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Identifying deep-groundwater discharge in Rivers of Eastern Ontario

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ABSTRACT

Interactions between surface water systems and groundwater systems are poorly understood. This research focuses on the surface water / groundwater interactions that use an electric conductivity and temperature (EC&T) drag probe in the Raisin River and South Nation Watershed.

To find groundwater seepages into rivers, a Reelogger Model 2001 probe (Solinst Canada Ltd) was dragged at the sediment-water interface to measure EC & T for several reaches of the Raisin River, the Castor River, the East Castor and the South Nation River. GPS position data was collected at the same time as the EC & T measurements which allows the data to be input into a GIS database for management decisions. During the summer, groundwater typically had higher EC and lower T values than the surface water, and so increases in EC occurring along with lower water temperatures were inferred to be deep-groundwater discharge locations. High EC values can be explained either by deep groundwater discharge (seeps) or by local anthropogenic loading of sediments into the river. In rivers with low permeability clay streambeds very few locations of significant discharge were detected using this method. The most significant discharge area, called the "Swimming Hole" by local residents, was surveyed at large and small scale and groundwater seepage was found to be present along the shore and in the middle. However, the EC&T probe appears to have identified relatively high flux discharge zones in the Castor and East Castor River at locations where highly permeable eskers cross the rivers. The survey identified approximately a 50 m area along the Castor river and a 100m area along the East Castor River where EC values were as high as 2000 μS/cm and temperature as low as 11°C. They were investigated and fluxes quantified by installing and testing piezometers and deploying seepage meters.

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1. Introduction

1.1 Background

Interactions between surface water systems and groundwater systems are poorly understood and yet, they are of importance when studying the hydrodynamics, the overall water balance and the ecological health of rivers and groundwater systems. From the surface water resource point of view, the hydrodynamics of the interaction are particularly important in management issues relating, for example, to flood control, waste discharge timing or permits to take water. Understanding groundwater / surface water interactions is also important from the groundwater resource perspective since surface waters can act as major areas of groundwater discharge and recharge. These interactions have an impact on both the quantity and the quality of the two resources, which in turn affect the quality of life of people and of ecological systems. Ecological systems are particularly vulnerable (and resilient at the same time) to contaminants from groundwater plumes or from surface water inputs (such as anthropogenic loading in urban settings or tile drains in agricultural areas). It is also well known that groundwater / surface water exchanges in streambeds can affect the distribution and health of benthic and hyporheic aquatic life within the streambeds (Conant, 2004). The vulnerability of water resources in general has prompted regulatory and legislative actions throughout the world.

In Ontario, the focus has been on potable water, with the introduction of the Clean Water Act (2006). The Act requires Source Water Protection Regions throughout the province to produce management plans that are based on on-going extensive technical work on assessing potable water resources. Groundwater / surface water interactions have been identified as an important element of this assessment, and for which there was little information available. The research presented in this thesis attempts to narrow this knowledge gap.

Groundwater-surface water interactions have been identified and quantified using a variety of techniques and field equipment. They include seepage meters alone or with piezometers (Freeze and Cherry, 1979), piezometer tests for hydraulic conductivity and flux (Lee, 1985), streambed temperature mapping (Conant, 2004) and geochemistry comparisons between surface and groundwater. These techniques produce measurements and samples at a fine scale

(scale of the river reach), and obtaining information over a large region can be expensive and time consuming.

An alternate but less accurate and less complete technique that can be used as a reconnaissance tool at the basin scale is the electrical conductivity and temperature (EC&T) drag probe. The technique was used successfully during the summers of 2002 and 2003, in a pilot survey by Janet Kingsley, which determined that the EC&T at the water-sediment interface could be used as an indicator of deep-groundwater seepage into the South Nation River (Kingsley, 2005). EC&T mapping is a simple, inexpensive, qualitative approach that can cover a large territory in a relatively short time. The research presented in this thesis focuses on surface-groundwater interactions, using the EC&T drag probe method along with complementary methods, in two watersheds: the Raisin River and the South Nation Watersheds. The study sites are described in detail in the following section.

1.2 Scope of Work

The Raisin River (RR) and the South Nation River (SNR) Watersheds are located in Eastern Ontario and they comprise the majority of the Raisin-South Nation Source Water Protection Region, depicted in Figure 1.1.

The Raisin River Watershed is located north of Cornwall and drains generally eastward and southeastwardly in its lower reaches into the St Lawrence River. This basin is a small agricultural watershed that was studied during 2005-2006 as part of the watershed and Environment Resource Assessment Project (WERAP) The WERAP is a broad interdisciplinary study lead by nine professors from the University of Ottawa, Queen's University and the University of Waterloo and involving undergraduate and graduate students. The WERAP was carried out in collaboration with the Raisin River Conservation Authority (RRCA) and the St Lawrence River Institute of Environmental Science (SLRIES). Other relevant hydrogeology projects among the interdisciplinary research group were undertaken in the area: a study of the groundwater geochemistry and the potential for groundwater contamination from agricultural sources by Martin Suchy, of the Department of Earth Science (University of Ottawa) (Suchy, 2008, M.Sc. in progress); a study of biological indicators of groundwater seepage into the river, by Lieserl Woods, also of the Department of Earth

Sciences (University of Ottawa) (Woods, 2008, M.Sc. in progress); a study of streambed temperature mapping as a groundwater discharge indicator by Dalton McGuinty (McGuinty, 2007); and a study of an electro-magnetic probe as a groundwater seepage tool by Caroline Gagné (Gagné, 2007), the last two, undergraduate students from the Environmental Sciences Program at the University of Ottawa. The WERAP's mandate was to monitor and evaluate the ecological health of the Raisin River Watershed in a holistic approach. The research presented in this thesis completes and uses information and data gathered in the Raisin River Watershed by others as part of the WERAP.

The South Nation River (SNR) Watershed is located north of the Raisin Region, and drains northeastwardly, into the Ottawa River. Three sites were studied in the SNR Watershed during the summer / fall 2006. They comprised two of its tributaries, the Castor and East Castor Rivers, near the Village of Embrun, and an 8 km long reach of the main trunk of the SNR between the villages of Winchester and Chesterville. The investigation on these rivers was undertaken to complement a study of buried sand and gravel esker systems in the area (Charland and Robin, 2007). The study is in collaboration with the University of Ottawa, the South Nation Conservation Authority (SNCA) and the Geological Survey of Canada (GSC).

1.3 Objectives

The main objective of the thesis was to conduct an Electrical Conductivity and Temperature (EC&T) survey to identify possible deep-groundwater discharge in the Raisin River and in the South Nation Watersheds, Eastern Ontario. The survey was conducted during the summers of 2