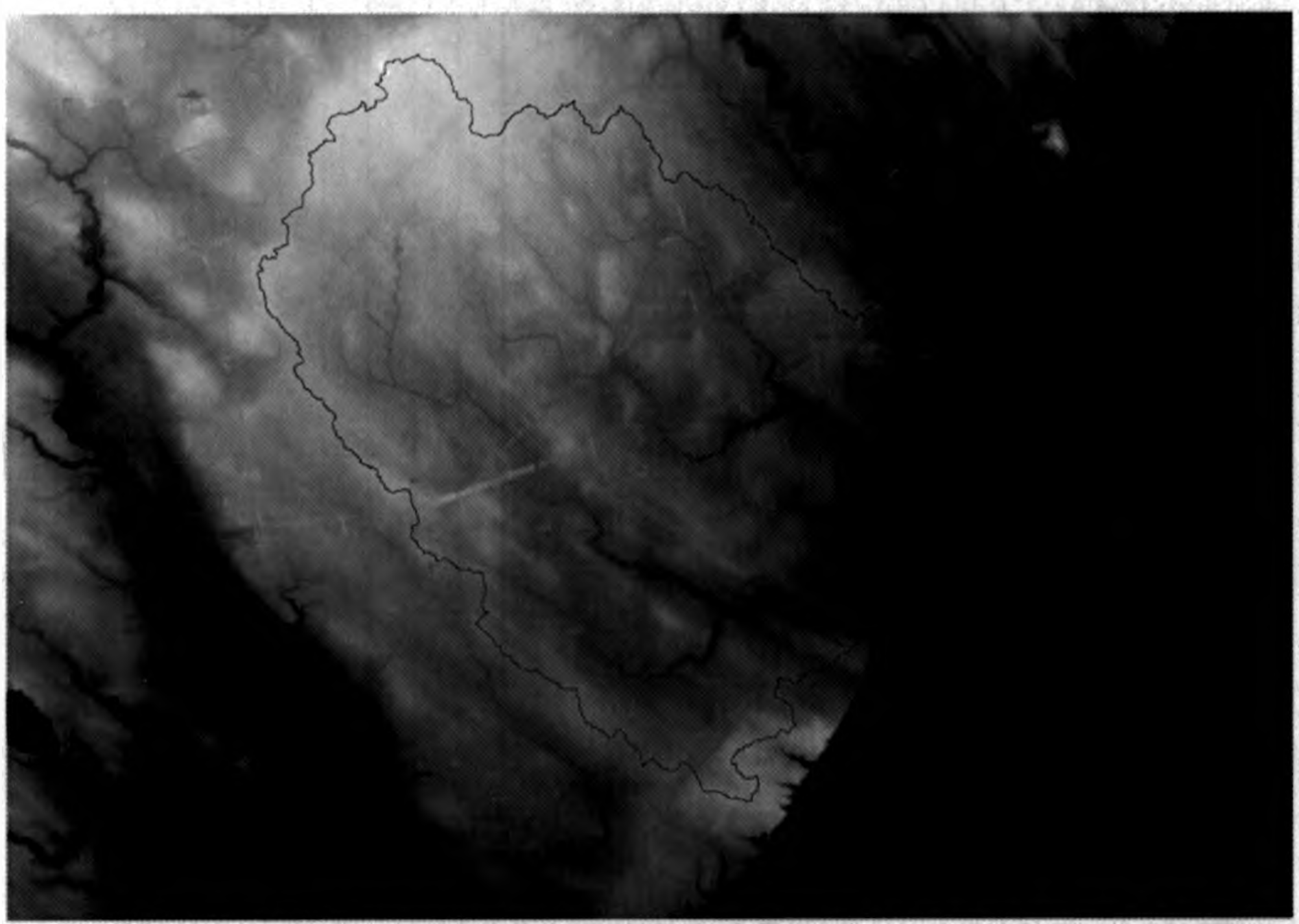


Figure 3.6 ***Provincial DEM v.2.0 with Highland Creek basin outline.*** *(OMNR, 2005)*

A 1-metre contour map for Highland Creek is available that was generated by the OMNR using elevations extracted photogrammetrically from 2002 aerial photography (Regional Municipality of York, 2001). The OMNR then converted the points from this analysis to a TIN (triangulated irregular network) model and then converted this to contours. This information is used here to check elevation values from the Ontario Pronvicial DEM v.2. Elevations were extracted from the contourline maps by matching each contour line that crosses Highland Creek with the downstream distance of the GIS stream. Figure 3.7 compares the DEM-extracted elevations to the contour map elevations. It is difficult to compare the elevations in any other way since there are very few elevation points from the contour maps. However, simple observation of the correspondence of elevations confirms that the DEM data, although converted to grid elevations and extracted from a number of different sources and years (see Fig. 3.2), reflects true ground or channel bed elevations from large-scale mapping.

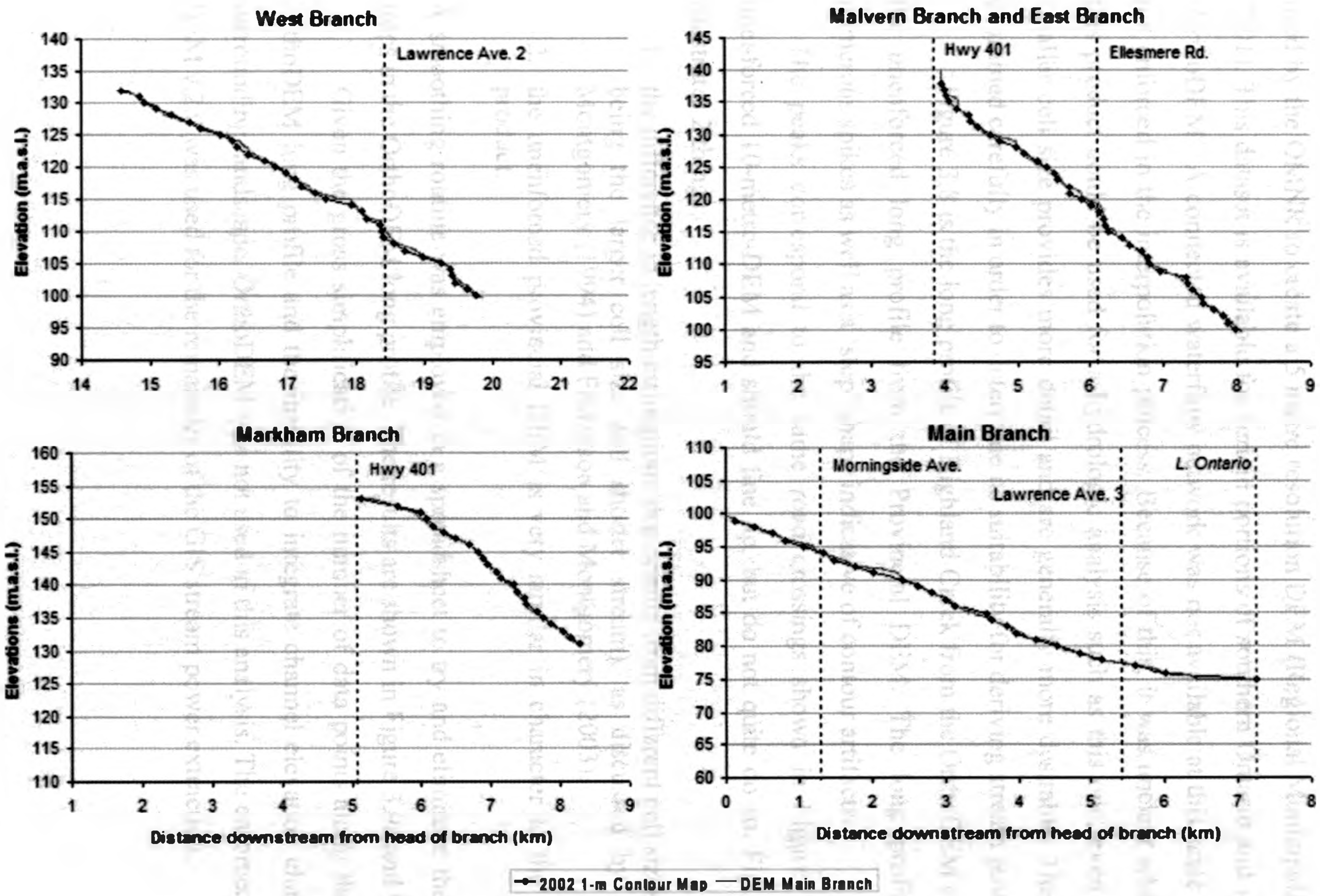


Figure 3.7 Comparison of DEM with 1-metre contour elevations.

The labels 'Lawrence Ave. 2' and 'Lawrence Ave. 3' refer to the second and third intersections, respectively, of Highland Creek with Lawrence Ave. in the downstream direction.

3.1.2 OrthoDEM

The 2002 1-metre contour map used in section 3.1.1 to compare elevation values was also used by the OMNR to create a 5 metre resolution DEM (Regional Municipality of York, 2001). This dataset is available for certain portions of southern Ontario and is called the 'OrthoDEM'. A connected waterflow network was not available at this scale and so was not enforced in the interpolation process. Because of this, it was unclear whether or not this product could be used for a hydrologic analysis such as this one, even though the smaller cell size provides more detail and are generally more desirable. The DEM was examined carefully in order to determine its suitability for deriving stream power maps.

Figure 3.8 is the long profile of Highland Creek from the OrthoDEM compared to the unenforced long profile from the Provincial DEM. The long profile contains numerous spikes as well as a 'step' shape indicative of contour artifacts.

The peaks correspond to the same road crossings shown in Figure 3.5 for the unenforced 10-metre-DEM and should line up, but do not quite do so. Figure 3.8 thus illustrates 2 things:

1. the difference in length estimations that results from different cell sizes (light grey being the larger cell size and shorter stream), as discussed by Zhang and Montgomery (1994) and Finlayson and Montgomery (2003).
2. the unenforced provincial DEM is very similar in character to the OrthoDEM product.

A smoothing routine was employed in a spreadsheet to try and eliminate the peaks and steps in the OrthoDEM long profile. The results are shown in Figure 3.9a and b.

Given the gross simplification of the number of data points along the smoothed OrthoDEM long profile and the inability to integrate channel elevation changes to the surrounding landscape, OrthoDEM was not used in this analysis. The enforced Provincial DEM v.2.0 was used for the remainder of the GIS stream power extraction.

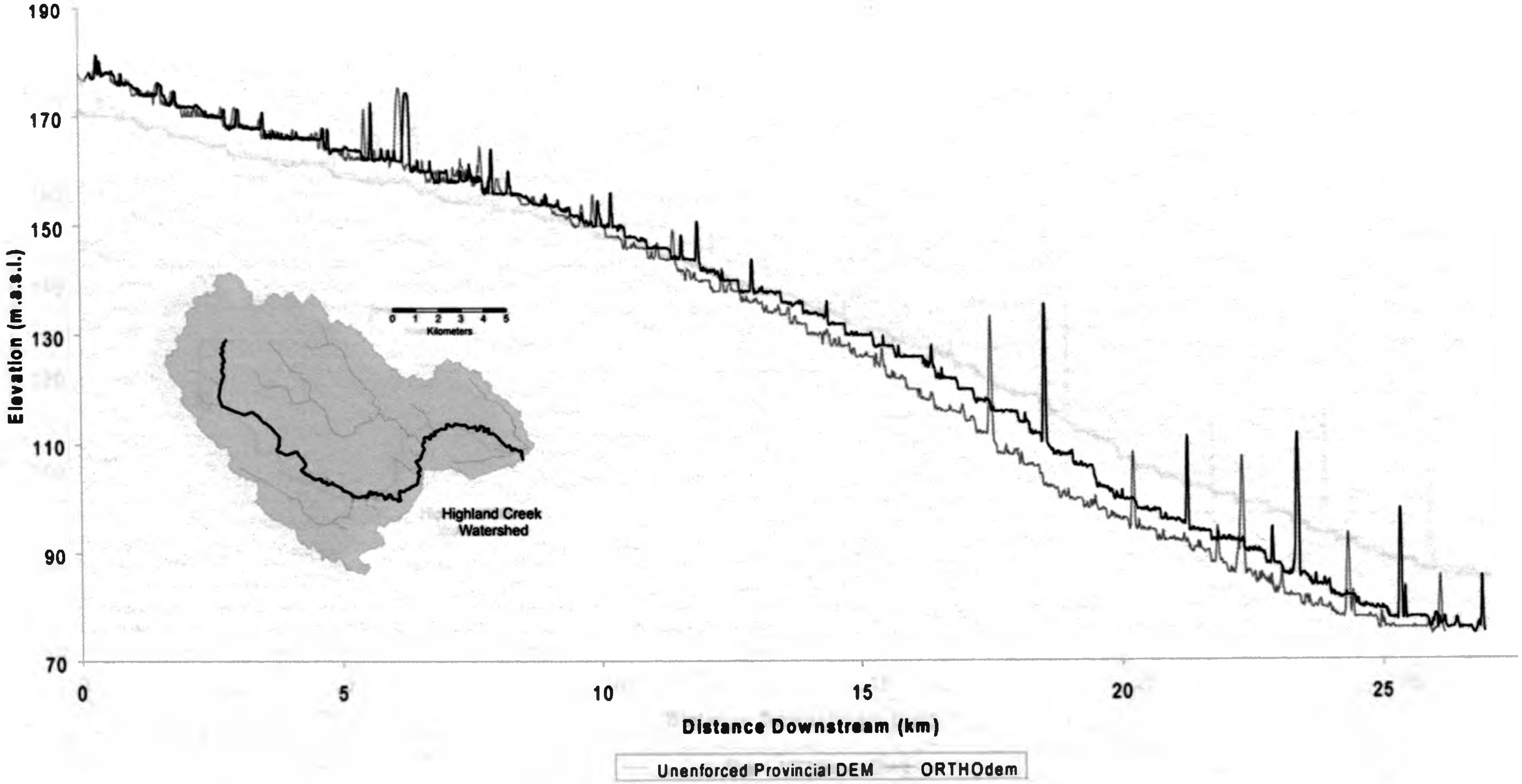


Figure 3.8 Comparison between OrthoDEM and the unenforced Provincial DEM.
Long profile of the westernmost branch of Highland Creek extracted from OrthoDEM (5m cells, shown in black) and compared to the Provincial DEM (10 m cell size and shown in grey).

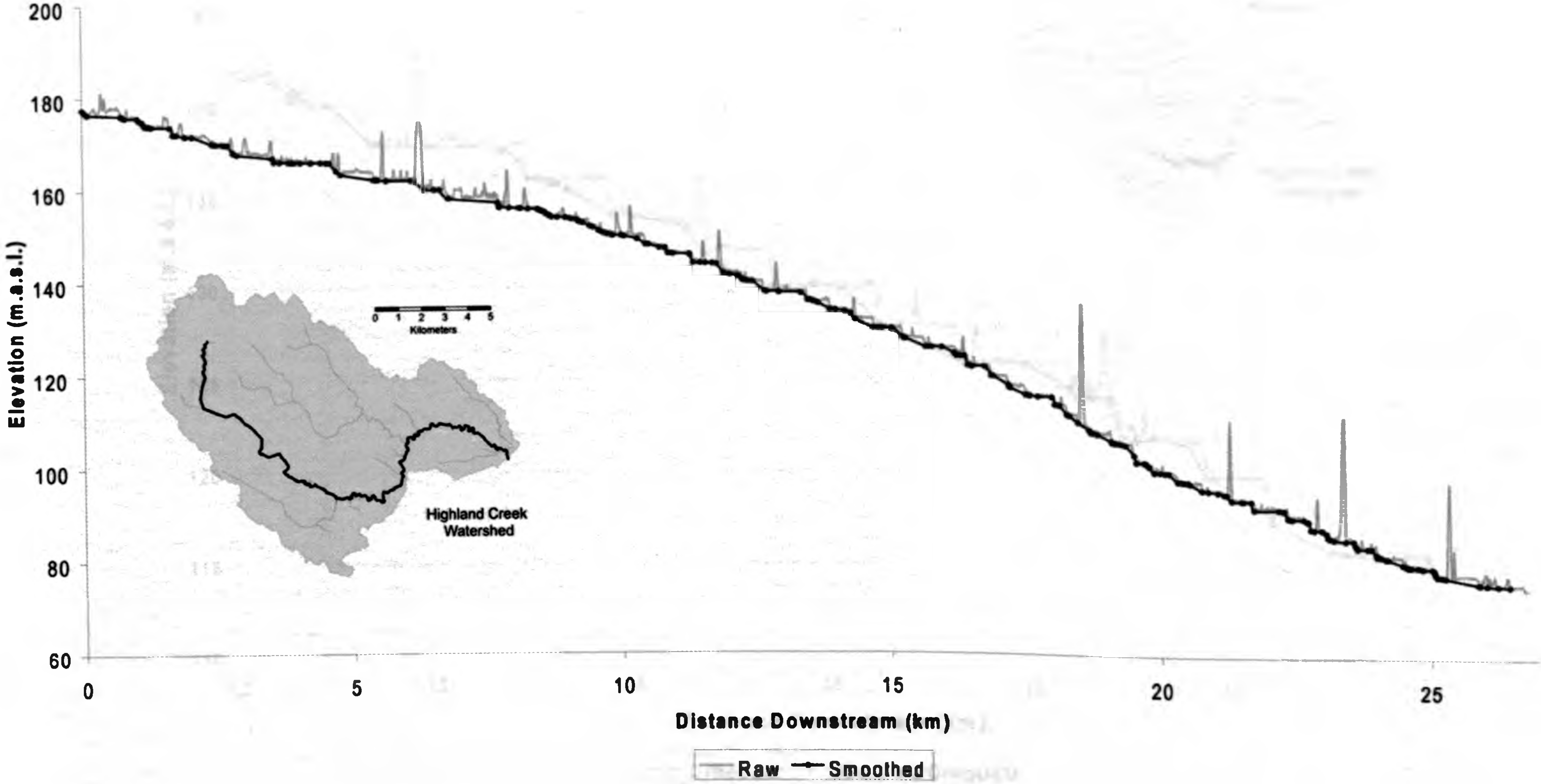


Figure 3.9a OrthoDEM long profile comparison: raw and smoothed.
The number of data points has been significantly reduced from over 4500 points to approximately 273.

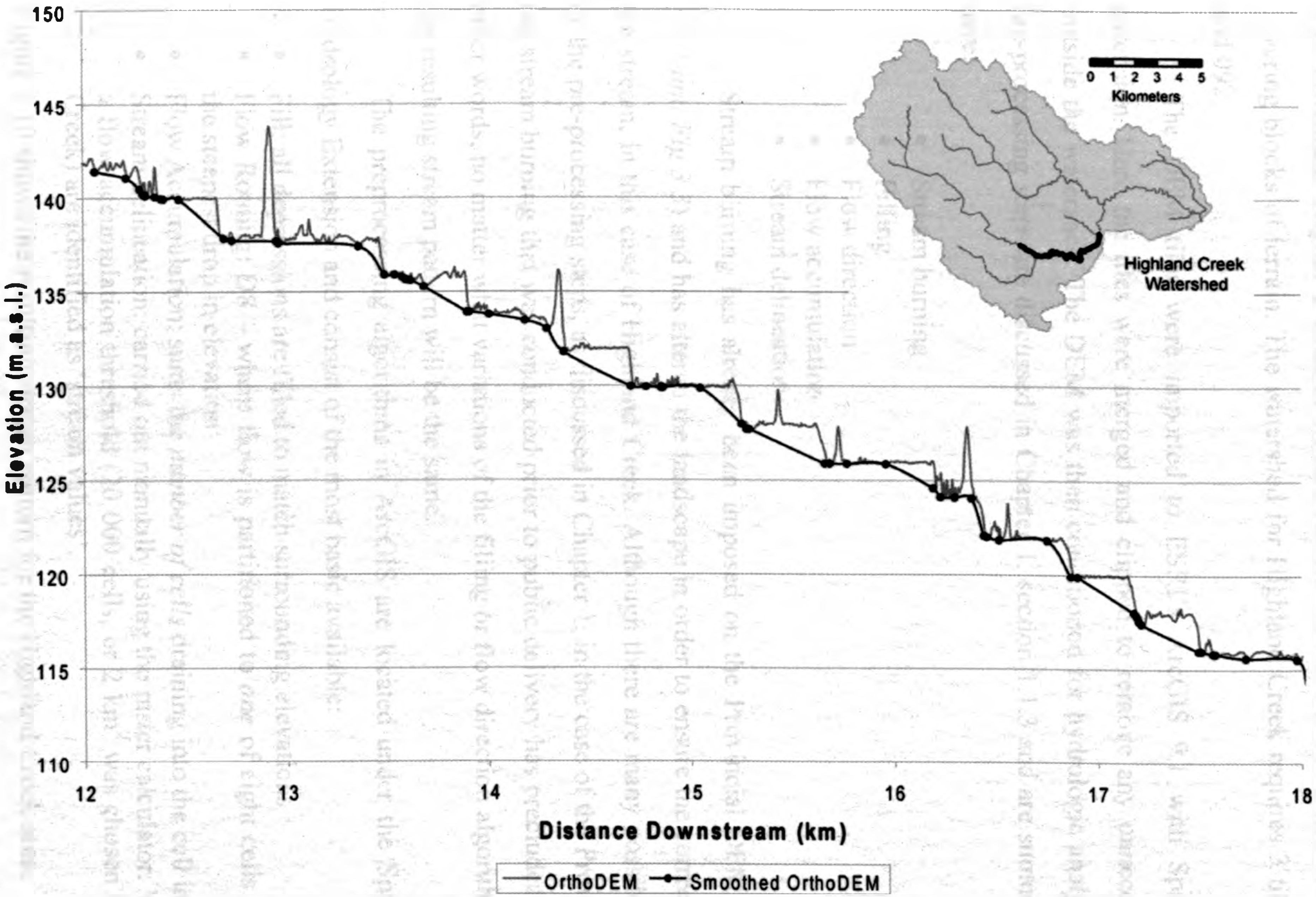


Figure 3.9b Close-up of OrthoDEM
Close-up of kilometres 12 to 18 of the long profile in a). Note the 'stepped' nature of the OrthoDEM (grey) and the considerably simplified smoothed profile (black).

3.2 GIS Pre-processing steps

The Provincial Digital Elevation Model (DEM) v.2 is available as a series of tiles covering blocks of terrain. The watershed for Highland Creek requires 3 tiles: 087, 091 and 092.

The DEM tiles were imported to ESRI's ArcGIS 9.1 with Spatial Analyst extension. Here the tiles were merged and clipped to remove any unnecessary image outside the watershed. The DEM was then conditioned for hydrologic analysis. General pre-processing steps are discussed in Chapter 1, section 1.1.3 and are summarized again here:

- Stream burning
- Filling
- Flow direction
- Flow accumulation
- Stream delineation.

Stream burning has already been imposed on the Provincial DEM (*see section 3.1.1 and Fig 3.3*) and has altered the landscape in order to ensure the correct location of the stream, in this case of Highland Creek. Although there are many possible variations of the pre-processing steps, as discussed in Chapter 1, in the case of the Provincial DEM, the stream burning that was conducted prior to public delivery has precluded their use. In other words, no matter what variations of the filling or flow direction algorithms are used, the resulting stream pattern will be the same.

The preprocessing algorithms in ArcGIS are located under the Spatial Analyst Hydrology Extension and consist of the most basic available:

- Fill: all depressions are filled to match surrounding elevations
- Flow Routing: D8 – where flow is partitioned to *one* of eight cells according to the steepest drop in elevation
- Flow Accumulation: sums the *number of cells* draining into the cell in question
- Stream delineation: carried out manually using the raster calculator. Values above a flow accumulation threshold (20 000 cells, or 2 km^2 was chosen for Highland Creek) are identified as 'stream values'.

Figure 3.10 shows the resulting stream pattern for the Highland Creek area.

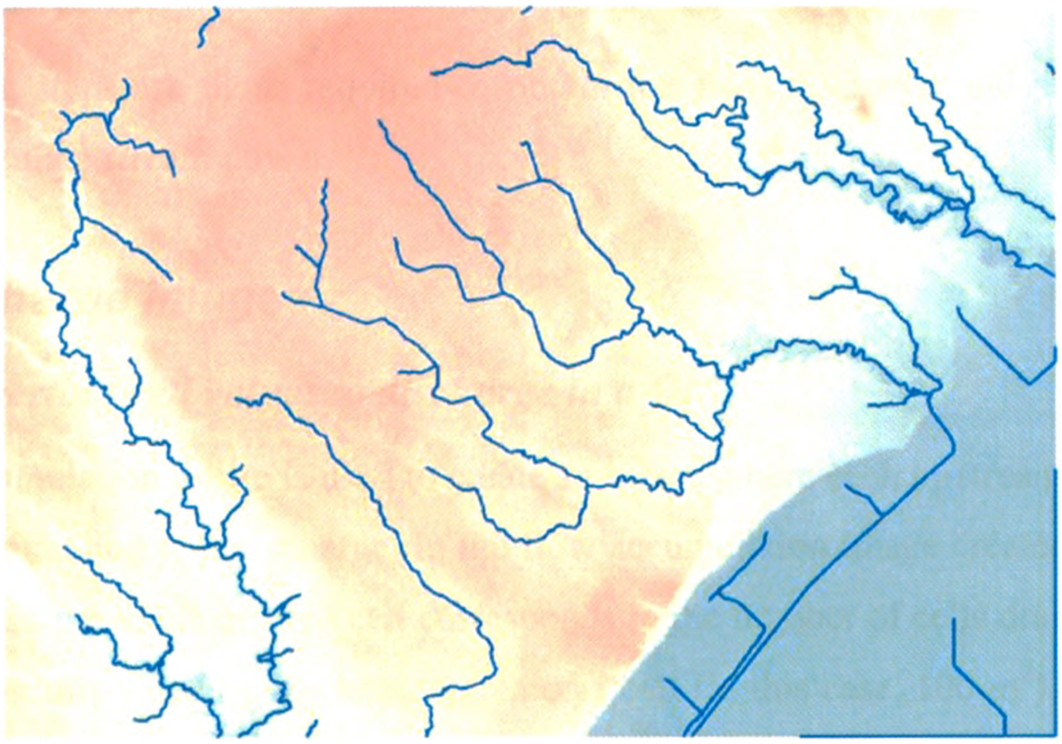


Figure 3.10 GIS-derived streams for Highland Creek area.

The next step consists of identifying the watershed, or all cells draining to a "pour point". This algorithm is called 'watershed' and the point used in this case corresponds to the outlet of Highland Creek into Lake Ontario. The stream image (Fig. 3.10) as well as the watershed image are binary images (composed only of values 1 or 0, where 1 is the stream and the watershed, respectively) and they are multiplied together to eliminate all non-Highland Creek streams (Fig. 3.11).

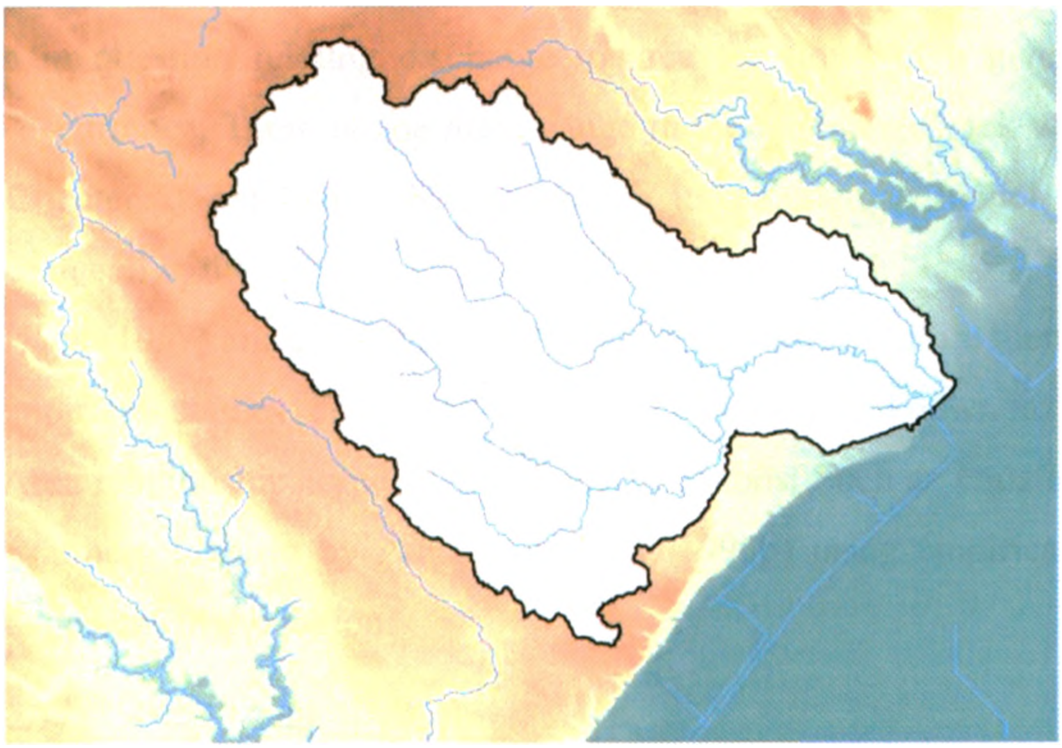


Figure 3.11 GIS-derived watershed for Highland Creek.

3.3 GIS analysis

The following steps are those required to obtain the final discharge and slope images needed to calculate stream power.

3.3.1 Discharge images

3.3.1.1 Converting cell values to discharge in a GIS

The flow accumulation image is used to create an image where each in-stream cell carries a value corresponding to a discharge. In the flow accumulation image created by ESRI's Spatial Analyst, the value of each cell corresponds to the number of cells draining into it. By multiplying this value by the known area of a cell (in this case, 100 m^2), the cells in the new image now contain the area that drains into them. By using a discharge to area relationship, further calculation transforms these area values into a flow in m^3s^{-1}.

3.3.1.2 Obtaining a discharge to area relationship

A discharge (Q) to drainage area (A) relationship takes the form of the power relationship

$$Y = \alpha X^{\beta} \qquad \textit{Eq. 6}$$

where, Y = discharge, X = drainage area and α and β are constants that vary for different locations, depending on variables such as climate and surficial geology.

Defining this relationship requires obtaining a sufficient amount of empirical data for the region in question relating discharge to area for flows of a given estimated probability of occurrence. There is one main gauge in the Highland Creek watershed, as described in Chapter 2, but this is hardly enough information to model an accurate discharge for each cell in the stream.

Since Hack (1957) and Leopold et. al (1964), and possibly before then, there have been many empirical studies conducted to produce what are known as 'Regional' Discharge to Area relationships typical for specific locations. Such an equation has been compiled for southern Ontario by Annable (1996a; 1996b) using empirical data from (non-urban) gauge sites in the region:

$$Q = 0.52 A_d^{0.75} \qquad \textit{Eq. 7}$$

This equation was compiled using bankfull discharges, as calibrated from Log-Pearson

Type III distributions describing the annual maximum instantaneous discharges at each station with gauge managers' descriptions of bankfull field indicators (Annable, 1996a). The average bankfull flow frequency return interval for all rivers in the database is 1.6 years (Annable, 1996b).

The problem with this equation is that it was compiled using data for primarily rural watersheds. Given that the Highland Creek watershed is almost entirely urbanized and that its hydrology is demonstrably different from surrounding watersheds (see Chapter 2) we cannot expect that the above equation will fit its characteristics. Indeed, this disparity is illustrated by plotting the 2-yr return interval flood for all gauges within a 50 km radius of the Highland Creek gauge alongside the regional equation (Figure 3.12).

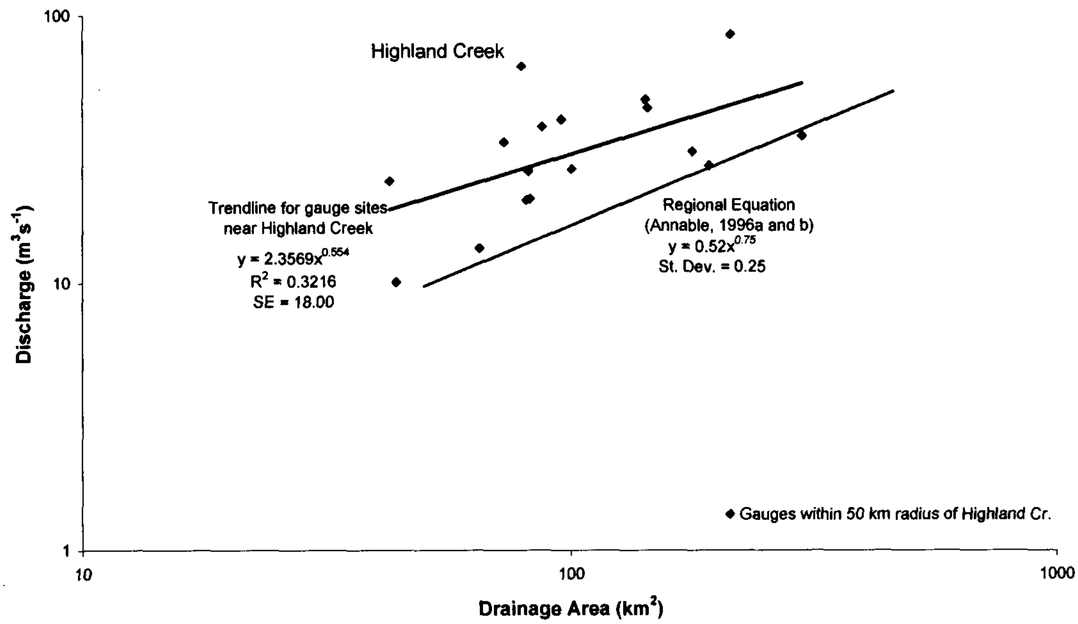


Figure 3.12 Discharge to area relationships for the area surrounding Highland Creek. *2-yr RI discharges for gauges within a 50 km radius of Highland Creek are plotted alongside the Regional Equation from Annable (1996a, 1996b). The Regional Equation does not adequately capture the discharge to area characteristics of Highland Creek. Regression statistics for the trendline representing gauge sites near Highland Creek are presented in Appendix B.*

HYDAT, the hydrometric data from the Water Survey of Canada, assembles information on each basin for which streamflow records exist. Based on Land Classification 24, 'Settlement and Developed Land', out of all of Ontario, only 12 stations have a value higher than 50% and these are highlighted in Figure 3.13. Seven of these occur within a 50 km radius of Highland Creek and are highlighted in the inset of Figure 3.13. Only 3 gauges in Ontario are more than 75% 'settled and developed': Highland Creek, Mimico Creek and Walker Creek. Highland Creek is 85.11% 'settled and developed'. In addition to this lack of equivalent basins, the period of record during which these basins have been urbanized is rather short. This means that even if there were a large number of gauge sites to fit this category, the number of years of record during which they have been urbanized is likely to be insufficient for establishing characteristic flows. Increasing urbanization therefore presents an issue in flow prediction from basin area and land cover for all of southern Ontario. For this reason, a regional-type equation was not used for Highland Creek in this thesis.

Although an appropriate existing regional discharge to area relationship would make the stream power calculation more straightforward and readily applied to other cases, it is possible to proceed without one. The discharge equation is area dependent and is applied to the flow accumulation area. In the absence of appropriate scaling factors, using the flow accumulation image combined with local channel slope would still produce a map of *relative* stream power which would still have value in stream assessment.

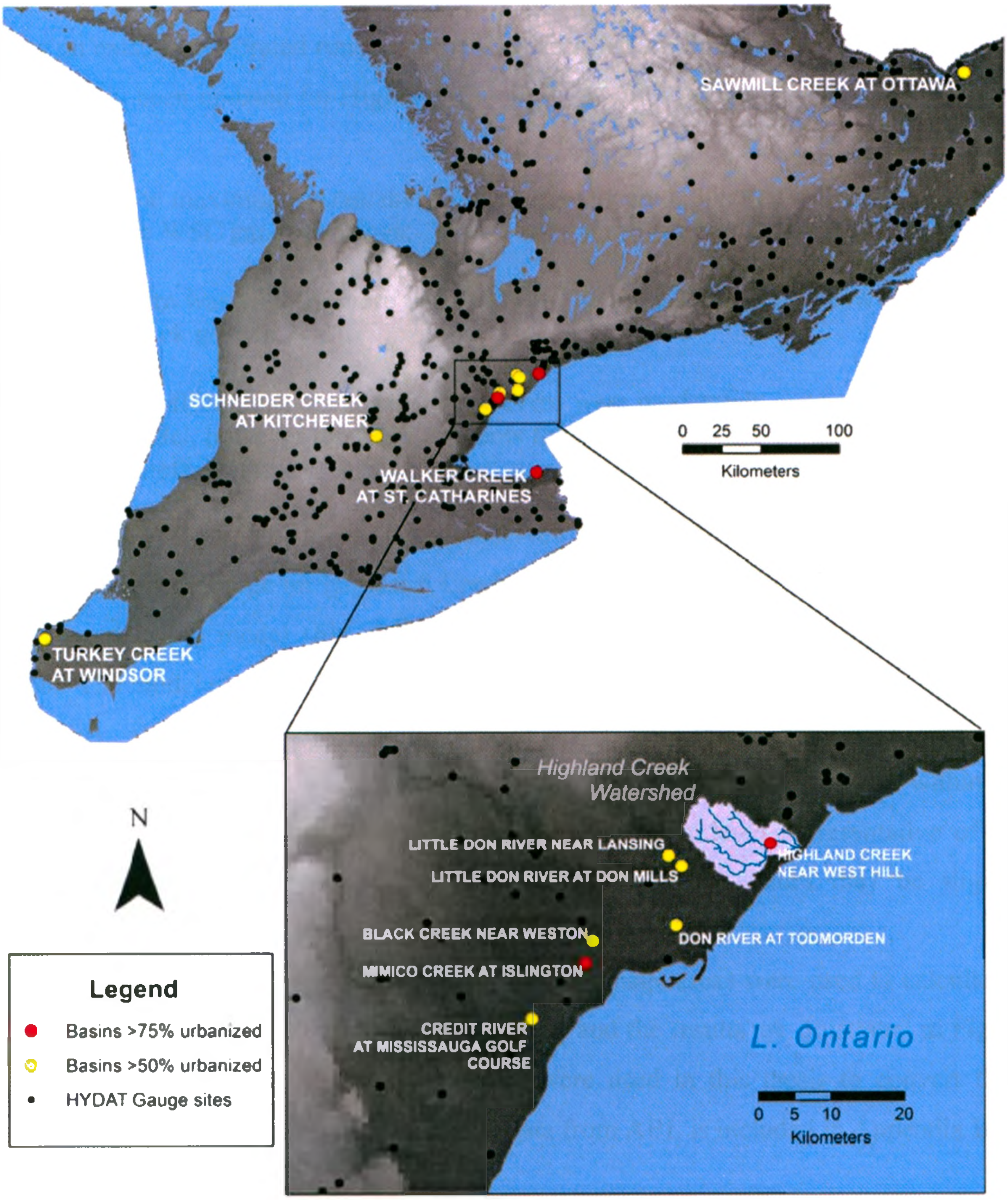


Figure 3.13 Hydat gauge sites of southern Ontario.
Inset shows cluster of gauges in the Greater Toronto Area classed as 'urbanized'.

3.3.1.3 Area-discharge curve for Highland Creek

In the case of Highland Creek (and probably in some other cases) flows can be estimated using an existing calibrated runoff model. As described in Chapter 2, a hydrologic model has recently been updated for Highland Creek (ABL, 2004). The report concludes that in this model

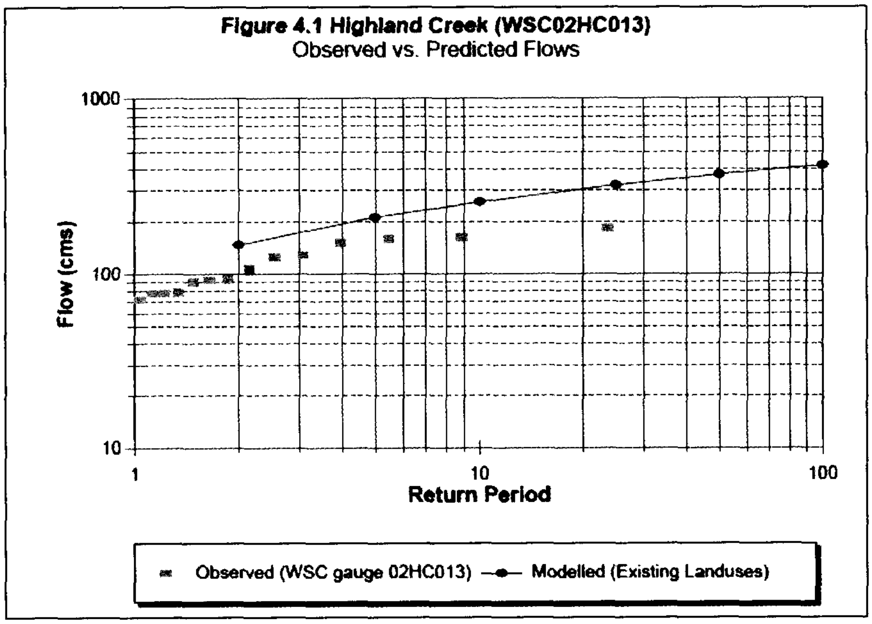
- The maximum instantaneous discharges[1] were calibrated to within +/-10% of the WSC gauge readings;
- there was slightly more variability in the model results at the West Highland Creek gauges;
- runoff volumes for a small flow event were moderately over-estimated by the model, however this only accounts for a difference of 1-2 mm of the observed runoff depths.

Figure 3.14a is a graph of modeled and observed flows for different recurrence intervals at the main WSC gauge on Highland Creek along with a map of the location of the 27 nodes used in the model (Fig. 3.14b). The graph illustrates the final accuracy of the model. The modeled flows are slightly overestimated, but ABL maintains that, given the variability associated with rainfall data and the uncertainty associated with the measurement of streamflow and rainfall, and the fact that modeled flows are within +/-10% of the WSC recorded flows, the model can be considered representative of the watershed. It is worth bearing in mind that stream power values may be slightly overestimated using these discharges.

These peak flow rates and the associated drainage areas were used to calculate a discharge to area relationship for Highland Creek and the results are illustrated in Figure 3.15. The resulting relationships (Table 3.1) were used in this thesis to convert flow accumulation areas to discharge values. The data from ABL is included in Appendix B.

[1] ABL report says "peak flow rates", personal communication via email with Greg Frew of ABL on October 16th, 2008 clarifies that these are maximum instantaneous discharges.

a)



b)

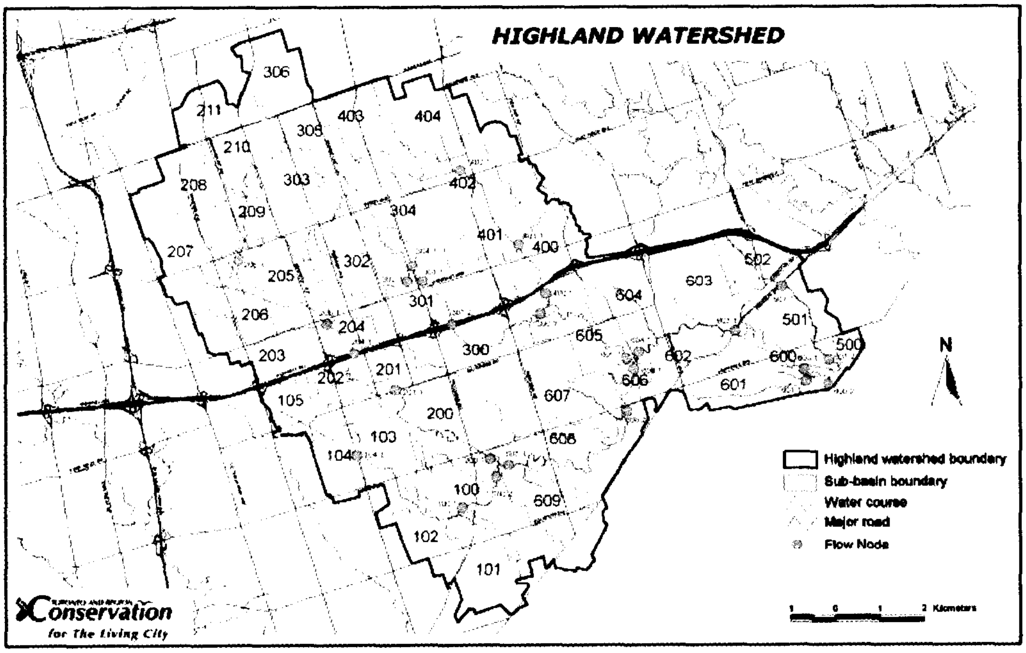


Figure 3.14 Results of hydrologic modeling for Highland Creek.
a) Observed versus predicted flows for Highland Creek from the hydrologic model.
b) Map of the location of flow nodes used for the model.
(Aquafor Beech Limited, 2004)

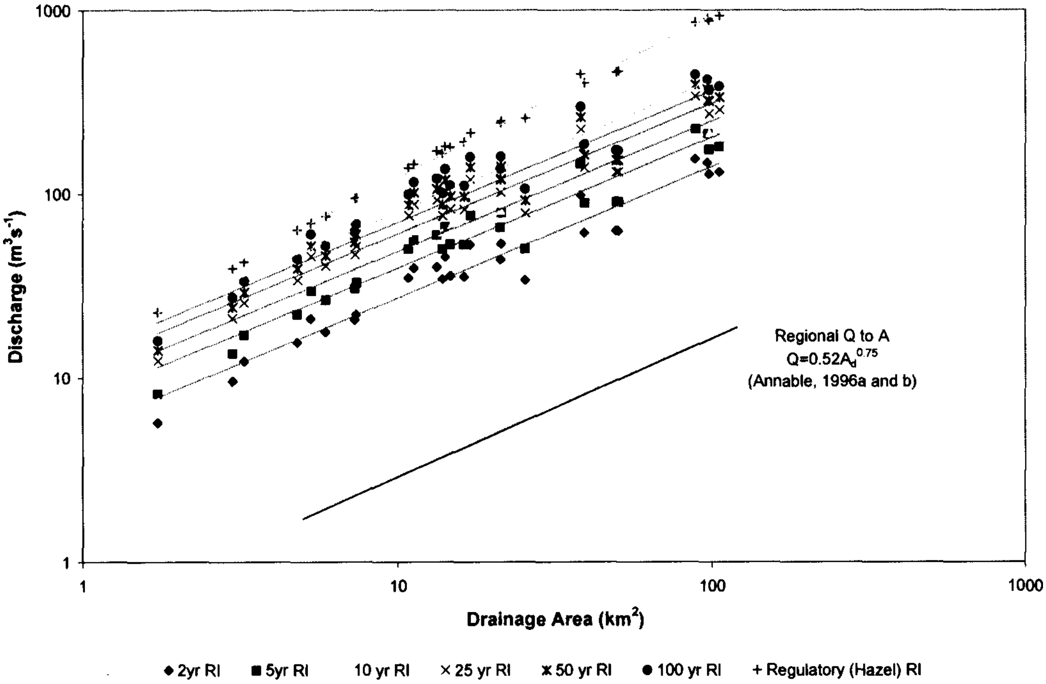


Figure 3.15 Discharge to area relationships for Highland Creek derived from hydrologic model. *Discharge to Area Relationships derived from results of Aquafor Beech Limited (2004) hydrologic modeling of Highland Creek. Drainage areas are based on the use of 27 'flow nodes' where discharge was measured and modeled. The regression statistics for the discharge to area relationships are presented in Appendix B.*

Table 3.1 Discharge to Drainage Area Relationships from Hydrologic Model.

Return Interval Discharge	Q to A Power Relationship	Standard Error	R^2
2 yr	$y = 5.2903x^{0.7121}$	13.19	0.91
5 yr	$y = 7.7449x^{0.7087}$	20.55	0.89
10 yr	$y = 9.5253x^{0.7087}$	25.49	0.88
25 yr	$y = 11.871x^{0.7087}$	31.09	0.89
50 yr	$y = 13.571x^{0.7132}$	35.82	0.89
100 yr	$y = 15.466x^{0.7135}$	40.4	0.89
Regulatory (Hazel)	$y = 15.901x^{0.8867}$	24.57	0.99

3.3.1.4 Applying modeled discharges in GIS

The discharge to area relationships obtained from the analysis of the ABL Hydrologic Report data were used to model discharge in the GIS. It is important to note that the trendlines representing the area-to-discharge relationships all have very similar slopes. This means that, with respect to the GIS discharge images, even though the absolute values for different return intervals are different, the overall pattern in each discharge image is virtually identical. Thus, in the GIS images, the locations of the highest and lowest values will remain identical for the 2 yr to 100 yr discharge images. Three different recurrence interval discharge relationships were used for the stream power calculations, to illustrate the range of stream power values expected:

2-year RI – to represent typical annual flood flows

10-year RI – to represent channel-forming events

Regulatory Flood RI – to represent maximum flood event possibilities.

The respective discharge to area relationships were applied to the flow accumulation image using ESRI's raster calculator to create these three discharge images.

3.3.1.5 Verifying drainage areas

The discharges for both the HECRAS model and the DEM analysis ultimately come from the OTTHYMO model output described in this section. In order to verify the DEM results with those from the hydrological model, it is more pertinent to compare the different drainage areas assigned to the particular nodes in the Highland Creek system by both the OTTHYMO model and the DEM analysis. The 27 nodes that are the basis for the OTTHYMO model and are illustrated in Figure 3.14b, were identified in the Highland Creek channel network. The GIS-generated drainage area was extracted from the flow accumulation image for each of these points and plotted against the drainage areas assigned in the OTTHYMO model (Fig. 3.16)

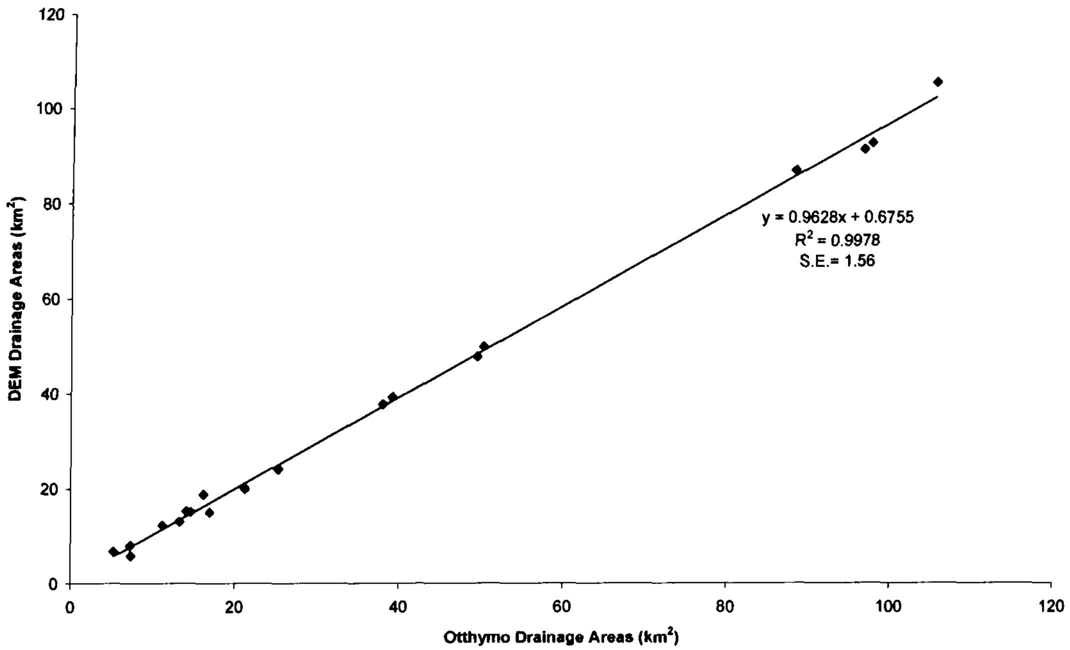


Figure 3.16 Comparison of drainage areas used in hydrologic model and for GIS analysis. *Scatterplot with regression line showing correlation of drainage area from OTTHYMO to drainage area from GIS ananlysis.Regression statistics are presented in Appendix D.*

The regression is significant and has a near perfect r-squared value of 0.9978 and a y-intercept very close to zero. The standard error of the estimate for y is 1.56. The confidence limits for the slope are 0.94 and 0.98, meaning that the slope is significantly different from 1. The slope is still extremely close to 1 however, and the standard errors are very small. Consequently, discharge values from the DEM analysis, based on upstream drainage area, and the OTTHYMO model, and therefore the HEC-RAS model, are almost identical for a given location in the stream network.

3.3.2 Calculating slope

Slope is the second variable needed to calculate cross-sectional stream power and can be obtained in a number of ways. When measured in the field, slope consists of a change in elevation over a measured distance. In the case of streams, that distance is often measured along the stream centerline, also known as the thalweg. The distance over which slope is

measured is variable and resulting values can change significantly depending on the distance used. Four different methods of calculating slope from a DEM are described in the following section.

3.3.2.1 Standard GIS slope

In GIS, the standard method of calculating slope involves using a 'kernel' or 'window' measuring 3 cells by 3 cells. The slope for the middle cell of this kernel is calculated by measuring the change in elevation from that cell to the outer cells and dividing that rise by the distance between the two cells (in the case of a 10 m cell DEM, a straight distance is 10 m while a diagonal distance is 14.14 m). A total of 8 slopes are calculated, one for each direction from the centre cell and, depending on the algorithm being used, either an average or the maximum of these slopes is the value placed in the centre cell. A large number of articles have been published on the accuracy of these different types of slope calculation (*see* Jones, 1998), however, none of these is acceptable for calculating the slope of the stream channel. The problem with the above methods is that large slopes are often assigned to in-stream cells with high banks, even though the actual channel slope is not especially large (Wobus et al., 2006).

A few GIS algorithms exist that calculate slope according to the steepest *drop* in elevation from the middle cell. The 'Maximum Downward Slope' function in the program TAS (Terrain Analysis System) and the 'Drop Raster' option in the Flow Accumulation algorithm in ArcGIS are supposed to calculate slope on a cell by cell basis in a downstream direction. The latter has been tested by the author and found to give only 2 alternating values. It is unclear whether this is a problem with the script or the input. In any event, examination of the results from the TAS algorithm revealed further shortcomings. The distance over which each slope value is measured is very small compared to the overall length of stream (in the case of Highland Creek, distances of 10 metres, compared to a total stream length of over 50 km), and the resulting slopes have a high degree of variability (*see* Wobus et al., 2006).

Alternative slope algorithms have been developed to overcome the aforementioned problems with the standard GIS slope. The following three types of slope are more

specialized, but the disadvantage is that there are no built-in algorithms in ArcGIS to calculate them. The DEM stream values thus must be extracted to a spreadsheet program such as Microsoft Excel, and the calculations completed outside the GIS. A programming script was written to do this based on the original flow direction file (*schematic in Appendix C*) (Van de Wiel, 2008). Elevation values for the channel are listed in the spreadsheet program along with their coordinates and the distance along the stream in tabular form and in order from upstream to downstream. Specific calculation methods will be discussed with each slope type.

3.3.2.2 Polynomial slopes

Another method to calculate slopes from a DEM, as described by Jain et al. (2006), is to fit a polynomial curve to the long profile and use the tangent of that line at various points as a slope measurement in the stream power equation. There is an advantage to this generalization in terms of the 'basin scale' type analysis, however, there are two disadvantages:

1) sudden, but real, changes in slope are smoothed out;
2) assumes that the smoothed profile produced by a mathematical equation is closer to reality than the variable slope extracted by the GIS.

In order to calculate this slope in the spreadsheet program, the 'Add Trendline' function was used in Microsoft Excel on a graph of the long profile of each branch of Highland Creek. The polynomial equation for the line of best fit was displayed and then copied into the spreadsheet to reproduce smoothed elevation values for each cell. The cell by cell slope was calculated for the smoothed elevation values. The result for the Malvern Branch of Highland Creek is shown in Figure 3.17.

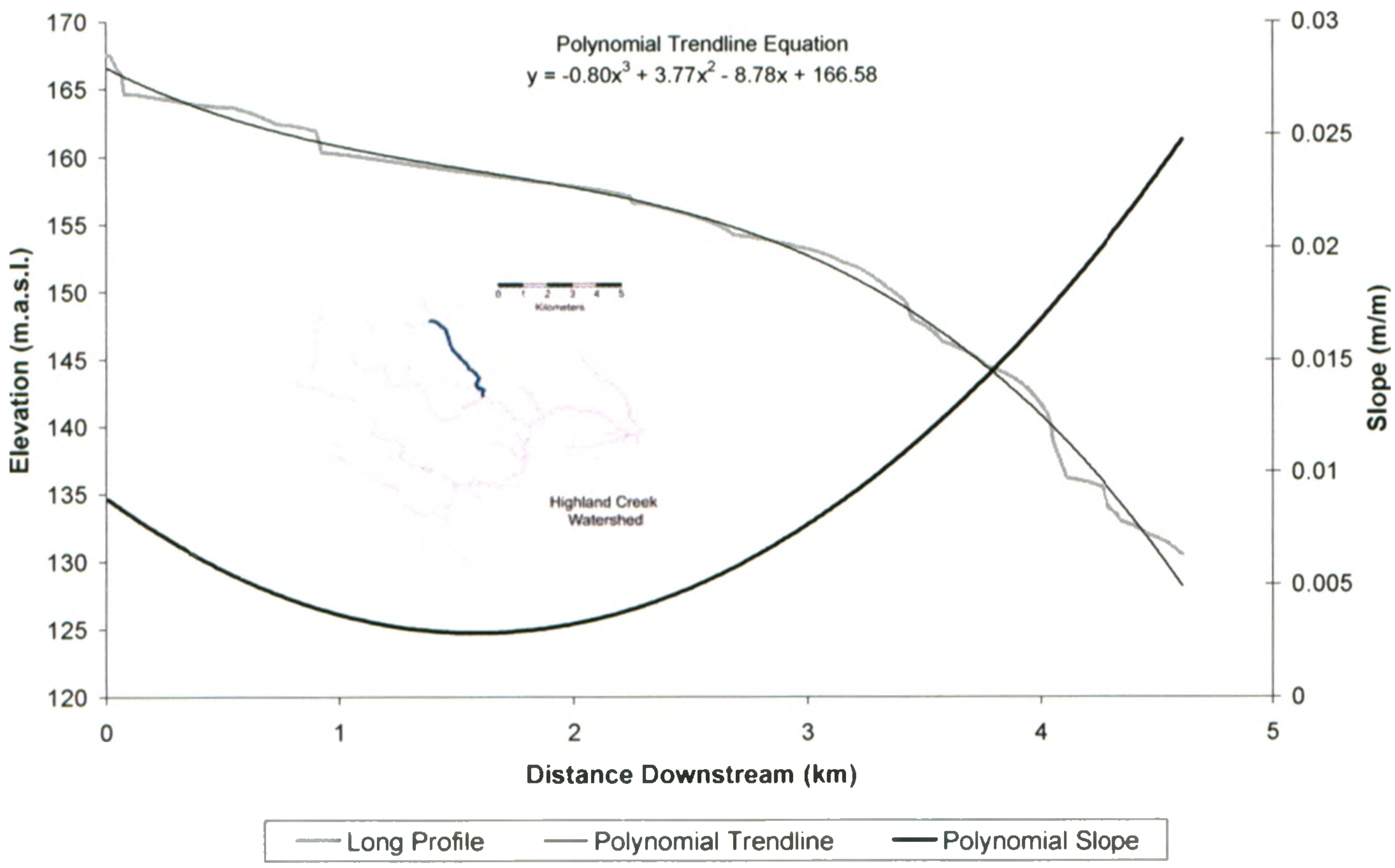


Figure 3.17 Polynomial slope for Malvern Branch.
This graph demonstrates the effect of calculating slope based on a polynomial trendline fit to the long profile.

3.3.2.3 Vertical slice slope

Vertical slice slope consists of measuring a change in distance over a constant *elevation* difference. Slopes calculated from topographic maps are technically vertical slice slopes since the contour interval is constant, but the distance between contour lines varies. This method has the advantage of remaining 'true' to the original contour information from which the elevations were interpolated (Reinfelds et al., 2004; Wobus et al., 2006), if the DEM is derived from contours. The disadvantage to this method is that all cells in between elevation changes are assigned identical slopes.

Although only part of the DEM was interpolated from contour lines, the same constant elevation difference was chosen for the entire DEM. In the spreadsheet, elevation differences of five metres were manually identified and pasted into a new row. This was not as time consuming as it might sound because there is only a change of 135 metres in elevation over the entire basin, which amounts to only twenty-seven 5-metre

increments. The distance between each of these 5-metre increments was used to calculate the slope for each branch. Figure 3.18 shows the results of the vertical slice slope for a portion of the West Branch. The vertical slice slope has dramatically fewer slope changes than a slope calculated on a cell by cell basis and does not characterize changes in the long profile very well.

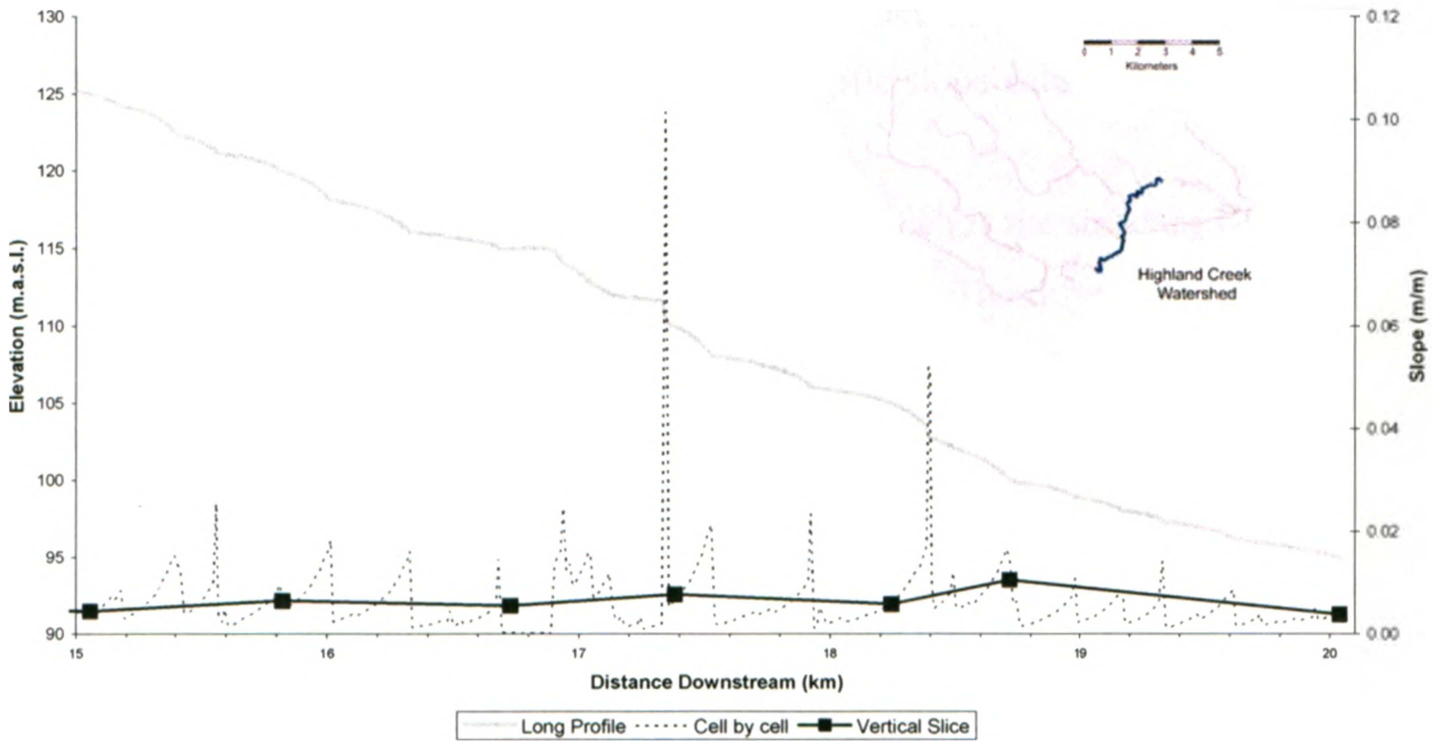


Figure 3.18 Comparison of horizontal and vertical slice slopes.

3.3.2.4 Horizontal slice slope

A horizontal slice slope measures elevation changes over constant *distances* (Hayakawa and Takashi, 2006; Jain et al., 2006). Jain et al. (2006) make the argument that since stream power is an expression of energy expenditure per unit *length*, slope should be measured using a constant length instead of a constant elevation difference if being used in a stream power calculation.

In the spreadsheet program, horizontal slice slope is calculated by choosing a constant number of cells between which to perform the calculation. For example, a horizontal slice of 100 metres corresponds to a distance of approximately 10 cells. The slope is calculated by measuring the change in elevation divided by the change in distance between values 10 cells apart (Fig. 3.19). The calculation moves down the

spreadsheet always measuring the rise and run ten cells apart. Unlike the vertical slice method, each cell has a unique slope value.

The run is not always exactly the same length, because where the river flows diagonally across a cell, the cell to cell distance is 14.14 metres instead of 10 metres. In the case of a 10 cell example, the run is typically about 100 metres. Statistics for the Bendale, West and Main Branches combined reveal that for a 10 cell spread, the longest run measures 127.3 metres, the average run is 106.3 metres and the standard deviation is 7.5. Because run values are calculated for each specific slope value, each individual slope value retains its precision.

Figure 3.20a compares the cell by cell slope, which is the standard GIS maximum downward slope, with a 500 metre horizontal slice slope. The difference in variability is quite large. Figure 3.20b shows a number of different horizontal slice slopes for a portion of the West Branch and with the long profile superimposed.

It is evident that the slope becomes more generalized as the distance over which it is measured increases (*see also* Hayakawa and Takashi, 2006; Jain et al., 2006). It is logical to conclude that choosing an appropriate absolute horizontal distance over which to measure slope would depend on the type of analysis that is being performed and on the length 'scale' of the river.

Elevation (m.a.s.l.)	RISE	Distance Downstream (m)	RUN	HS slope (10 cells) RISE/RUN
138 612		12950 65		
138 573		12960 65		
[illegible]		[illegible]		
138.505		12980.65		
138.476		12990.65		
138.442		13000.65		
138.391		13014.79		
138.348		13024.79		
138.282		13038.94		
138 227	0 385	13048 94	98	0 0039
138 166	0 406	13058 94	98	0 0041
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
138.024	0.460	13078.94	98	0.0049
137.950	0.526	13093.08	102	0.0051
137.898	0.544	13103.08	102	0.0053
137.841	0.550	13113.08	98	0.0056
137.739	0.609	13127.22	102	0.0059
137.723	0.558	13137.22	98	0.0057
137.699	0.528	13151.36	102	0.0052
137.672	0.494	13165.50	107	0.0046
137.650	0.449	13175.50	107	0.0042
137.630	0.394	13185.50	107	0.0037

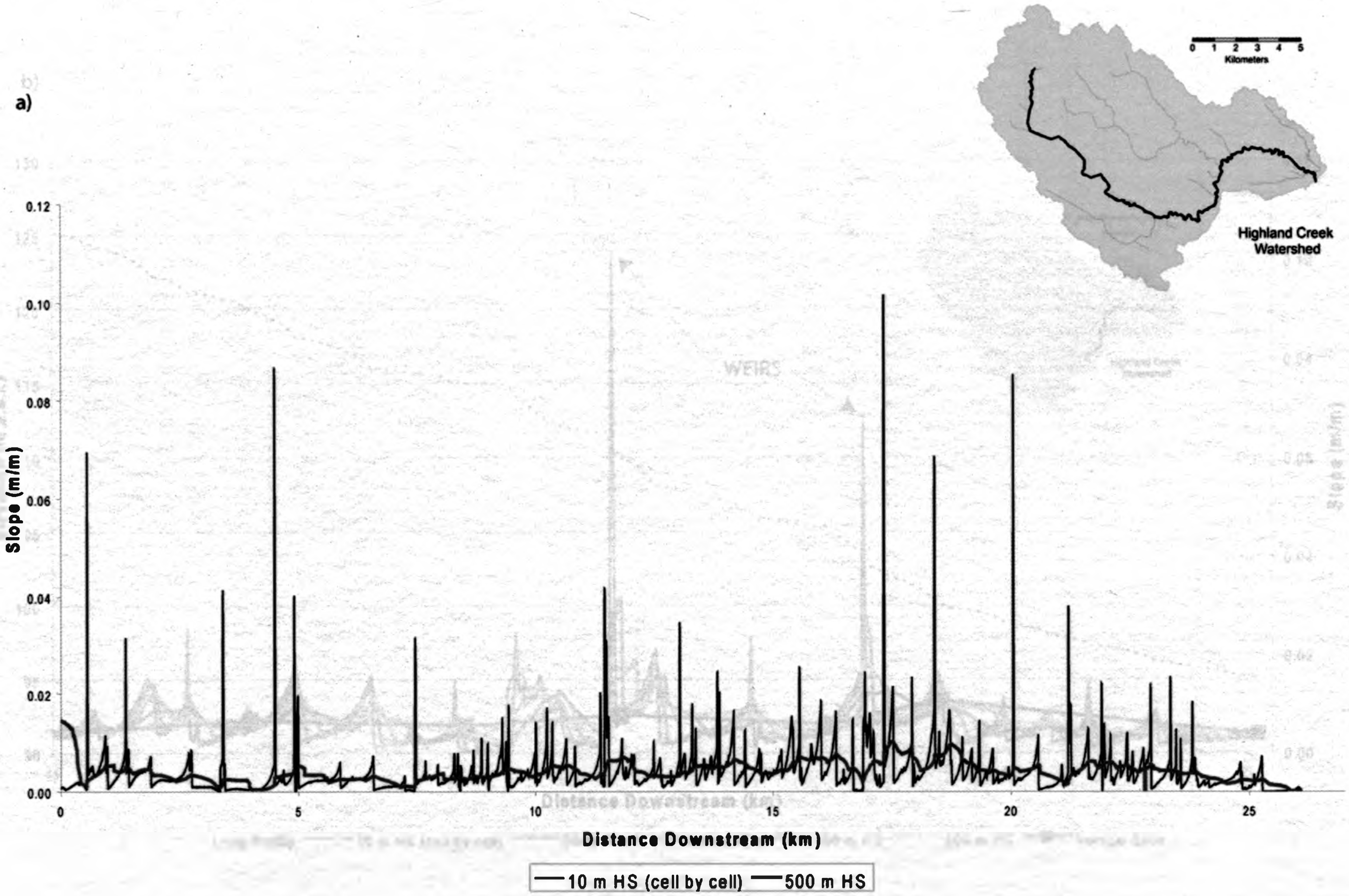
Figure 3.19 Calculating horizontal slice slope in a spreadsheet.
Slopes in the last column are calculated using a change in elevation and a change in distance that is 10 cells apart. In this way, each cell has a unique slope value calculated for it.

Figure 3.20 Comparison of different horizontal slice slopes.

a) (p.74) Comparison of two horizontal slice slopes derived for the western-most branch of Highland Creek. The blue depicts the large variability that is the result of calculating the slope cell by cell, as in the maximum downward slope algorithm. The red line demonstrates the smoothing effect of using a much larger distance, 500 metres in this case, over which to measure slope.

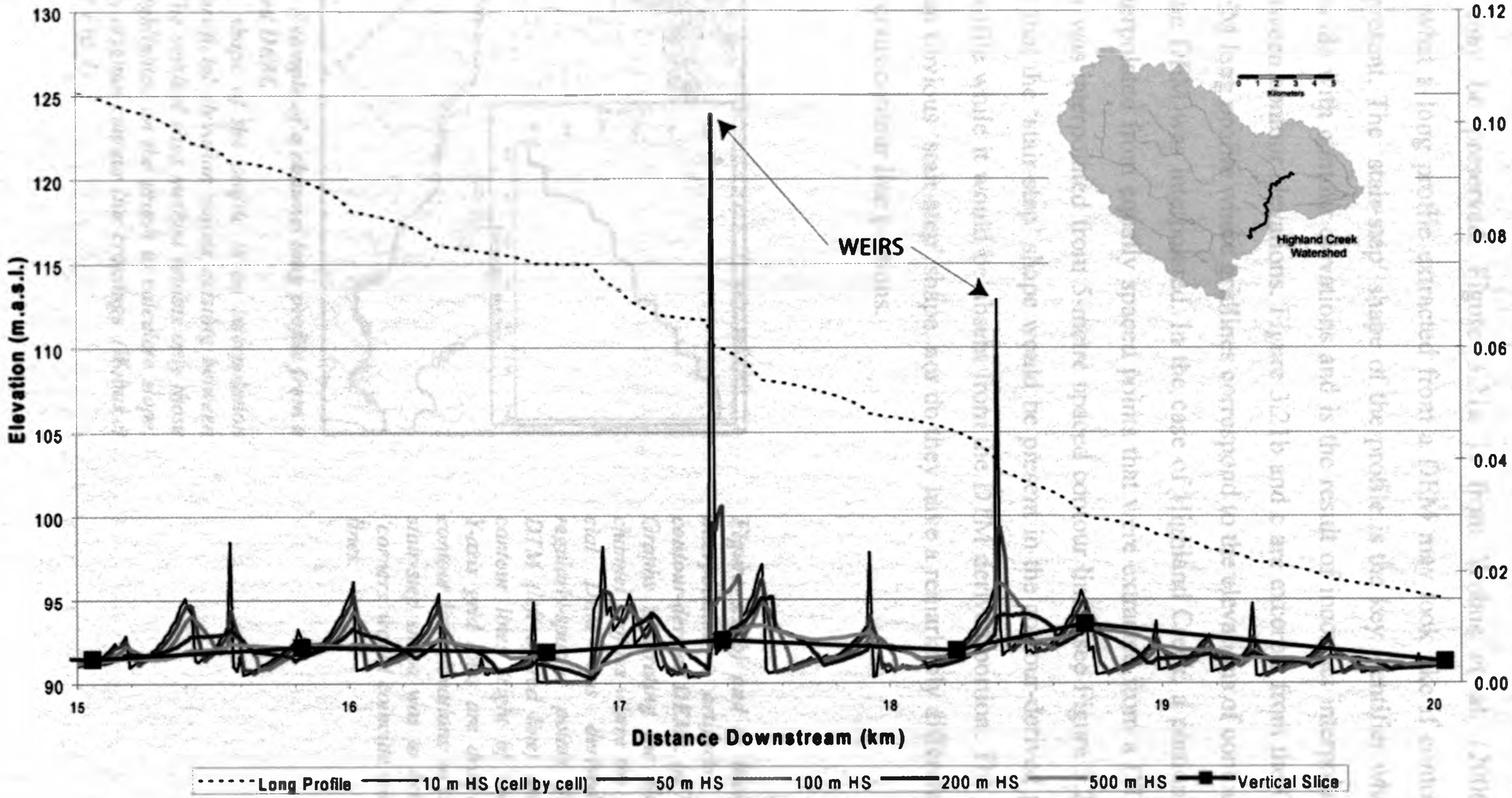
b) (p.75) Five different horizontal slice slopes calculated for a portion of Highland Creek's West Branch and plotted alongside long profile. The scale of this graph enables the comparison of the different horizontal slice slopes with each other and the long profile, as well as the vertical slice slope.

a)



Highland Creek Watershed
0 1 2 3 4 5
Kilometers
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Slope (m/m)
0
5
10
15
20
25
Distance Downstream (km)
10 m HS (cell by cell)
500 m HS

b)



Elevation (m.a.s.l.)
Slope (m/m)
Distance Downstream (km)
WEIRS
Highland Creek Watershed
Kilometers
130
125
120
115
110
105
100
95
90
0.12
0.10
0.08
0.06
0.04
0.02
0.00
15
16
17
18
19
20
Long Profile
10 m HS (cell by cell)
50 m HS
100 m HS
200 m HS
500 m HS
Vertical Slice

The risk in the horizontal slice slope is that contour artifacts from DEM interpolation may be preserved. Figure 3.21a is from Wobus et al. (2006) and demonstrates what a long profile extracted from a DEM may look like if contour line artifacts are present. The 'stair-step' shape of the profile is the key identifier where the 'corners' coincide with contour elevations and is the result of incorrect interpolation of elevations between contour elevations. Figure 3.21b and c are excerpts from the Ontario Provincial DEM long profile where gridlines correspond to the elevations of contour lines from which the DEM was interpolated. In the case of Highland Creek, a portion of the DEM was interpolated from equally spaced points that were extracted from a DTM and the remainder was interpolated from 5-metre spaced contour lines (see Figure 3.2). One would expect that the 'stair-step' shape would be present in the contour-derived portion of the long profile while it would be absent from the DTM derived portion. The graphs have neither an obvious 'stair-step' shape, nor do they have a remarkably different shape in the DTM versus contour line portions.

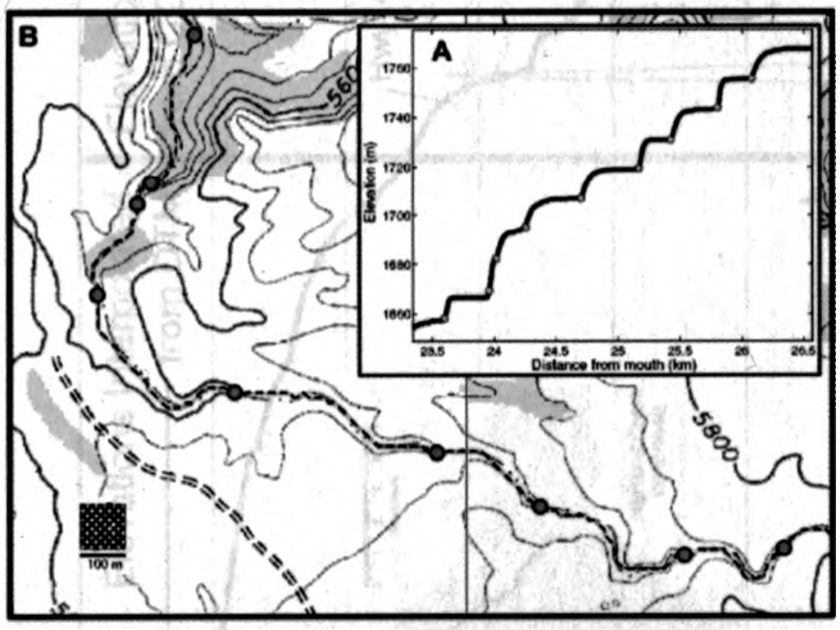
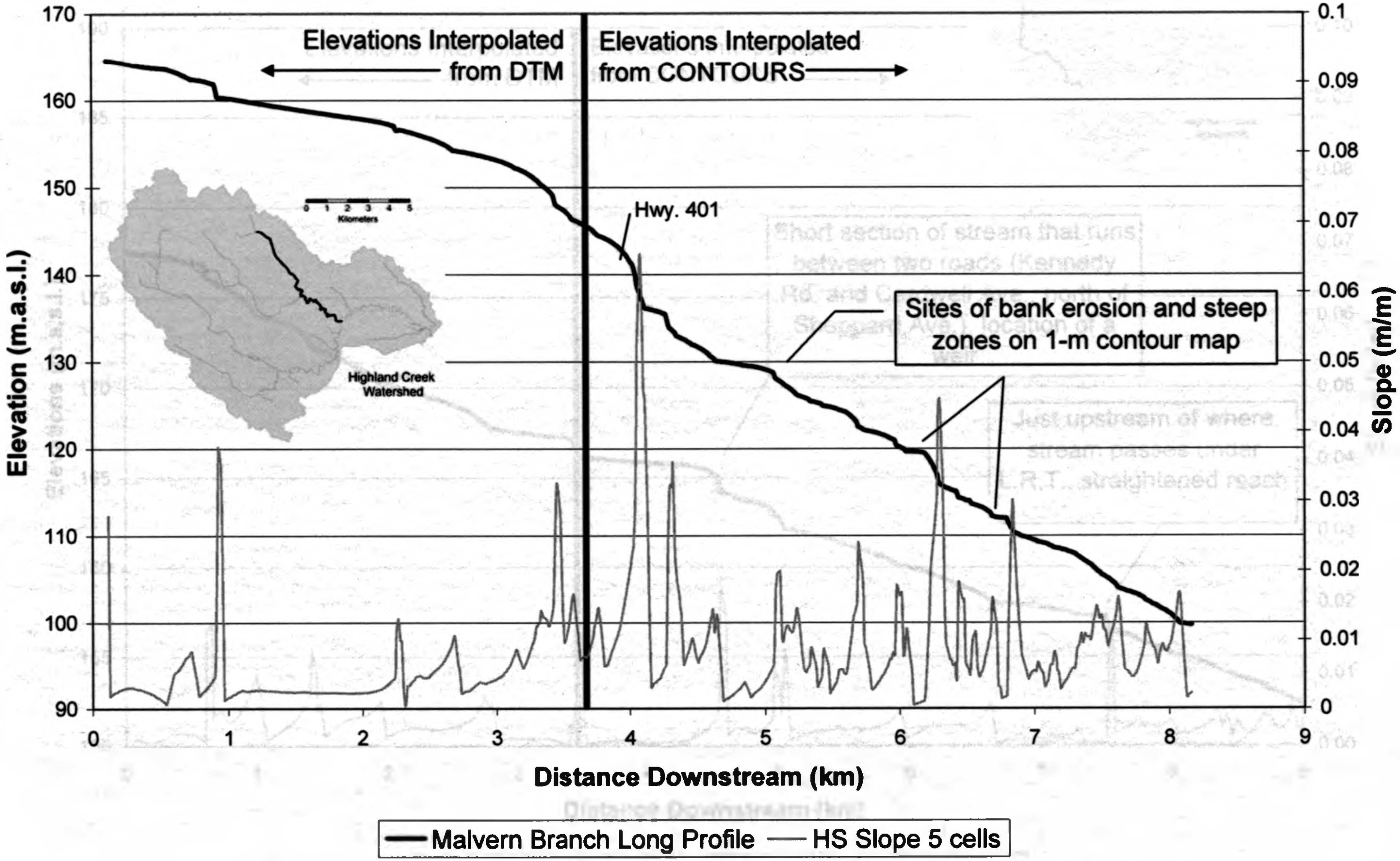
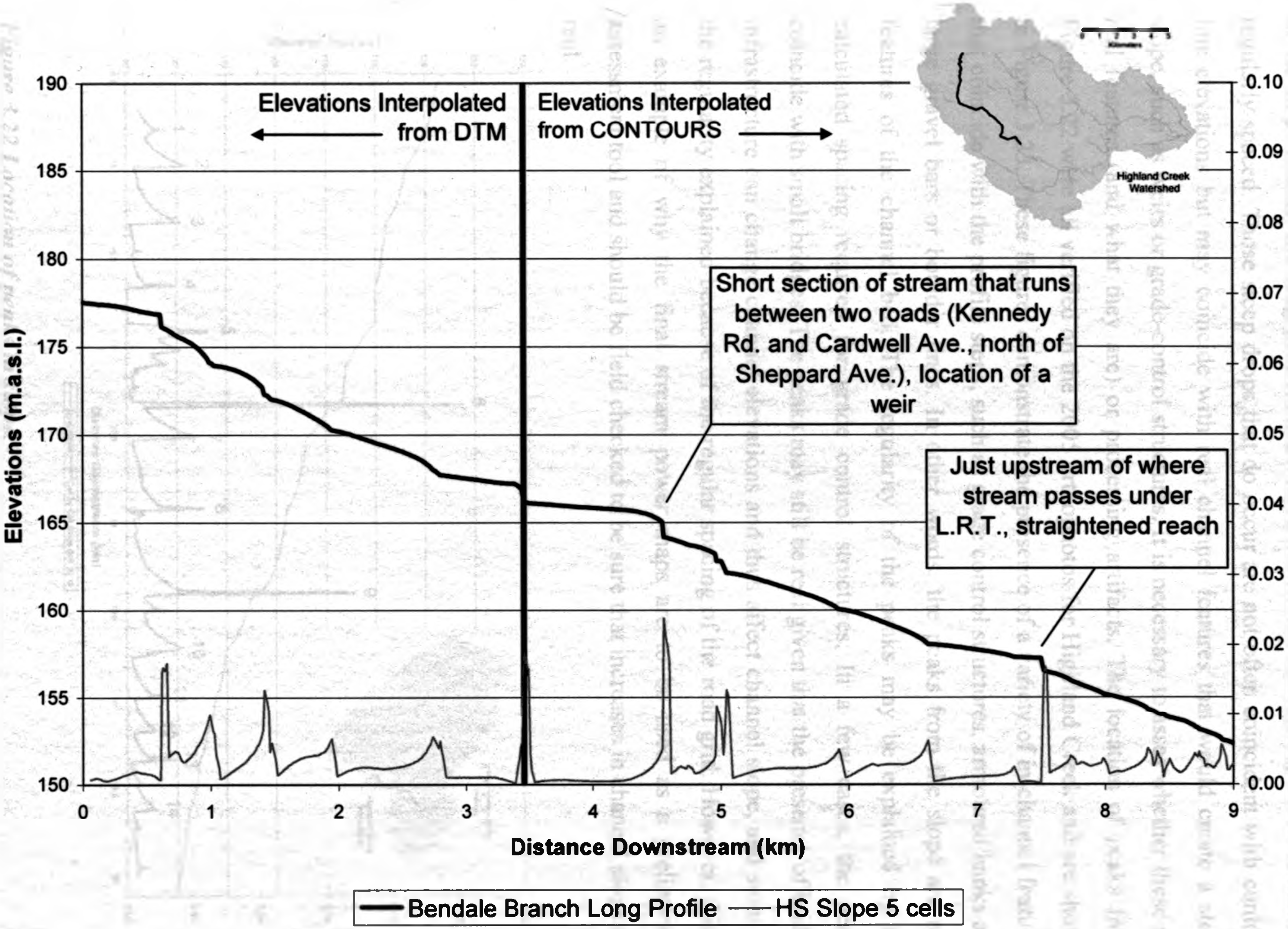


Figure 3.21a) Example of a channel long profile from a contour-derived DEM.
The 'stair-step' shape of the profile is an interpolation artifact with artificial elevation values existing between gray points. The vertical slice method retains only those gray points highlighted on the graph to calculate slope, thus using only original contour line crossings. (Wobus et al., 2006, their Fig. 1)

Figure 3.21b) and c) Identifying interpolation artifacts from contour-derived DEMs. *(p.77, 78)*
Graphs illustrating the shape of channel profiles where the Provincial DEM was derived from regularly-spaced points from a DTM (left of red line) and from contour lines (right of red line). Y-axis grid lines are drawn in at contour line elevations so that if a stair-step shape was to exist, step 'corners' would coincide with gridlines.


Elevations Interpolated from DTM
Elevations Interpolated from CONTOURS
Hwy. 401
Sites of bank erosion and steep zones on 1-m contour map
Highland Creek Watershed
Kilometers
0 1 2 3 4 5
Elevation (m.a.s.l.)
Slope (m/m)
Distance Downstream (km)
170
160
150
140
130
120
110
100
90
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
1
2
3
4
5
6
7
8
9
Malvern Branch Long Profile
HS Slope 5 cells



Elevations Interpolated from DTM
Elevations Interpolated from CONTOURS
Highland Creek Watershed
Kilometers
Short section of stream that runs between two roads (Kennedy Rd. and Cardwell Ave., north of Sheppard Ave.), location of a weir
Just upstream of where stream passes under L.R.T., straightened reach
Elevations (m.a.s.l.)
Slope (m/m)
Distance Downstream (km)
190
185
180
175
170
165
160
155
150
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0
1
2
3
4
5
6
7
8
9
Bendale Branch Long Profile
HS Slope 5 cells

Despite the preceding evidence that shows that there are no contour-line artifacts in the slope results, the long-profiles often have occasional short, steep sections that are regularly spaced. Those steep drops that do occur are not often coincident with contour line elevations but may coincide with real channel features that would create a steep slope, such as weirs or grade-control structures. It is necessary to asses whether these are real features (and what they are) or processing artifacts. The location of peaks from Figure 3.22 were all verified on the 2005 orthophotos for Highland Creek and are shown in Figure 3.23. These figures demonstrate the presence of a variety of in-channel features that coincide with the profile steps, such as grade control structures, armoured banks and large gravel bars or boulder lines. In other words, the peaks from the slope are real features of the channel bed. The regularity of the peaks may be explained by the calculated spacing required for grade control structures. In a few cases, the peaks coincide with small bridges. The peaks may still be real given that the presence of bridge infrastructure can change channel elevations and thus affect channel slope, and some of the regularity explained because of the regular spacing of the road grid. However, this is an example of why the final stream power maps are to be used as a preliminary assessment tool and should be field checked to be sure that increases in channel slope are real.

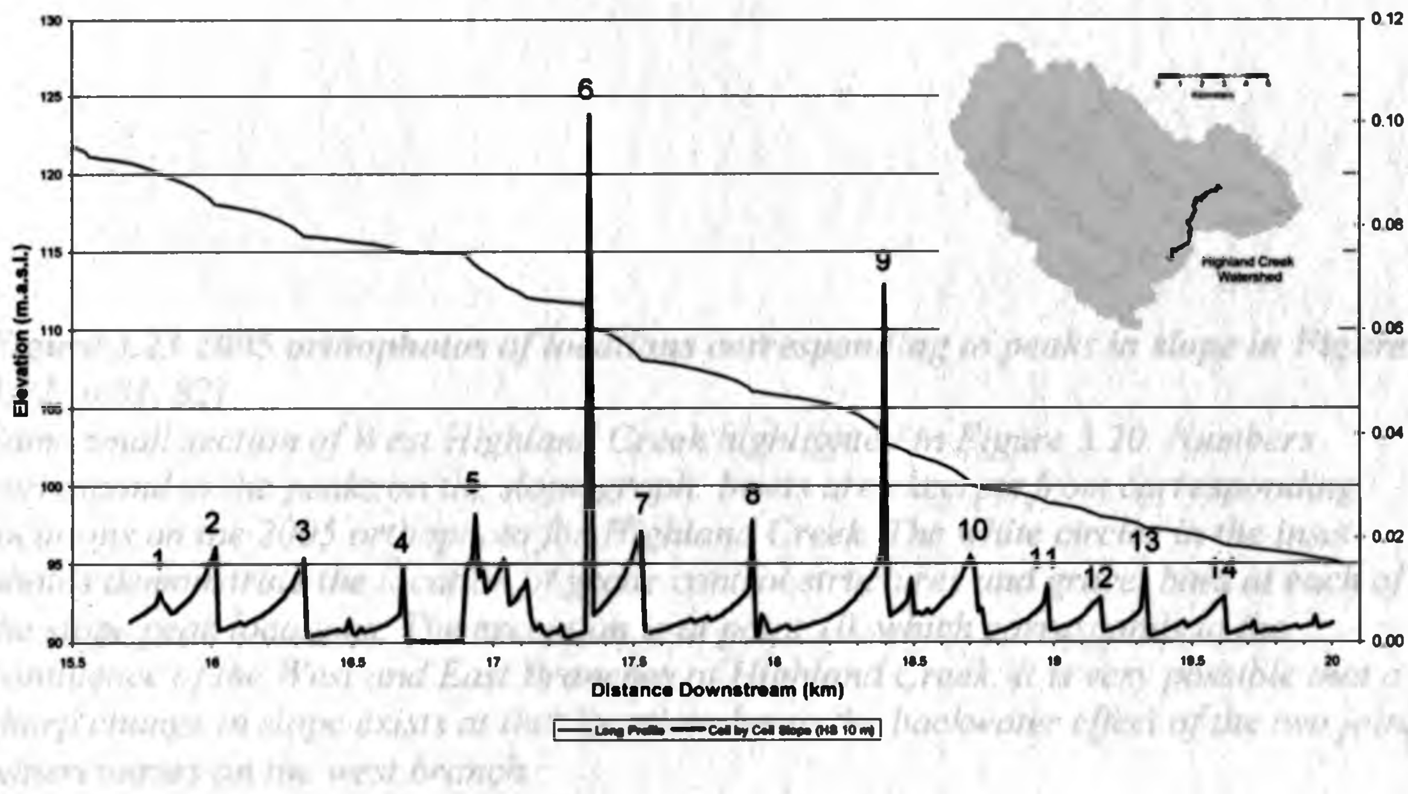


Figure 3.22 Location of peaks in slope.
The peaks identified here are for reference with Figure 3.23.

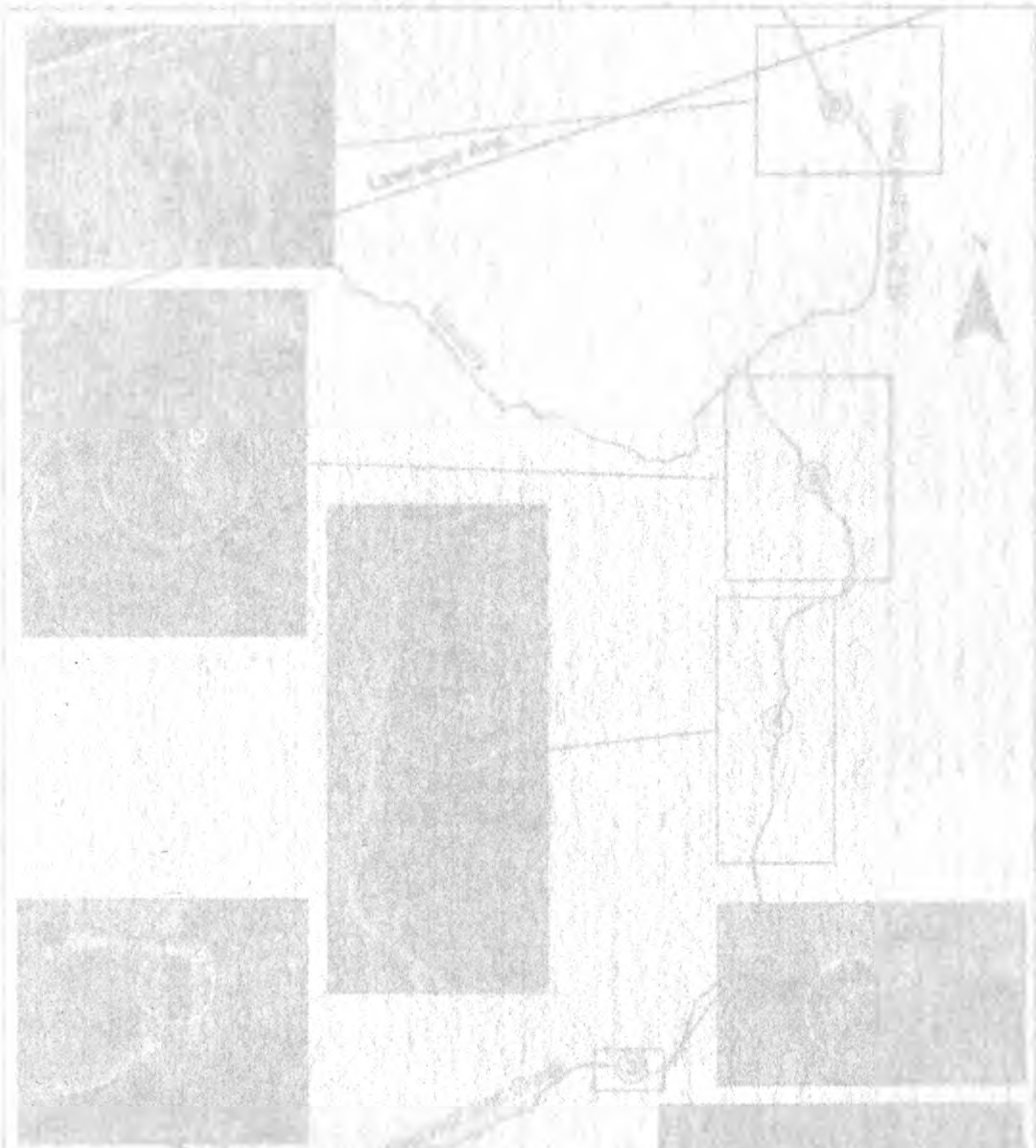
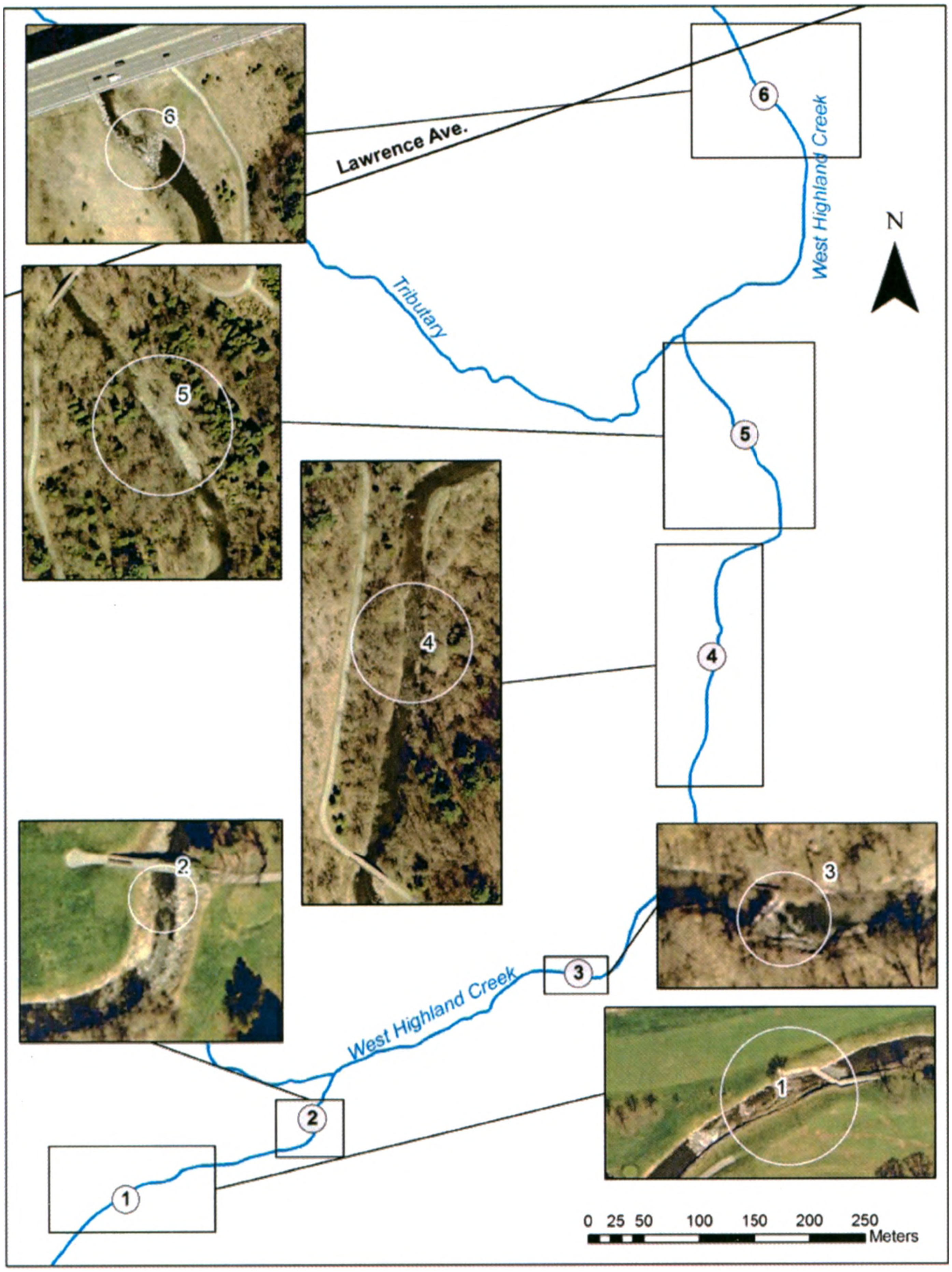
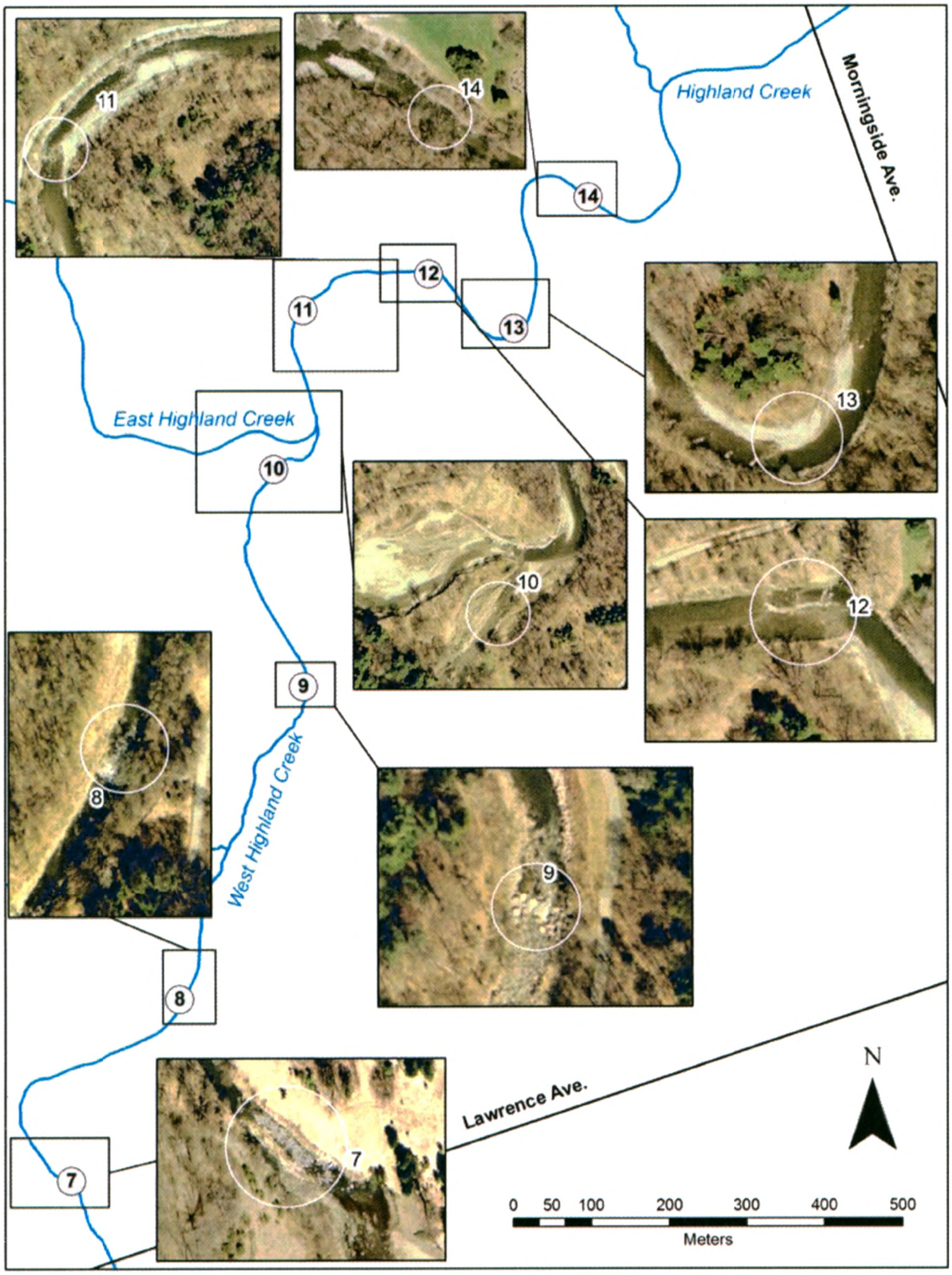


Figure 3.23 2005 orthophotos of locations corresponding to peaks in slope in Figure 3.22.(p.81, 82)

Same small section of West Highland Creek highlighted in Figure 3.20. Numbers correspond to the peaks on the slope graph. Insets are excerpts from corresponding locations on the 2005 orthophoto for Highland Creek. The white circles in the inset photos demonstrate the location of grade control structures and gravel bars at each of the slope peak locations. The exception is at point 10, which corresponds to the confluence of the West and East Branches of Highland Creek. It is very possible that a sharp change in slope exists at that location due to the backwater effect of the two joining watercourses on the west branch.



Lawrence Ave.
Tributary
West Highland Creek
West Highland Creek
N
1
2
3
4
5
6
0 25 50 100 150 200 250
Meters


Highland Creek
Morningside Ave.
East Highland Creek
West Highland Creek
Lawrence Ave.
N
0 50 100 200 300 400 500
Meters
7
8
9
10
11
12
13
14

The provincial DEM was carefully examined in order to choose the most appropriate method for calculating slope. Considering the energy distribution argument by Jain et al. (2006), the fact that the DEM long profiles do not seem to exhibit the unrealistic 'stair-step' shape described by Wobus et al. (2006), and the existence of structures in the stream that create a stepped profile, the horizontal slice method was chosen for this analysis.

For the purpose of this thesis, two different slope-types (the 50-metre and 200-metre distance slopes) were used to compare results from two different levels of smoothing. Another script was written to return the calculated slope values to the GIS to continue the raster analysis (Van de Wiel, 2008). A schematic of this script is also included in Appendix C.

3.3.2.5 Verification of slope values

As part of the Regional Monitoring Program commissioned by the Toronto Region Conservation Authority, eighteen reaches along Highland Creek were surveyed in 2002 (Figure 3.24). These vary in length but average 430 metres. The measurements, taken from the channel bed, were not tied in to a geodetic datum but can, and will, be used here to compare the slope values for each of these reaches.

Figure 3.25 is a regression plot of the 18 slopes measured in the field and extracted from the DEM for the same locations. Slopes for both data sources were calculated by dividing the total elevation difference for the reach in question by the total length of that reach. The method is similar to that of the horizontal slice method, except that each measurement has a different horizontal slice. In Figure 4.6, the points are colour-coded to indicate those that use a horizontal slice (or distance) that is larger than 430 m (red) and those that use a distance that is smaller than 430 m (green). The regression shown in the scatterplot is significant, its slope is not significantly different from 1 and the error is on the order of 10%. This shows that DEM-derived slopes for the 18 reaches are not significantly different from the slopes measured by ground survey in 2005.

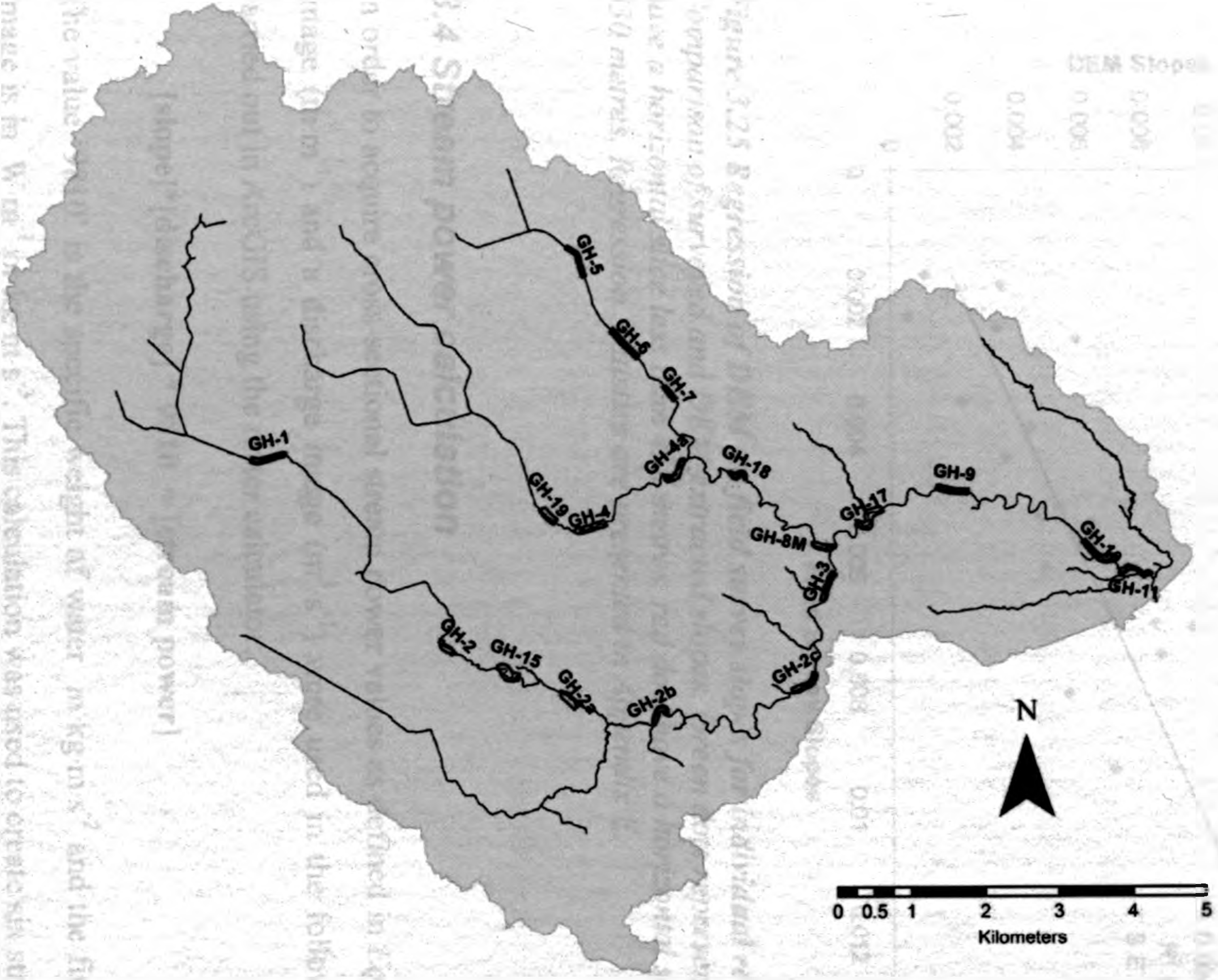


Figure 3.24 Location of reaches surveyed in 2005 and used for comparison to DEM slopes.

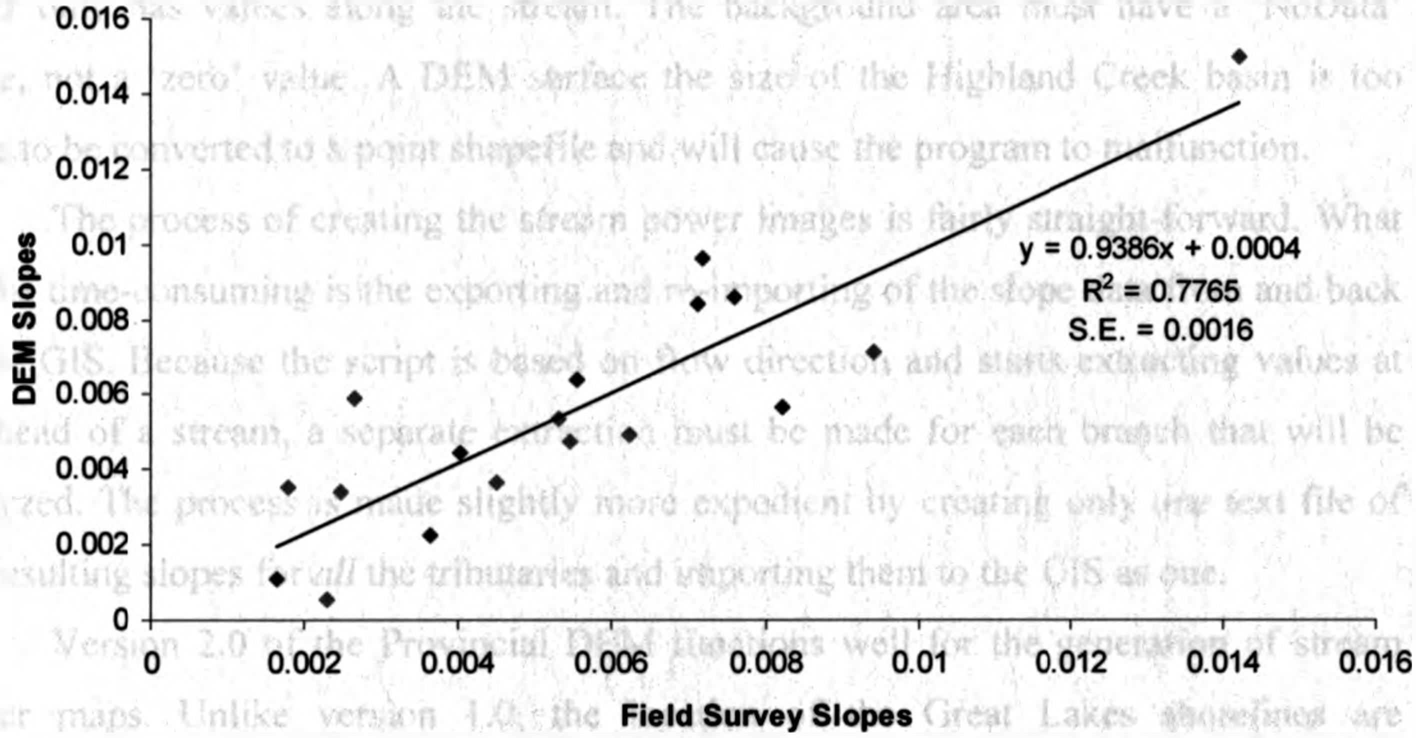


Figure 3.25 Regression of DEM vs. field survey slopes for individual reaches. *Comparison of surveyed and DEM-extracted slopes. Green dots represent slopes that have a horizontal slice less than 430 metres, red dots have a horizontal slice greater than 430 metres. Regression Statistics are presented in Appendix E.*

3.4 Stream power calculation

In order to acquire cross-sectional stream power values as defined in *Equation 2*, a slope image ($m{\cdot}m^{-1}$) and a discharge image ($m^3{\cdot}s^{-1}$) were used in the following calculation, carried out in ArcGIS using the raster calculator:

[slope]*[discharge] * 9810 = [stream power]

The value '9810' is the specific weight of water in $kg{\cdot}m{\cdot}s^{-2}$ and the final stream power image is in $W{\cdot}m^{-1}$ or $kg{\cdot}m{\cdot}s^{-3}$. This calculation was used to create six stream power maps using different slope (50 metre and 200 metre horizontal slices) and discharge images (2-yr, 10-yr and Regulatory Flood return interval discharges.

To help display the values, the raster stream power images were all converted to 'point' shapefiles using Spatial Analyst. This is done in order to access many mapping and display options in ArcMap, especially to enlarge the size of the points for greater

visibility. Before this is attempted though, it is important to ensure that the stream power raster only has values along the stream. The background area must have a 'NoData' value, not a 'zero' value. A DEM surface the size of the Highland Creek basin is too large to be converted to a point shapefile and will cause the program to malfunction.

The process of creating the stream power images is fairly straight-forward. What can be time-consuming is the exporting and re-importing of the slope data from and back to the GIS. Because the script is based on flow direction and starts extracting values at the head of a stream, a separate extraction must be made for each branch that will be analyzed. The process is made slightly more expedient by creating only *one* text file of the resulting slopes for *all* the tributaries and importing them to the GIS as one.

Version 2.0 of the Provincial DEM functions well for the generation of stream power maps. Unlike version 1.0, the location of the Great Lakes shorelines are incorporated into the DEM and there are no longer discrepancies between adjoining tiles, at least for the Highland Creek area.

The stream power images described in this chapter are the basis for the maps and analysis in Chapter 4. The values extracted from these images, as well as the slope and discharge images, are used in Chapter 5 to validate results and compare with other channel assessments.

Note: If using Microsoft Excel trendlines to characterize a discharge to drainage area relationships or calculating polynomial equation-based slopes, it is important to display the correct number of significant figures in the trendline equations before using them to generate values. By right-clicking on the trendline equation and clicking on the 'Format Data Labels' option, four tabs are displayed. The 'Number' tab allows you to select the display type 'scientific notation' and specify the number of decimal places. The values generated by the manual reproduction of the equation should be checked to ensure they match the excel-generated trendline.

Chapter 4:

Stream power maps and their application in stream channel analysis and assessment

The goal of this thesis is to produce stream power maps in a GIS. This chapter is a presentation of these maps as well as an analysis of the DEM-derived values. The case of Highland Creek illustrates how this approach yields a useful outcome for understanding stream dynamics and stability as part of a stream assessment process.

4.1 Stream power results for Highland Creek

The stream power analysis produced six different images based on different return interval discharges (2-yr, 10-yr and Regulatory Flood) and two different slope images using horizontal slices of 50 and 200 metres. The naming convention used for each image consists of the discharge followed by the slope type, thus:

Table 4.1 Stream power image names and description

File name	Description
2_50	2-yr return interval discharge with 50 metre horizontal slice slope
2_200	2-yr return interval discharge with 200 metre horizontal slice slope
10_50	10-yr return interval discharge with 50 metre horizontal slice slope
10_200	10-yr return interval discharge with 200 metre horizontal slice slope
R_50	Regulatory flood with 50 metre horizontal slice slope
R_200	Regulatory flood with 200 metre horizontal slice slope

Each image consists of 3660 points along the main branches of Highland Creek. Figure 4.1 illustrates the geographical divisions and assigned names used in the GIS analysis. These correspond to the reach names in graph titles in this chapter.

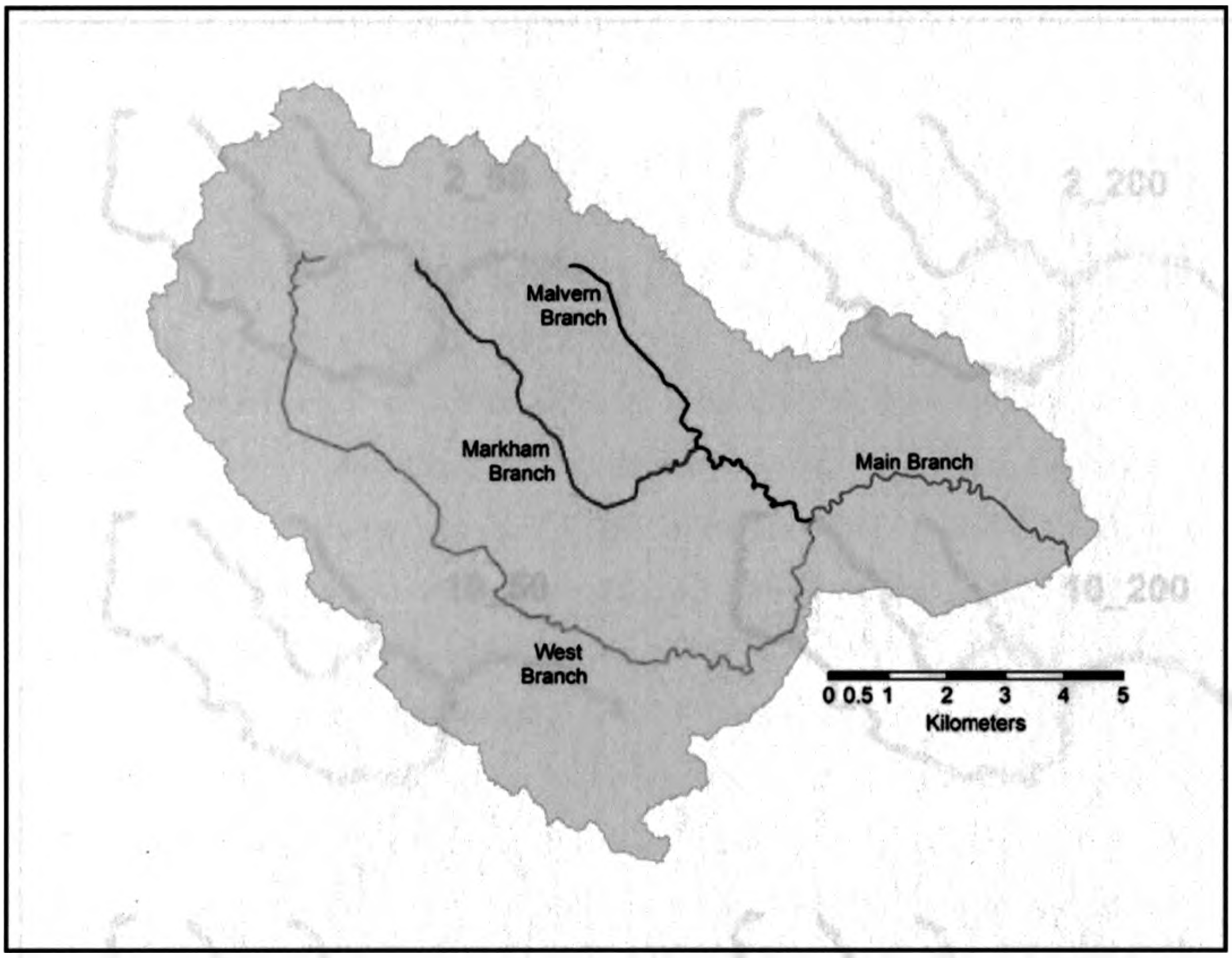


Figure 4.1
Branches mapped in GIS stream power analysis described in this chapter.

Mapping the calculated values of stream power allows the visualization of energy expenditure throughout a stream network and shows where the stream power variations are occurring in relation to the river and other structures present in the basin. Only a few examples of stream power *maps* are known to exist in the literature. Lane et al. (2008) have created the SCIMAP Framework, an automated program that generates maps describing fine sediment dynamics and deposition within a catchment. Among these automatic maps is a simple and unprocessed relative stream power map based on local cell slope and catchment area for the entire land surface. Finlayson et al. (2002) create stream power maps for entire basins in the Himalayas using the kernel method of calculating slopes on a DEM with a resolution of 853 metres. Fonstad (2003) maps the stream power values he has calculated for surveyed cross-sections in a basin. The example presented here (Fig. 4.2) consists of *continous* mapping of cross-sectional stream power calculated using a *channel long profile* slope.

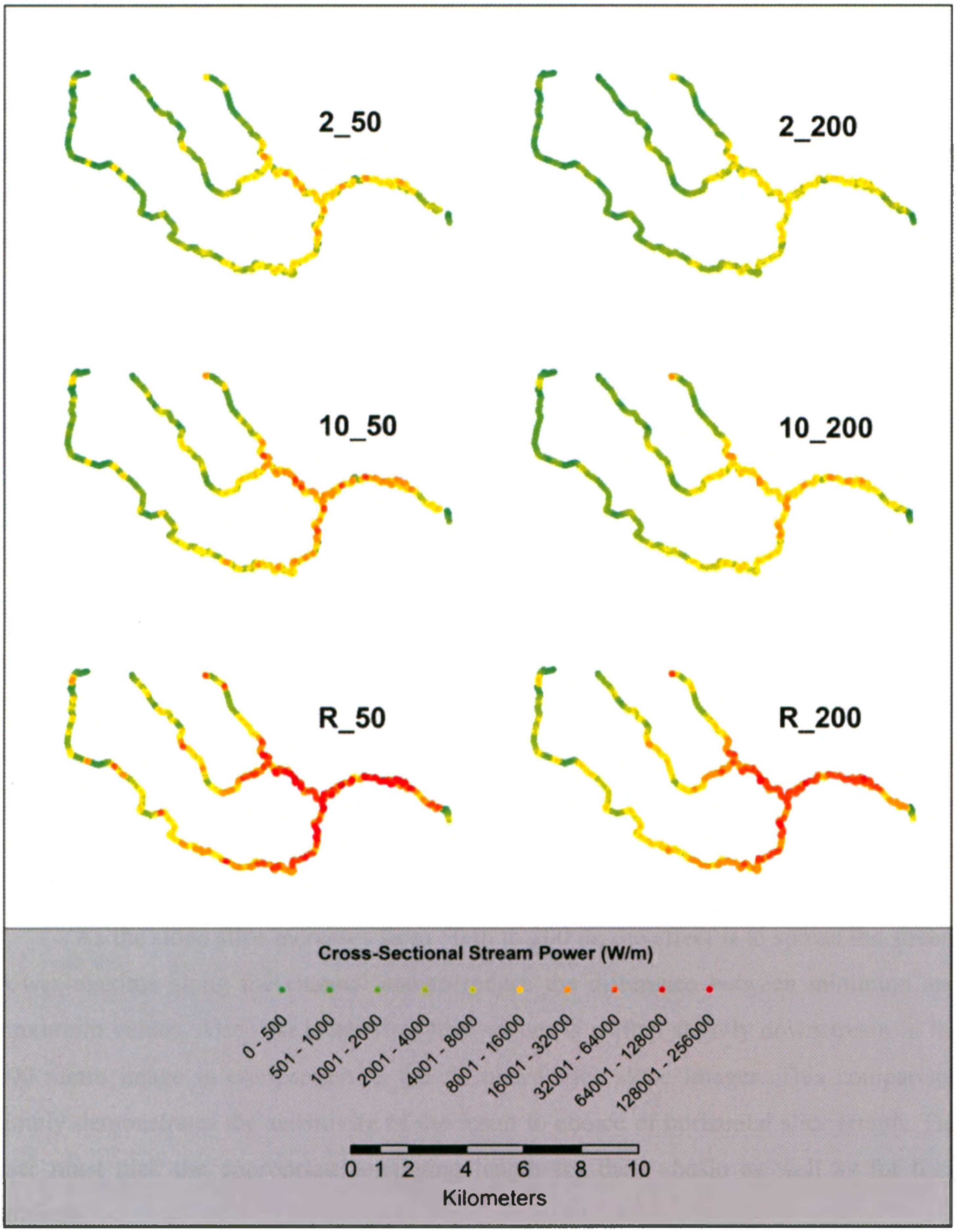


Figure 4.2 Cross-sectional stream power maps for Highland Creek.
Map numbers correspond to 'return interval discharge'_'horizontal slice slope' used to calculate the values in each image. Values are summarized in Table 4.1.

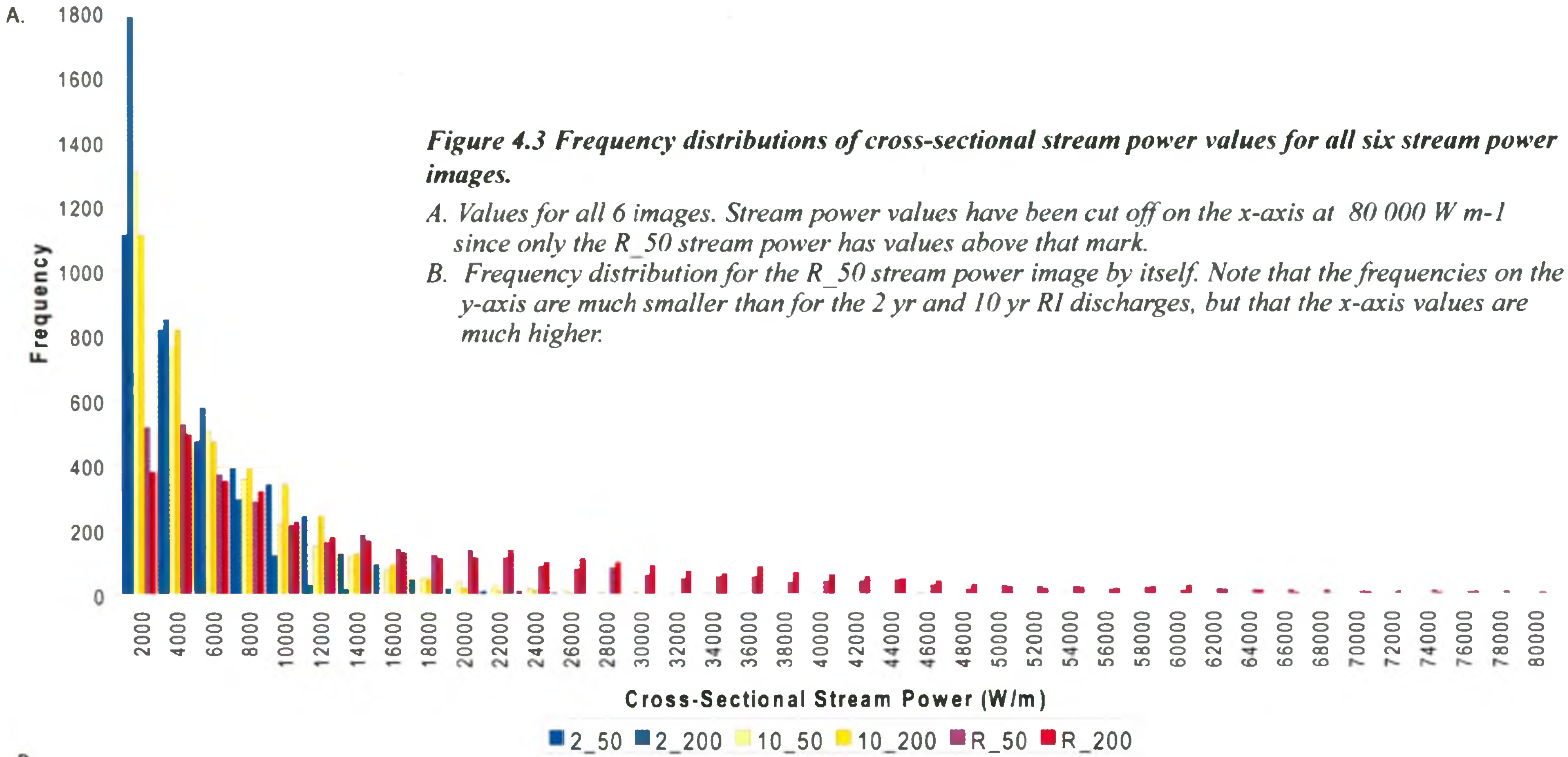
This first set of stream power maps is displayed using the same classification for all images. This is done in order to be able to compare the images to one another. The class limits increase exponentially because the data has a strong positive skew, as shown in the frequency distribution (Figure 4.3). The tails of the frequency distributions represent the maximum values of cross-sectional stream power and in the first set of maps are all shown in shades of orange and red.

It is important to note that although these classification options were chosen for the display of maps in this thesis, it is extremely easy to change map displays in the GIS. Different classification methods are programmed into ArcGIS and the person using the method described in this thesis to calculate GIS-based stream power would be able to explore and display the data in a number of ways. Examples of some of the different ways to present the stream power results will be shown later in this chapter.

Although the actual values differ between maps, the same spatial pattern of relative high and low stream power is similar in all cases. This is because the discharge-to-area relationships used to create discharge images all have very similar slopes (*see* Fig. 3.15). The 2- and 10-yr RI relationships have near identical slopes and the Regulatory discharge has a slightly steeper slope. This means that, although the absolute values of discharge change with changing recurrence interval of the flow, the locations of the relative maxima are virtually identical for the 2-yr and the 10-yr RI discharges and only marginally different for the Regulatory discharge.

As the slope slice increases from 50 m to 200 m, the effect is to spread the stream power maxima along the channel and to reduce the difference between minimum and maximum values. Also, the location of high values is shifted slightly downstream in the 200 metre image in comparison to the 50 metre slice slope images. This comparison simply demonstrates the sensitivity of the result to choice of horizontal slice length. The user must pick the appropriate averaging length for their basin as well as for their analysis.

A number of studies have noted the relative dominance of slope in controlling the downstream distribution of stream power in a river system (Graf, 1983; Magilligan, 1992; Lecce, 1997; Brooks and Lawrence, 1999; Knighton, 1999; Reinfelds et al., 2004). Figure 4.4 shows the slope and stream power results for the 10 yr return interval discharge and



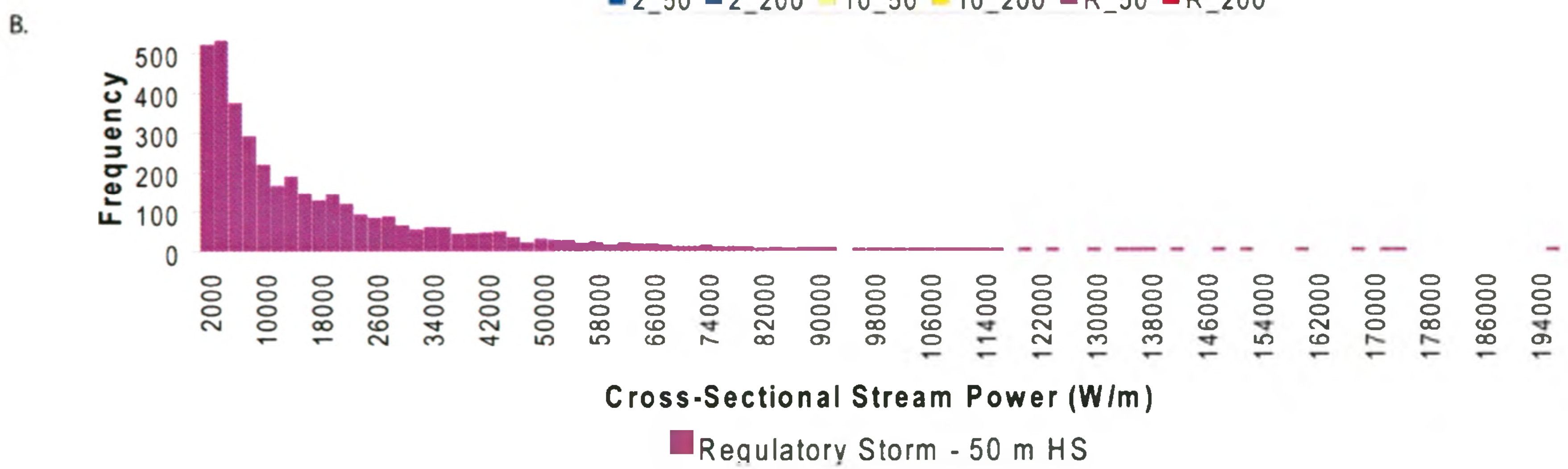


Figure 4.3 Frequency distributions of cross-sectional stream power values for all six stream power images.

A. Values for all 6 images. Stream power values have been cut off on the x-axis at 80 000 W m-1 since only the R_50 stream power has values above that mark.

B. Frequency distribution for the R_50 stream power image by itself. Note that the frequencies on the y-axis are much smaller than for the 2 yr and 10 yr RI discharges, but that the x-axis values are much higher.

the 200-metre slice slope. This demonstrates that local variation in stream power is very closely tied to fluctuations in slope. Slope shows a large variability and low predictability within the basin compared to discharge, the other major component of the stream power equation. Discharge increases relatively steadily, or at least predictably at tributary inputs, so it is logical that the more variable slope will have a greater apparent effect on local variations in stream power. Rapid fluctuations in energy are visible on a local scale in all rivers. Some sections are deep and 'quiet', while others are shallow and have faster moving current. The local variability in stream power is a reflection of how streams function.

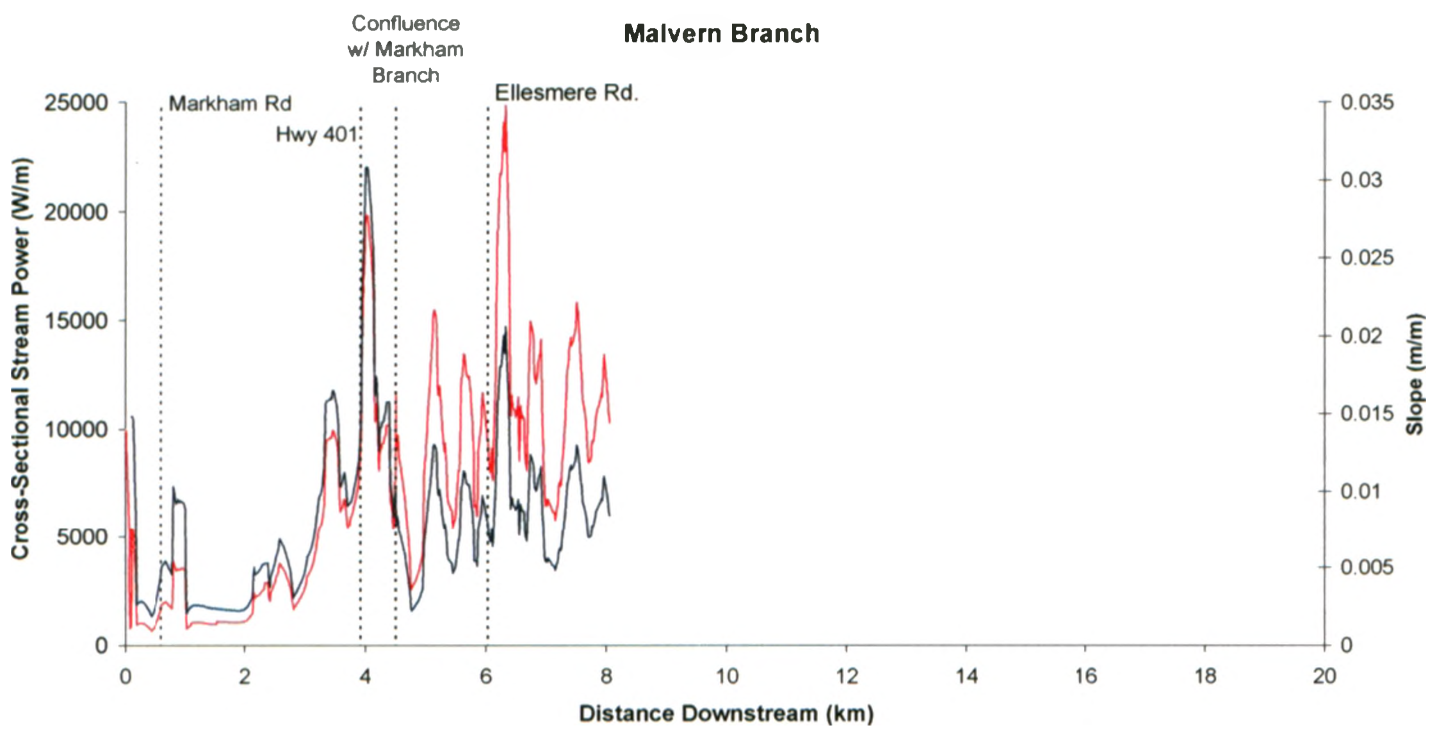
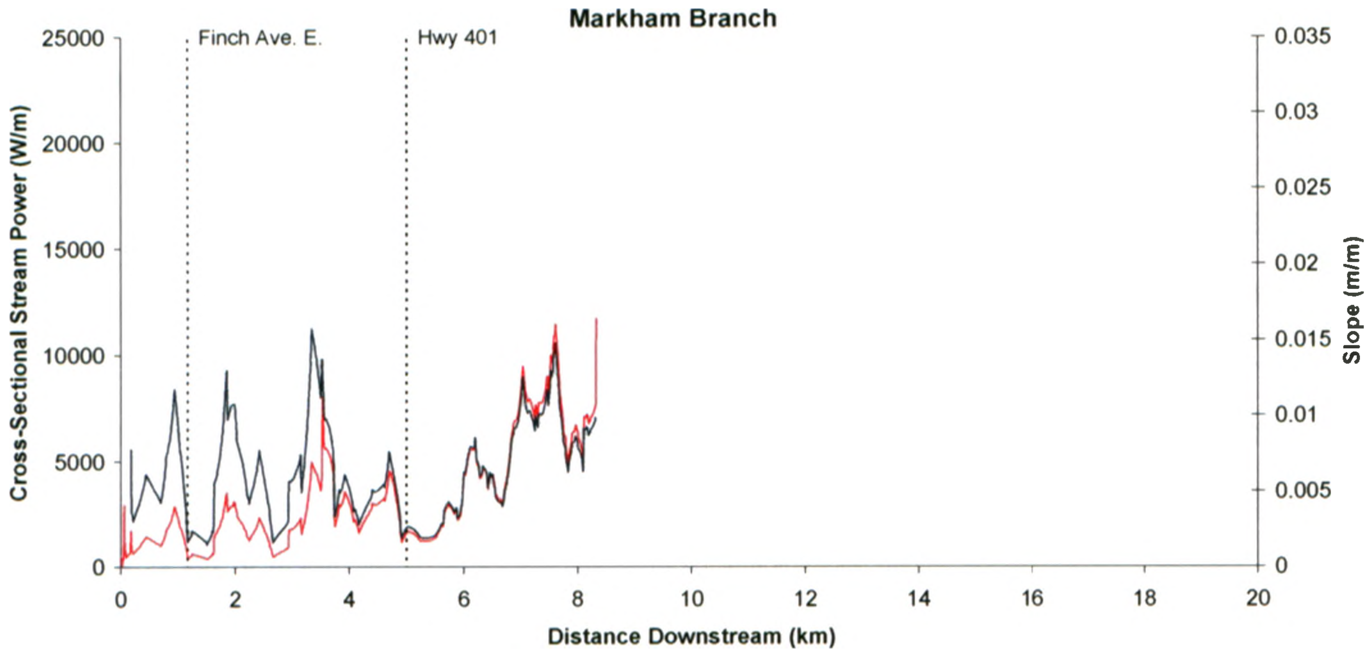
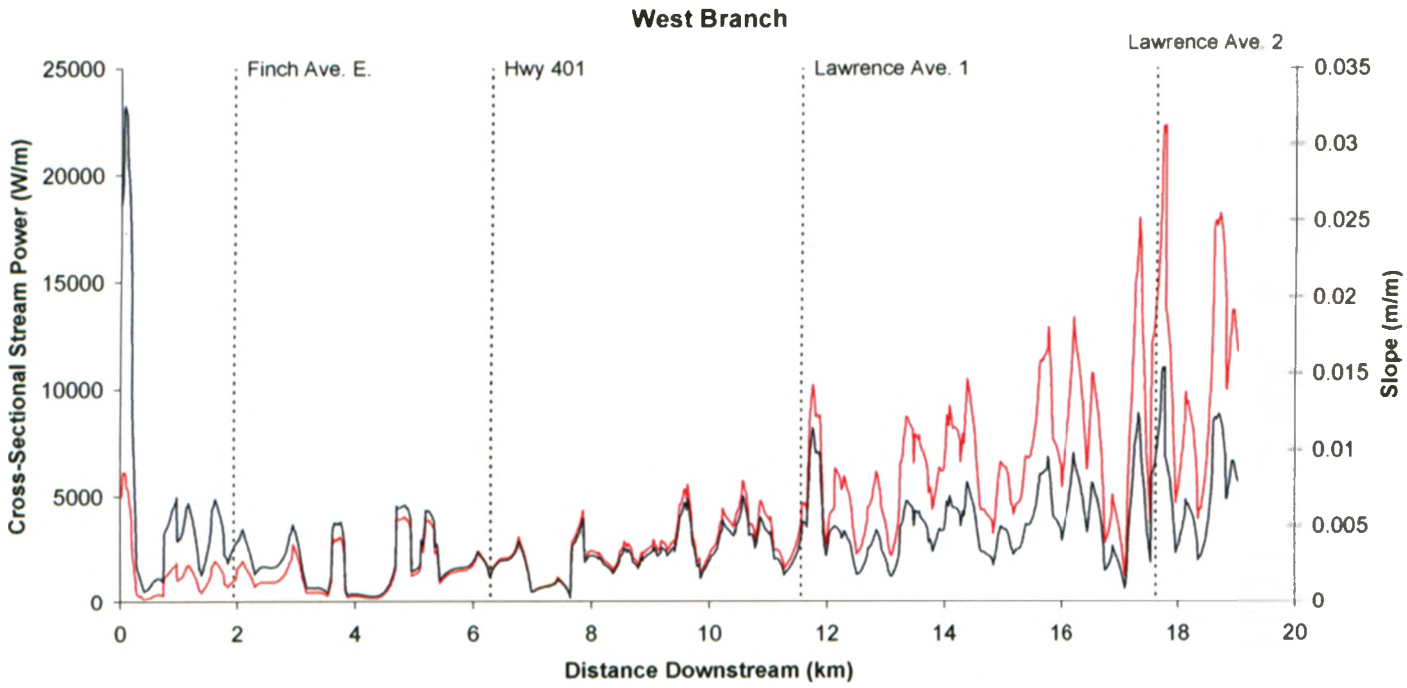
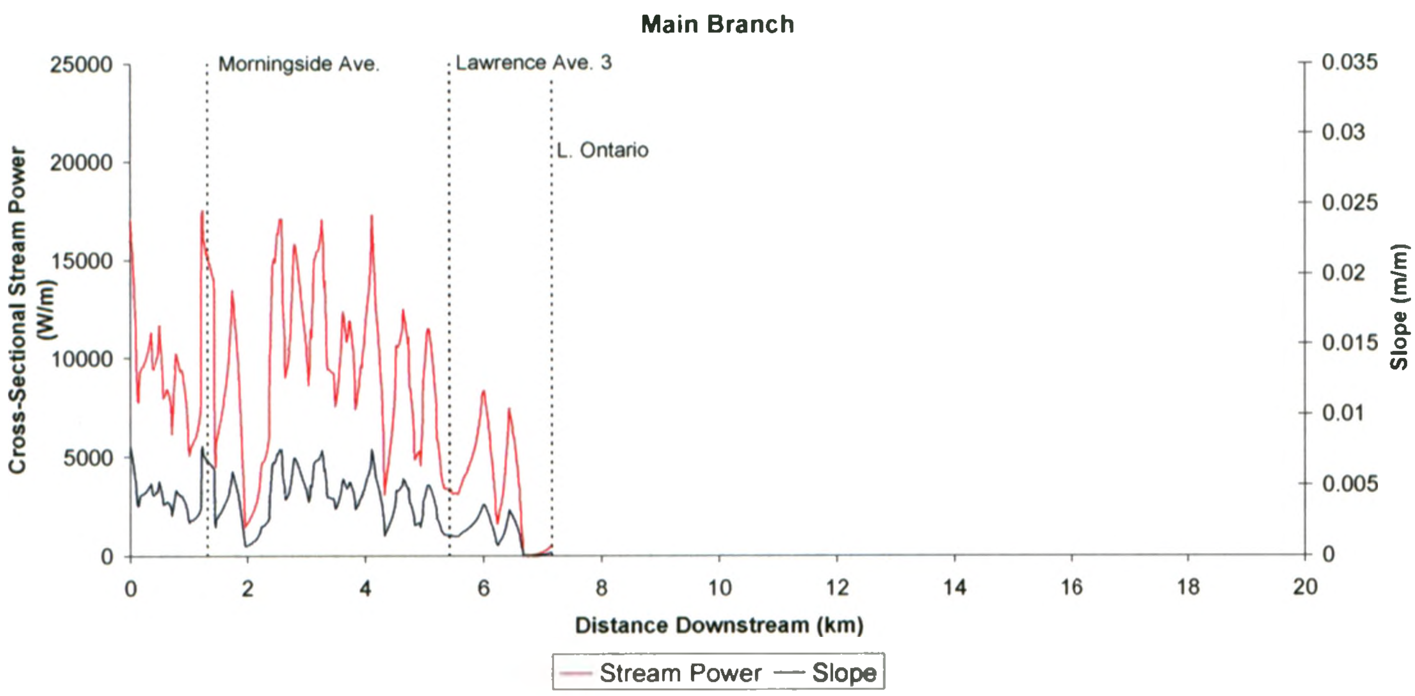


Figure 4.4 Stream power and slope comparisons.
Graphs of stream power and slope for each branch demonstrating the close relationship between stream power and slope.(p.92-93)


Markham Branch
Finch Ave. E.
Hwy 401
Cross-Sectional Stream Power (W/m)
Slope (m/m)
Distance Downstream (km)
25000
20000
15000
10000
5000
0
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0 2 4 6 8 10 12 14 16 18 20


West Branch
Finch Ave. E.
Hwy 401
Lawrence Ave. 1
Lawrence Ave. 2
Cross-Sectional Stream Power (W/m)
Slope (m/m)
Distance Downstream (km)
25000
20000
15000
10000
5000
0
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0 2 4 6 8 10 12 14 16 18 20


Main Branch
Morningside Ave.
Lawrence Ave. 3
L. Ontario
Cross-Sectional Stream Power (W/m)
Slope (m/m)
Distance Downstream (km)
25000
20000
15000
10000
5000
0
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0 2 4 6 8 10 12 14 16 18 20
Stream Power
Slope

However, despite this local control by channel slope, it is still important to calculate stream power so as to include discharge effects at tributaries, over the length of the system and at different flow stages. Table 4.2 lists the summary statistics for all six stream power images. It shows that the higher discharges have a larger spread of cross-sectional stream power values. The mean of the cross-sectional stream power values increases with discharge recurrence interval and decreases with increasing horizontal slice slope. The image with the largest standard deviation is by far the R_50 image; it has the longest tail on the frequency distribution graph and is shown separately from the other images in Figure 4.3 for this reason.

Table 4.2 Summary statistics for stream power images.

Return Interval Discharge	**2**	**2**	**10**	**10**	**Regulatory**	**Regulatory**
Horizontal Interval used to calculate slope	***50 m***	***200 m***	***50 m***	***200 m***	***50 m***	***200 m***
Mean	2879	2883	5122	5129	16257	16296
Median	1780	2085	3167	3715	9262	10705
Standard Deviation	3265	2464	5801	4376	19664	15173
Maximum	30294	13982	53880	24868	195550	78925
Minimum	7	20	12	36	43	97
Number of points	3660	3660	3660	3660	3660	3660

**Values refer to Cross-sectional Stream Power Values (W m^{-1}), rounded to nearest integer*

These stream power values are reasonable since we know that the East Branch of Highland Creek had a peak discharge of about 450 m^3s^{-1} during the 2005 flood. With an approximate slope of 0.01, that results in a stream power of near 45000 W m^{-1} with the possibility of locally higher values where the slope was steeper. The maximum values calculated for Highland Creek are high compared to those found in the literature and in fact rank with stream powers given by Baker and Costa (1987) for 35 "catastrophic" floods in the US. The Highland Creek Regulatory Flood maximum of 195,500 W m^{-1} would rank #16 on their list of extreme floods. Both Baker and Costa's (1987) and Highland Creek's calculations are based on instantaneous maximum discharges.

In the Saguenay Region of Quebec, Canada, the Ha!Ha! River underwent very significant geomorphic changes following record-breaking precipitation and a dam

failure (Lapointe et al., 1998). Stream power values for that flood are estimated to have been between 1000 and 4500 W m^{-2} and caused 6 to 10 metres of incision and extensive widening (Lapointe et al., 1998). To compare with cross-sectional stream power values for Highland Creek, a generous estimate of 100 metres for width (see Brooks and Lawrence, 1999) is multiplied back into the values to give 100,000 and 450,000 $W{\cdot}m^{-1}$. The discharges experienced in this flood are estimated to be more than an order of magnitude higher than the previously recorded maximum instantaneous discharge for the Ha!Ha! River (Brooks and Lawrence, 1999), yet the stream powers still compare to Highland Creek Regulatory flood stream powers.

The correspondence of values may be partly because maximum stream power values from Highland Creek are based on local slopes whereas the Baker and Costa (1987) analysis and the Ha!Ha! river estimates use general reach averages. However, Baker and Costa (1987) say that such high values of stream power typically require *bedrock canyons*, and that alluvial systems of similar magnitude (ex. the Amazon and the Mississippi) have little potential for very high values of stream power. This is likely because bedrock channels, unlike alluvial channels, are unable to adjust their slope. If estimated using Griffiths' rational regime equation (1981), Highland Creek is four times as steep as an equilibrium alluvial river with similar discharges and bed material (coarse gravel). Highland Creek has been classified as 'semi-alluvial' *(see* Ashmore and Church, 2001). These types of rivers have been compared to bedrock rivers in some aspects of form and process, and it seems that high stream power potential may be another interesting characteristic of these streams in which slope may be well in excess of that for an alluvial channel with similar discharge and bed material.

4.2 Map-based stream power analysis

The stream power maps are a departure point for a number of different types of analyses that might be used in analyzing the river system. The following are examples based on the Highland Creek results.

4.2.1 Historical analysis of stream power values

It is possible to generate pre-urbanization values of stream power for Highland Creek using pre-urbanization discharges. These must be based on historical flow analysis (O'Neil, 2008) because no flow modelling exists for the basin in its pre-urban state. The results are likely to be an understimation of stream power since slopes are believed to have increased along Highland Creek due to stream engineering and channel realignments. The pre-urban stream power maps shown in Figure 4.5 show roughly that the peak stream power values were considerably lower prior to urbanization.

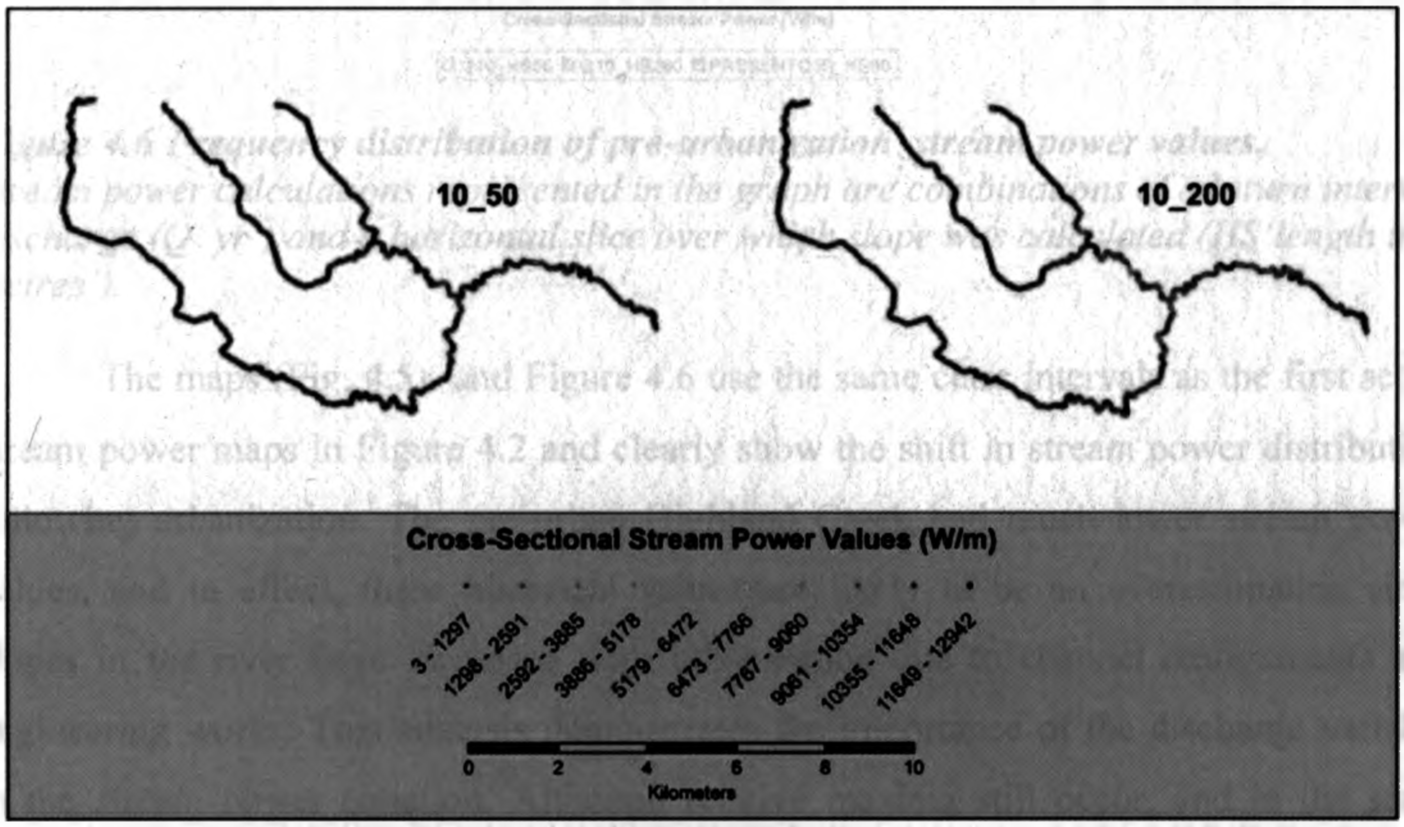


Figure 4.5 Pre-urbanization stream power distribution.
Cross-sectional stream power values derived from pre-urbanization 10-yr RI maximum instantaneous discharges and two types of horizontal slice slopes, 50 metres and 200 metres.

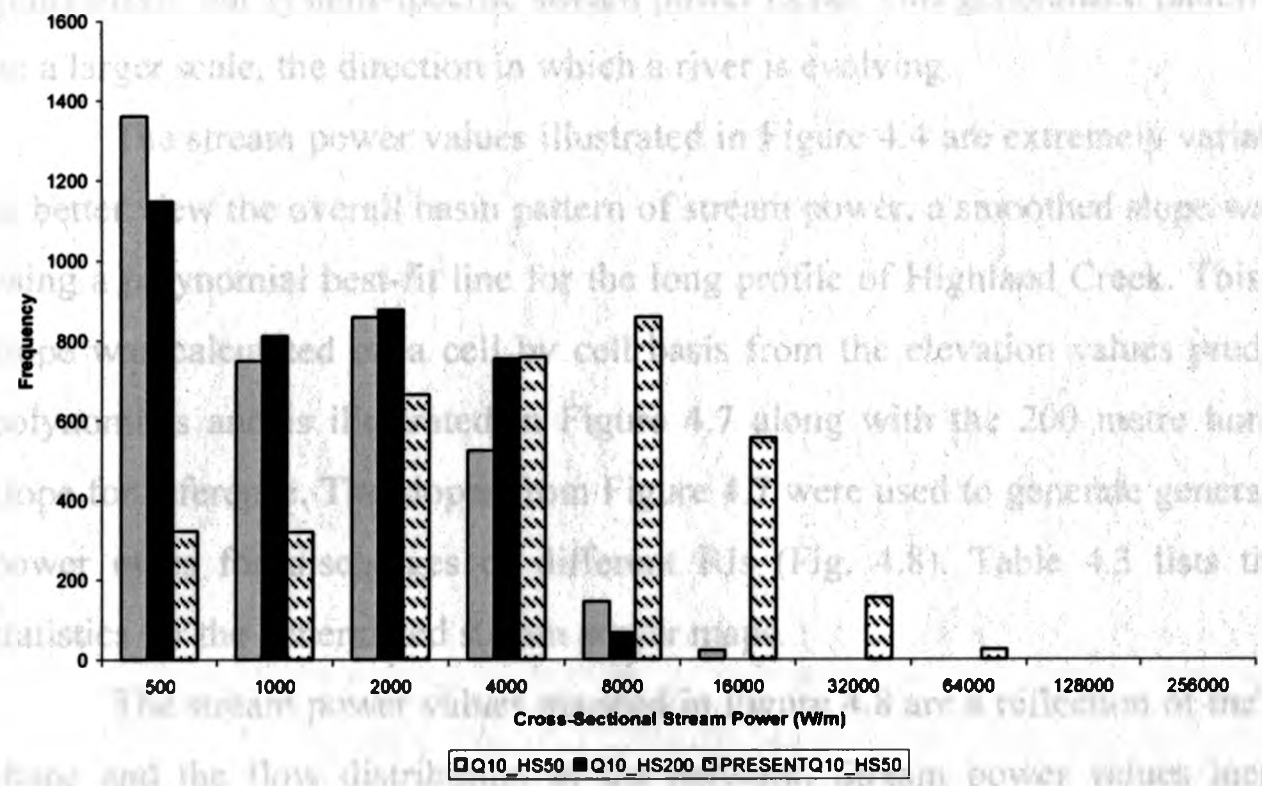


Figure 4.6 Frequency distribution of pre-urbanization stream power values. *Stream power calculations represented in the graph are combinations of a return interval discharge (Q' yr') and a horizontal slice over which slope was calculated (HS'length in metres').*

The maps (Fig. 4.5) and Figure 4.6 use the same class intervals as the first set of stream power maps in Figure 4.2 and clearly show the shift in stream power distribution following urbanization. The pre-urban Highland Creek had much lower stream power values, and in effect, these historical values are likely to be an overestimation since slopes in the river have increased with urbanization due to channel realignments and engineering works. This analysis demonstrates the importance of the discharge variable in the stream power equation. Although relative maxima still occur, and in the same general locations as the present-day maxima, the historical values are not nearly as likely to cross erosion thresholds.

4.2.2 Basin-wide pattern of stream power

Knighton (1999) concludes that it is inappropriate to use hydraulic geometry relationships to model stream power over a whole basin because the variations in slope at the local scale and also in distribution of flow in each basin are too great. Stream power must be calculated on a case by case basis. However, using a smoothed slope fitted for a particular river, similar to Jain et al.'s (2006) 'curve fitting', can result in a more

generalized, but system-specific stream power trend. This generalized pattern may reveal on a larger scale, the direction in which a river is evolving.

The stream power values illustrated in Figure 4.4 are extremely variable. In order to better view the overall basin pattern of stream power, a smoothed slope was calculated using a polynomial best-fit line for the long profile of Highland Creek. This generalized slope was calculated on a cell by cell basis from the elevation values predicted by the polynomials and is illustrated in Figure 4.7 along with the 200 metre horizontal slice slope for reference. The slopes from Figure 4.7 were used to generate generalized stream power maps for discharges of different RIs (Fig. 4.8). Table 4.3 lists the summary statistics for the generalized stream power maps.

The stream power values mapped in Figure 4.8 are a reflection of the long profile shape and the flow distribution in the network. Stream power values increase in the middle reach (e.g. in the vicinity of the confluence of Markham and Malvern branches) and are sustained downstream of the confluence of the east and west branches before dropping near Lake Ontario. The presence of this single mid-basin peak in stream power is in agreement with the findings of Knighton (1999) and Fonstad (2003). However, Jain et al. (2006), who have long profiles very similar in shape to Knighton's (1999), find that the second order polynomials they used to approximate their long profiles produce *two* stream power peaks. Although they anticipate that the magnitude and position of the peaks will vary from river to river, they suggest that a bimodal distribution is a more appropriate description of stream power distribution in a system.

In this case, four different polynomial equations were used to fit the different branches of Highland Creek, and these vary in order from second to fourth according to what best fit the long profiles of those branches. Yet, Highland Creek still only has a unimodal distribution of stream power. Highland Creek has a long profile very different in shape from those used by Knighton (1999) and Jain et al. (2006), and is compared to those in Figure 4.9. Highland Creek is a much smaller system and also has a smaller vertical drop. More importantly though, the other long profiles are concave in nature. Highland Creek's is slightly convex, almost straight. The low gradients at the upstream end and the steepest gradients in the middle of the basin that characterize Highland Creek are not typical long profiles for alluvial systems.

One possible reason for the location of the peak for Highland Creek is the result of the confluence of the two branch system in a mid-basin location that coincides with a change in surficial geology from a predominantly clay and till based area to a sandy plain (Fig. 4.10). Another possibility suggested by Martel (2008) is that the convex slope is a relic of the post-glacial cliff that must have existed at the mouth of the river and the edge of ancient Lake Iroquois. In other words, the apparent 'cliff' in the DEM around the Iroquois shoreline could have resulted in the present long profile shape, and thus the focus of energy expenditure in the basin on this section of the river.

This supports the general conclusion that there is no such thing as a ubiquitous stream power distribution (Knighton, 1999; Fonstad, 2003; Jain et al., 2006). Stream power must be calculated on a case by case basis as each system presents a unique combination of local and basin-scale changes in slope and flow distribution.

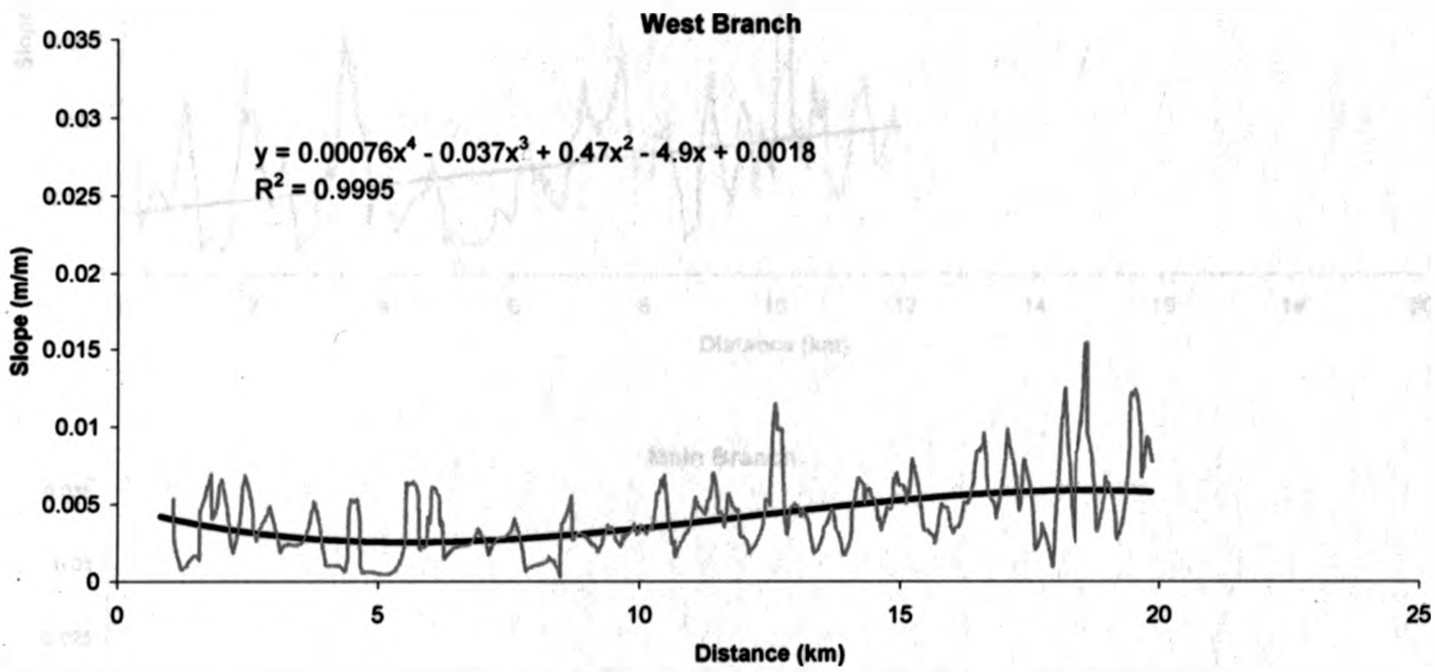


Figure 4.7 Polynomial slopes and 200 metre horizontal slice slopes. *(p.99-100)*
Slopes derived from polynomial lines of best fit for respective long profiles are shown in black. The 200 metre horizontal slice slope is shown in gray as a comparison. The polynomial equations and r-squared values are also displayed for each branch. The Main branch and West branch share the same equation because the line of best fit was derived for the both branches together.

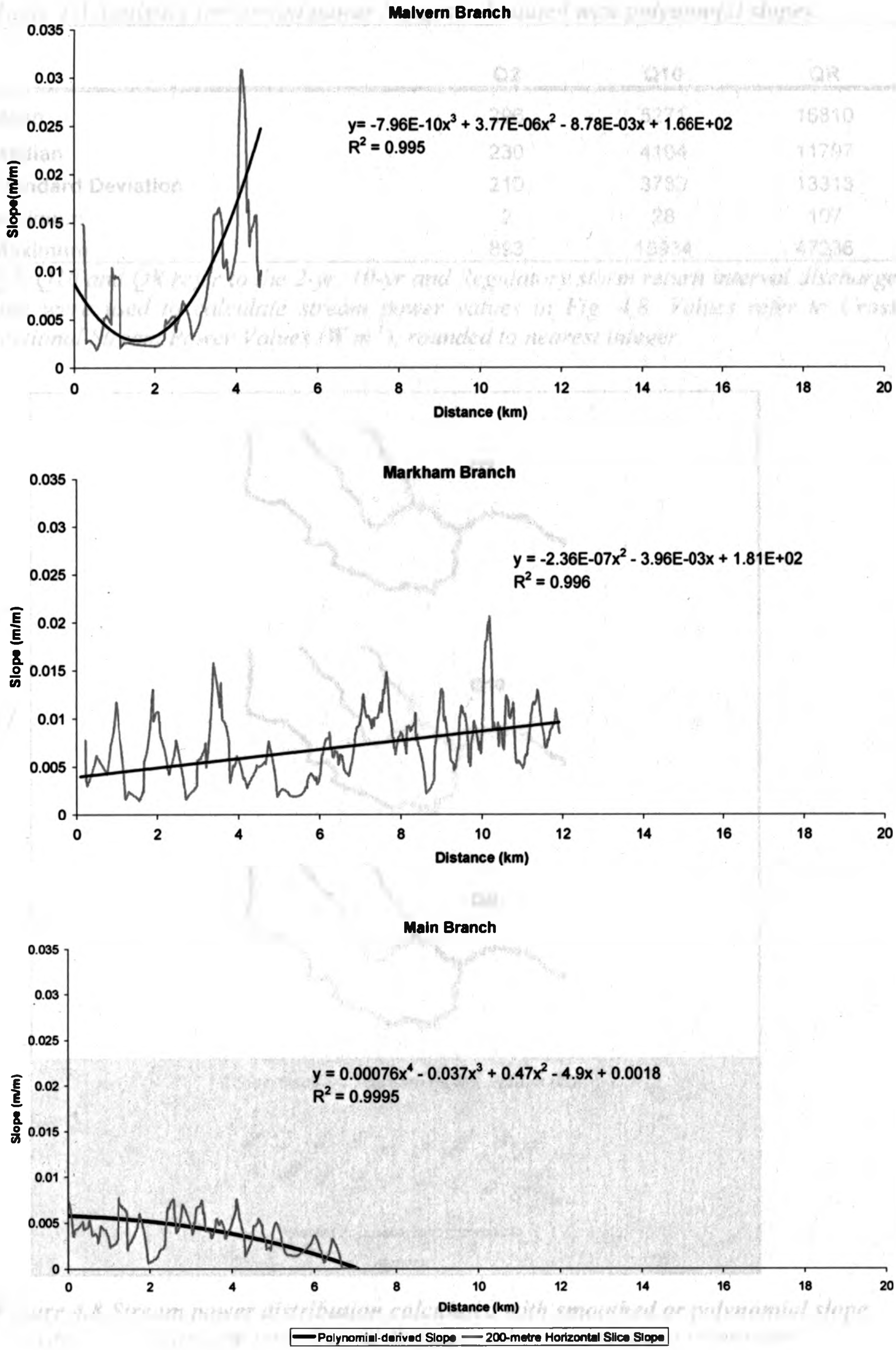

Malvern Branch
y= -7.96E-10x³ + 3.77E-06x² - 8.78E-03x + 1.66E+02
R² = 0.995
Slope(m/m)
Distance (km)
Markham Branch
y = -2.36E-07x² - 3.96E-03x + 1.81E+02
R² = 0.996
Slope (m/m)
Distance (km)
Main Branch
y = 0.00076x⁴ - 0.037x³ + 0.47x² - 4.9x + 0.0018
R² = 0.9995
Slope (m/m)
Distance (km)
Polynomial-derived Slope
200-metre Horizontal Slice Slope

Table 4.3 Statistics for stream power images calculated with polynomial slopes.

	Q2	Q10	QR
Mean	296	5271	16810
Median	230	4104	11797
Standard Deviation	210	3733	13313
Minimum	2	28	107
Maximum	893	15934	47236

Q2, Q10 and QR refer to the 2-yr, 10-yr and Regulatory storm return interval discharges that were used to calculate stream power values in Fig. 4.8. Values refer to Cross-sectional Stream Power Values (W m^{-1}), rounded to nearest integer.

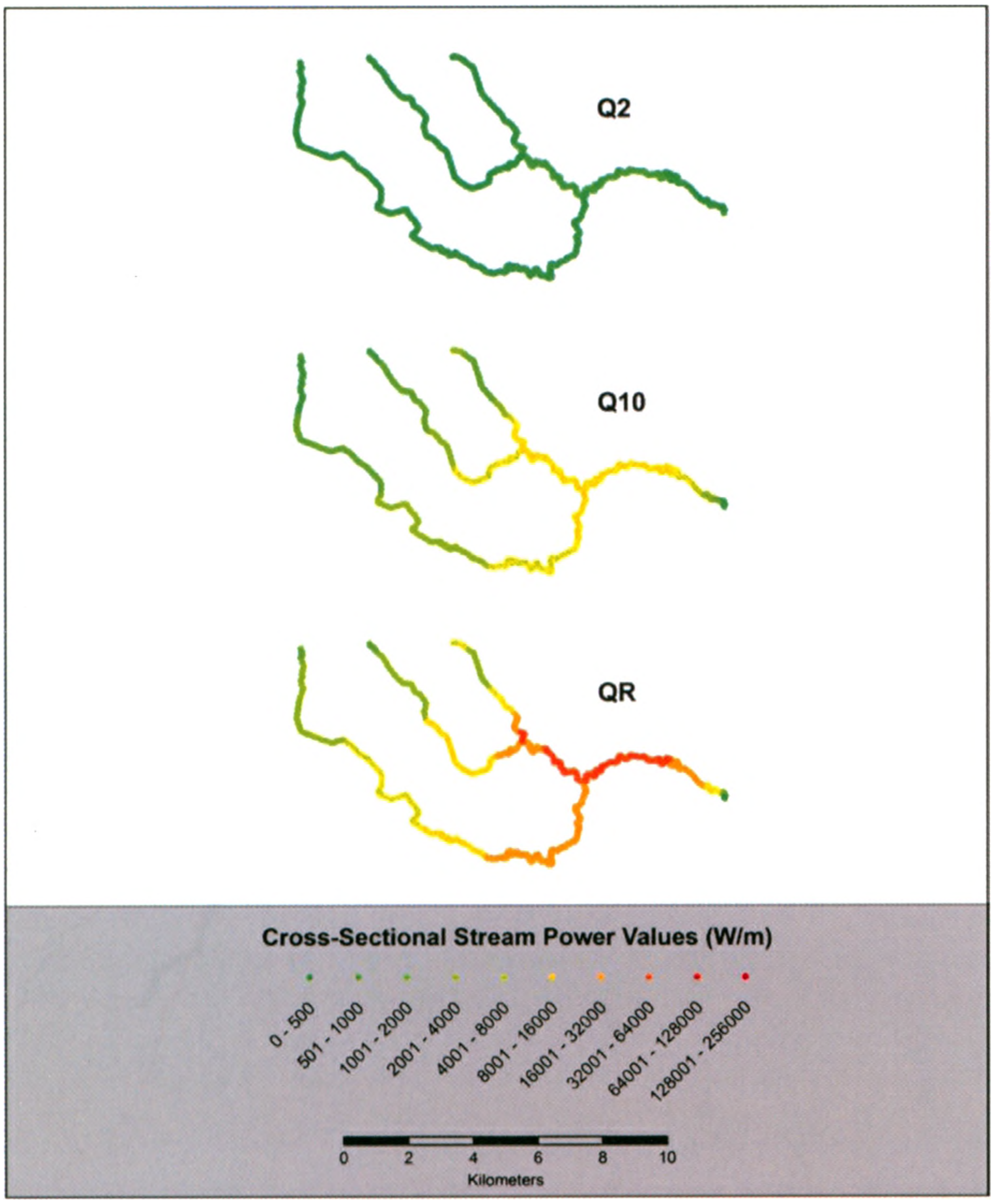


Figure 4.8 Stream power distribution calculated with smoothed or polynomial slope.
Map labels (Q'yr')refer to the return interval discharge used to calculate stream power values.

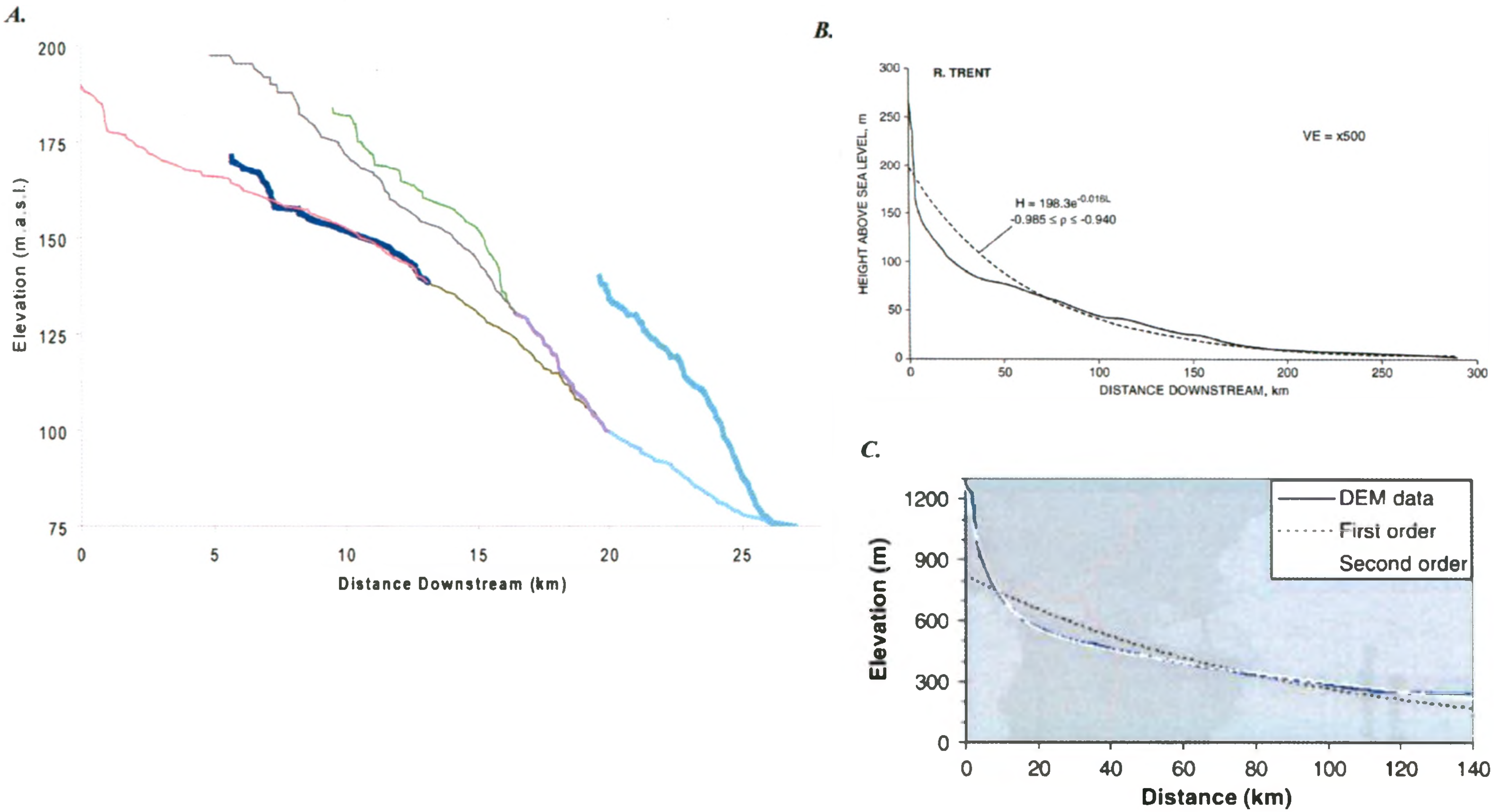


Figure 4.9 Comparison of Highland Creek long profile with long profiles used in other stream power distributions studies.

A. Branches of Highland Creek (see Fig. 2.3) Elevations taken from OMNR DEM v.2.

B. Long profile used by Knighton (1999) (portion of Knighton's Figure 4).

C. Long profile used by Jain et al. (2006) (portion of Jain et al's Figure 6).

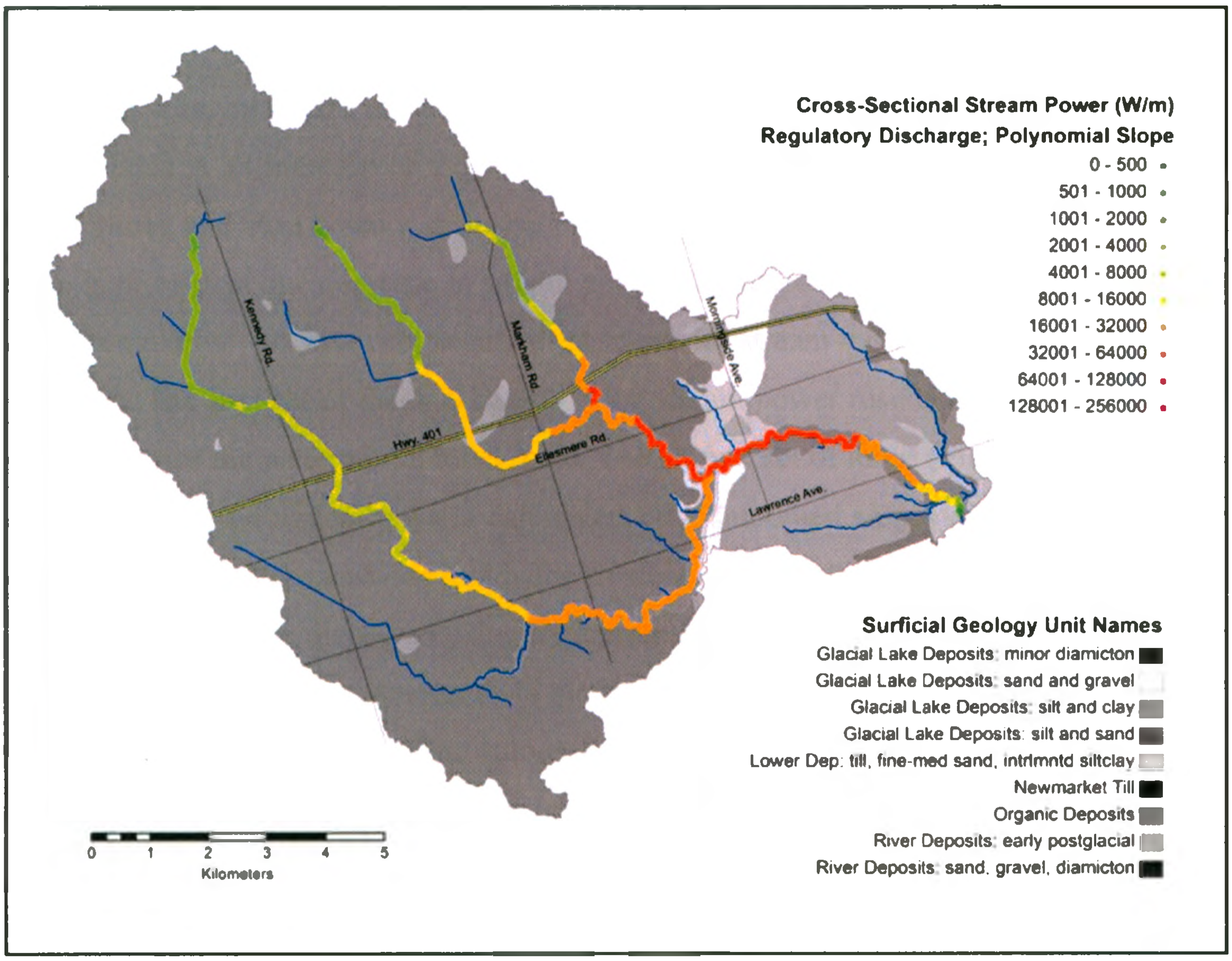


Figure 4.10 Stream power superimposed on a map of the surficial geology of the Highland Creek basin.
The surficial geology in this figure has been displayed in grayscale to more clearly see the stream power values. A colour map of the surficial geology is presented in Figure 2.4. (Sharpe et al., 2001; Ontario Fundamental Dataset, 2002)

4.2.3 Cumulative downstream change

Absolute values of stream power give the overall erosion or sediment transport potential at particular locations in a river, but examining cumulative increases or decreases in stream power may indicate instead a general tendency for degradation (downstream increase in sediment transport potential) or aggradation (downstream decrease in sediment transport potential). Examining the downstream changes in stream power can help to identify locations of sediment transport discontinuities (Reinfelds et al., 2004). The following two sets of maps (Fig. 4.11 and 4.12) identify reaches that have a large

cumulative increase or decrease in stream power values, which can be equated with areas where erosion (sediment transport) or deposition (sediment accumulation) might be occurring. The values are calculated first by determining whether each successive stream power value is an increase or a decrease from the upstream value. Successive increases are summed and stop when a decrease in stream power is encountered. At that point, if there is more than one decrease in stream power, the successive decreases are summed to give cumulative positive or negative changes in stream power in the downstream direction. The first set of maps is based on the stream power results calculated in section 4.1 and shows the pattern on a local scale. The second set of maps (Figure 4.12) is based on the generalized stream powers calculated with smoothed slopes discussed in section 4.2.2 and shows the basin-wide trends for erosion and deposition.

The maps are displayed using a dichromatic colour ramp so that values nearest 0 (or the *small* increases or decreases in stream power) have a lighter intensity, while the colours at the extreme ends of the colour scale (the *large* increases or decreases in stream power) have a stronger intensity. The increases in stream power, where erosive potential is high, are shown in shades of orange. The decreases in stream power, where depositional potential is high, are shown in shades of blue.

As is expected, the magnitude of the downstream changes increase with increasing RI discharge. The largest increases in stream power as well as the largest decreases in stream power occur in the Regulatory flood stream power image in both sets of maps.

On a local scale (Fig. 4.11), it is interesting to note that many of the large increases in stream power are matched by large decreases in stream power occurring slightly downstream. This implies that downstream of each location where erosion is occurring, deposition is occurring. This is logical from a sediment budget perspective and supports the notion discussed in Section 4.1 that rivers have large local fluctuations in power.

On the basin scale, the second set of maps (Fig. 4.12) shows that erosion potential is greatest along the East Branch and the upper part of the West Branch and that deposition is more likely to occur along the main branch, especially approaching Lake Ontario. The 'erosive' section of the West Branch ends before the confluence of the two

branches, and the likelihood for deposition increases downstream along the Main Branch achieving its maximum at the mouth. The East Branch, identified as ‘erosive’ in these maps, does in fact coincide with real erosion on the stream which will be discussed in section 4.2.6. The ‘premature’ end of the erosive values on the West Branch are indicative of the gentler slope leading into the confluence of the two branches. The lower end of the Main Branch is a ‘low energy’ reach where few, if any, remediation efforts are undertaken. In this location, the river is wider and shallower than upstream and has an extensive floodplain with gently sloped walls.

The identification of downstream changes in stream power allows problem areas in extreme floods to be anticipated and potential problem sites to be prioritized. The largest increases in stream power are more likely to experience erosion than single point maximums, and the same is true of deposition for the largest decreases in stream power.

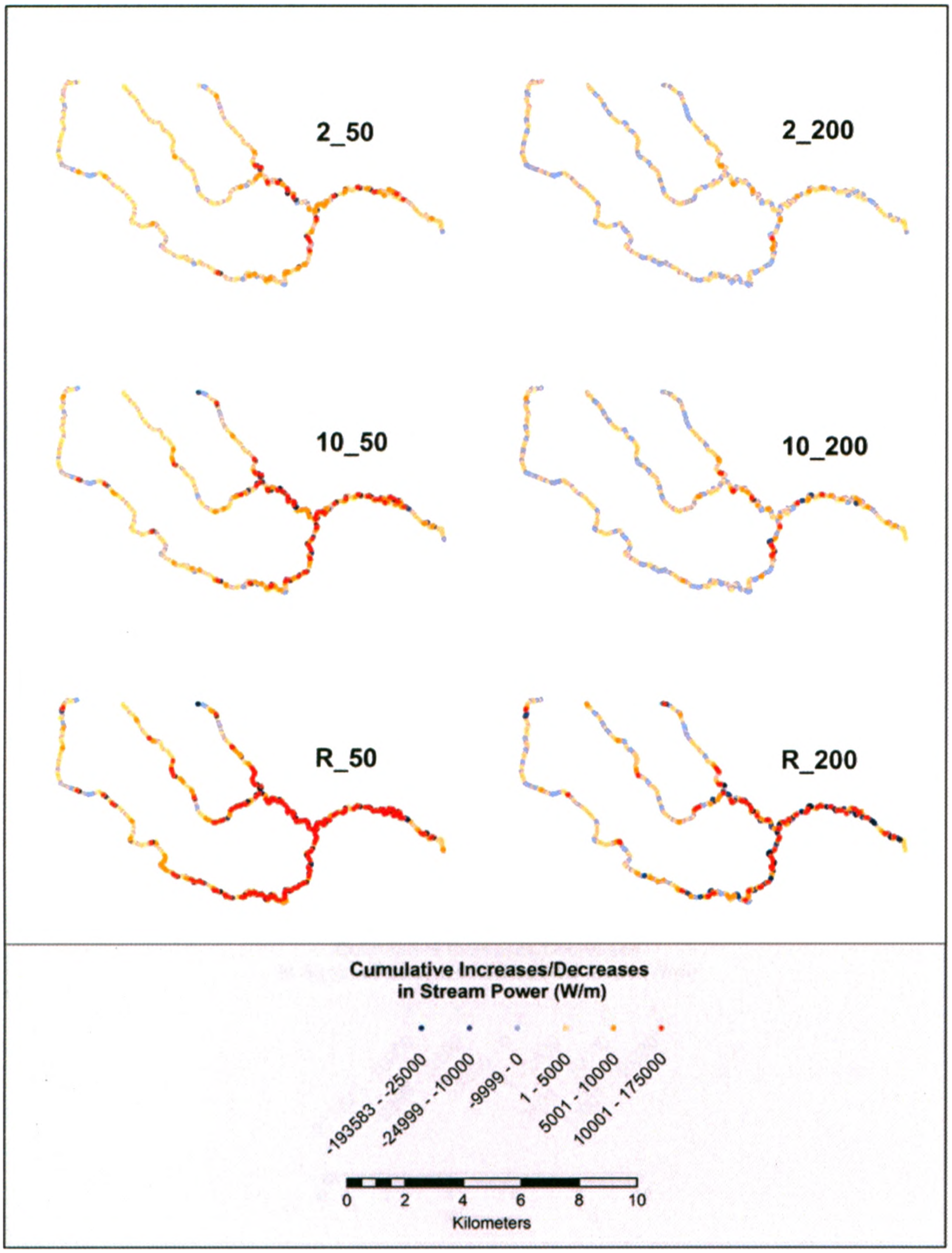


Figure 4.11 Maps of downstream cumulative change in stream power.
Map labels refer to return interval discharge and length of horizontal slice slope used to calculate stream power values (Q_HS).

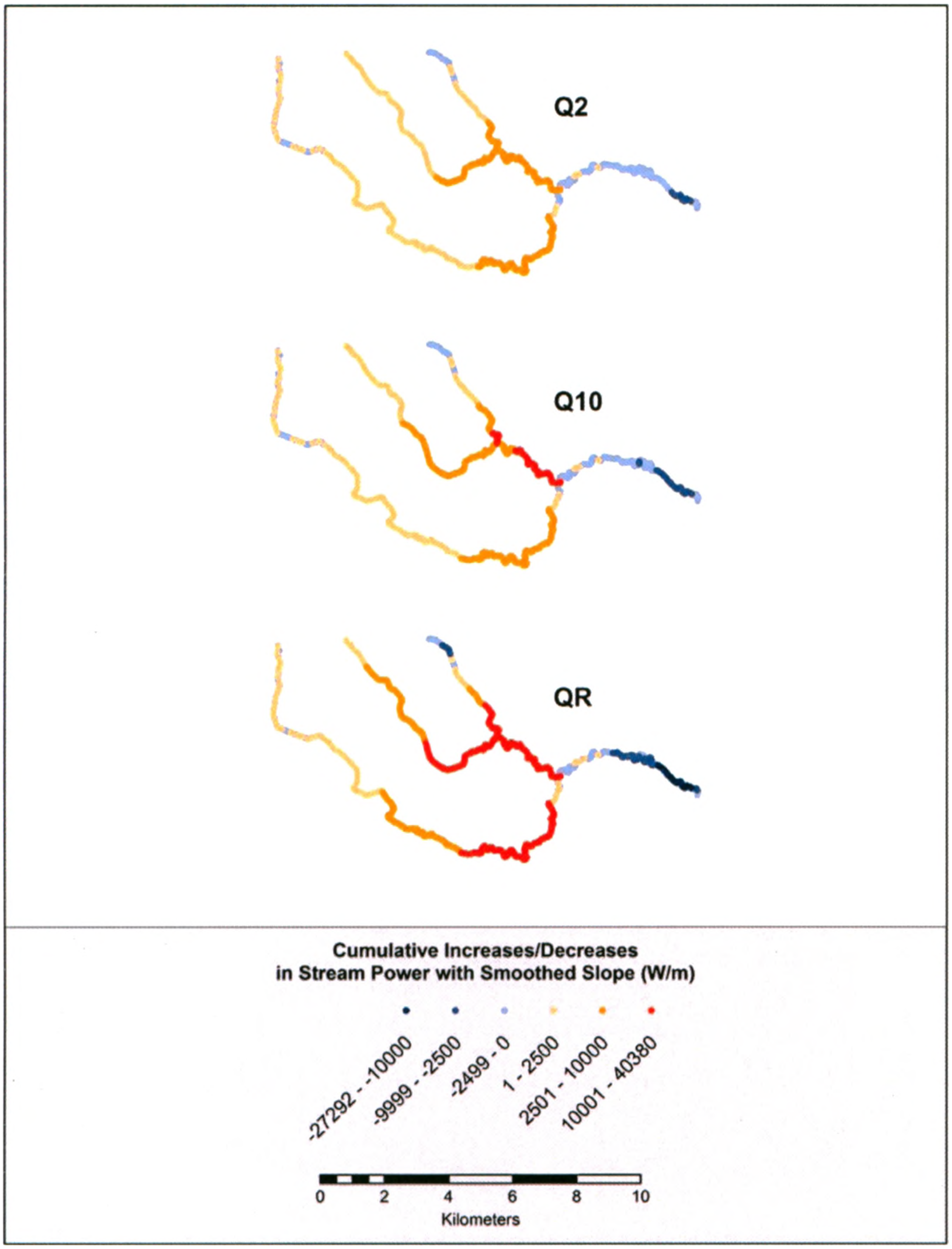


Figure 4.12 Downstream change in stream power calculated with a smoothed slope. *Map labels refer to return interval discharge used to calculate stream power values (Q'yr').*

4.2.4 Stream power threshold

In terms of channel monitoring and erosion prediction, we are mostly interested in the highest values of stream power in the basin or power in excess of the erosion threshold. An interesting way to view the maps is to identify a stream power threshold above which work is actually being done by the stream. In these following maps (Fig. 4.13), the mean of the entire data set was used as an arbitrary threshold just to demonstrate the idea. The points falling below the mean are displayed in green, the remaining tail portion from the frequency distribution is divided into two with the next highest values displayed in orange and the highest values displayed in red. The result is a map in which there are many green or 'safe' areas corresponding to low stream power, a smaller number of orange or 'potentially erosive' areas and an even smaller number of red points where stream power values are so high that it is extremely likely that the stream is unstable or subject to rapid adjustment during high flows.

Mean stream power can be calculated if the channel width is known (see Table 1.1, *Eq. 3*) and has the same units as shear stress. If the critical shear stress above which erosion occurs is known, then this can be used in the classification scheme of the map as a standard entrainment threshold. Similarly, a threshold could be based on observation of erosion occurring under known flows. Once this threshold is determined, using it in the map classification allows for the easy identification of locations that are at-risk.

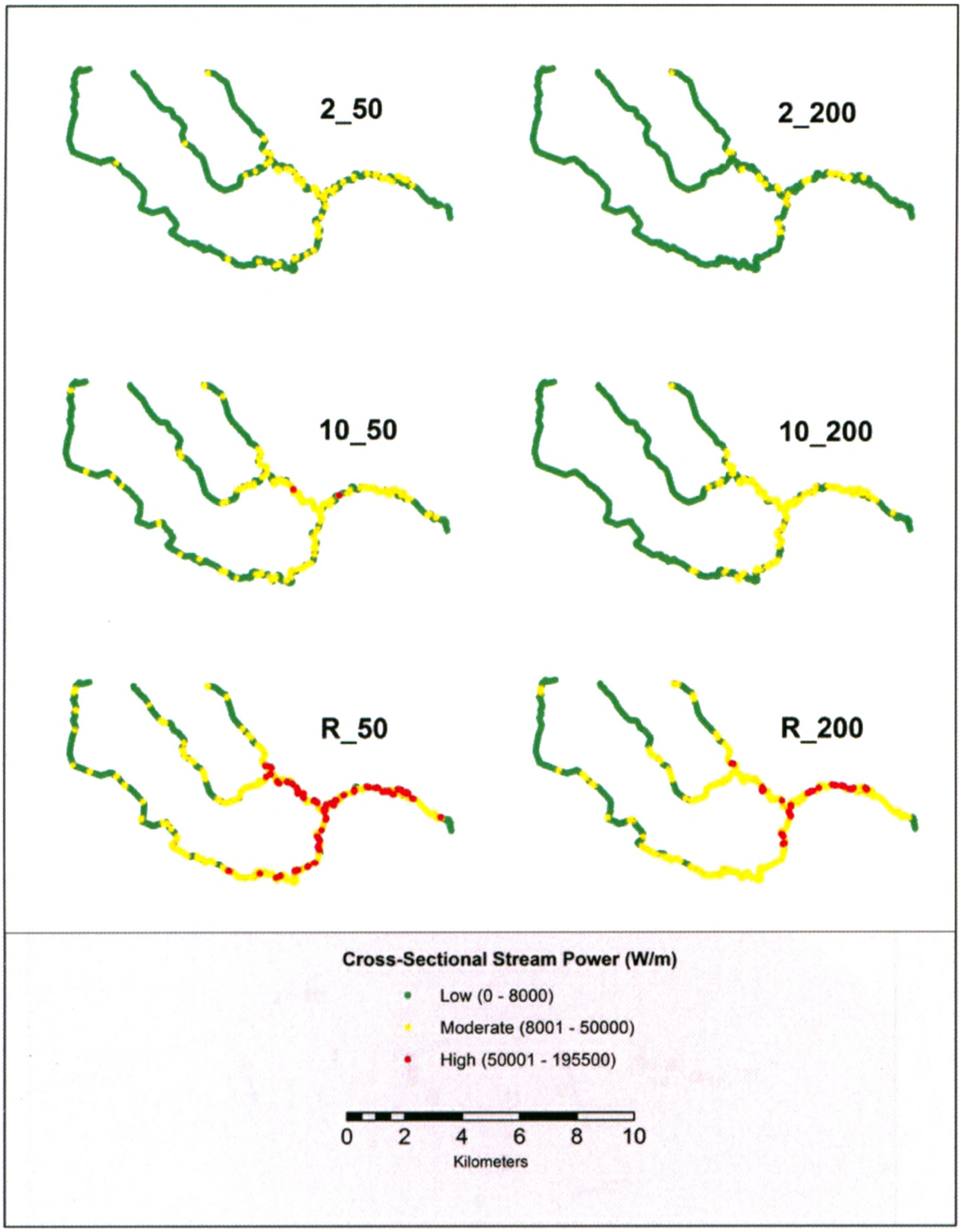


Figure 4.13 Maps of Erosion Potential

These stream power maps are based on the use of a threshold value below which erosion is unlikely to occur. If boundary material information is available, the critical shear stress can be used as a threshold instead. Map labels refer to return interval discharge and length of horizontal slice slope used to calculate stream power values (Q_HS).

4.2.5 Sites of maximum and minimum stream power

Since we are interested in the points of maximum stream power, it is interesting to highlight these points on a map to identify their location. High points tend to occur in clusters, and so the top ten separate locations instead of the top ten values have been identified in Figure 4.14. There are six different images to consider, but the locations from the 2_5 and 10_5 images are identical, and the 2_20 and 10_20 images are identical. The corresponding Regulatory discharge images have only 2 points that are different from the 2-yr and 10-yr recurrent discharges. Thus, if the top ten values from each stream power image is mapped, the result is a total of fifteen points. The values of these points are given in Table 4.4.

Figure 4.15 shows the ten locations with maximum cumulative increase in values of stream power for each image. Again, the 2-yr and 10-yr return interval discharge calculations have identical maximums with the Regulatory discharge images having slightly different points. Table 4.5 lists the actual stream power values for each point.

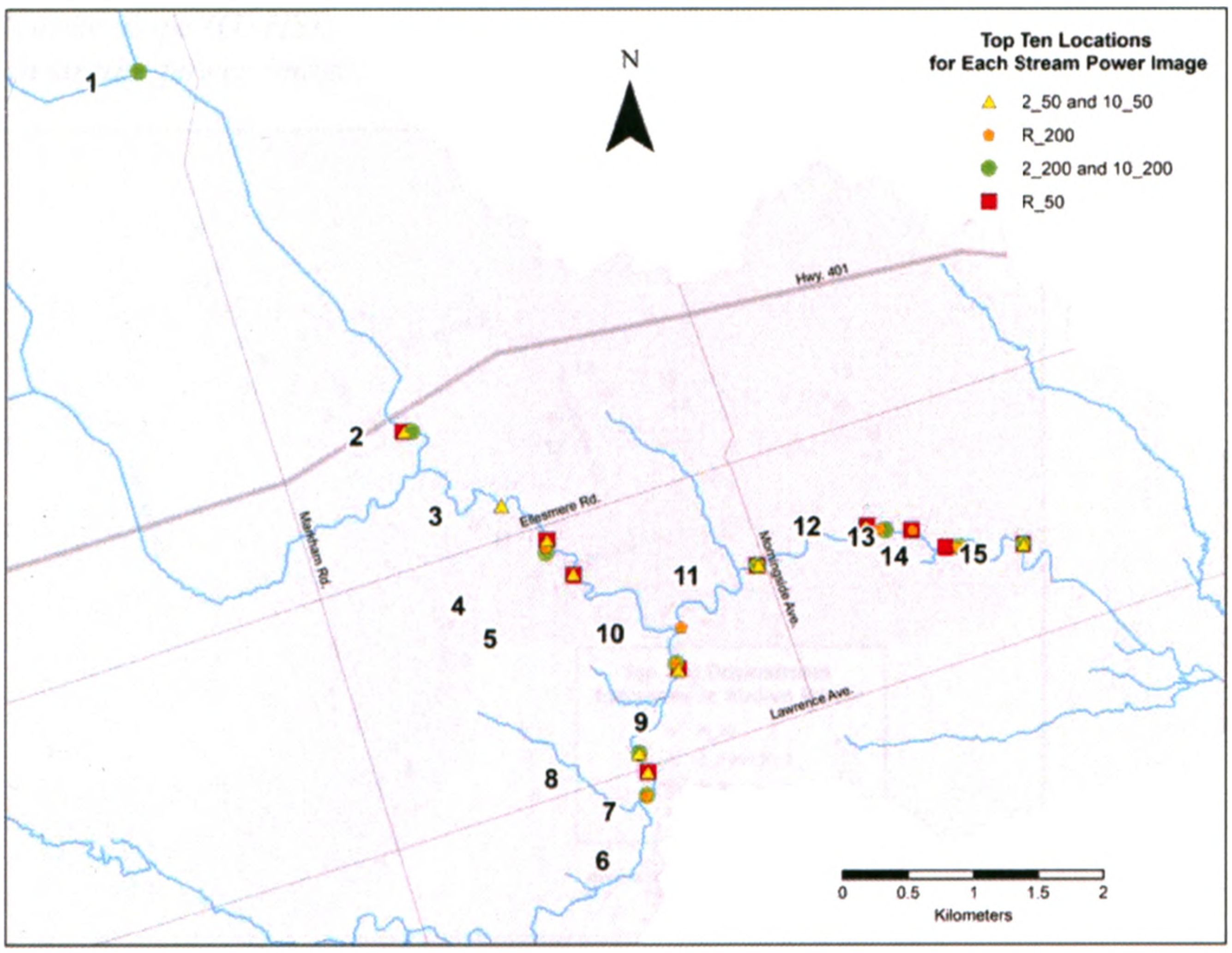


Figure 4.14 Top ten maximum stream power sites for each stream power image. *Values listed in Table 4.4*

Table 4.4 Top ten maximum stream power sites for each stream power image.

Point number on map	Stream Power Image					
	2_50	10_50	r_50	2_200	10_200	r_200
1				10711	19160	
2	22233	41784	113004	11122	19842	
3	16020	28495				
4	30293	53879	170909	13554	24106	76475
5	20461	36390	115568			
6				10125	17993	59766
7	25734	45730	151955			
8	13680	26955		12558	22315	74172
9	23069	40991	136716	10236	18188	60664
10						63106
11	29723	52418	195549	9919	17589	65365
12	16733	39303	129625	9672	17151	63855
13			94745			59062
14			96805	9644	17101	61215
15	16043	28447	106137	9757	17300	64549

Ten cross-sectional stream power values (W/m) are listed for each stream power image and correspond to the ten locations of maximum stream power. Because the locations of the maximum values are often identical between images, they have been given location numbers that correspond to the map in Figure 4.14. Stream power image names are composed of the return interval discharge and the length of horizontal slice used to calculate slope (Q_HS). Grey highlights identify the highest stream power values for each stream power image.

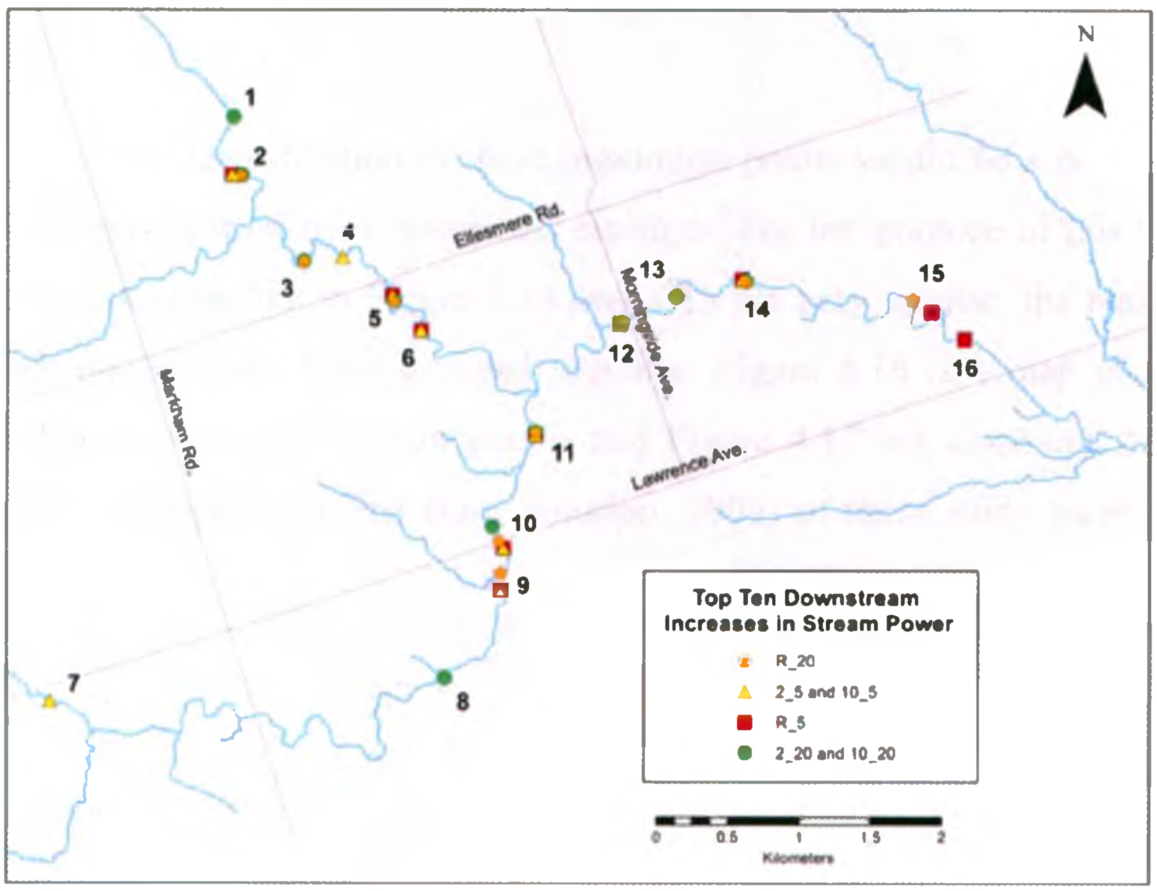


Figure 4.15 Top ten downstream increases in stream power for each stream power image. *Values listed in Table 4.5.*

Table 4.5 Top ten downstream increases in stream power for each stream power image.

Point number on map	Stream Power Image					
	2_50	10_50	r_50	2_200	10_200	r_200
1				4489	8010	
2	16479	37997	102883	7982	14238	38795
3						40802
4	12686	22564		7253	12900	
5	29944	53258	168940	7912	14072	44639
6	19456	34604	109897			
7	13420	23905				
8				4426	7868	
9	12677	22533	73854			55757
10	22425	39850	132417	10416	18510	61529
11	20930	37189	124068	7590	13488	44992
12	26083	46252	171599	7057	12513	46600
13				5077	9003	33475
14	20128	35691	132869	5856	10385	38663
15			78875			29004
16			71471			

Ten cross-sectional stream power values (W/m) are listed for each stream power image and correspond to the ten locations of maximum stream power increases. *Because the locations of the maximum values are often identical between images, they have been given location numbers that correspond to the map in Figure 4.15. Stream power image names are composed of the return interval discharge and the length of horizontal slice used to calculate slope (Q_HS).Grey highlights identify the highest stream power values for each stream power image.*

The identification of these maximum points would be a good starting point for a field investigation by a watershed manager. For the purpose of this thesis, and because locations identified in Figure 4.14 and 4.15 are very similar, the maximum points from both images have been grouped together. Figure 4.16 is a map of the occurrences of maximum values of stream power and Figure 4.17 are close-ups from the 2005 (pre-storm) orthophotos (First Base Solution, 2005) of those same locations on the ground.

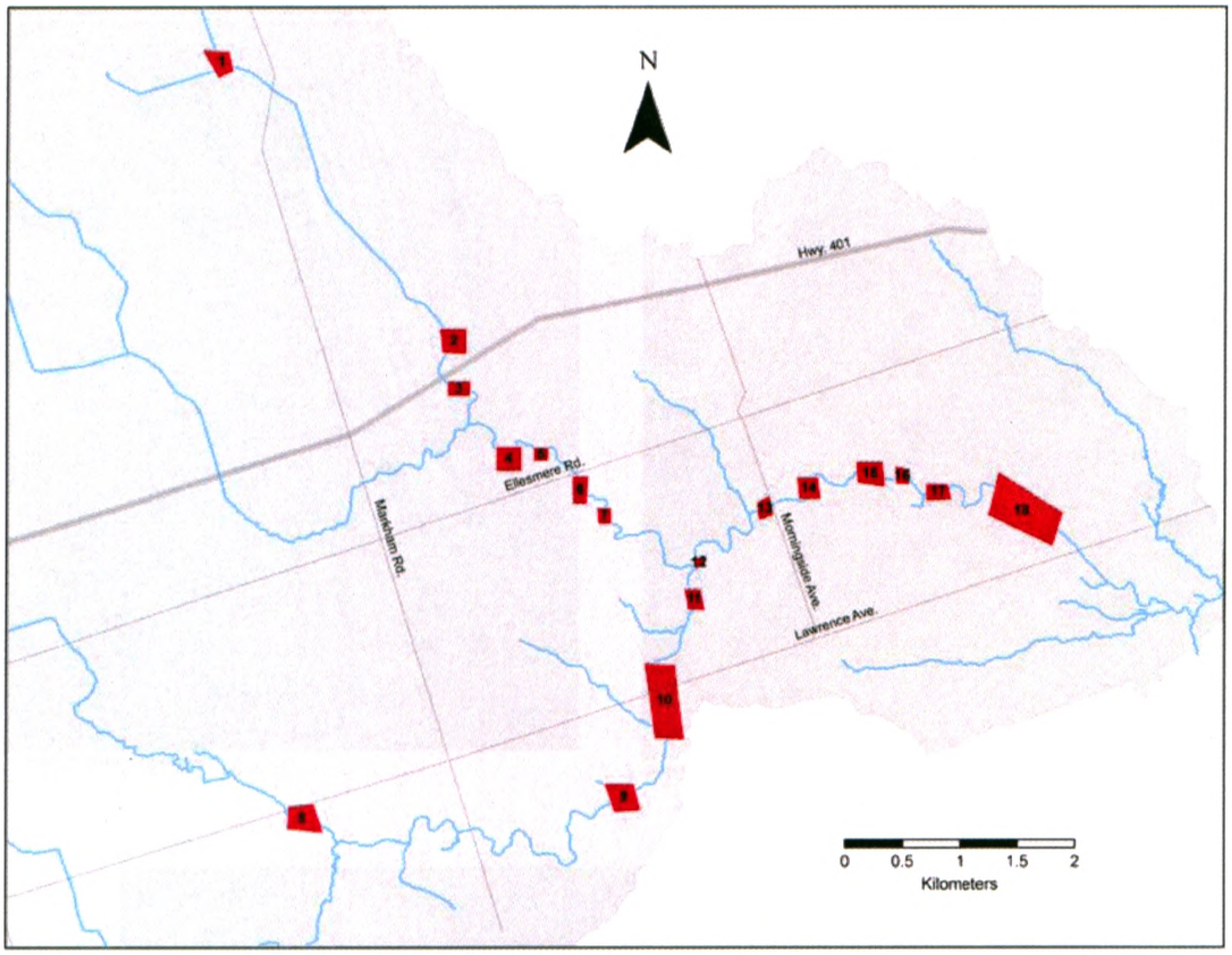
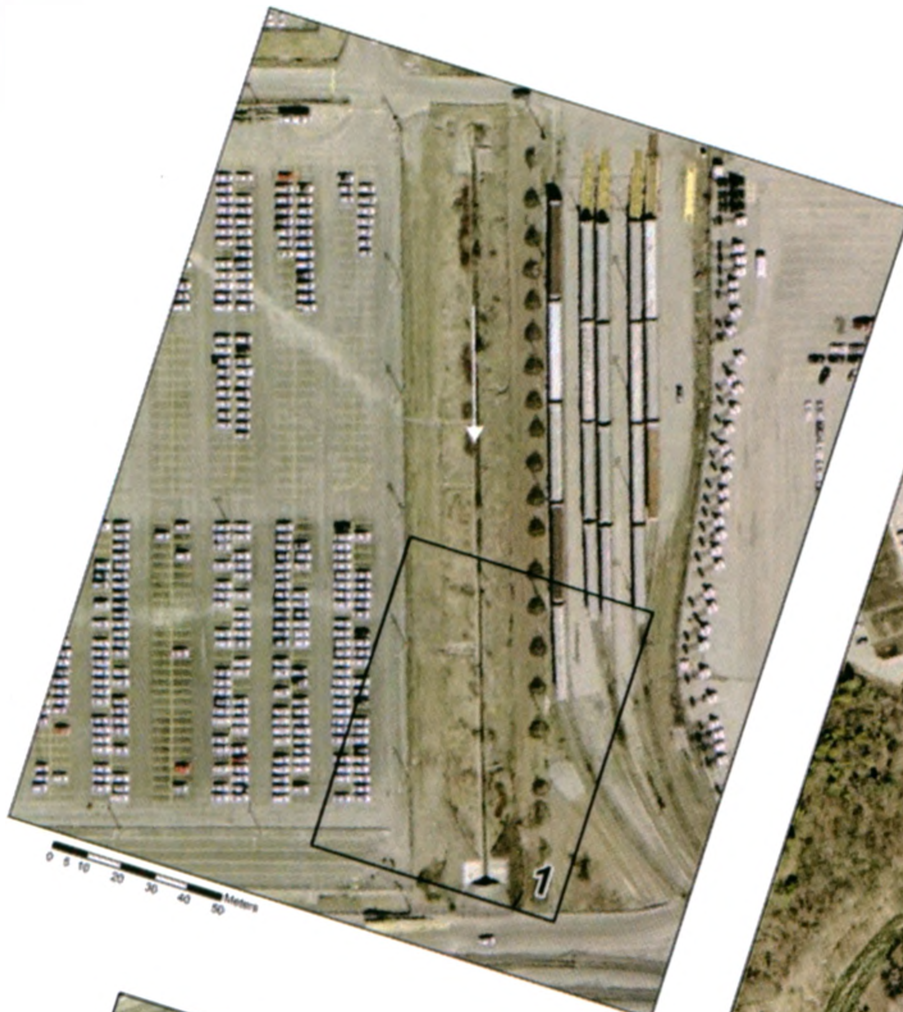


Figure 4.16 Location of stream power maxima identified in Figures 4.14 and 4.15.

Figure 4.17 Orthophoto close-ups of maximum stream power points.*(p.114-118)*
Numbers in each photo correspond to those in Figure 4.16.


1
0 5 10 20 30 40 50 Meters

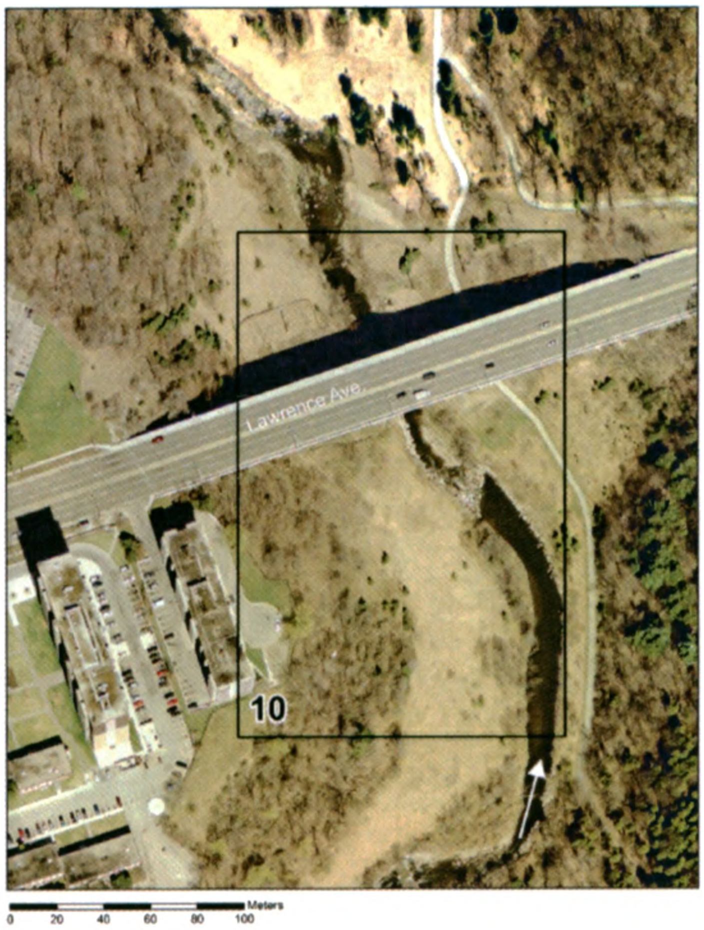

Milner Ave
2
Hwy 401
0 10 20 40 60 80 100 Meters


Hwy 401
3
0 10 20 40 60 80 100 Meters


4
5
Meters
0
40
80
120
160
200

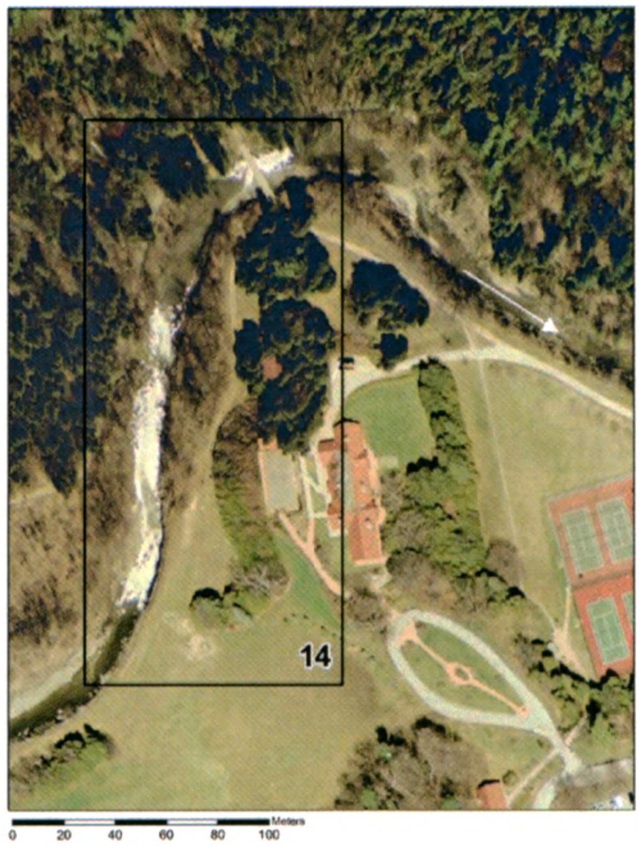

Ellesmere Rd.
6
7
0
30
60
90
120
150 Meters

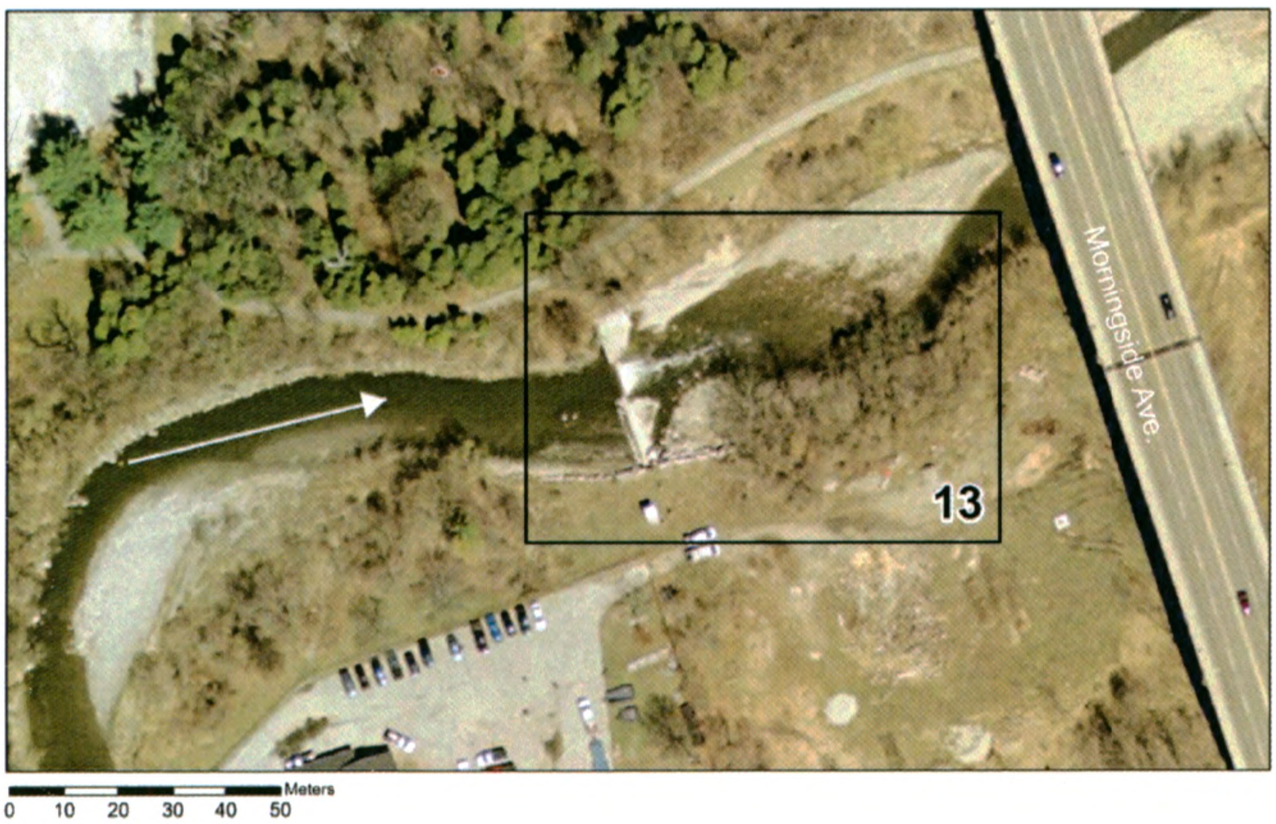

Lawrence Ave.
8
0 30 60 90 120 150 Meters


Lawrence Ave.
10
Meters
0 20 40 60 80 100


9
Meters
0 10 20 30 40 50

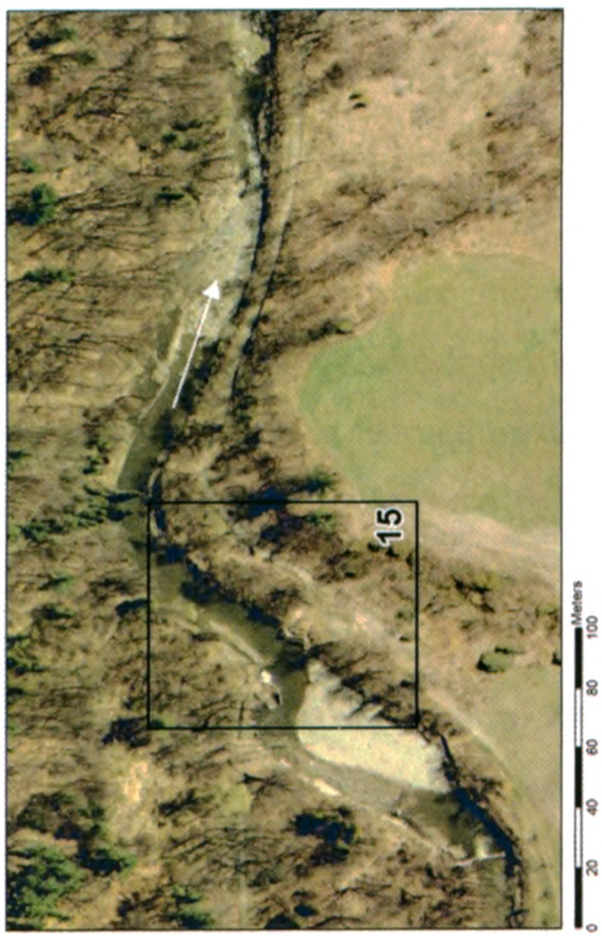

Confluence between
East and West
Highland Creek
12
11
Meters
0 20 40 60 80 100

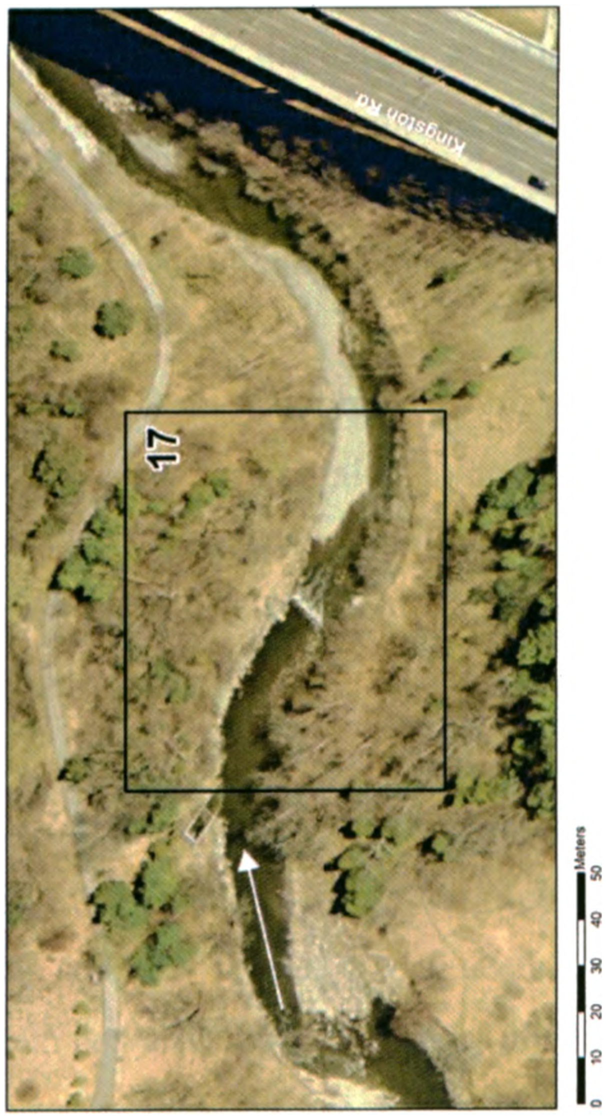

14
Meters
0 20 40 60 80 100


Morningside Ave.
13
Meters
0 10 20 30 40 50


16
Old Kingston Rd.
0 10 20 30 40 50
Meters


18
0 40 80 120 160 200
Meters


15
0 20 40 60 80 100
Meters


17
Kingston Rd.
0 10 20 30 40 50
Meters

The locations of maximum stream power have in common that most of them have been subjected to some kind of engineering. Drop structures are visible in sites 2, 5, 6, 7, 8, 9, 13, 15 and 17. The drop structures are especially common downstream of bridge crossings and are likely to be weirs placed with the intention of protecting the upstream infrastructure. Another reason for the placing of weirs is to slow erosion where the slope is already steep. The points immediately downstream of these structures are now at greater risk of erosion, according to the stream power distribution found in this analysis. This is a good example of the type of problem encountered in an urban channel. Weirs are often put into place to focus energy expenditure at a particular point and to prevent erosion under bridges, for example. However, weirs are necessitated by the steepness of the reaches and so it is difficult to say if the high stream power or the drop structure came first.

Other sections have been straightened or have had their banks and bed reinforced with artificial materials (sites 1, 2, 9, 14 and 16). This is especially severe in the headwater region of Highland Creek, but because of the low discharges experienced there, high stream powers rarely result. Point 1 is an exception to this and according to the DEM is the location of a sustained drop in elevation at the confluence of two first order branches. In the other cases, it is likely that erosion was already underway in these locations when the reinforcements were put into place.

A few of the reaches are immediately downstream from major roads or highways (sites 3, 6, 10 and 11). These locations were subject to changes (straightening and re-alignment) during the construction of the bridges and usually have reinforced banks under the bridge. Runoff from the roads may also be directed into the streams at those locations thereby increasing the discharge, although this would not have been detected by the DEM flow model.

Site 12 is just downstream of the confluence of the east and west branches and is the result of the sudden large increase in discharge. Site 4 is just downstream of a large gravel bar. It is not obvious from the photo is this is naturally formed or engineered, but does result in a drop in slope that causes a high stream power value. Site 18 does not have any of the obvious markers for high stream power present at the other sites. The site shown in the map has a large area because each of the stream power images shows this

maximum in a slightly different location. This is a result of the shift in location caused by estimating the slope with different horizontal slices. This site seems to be a natural local variation in slope.

It is clear that locations of stream power maxima coincide with locations that are very straight or steep. In the case of Highland Creek, a river that has been extensively interfered with, these often correspond to locations that have been artificially straightened or steepened.

Figure 4.18 is a map of the combined location of stream power minimums from the original data described in section 4.1. These minimum stream power values are between 6 and 500 $W \cdot m^{-1}$ with the smallest of these occurring in the 2_50 image and the largest occurring in the R_50 image.The minimum values mostly correspond to headwater locations, which in the Highland Creek basin correspond to locations with low slope and low discharge. Points 6, 7 and 13 however are not in the headwaters region. The orthophotos of corresponding to these locations are shown in Figure 4.19.

Point 7 and Point 13 are locations where the slope is very low. Point 7 seems to have a naturally gentle slope, and point 13 is at the mouth and would be expected to be low. Point 6 however is at the end of a long reach of the river that has been straightened to run parallel to a light rail transit line. The location identified in the GIS corresponds to a short section of the creek with very low slope. Since the channel is in concrete in this location, it must have been constructed this way. Interestingly, the values of stream power go from below 100 Wm^{-1} to over 4000 in the space of one cell in the 2_5 image, suggesting that the energy is being concentrated at the end of the channelized reach instead of being dissipated more evenly throughout the entire reach.

Examination of the orthophotos for Highland Creek supports the suggestion that the locations of stream power maxima and minima that have been identified by the DEM analysis are indeed true locations of stream power discontinuities.

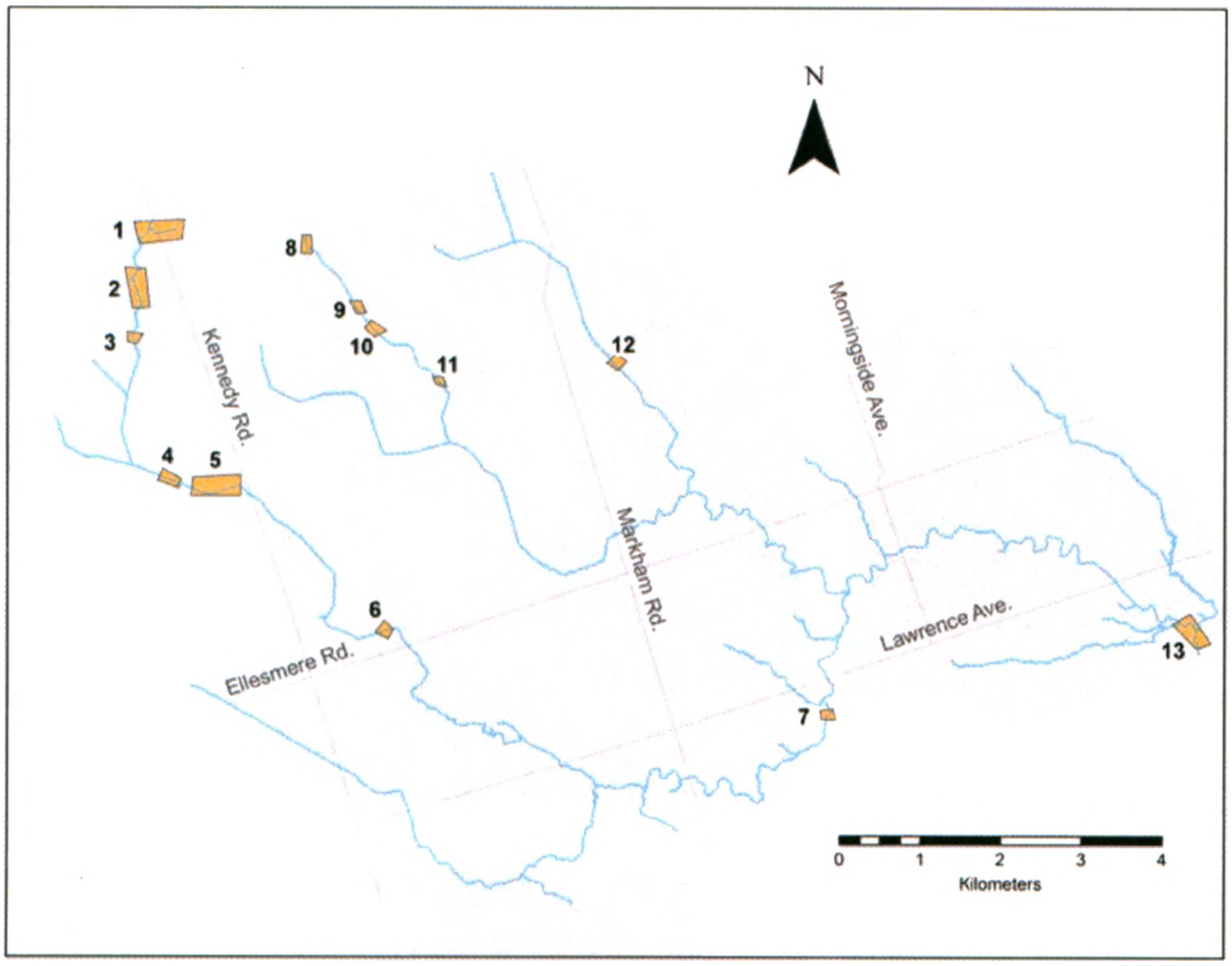


Figure 4.18 Location of stream power minima.

Figure 4.19 Orthophoto close-ups of stream power minima.
Numbers in each photo corresponds to those in Figure 4.18.

4.2.6 Geomorphic change due to 2005 flood

As mentioned in Chapter 2, a large rainstorm affected the Highland Creek watershed on August 19th, 2005 that exceeded the 100-yr return period depth at the City of Toronto gauge (TRCA, 2006). This event led to flooding and large scale erosion in many reaches

along Highland Creek and in other area rivers. The focus of this section is to compare the apparent risk from the stream power maps with actual change that occurred during the flood.

The location of the highest maximum stream power from the DEM analysis corresponds to the portion of East Highland Creek that flows from south of Ellesmere Rd. to the confluence with the West Branch. On Figure 4.16, this corresponds to site numbers 6 and 7. This corresponds to a reach known to the TRCA as 'H8', possibly the reach that underwent the greatest geomorphic change in all of Highland Creek during the flood of 2005. In effect, the distribution of precipitation during the event suggests that the East Branch of Highland Creek would have had higher discharges than the West Branch. Figure 4.20 is a composite of the pre- and post-flood airphotos for this reach.

Under the bridge, armourstone reinforcements were moved into the channel and bridge footings were exposed due to incision. The rocky ramp present in the downstream red box from Fig. 4.20A was bypassed by lateral erosion on the left bank exposing and undercutting a sanitary sewer. Up to 120 metres of lateral migration occurred in this location. A section of channel was cutoff, and the black lines in the post-flood photo are temporary berms put into place after the flood to isolate the sewer break. There was also some channel migration at the confluence between the east and west branches, the downstream end of the photo. A large sand deposit now exists at that location, implying a rapid drop in stream power, possibly the result of backwater.

The large scale erosion and adjustment that occurred in this reach supports using the stream power analysis as a predictor of unstable reaches.

A. Pre-flood

B. Post-flood

Figure 4.20 Orthophotos of valley segment H8, pre- and post- 2005 flood.
Orthophotos of valley segment H8, the East Branch of Highland Creek south of Ellesmere Rd. to the confluence of the east and west branches.

A) H8 before the flood of August 19th 2005.

B) The same reach after the flood. Red squares on photo A represent locations of maximum stream power identified in the GIS analysis. Note the widening in the upstream reach and the channel cutoff near the centre of the photo.

4.2.7 Other mapping ideas

With the calculation of stream power data in a GIS, the task of cross-referencing other data sources is simplified and the resulting visual and spatial organization of the display is a great advantage. A few interesting items to map with stream power that happen to be available for Highland Creek are in-stream barriers (or drop structures) (Figure 4.21) and bank materials and bank protection work (Figure 4.22).

In the case of Highland Creek, there are actually too many drop structures (Fig. 4.21) to be able to draw any reasonable conclusions from the map. If there were fewer of them, then it would be possible to correlate the incidence of peaks in stream power with the location of in-stream barriers. Given the large number of barriers in Highland Creek, information about the drop height and construction of the barriers would be needed to make a meaningful assessment. The presence of all these structures does however help to explain the rapid oscillation in slope along the Highland Creek long profile.

It is possible that an erratic stream power pattern such as the one observed for Highland Creek is common to urbanized channels because of the engineering structures found in the creek.

The artificial banks mapped in Figure 4.22 are the interpretation of field notes provided to the author by Aquafor Beech Limited. With more detailed information on substrate, high stream power values in these locations may provide information on the suitability and success of certain structures. If artificial banks can be assumed to have a higher erosional threshold than natural banks, then presumably, their presence would result in an increase in mean stream power because of possible constraint on channel width, and possibly incision of the stream in those reaches. Potential for incision could be assessed using critical shear stress data as discussed in section 4.2.4. Incision below the level of engineering would of course compromise the bank structures and may be responsible for failures. It may also be likely that natural reaches immediately downstream from engineered reaches are at greater risk for erosion due to the constrictions and possibly reduced channel roughness present in the engineered reaches. As has been suggested, the DEM stream power analysis is to be used as a first-step approach to assessing channel stability and locating potential problem areas. This is an example of a logical next step in field analysis for the watershed manager.

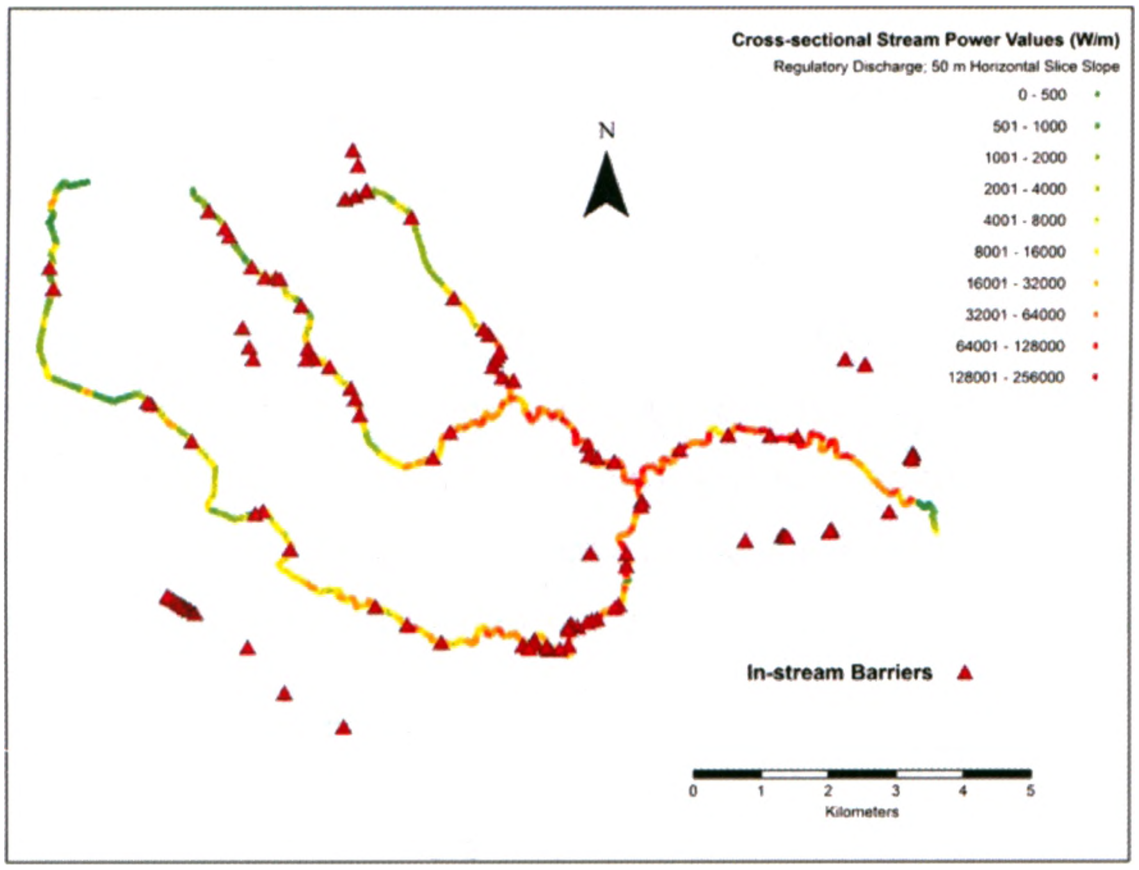


Figure 4.21 In-stream barriers.
This information was collected as part of a fish habitat survey by the Toronto Region Conservation Authority (1999). It serves a geomorphic purpose in that it also identifies locations of steep slope in the channel.

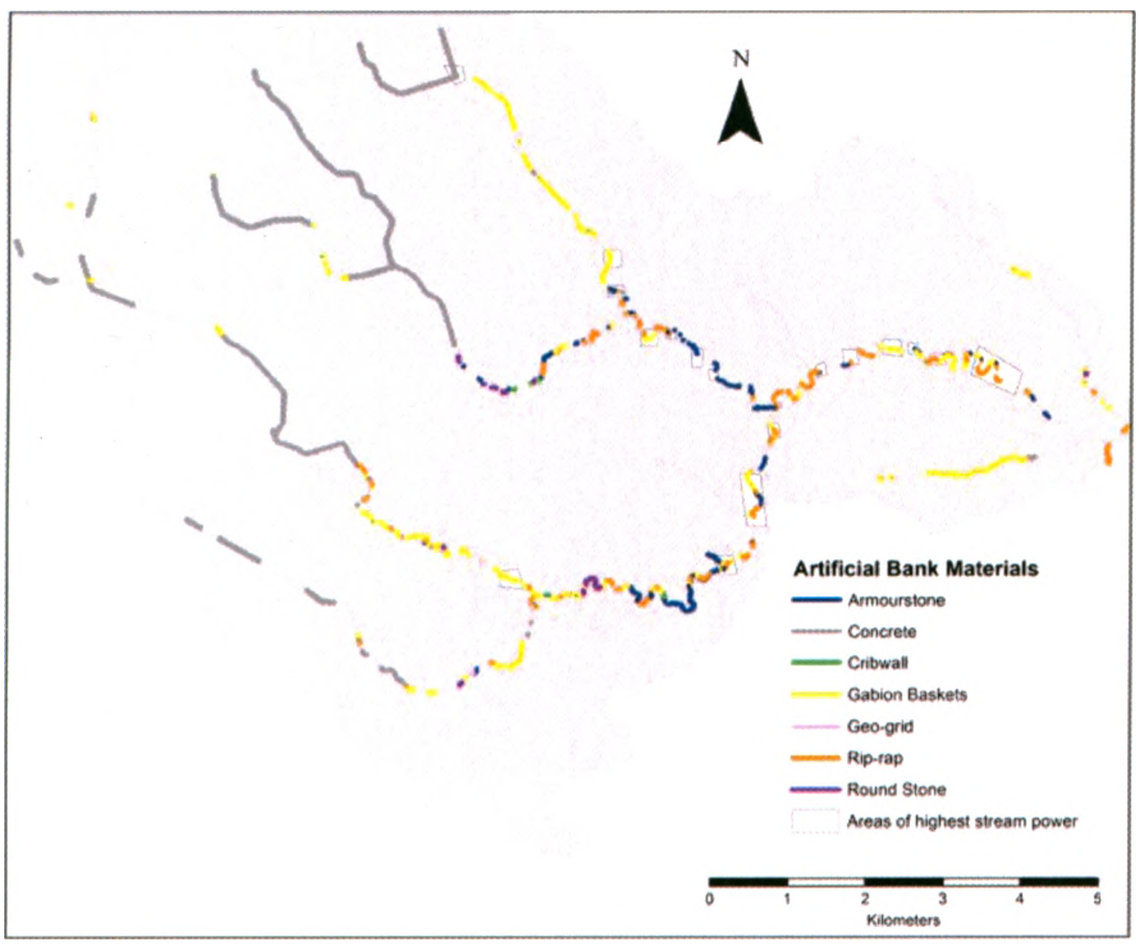


Figure 4.22 Artificial bank material in Highland Creek. *(Aquafor Beech Ltd., 2007).*

The map of stream power and surficial geology presented earlier in the chapter (Fig. 4.10) may also aid in interpretation of stream power distribution and channel stability. Although in this case there is no obvious correlation between sediment type and sites of maximum stream power, it may be possible to correlate sediment type with a critical erosion threshold (see section 4.2.4). If this was possible, there might be different critical stream power values in different sediments that would be cause for concern or at least count as markers for further investigation. It is conceivable that a particular area of the basin is at higher risk for erosion than another. The 'Newmarket Till' and 'Glacial Lake Deposits: silt and sand' that make up the majority of the basin are certain to have different erodibility thresholds. However, the reduced slopes present at the downstream end of Highland Creek, and that are typical of many rivers, result in lower stream power values and a reduced risk for sediment transport and erosion in these locations. It is important to note, however, that the materials identified as surface materials on the surficial geology map may not be present at the elevation of the channel because of incision into underlying material.

Mapping stream power values is an effective tool for visualizing the distribution of stream power throughout the basin. The GIS method for calculating stream power that was described in Chapter 3 was successful in generating usable maps of stream power that can be displayed in a number of ways. Sites of maximum stream power correspond to locations of increased energy in the field and are a good starting point for field investigations. The use of a GIS for displaying stream power values allows for different relationships to be established more easily by overlaying other available datasets. Figure 4.23 is an example of a final stream power map that might be used for presentation purposes. It includes the road and hydrologic network.

The next chapter will assess whether the results of the DEM analysis correspond to other methods of stream assessment.

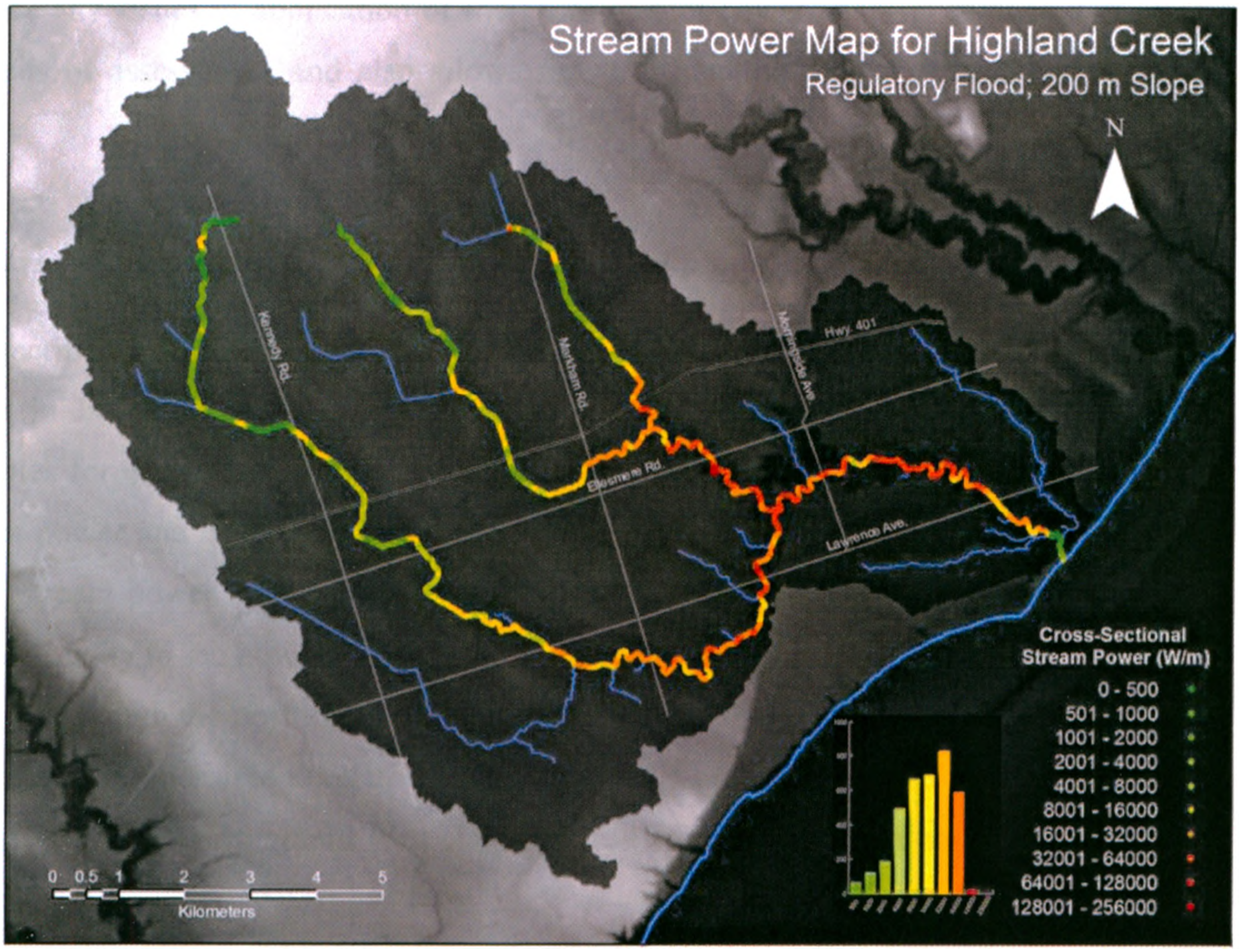


Figure 4.23 Stream power map presentation example.
An example of one way to present the final stream power results in map form.

Chapter 5:

Reliability and comparability of DEM-based stream power analysis

The results of the stream power mapping (Ch. 4) can be compared to other methods of stream assessment. Results from two other methods of assessment are available for Highland Creek:

- Hydraulic model (HEC-RAS) completed in 2007 (from TRCA)
- Rapid Geomorphic Assessment on seven reaches (Parish Geomorphic, 2003).

The purpose of this chapter is to articulate whether the stream power mapping represents the system in the same way as an RGA and a HEC-RAS model. The data can be used to identify any issues in application of the DEM stream power analysis compared to other methods of assessment, and also allows for an evaluation of the precision of the GIS results.

5.1 HEC-RAS: Slope and stream power comparisons

As described in Chapter 2, section 2.6, a HEC-RAS model was completed for Highland Creek in January 2007. As part of the simulation, HEC-RAS computes a number of variables for each 'river station', or cross-section (*see Figure 2.17*). Of these variables, stream power and energy grade slope, were compared to the GIS extracted values. The DEM stream power analysis is not hydraulics-based, but the HEC-RAS model presents an opportunity to see how the DEM slopes compare with hydraulically computed values.

Although the position of each cross-section along the HEC-RAS stream profile is known, it is not possible to relate these positions in a precise manner to the DEM-derived stream. The following graphs plot data using distance downstream based on the DEM-derived stream. Every effort has been made to correct the distance along the HEC-RAS stream to match that of the GIS stream. The result is that the beginning and end of each plot coincide while the centre of the plots may be displaced by a few metres. This is the result of different stream lengths being calculated by different methods, as demonstrated in Section 3.1.2 where the 10-metre DEM and 5-metre DEM streams result in different

lengths. That said, the following shows that GIS results are accurate on a basin-scale and are comparable with the hydraulic analysis from HEC-RAS.

5.1.1 Slope comparison

Slopes calculated in HEC-RAS consist of an energy grade slope of the water surface based on a 1D solution of the flow equations, which produces a physically-based water surface gradient for given discharge, channel bed profile and cross-section (and valley) geometry. The DEM slopes used in the stream power mapping are derived from topography alone and are only an approximation of channel or water surface slope that do not account for channel hydraulics at different flow levels. The HEC-RAS water surface used in these comparisons is the 2-yr RI water surface because it is the lowest flow in the model and is therefore the closest to the channel bed surface, which is the slope calculated in the GIS analysis. A 200 metre horizontal slice slope was chosen as the DEM slope to compare with because this horizontal interval most-closely matches the distances between HEC-RAS stations.

In the following graphs (Figure 5.1), the HEC-RAS slopes are in blue and the DEM slopes in orange. A third order polynomial trendline is displayed in corresponding colour for each reach. The reach names correspond to those shown in Figure 4.1.

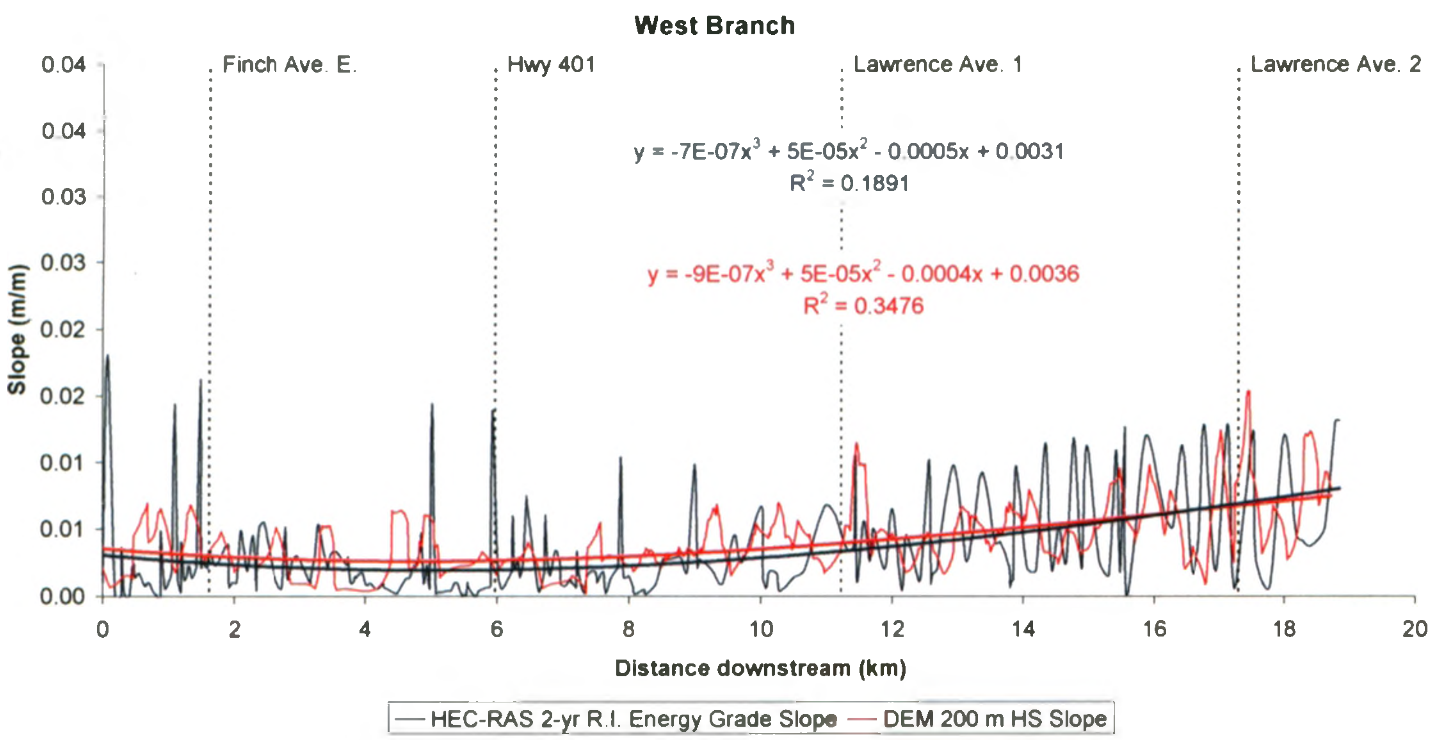
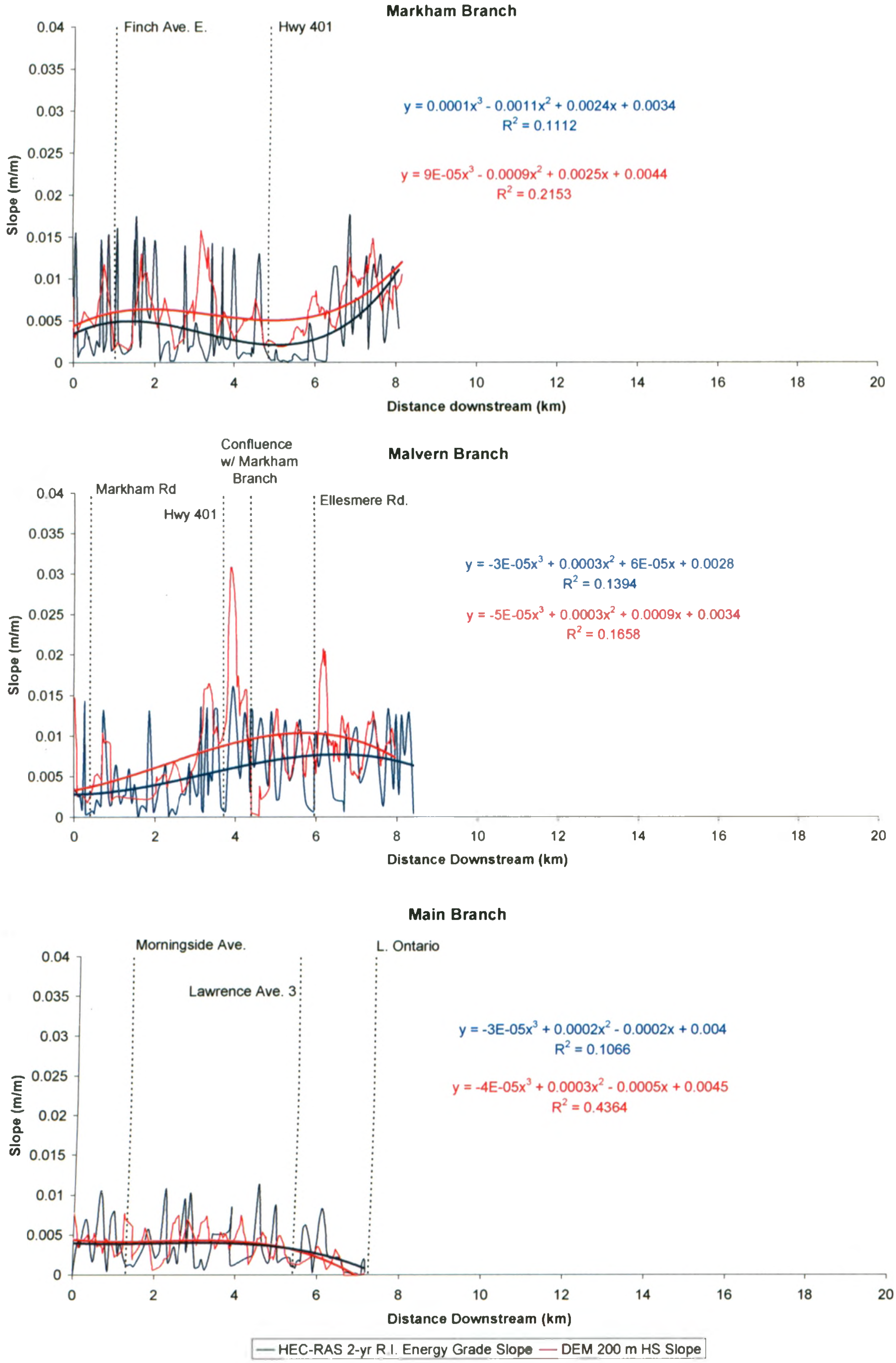


Figure 5.1 Comparison of slopes extracted from HEC-RAS and DEM. *(p.132-133)*


Markham Branch
Finch Ave. E.
Hwy 401
y = 0.0001x³ - 0.0011x² + 0.0024x + 0.0034
R² = 0.1112
y = 9E-05x³ - 0.0009x² + 0.0025x + 0.0044
R² = 0.2153
Slope (m/m)
Distance downstream (km)
Malvern Branch
Confluence w/ Markham Branch
Markham Rd
Hwy 401
Ellesmere Rd.
y = -3E-05x³ + 0.0003x² + 6E-05x + 0.0028
R² = 0.1394
y = -5E-05x³ + 0.0003x² + 0.0009x + 0.0034
R² = 0.1658
Slope (m/m)
Distance Downstream (km)
Main Branch
Morningside Ave.
Lawrence Ave. 3
L. Ontario
y = -3E-05x³ + 0.0002x² - 0.0002x + 0.004
R² = 0.1066
y = -4E-05x³ + 0.0003x² - 0.0005x + 0.0045
R² = 0.4364
Slope (m/m)
Distance Downstream (km)
HEC-RAS 2-yr R.I. Energy Grade Slope
DEM 200 m HS Slope

The polynomial trend lines show matching trends between DEM and HEC-RAS slopes for each reach. However, the trend lines also show that slope values are generally overestimated in the DEM compared to HEC for the Markham and Malvern Branches, and very slightly for the West and Main Branches. This may be because the HEC-RAS slope is a water surface slope and the DEM is theoretically a channel bed slope. The water surface would be smoother and thus the slopes estimated from that surface would be smaller than those estimated from the channel bed. Also, in the HEC-RAS model, backwater effects may be present that cannot be modelled in the DEM. In the downstream ends of the West and Main branches, the slopes are very slightly underestimated by the DEM. Another reason the values and the best-fit lines do not match is that the HEC-RAS and DEM lengths may be out of phase. Also, the high variation in horizontal distances between stations in HEC-RAS, and thus the variation in horizontal length over which slope is estimated compared to the constant horizontal 'slice' used in the DEM analysis is another reason for differences in magnitude and location of values.

In terms of absolute values, the largest difference in slope is on the order of 0.015 $m \cdot m^{-1}$ near kilometer 4 of the Malvern Branch. This peak corresponds to the location of a peak in slope in the HEC-RAS output as well, but the DEM estimation is double the HEC-RAS estimation. This happens to be the intersection of Highland Creek with Highway 401. Another such overestimation occurs at kilometer 5 of the Malvern Branch where Ellesmere Rd crosses the valley. It is difficult to say that one source is more, or less, correct than the other since the magnitude of slope is a reflection of the scale over which it is measured. On the ground however, there is a bed step under the Ellesmere Rd. bridge and both these reaches appear very energetic. Although they differ in the slope values, both the DEM and the HEC-RAS model have identified these locations as being steeper than those upstream and downstream.

In order to make a statistical comparison of the slopes from the HEC-RAS model and the DEM analysis, the slope values were tested as a whole dataset. A frequency distribution was made for each branch comparing the number of slope values in each class for the HEC-RAS model and the DEM analysis. A regression analysis was performed to compare the frequency distributions. Table 5.1 shows the frequency

distributions for each branch. The regressions are all significant and Table 5.2 lists the resulting standard error and r-squared values. For all branches except the West Branch, the slope of the regression is not significantly different from 1. This may simply be because the West Branch is longer than the others.

The nature of the differences in slope suggests that interpretations should be made on a reach scale and that local spikes need to be treated cautiously. Overall, the datasets are statistically similar and the maximum and minimum slope values from the DEM are within the same bounds as the values from HEC-RAS.

Table 5.1 Frequency distributions for HEC-RAS and DEM-derived slope values.

WEST BRANCH					MARKHAM BRANCH				
Slope Classes	DEM *Frequency*	%	HEC-RAS *Frequency*	%	*Slope Classes*	DEM *Frequency*	%	HEC-RAS *Frequency*	%
0.0000	0	0	1	0.40%	0.0001	0	0.00%	1	0.82%
0.0012	161	10.00%	88	34.92%	0.0017	8	0.82%	51	41.80%
0.0024	255	15.84%	66	26.19%	0.0033	146	14.91%	33	27.05%
0.0036	386	23.98%	30	11.90%	0.0049	121	12.36%	8	6.56%
0.0048	265	16.46%	19	7.54%	0.0065	192	19.61%	4	3.28%
0.0060	227	14.10%	15	5.95%	0.0081	153	15.63%	3	2.46%
0.0072	147	9.13%	7	2.78%	0.0097	139	14.20%	1	0.82%
0.0084	50	3.11%	1	0.40%	0.0113	122	12.46%	1	0.82%
0.0097	41	2.55%	1	0.40%	0.0129	49	5.01%	6	4.92%
0.0109	26	1.61%	6	2.38%	0.0145	25	2.55%	5	4.10%
0.0121	20	1.24%	7	2.78%	0.0160	10	1.02%	6	4.92%
0.0133	9	0.56%	6	2.38%	More	14	1.43%	3	2.46%
0.0145	3	0.19%	3	1.19%					
0.0157	4	0.25%	0	0.00%					
0.0169	0	0.00%	1	0.40%					
More	16	0.99%	1	0.40%					

MALVERN BRANCH					MAIN BRANCH				
Slope Classes	DEM *Frequency*	%	HEC-RAS *Frequency*	%	*Slope Classes*	DEM *Frequency*	%	HEC-RAS *Frequency*	%
0.0002	0	0.00%	1	0.91%	0.0001	33	5.36%	1	1.37%
0.0017	18	2.74%	29	26.36%	0.0026	178	28.90%	41	56.16%
0.0033	140	21.31%	22	20.00%	0.0051	278	45.13%	12	16.44%
0.0049	48	7.31%	15	13.64%	0.0076	125	20.29%	9	12.33%
0.0064	95	14.46%	7	6.36%	0.0101	2	0.32%	5	6.85%
0.0080	55	8.37%	8	7.27%	0.0125	0	0.00%	4	5.48%
0.0096	95	14.46%	1	0.91%	0.0150	0	0.00%	0	0.00%
0.0111	81	12.33%	6	5.45%	0.0175	0	0.00%	0	0.00%
0.0127	38	5.78%	6	5.45%	More	0	0.00%	1	1.37%
0.0143	12	1.83%	14	12.73%					
More	75	11.42%	1	0.91%					

Slope values for each branch of Highland Creek are sorted into classes to compare between HEC-RAS and DEM-derived.

Table 5.2 Regression statistics from values paired in Table 5.1.

Branch Name	Standard Error	R^2 value
West	0.114	0.898
Markham	0.233	0.683
Malvern	0.118	0.898
Main	0.106	0.922

5.1.2 Stream power comparisons

Stream power in HEC-RAS is calculated by multiplying the average flow velocity and the shear stress[1] for a cross-section (Dyhouse et al., 2003). Effectively, this results in a mean stream power, since the hydraulic radius of the cross-section is taken into account (*see Equation 3, section 1.1.2,* also often referred to as 'unit stream power' in the literature). In order to compare to the DEM-derived or cross-sectional stream power calculated in this thesis, the HEC-RAS stream power was converted by dividing out the wetted perimeter for each HEC-RAS cross-section. Figure 5.2 uses stream power values that were calculated using the 10-year R.I flood in both HEC-RAS and the DEM. The DEM values also used the 200 m horizontal slice slope. As in the slope comparison graphs, the DEM values are shown in orange, and the HEC-RAS values in blue.

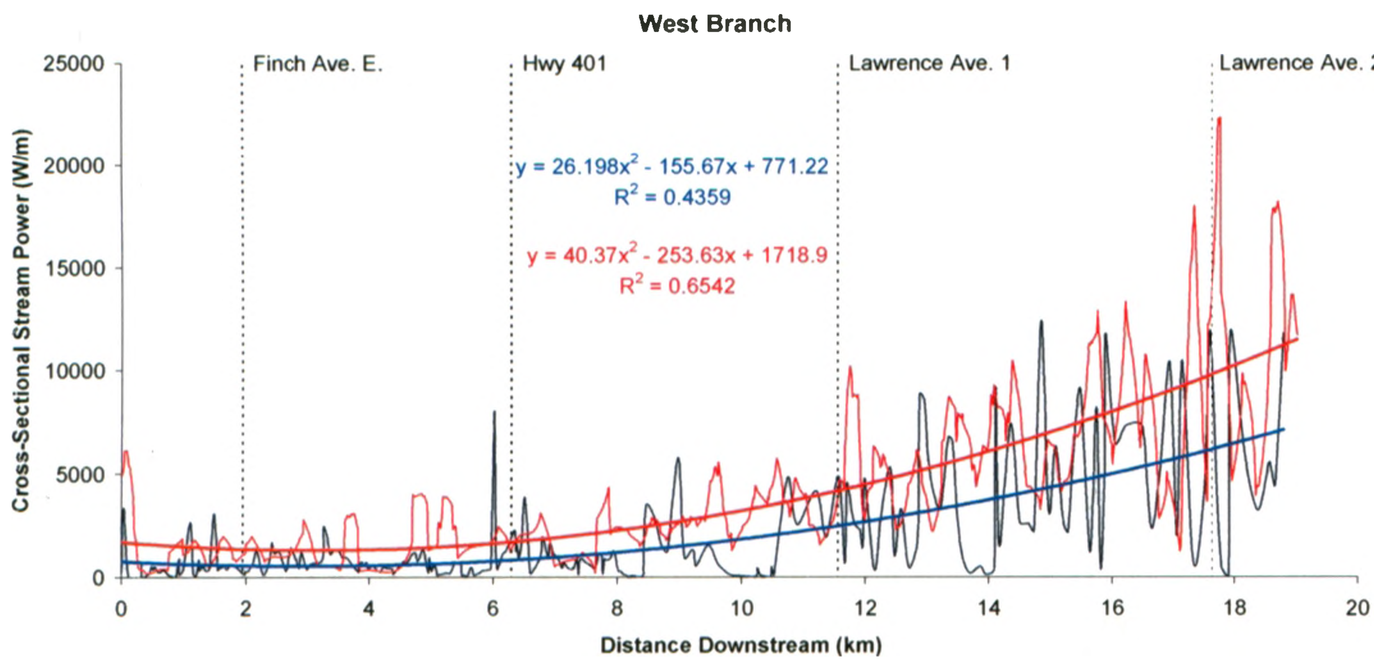


Figure 5.2 Comparison of stream power derived in HEC-RAS and the DEM. *(p.134-135)*

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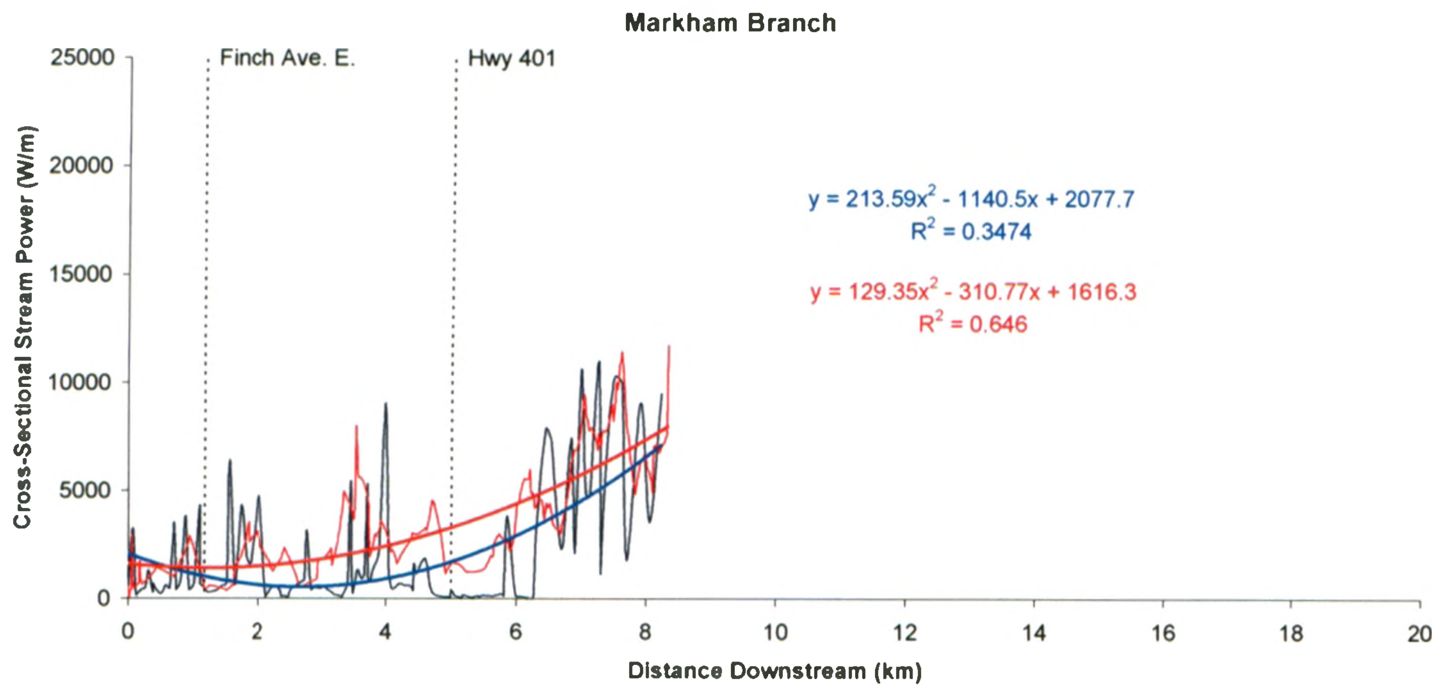
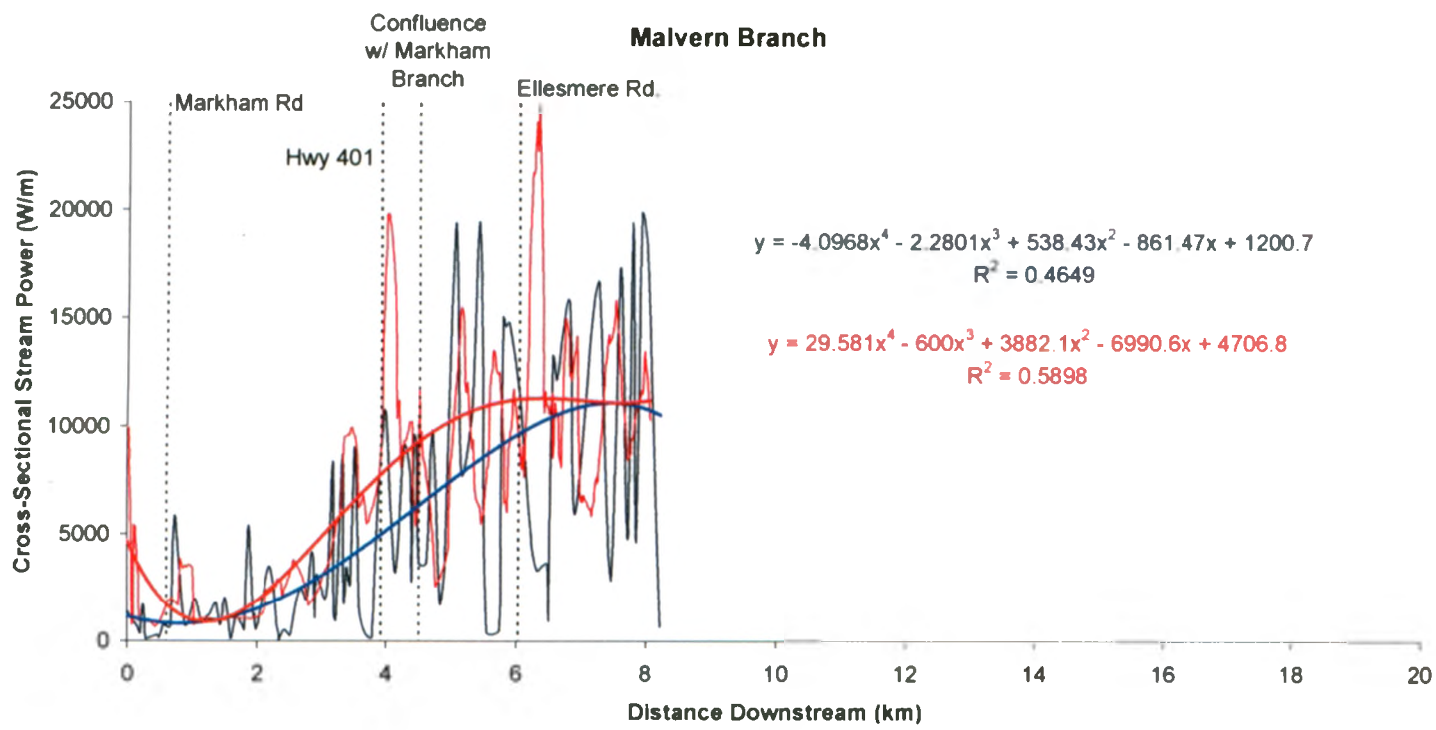
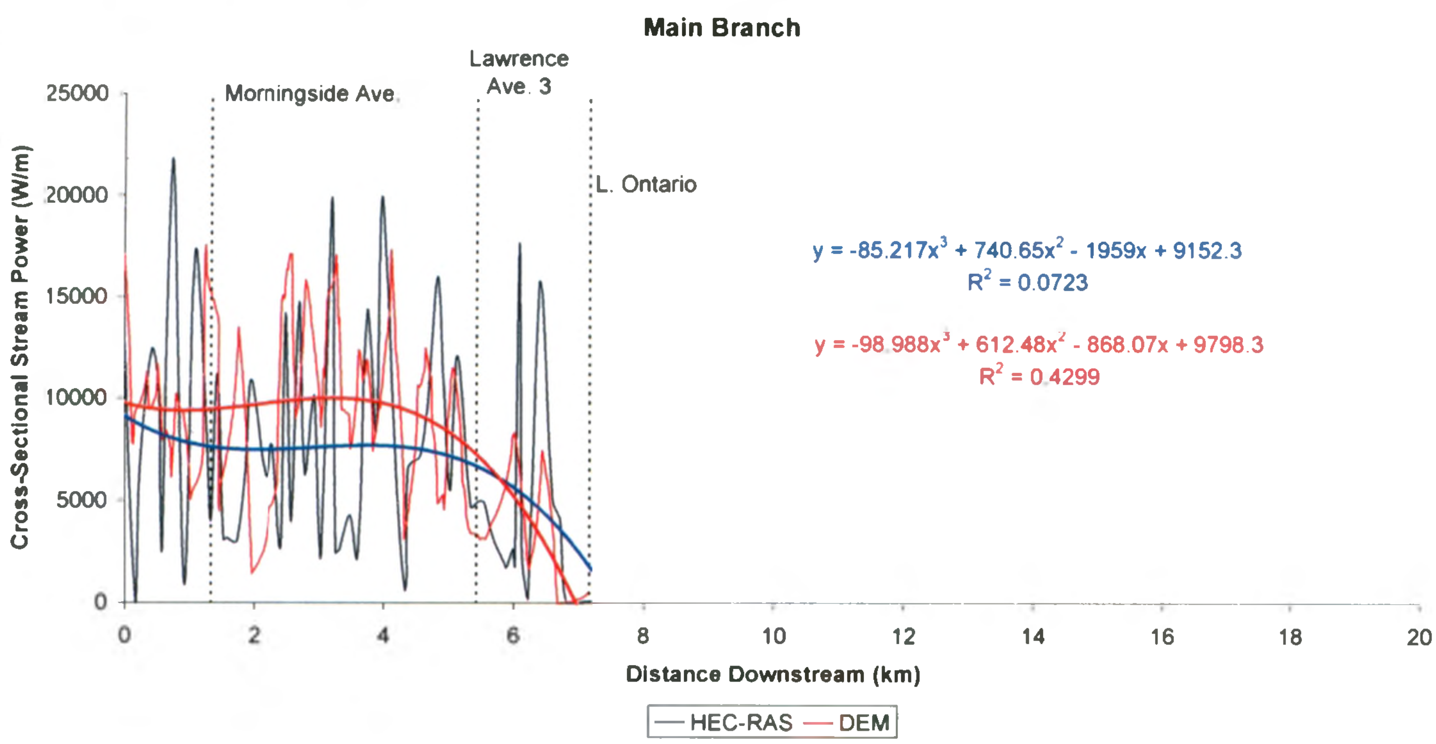
[1] Shear stress in the HEC-RAS model is computed using the following equation:

$\tau = \gamma \cdot R \cdot sf$ where
- τ = shear stress (lbs/ft², N/m²)
- γ = unit weight of water (62.4 lb/ft³ or 1000 kg/m³)
- R = hydraulic radius (ft, m)
- sf = friction slope (ft/ft, m/m)


Markham Branch
Finch Ave. E.
Hwy 401
y = 213.59x² - 1140.5x + 2077.7
R² = 0.3474
y = 129.35x² - 310.77x + 1616.3
R² = 0.646
Cross-Sectional Stream Power (W/m)
Distance Downstream (km)


Malvern Branch
Markham Rd
Hwy 401
Confluence w/ Markham Branch
Ellesmere Rd.
y = -4.0968x⁴ - 2.2801x³ + 538.43x² - 861.47x + 1200.7
R² = 0.4649
y = 29.581x⁴ - 600x³ + 3882.1x² - 6990.6x + 4706.8
R² = 0.5898
Cross-Sectional Stream Power (W/m)
Distance Downstream (km)


Main Branch
Morningside Ave.
Lawrence Ave. 3
L. Ontario
y = -85.217x³ + 740.65x² - 1959x + 9152.3
R² = 0.0723
y = -98.988x³ + 612.48x² - 868.07x + 9798.3
R² = 0.4299
Cross-Sectional Stream Power (W/m)
Distance Downstream (km)
HEC-RAS
DEM

DEM derived discharges (*Section 3.3.1*) and slopes (*Section 3.3.2*) have already been shown to be similar to HEC-RAS derived values. It is expected that the stream power values would also compare favourably to one another. Indeed, for all four reaches, the magnitude of stream power from both HEC-RAS and the DEM is the same. Since slope is part of the stream power calculation, it is to be expected that the same peculiarities demonstrated in Figure 5.1 are visible in Figure 5.2. The stream power values seem to be slightly higher in the DEM than in the HEC-RAS results. Although the peaks and valleys in DEM-derived stream power are not always in the exact same locations as the HEC-RAS stream power, the distribution and overall trends are the same.

5.2 Rapid Geomorphic Assessments

The Rapid Geomorphic Assessment (RGA) is a tool that was developed by the Ontario Ministry of the Environment (1999) to help standardize assessment of urban channels. As described in section 1.1.1, this method is often used by consultants in southern Ontario. The completion of an RGA requires that a list of indicators be identified to help classify channels according to stability. Table 5.3 lists the possible RGA scores and their meaning. The map in Figure 5.3 shows those valley segments that were evaluated using RGAs in 2002 (Parish Geomorphic, 2003) and the results of that assessment.

Table 5.3 Description of RGA stability indexes.

Stability Index	Classification
≤ 0.2	Channel is in regime of stable
0.21 - 0.4	Channel is in transitional state
> 0.4	Channel is stressed and evidence of instability is present

See Appendix A for example of Rapid Geomorphic Assessment worksheet.

It is difficult to draw any conclusions from the RGA results since so few reaches were assessed. As a result, there is little correspondence between maximum stream power values from the GIS analysis and the reaches that are considered 'stressed' according to the RGA. Valley Segment 'GH-9' is the only site that actually coincides with one of the sites of maximum stream power, and it has been classed as 'stressed' by the RGA. A further difficulty is that none of the RGA assessed reaches were classed as stable, making

it difficult to compare to the GIS results. It is apparent that choosing what reaches to assess is a problem in a large watershed, all of which is urbanized causing wide-spread channel adjustment. This much is clear: the GIS stream power analysis can help to identify which areas to focus on using an RGA or other assessment tool and can cover the entire network to provide a basin-wide synthesis of relative erosion risk. Having information about bed or bank material can help to establish an erosion threshold like the one discussed in Section 4.2.4 and would be an excellent starting point for more focused follow-up studies.

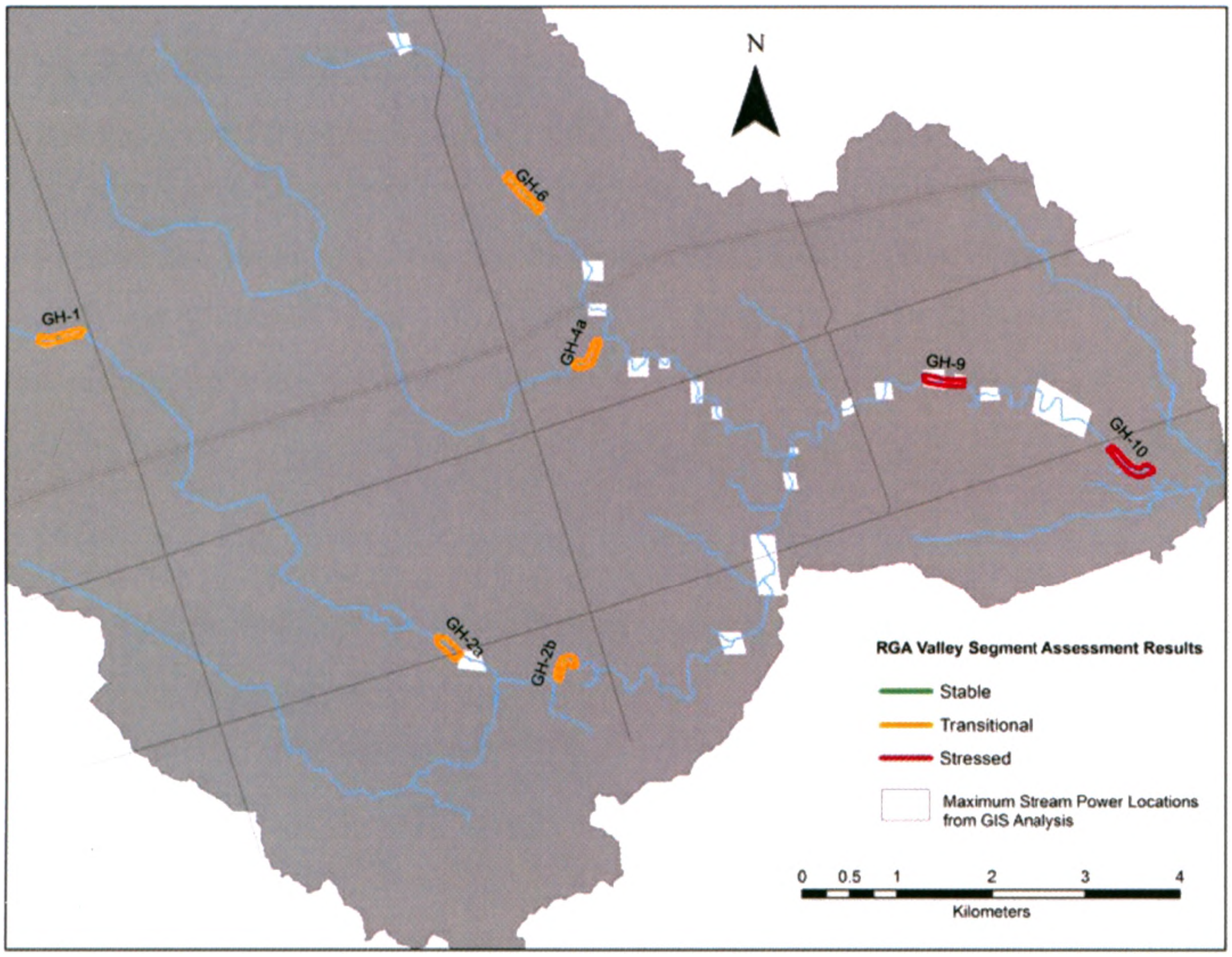


Figure 5.3 RGA Results for selected reaches in Highland Creek.
Reaches that were assessed using RGA in 2002 (Parish Geomorphic, 2003), colour-coded according to results. White rectangles correspond to maximum stream power values identified from DEM analysis in Figure 4.16.

It is clear from the comparisons in this section that the values of DEM-derived stream power are very similar to those derived from a full hydraulic analysis. The HEC-RAS model has a very large number of adjustable parameters and requires considerable insight, training and experience to use reliably and, in many applications, tends to be subject to considerable 'tuning' for a given case. The stream power analysis has only two types of variables to enter thus is much more straightforward to apply and requires no channel-scale information. The DEM analysis also has the advantage of being objective (compared to RGA), reproducible and quick.

Chapter 6: Discussion and conclusion

Rivers in urbanized areas require management of one form or another to identify and mitigate the consequences of urbanization. Urban rivers are especially vulnerable because of the potential magnitude of hydrologic and other changes and the risk to urban infrastructure along river valleys associated with increased channel instability and morphological adjustment (e.g. widening and incision). Effective management of such rivers requires reliable assessment of stream stability, morphology and dynamics.

A number of geomorphic stream assessment tools exist that are currently used in various jurisdictions. They range from descriptive indicators of channel state, such as Rapid Geomorphic Assessment, that may be of uncertain reliability or repeatability, to physically-based modeling tools, such as HEC-RAS that provide continuous hydraulic data from which channel stability may be assessed, but which require considerable training and data to yield useful results. Especially in southern Ontario, where urbanization is spreading rapidly and hydrogeomorphic impacts are the greatest, an assessment tool is needed that is objective, accessible, reliable, rapid and repeatable, in order to provide physically-based reconnaissance assessment of stream channels.

This thesis proposes a GIS-based method that fits these needs by quantifying the driving forces of a fluvial system to help predict channel stability and instability. Using topographic data only, a standard method of calculating stream power in a GIS has been developed. Keeping this data in GIS form, that is to say in map-form, has allowed spatial analysis of the stream power distribution in the entire basin and a comparison of the results with those of independent assessments by the Conservation Authority and consultants, from one-dimensional hydraulic models and observed channel changes following a major flood event.

The basin of Highland Creek near the city of Toronto, Ontario has been used as a case study on which to base the development of the method. The Highland Creek basin is almost completely urbanized (85%) and ongoing instability and adjustment has caused considerable expenditures in channel engineering and infrastructure protection or repair, and, more recently, on channel re-construction and naturalization. A large amount of data is available quantifying different aspects of the river. That data is used in this thesis to

verify the results of the GIS stream power calculation as well as the effectiveness of the stream power maps as an assessment tool.

6.1 Method for creating maps of stream power

A method has been presented here that uses cross-sectional stream power ($W{\cdot}m^{-1}$) as a basis for a standardized, DEM-based assessment. The model is easily accessible and requires very little data and few tools:

- the Provincial DEM v.2 (OMNR, 2005)
- a discharge to area relationship
- ESRI ArcGIS with ArcView license and Spatial Analyst extension
- Script for extraction of channel values to spreadsheet
- Script for return of calculated values to GIS.

ArcGIS is a widely-used GIS program and the ArcView license is the most economical option available from ESRI. A schematic of each script is included in Appendix C. Channel bed elevations from the DEM were tested against 1-metre contours for the Highland Creek basin and were found to correspond very well. The Provincial DEM is determined to be of excellent quality and is available for all of southern Ontario at reasonable cost.

The stream power maps for a whole basin can be created in approximately 2 work days, depending on prior knowledge of GIS hydrologic analysis and familiarity with Provincial DEMs and ArcGIS. The resulting stream power maps are objective and standardized.

6.2 Reliability of GIS results

A number of data sources are available for Highland Creek that were used to verify the accuracy of the DEM analysis.

The stream power calculation requires discharge and slope for each cell in the stream. Computing discharge based on a DEM requires the use of a discharge to area relationship. Regional curves are not acceptable proxies for urbanized areas, unless they are explicitly developed for highly-urbanized watersheds, and it is important to find a

suitable equation to properly approximate discharge. In the case of Highland Creek, a pre-existing hydrologic model was used as the basis for the derivation of such a relationship. This type of analysis is likely to be available for many urban watersheds in Ontario. The distribution of drainage area values calculated using the DEM was found to be almost identical to that of the hydrologic model but would need to be confirmed in each case.

Deriving channel slope from a DEM requires the extraction of elevation values from the GIS to a spreadsheet program. Different methods of calculating slope were thoroughly examined and verified using airphotos, road maps, and field survey. DEM-derived slopes were found to be accurate and it was shown that the periodic increases and decreases in slope are not artifacts of the data from which the DEM was derived but are real features of the channel.

The highest stream power values in the Highland Creek basin were identified just downstream of the Ellesmere Rd. bridge and is the location of large scale channel adjustment during the flood of August 19th, 2005 and the site of extensive channel construction after the flood. Other sites of maximum stream power were identified and found almost always to correspond to the location of drop structures and artificial channel straightening or bed and bank reinforcements.

Examination of the basin-wide pattern of stream power using smoothed slope values revealed a mid-basin peak, but confirmed that stream power must be evaluated separately for each case because of unique combinations of slope, discharge and sediment distributions. This may be especially true of urban channels due to the presence of structures and artificial changes.

Pre-urbanization discharges were used to create a set of pre-urban stream power maps. These confirm the theory that present day flows have much greater power and are capable of doing more work, thus causing more erosion, than flows prior to the 1970's.

6.3 Suitability of stream power mapping for river stability assessment

Data from two commonly used stream assessment methods were available for Highland Creek: a HEC-RAS hydraulic analysis and RGA scores for seven reaches.

The actual values derived from the DEM analysis were found to be of the same magnitude as those from a complete hydraulic analysis in HEC-RAS. The distribution and overall trends are also the same. The DEM-analysis requires much less experience and training and is much less data-intensive.

It was impossible to correlate the RGA results with the stream power maps because so few reaches were evaluated in the RGA analysis. This highlights one of the main problems with the RGA assessment method: that it is difficult to select which reaches to assess. One advantage of the stream power maps is that the analysis is simlutaneously conducted for the entire basin. At the very least, the maps of stream power are an objective way to determine which reaches of a river are at greater risk for erosion. This is an excellent first-step assessment tool to help identify where further monitoring efforts should be focused.

6.4 Recommendations for future research

Hydrologic information for urbanizing basins in southern Ontario is lacking. Developing an appropriate method for estimating discharge for ungauged basins, based on upstream drainage area, or other basin characteristics (especially land cover), would help fine-tune the stream power maps.

The method developed here derives the erosional energy expenditure in the system. A full analysis of channel stability also requires an assessment of erosional resistance such as the threshold stream power for different bed and bank material and the distribution of channel boundary materials within the catchment. Erosion criteria based on stream power are being developed for non-cohesive materials (e.g. Ferguson, 2005) but requires further research for cohesive materials such as glacial till. Developing erosion thresholds for different sediment types in southern Ontario streams would allow critical stream power values to be determined for different locations in a basin. One

possibility would be to measure the mean stream power (*Eq. 3*) threshold at locations where erosion is occurring and then converting these to a cross-sectional stream power by multiplying in the width. This may reveal a critical cross-sectional stream power that can be used as a threshold.

The urbanized basin presents a special case for GIS analysis. It would be useful to examine how routing stormwater through sewers affects drainage area, watershed boundaries and tributary inputs calculated using conventional GIS flow routing algorithms based on surface topography, and how these urbanized processes and boundaries can be modelled in a GIS. Another urban problem is that of reinforced beds and banks and it would be interesting to examine the effect that these have on stream power distribution throughout a basin.

6.5 Conclusion

Creating maps of stream power in a GIS, based on the Ontario Provincial DEM v.2, has produced values that are comparable with other methods. As shown by comparing to hydraulic model outputs, the stream profile from a DEM has been used successfully as an approximation of the water surface under 2 year flood conditions. The creation of the maps is standardized and objective and can be used as an assessment tool to determine which reaches are potentially unstable and where further investigation is required. It is a valuable first step in objective, quantitative geomorphic assessment.

Semi-alluvial streams like Highland Creek have unique long profiles and a potential for very high stream power values that require assessment to be carried out on a case by case basis. The DEM-based analysis allows for an in-depth examination of energy distribution over a whole basin that requires little time or data. This makes examining individual cases possible.

Although stream power values have been calculated in GIS in a few other studies, this research represents the first attempt at mapping cross-sectional stream power. It is also the first attempt at modeling southern Ontario rivers using Ontario DEM data. The DEM is of finer-scale than most other studies (10 m cells) and the basin studied is of moderate gradient, different from the high gradient examples used in other studies

(Finlayson et al., 2002; Finlayson and Montgomery, 2003; Reinfelds et al., 2004; Jain et al., 2006).

The DEM stream power analysis developed in this thesis is an example of a geomorphological dynamics assessment (Downs and Gregory, 2004). It takes into account the channel system as a whole and incorporates both basin-scale and local-scale parameters. Unlike the more popular channel classification methods of assessment (e.g. Rosgen, 1996; Ontario Ministry of the Enviconment, 1999), this method and its results are less prone to operator error and do not require any extensive training or prior knowledge of geomorphology. The method can be used in basins where no prior information or data has been collected. It produces an excellent first step in channel assessment and allows for time, knowledge and financial resources to be focused more appropriately on a reach scale. The DEM stream power analysis can be used even in areas where rapid land use change is occurring, unlike at-a-glance in-field inventory type assessment methods, because it is based on a physical parameter that is a known determinant of channel form and channel dynamics. The stream power maps are an objective and standardized way of locating energy maxima and minima within a basin.

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Appendix A

Sample RGA Worksheet

Table C.1: Summary of Rapid Geomorphic Assessment (RGA) Classification

FORM/ PROCESS (1)	GEOMORPHIC INDICATOR		PRESENT		FACTOR
	NO (2)	DESCRIPTION (3)	NO (4)	YES (5)	VALUE (6)
Evidence of Aggradation (AI)	1	Lobate bar			
	2	Coarse material in riffles embedded			
	3	Siltation in pools			
	4	Medial bars			
	5	Accretion on point bars			
	6	Poor longitudinal sorting of bed materials			
	7	Deposition in the overbank zone			
		SUM OF INDICES			
Evidence of Degradation (DI)	1	Exposed bridge footing(s)			
	2	Exposed sanitary/storm sewer/pipeline/etc.			
	3	Elevated stormsewer outfall(s)			
	4	Undermined gabion baskets/concrete aprons/etc.			
	5	Scour pools d/s of culverts/stormsewer outlets			
	6	Cut face on bar forms			
	7	Head cutting due to knick point migration			
	8	Terrace cut through older bar material			
	9	Suspended armor layer visible in bank			
	10	Channel worn into undisturbed overburden/bedrock			
		SUM OF INDICES			
Evidence of Widening (WI)	1	Fallen/leaning trees/fence posts/etc.			
	2	Occurrence of large organic debris			
	3	Exposed tree roots			
	4	Basal scour on inside meander bends			
	5	Basal scour on both sides of channel through riffle			
	6	Gabion baskets/concrete walls/etc. out flanked			
	7	Length of basal scour > 50% through subject reach			
	8	Exposed length of previously buried pipe/cable/etc.			
	9	Fracture lines along top of bank			
	10	Exposed building foundation			
		SUM OF INDICES			
Evidence of Planimetric Form Adjustment (PI)	1	Formation of cute(s)			
	2	Single thread channel to multiple channel			
	3	Evolution of pool-riffle form to low bed relief form			
	4	Cutoff channel(s)			
	5	Formation of island(s)			
	6	Thalweg alignment out of phase meander form			
	7	Bar forms poorly formed/reworked/removed			
		SUM OF INDICES			
STABILITY INDEX (SI) = (AI + DI + WI + PI) / m					

Table C.2: Interpretation of RGA Form Stability Index Value

Stability Index (SI) Value	Classification	Interpretation
$SI \leq 0.2$	In Regime	The channel morphology is within a range of variance for streams of similar hydrographic characteristics – evidence of instability is isolated or associated with normal river meander propagation processes
$0.21 \leq SI \leq 0.4$	Transitionally or Stressed	Channel morphology is within the range of variance for streams of similar hydrographic characteristics but the evidence of instability is frequent
$SI > 0.4$	In Adjustment	Channel morphology is not within the range of variance and evidence of instability is wide spread

Appendix B

Regressions for discharge to area relationships

Gauges within 50 km of Highland Creek

Regression Statistics	
Multiple R	0.41
R Square	0.17
Adjusted R^2	0.11
Standard Error	18.00
Observations	16.00

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	927.15	927.15	2.86	0.11
Residual	14	4536.19	324.01		
Total	15	5463.34			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	21.83	9.13	2.39	0.03	2.26	41.41	2.26	41.41
82	0.11	0.07	1.69	0.11	-0.03	0.25	-0.03	0.25

Recurrence Interval Discharges from ABL Hydrologic Modeling

2 yr

Regression Statistics	
Multiple R	0.95
R Square	0.91
Adjusted R Square	0.90
Standard Error	13.19
Observations	26.00

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1.00	40569.42	40569.42	233.13	0.00
Residual	24.00	4176.42	174.02		
Total	25.00	44745.85			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	16.49	3.57	4.62	0.00	9.12	23.87	9.12	23.87
3.24	1.26	0.08	15.27	0.00	1.09	1.43	1.09	1.43

5 yr

Regression Statistics	
Multiple R	0.94
R Square	0.89
Adjusted R Square	0.88
Standard Error	20.55
Observations	26.00

ANOVA

	df	SS	MS	F	Significance F
Regression	1.00	79306.48	79306.48	187.86	0.00
Residual	24.00	10131.54	422.15		
Total	25.00	89438.01			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	25.45	5.57	4.57	0.00	13.96	36.93	13.96	36.93
3.24	1.76	0.13	13.71	0.00	1.49	2.02	1.49	2.02

10 yr

Regression Statistics	
Multiple R	0.94
R Square	0.88
Adjusted R Square	0.88
Standard Error	25.49
Observations	26.00

ANOVA

	df	SS	MS	F	Significance F
Regression	1.00	118010.17	118010.17	181.70	0.00
Residual	24.00	15587.73	649.49		
Total	25.00	133597.90			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	31.76	6.90	4.60	0.00	17.51	46.01	17.51	46.01
3.24	2.14	0.16	13.48	0.00	1.82	2.47	1.82	2.47

25 yr

Regression Statistics	
Multiple R	0.94
R Square	0.89
Adjusted R Square	0.89
Standard Error	31.09
Observations	26.00

ANOVA

	df	SS	MS	F	Significance F
Regression	1.00	187389.67	187389.67	193.84	0.00
Residual	24.00	23201.65	966.74		
Total	25.00	210591.31			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	38.89	8.42	4.62	0.00	21.50	56.27	21.50	56.27
3.24	2.70	0.19	13.92	0.00	2.30	3.10	2.30	3.10

50 yr

Regression Statistics	
Multiple R	0.94
R Square	0.89
Adjusted R Square	0.89
Standard Error	35.82
Observations	26.00

ANOVA

	df	SS	MS	F	Significance F
Regression	1.00	252956.93	252956.93	197.19	0.00
Residual	24.00	30787.55	1282.81		
Total	25.00	283744.49			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	45.01	9.70	4.64	0.00	24.99	65.04	24.99	65.04
3.24	3.14	0.22	14.04	0.00	2.68	3.60	2.68	3.60

100 yr

Regression Statistics	
Multiple R	0.95
R Square	0.89
Adjusted R Square	0.89
Standard Error	40.40
Observations	26.00

ANOVA

	df	SS	MS	F	Significance F
Regression	1.00	328506.26	328506.26	201.25	0.00
Residual	24.00	39175.33	1632.31		
Total	25.00	367681.59			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	51.36	10.94	4.69	0.00	28.77	73.95	28.77	73.95
3.24	3.58	0.25	14.19	0.00	3.06	4.10	3.06	4.10

Regulatory

Regression Statistics	
Multiple R	1.00
R Square	0.99
Adjusted R Square	0.99
Standard Error	24.57
Observations	26.00

ANOVA

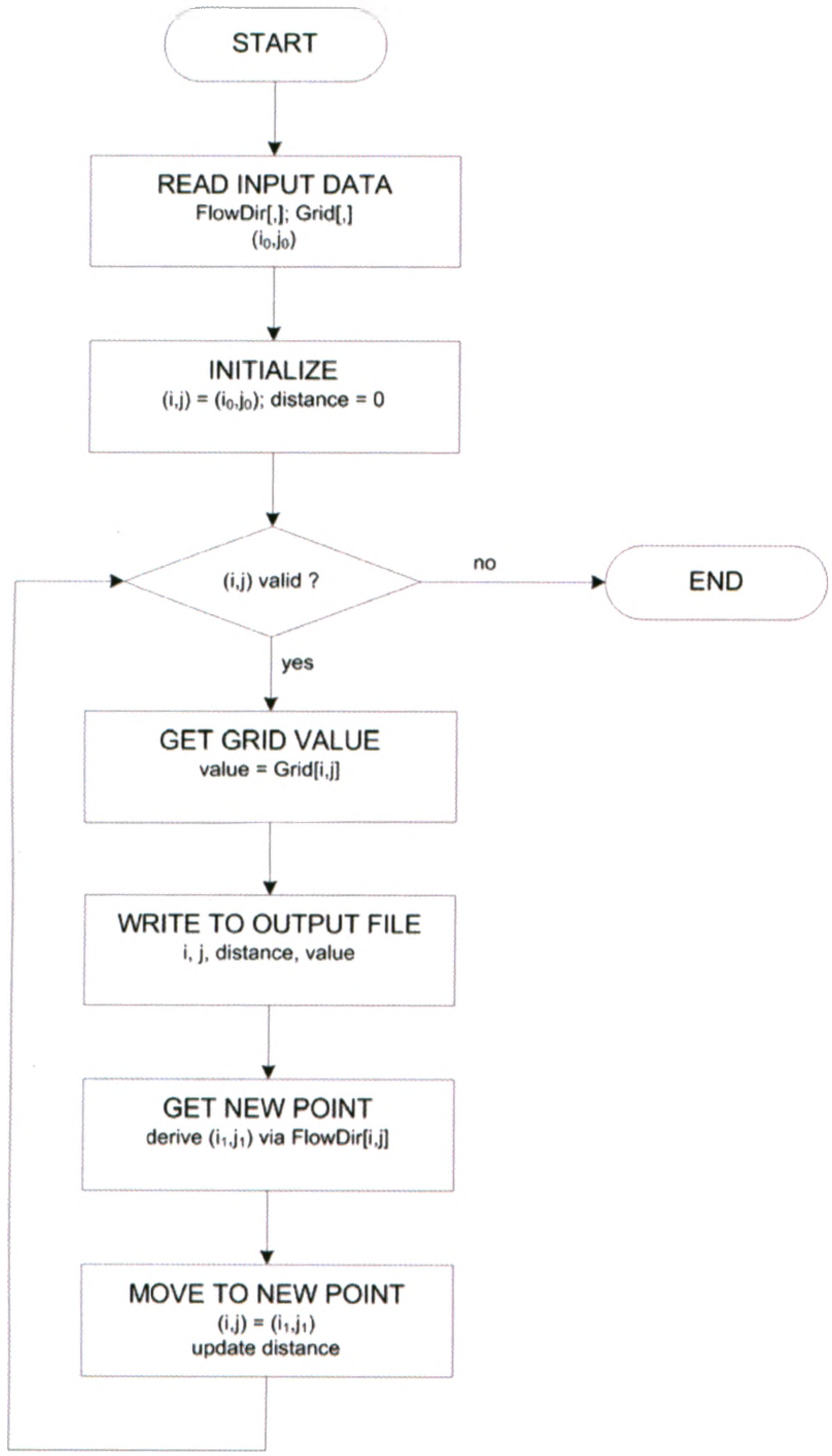
	df	SS	MS	F	Significance F
Regression	1.00	2015935.15	2015935.15	3338.96	0.00
Residual	24.00	14490.28	603.76		
Total	25.00	2030425.43			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	40.05	6.66	6.02	0.00	26.31	53.79	26.31	53.79
3.24	8.86	0.15	57.78	0.00	8.54	9.18	8.54	9.18

Appendix C

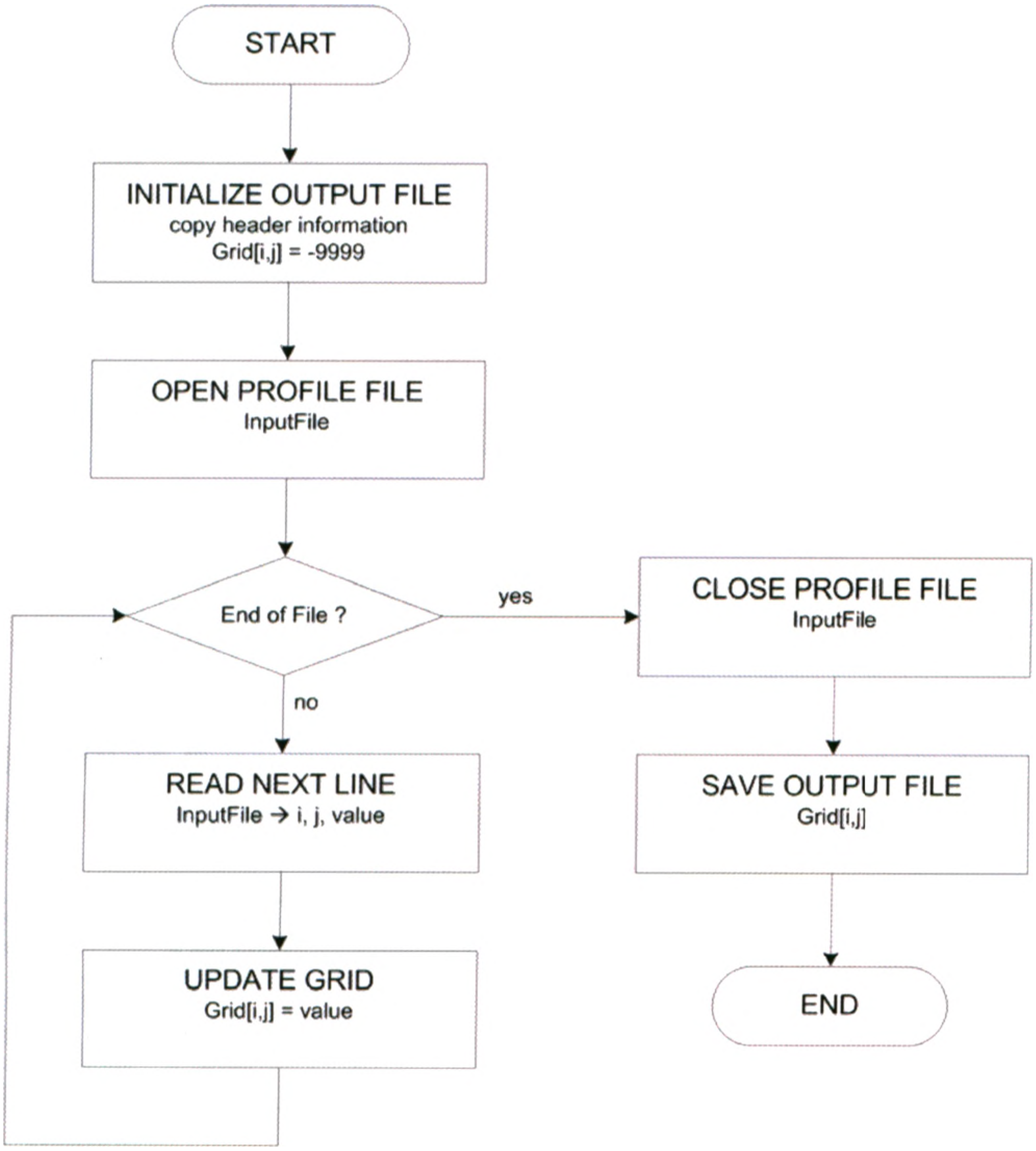
Script schematics

Profile Extractor



(Van de Wiel, 2008)

Profile Returner



(Van de Wiel, 2008)

Appendix D

Hydrologic model (Otthymo) and GIS drainage area comparison

Regression Statistics	
Multiple R	0.998892826
R Square	0.997786878
Adjusted R Square	0.997663927
Standard Error	1.561487137
Observations	20

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	19787.08	19787.08021	8115.3059	2.3646E-25
Residual	18	43.888357	2.438242079		
Total	19	19830.969			

	Coefficients	***Standard Error***	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	**0.675500893**	**0.527019**	1.281739219	0.216199	-0.43172489	1.78273	-0.432	1.7827
X Variable 1	**0.962791542**	**0.0106876**	90.08499238	2.365E-25	0.94033775	0.98525	0.9403	0.9852

Appendix E

Field survey slopes comparison

Regression Statistics	
Multiple R	0.88116927
R Square	0.77645928
Adjusted R Square	0.76248799
Standard Error	0.00165177
Observations	18

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.000152	0.000152	55.57533	1.36828E-06
Residual	16	4.37E-05	2.73E-06		
Total	17	0.000195			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.00041113	0.000796	0.516332	0.612685	-0.00128	0.00210	-0.00128	0.00210
X Variable 1	0.93863377	0.125909	7.454886	1.37E-06	0.67172	1.20555	0.67172	1.20555

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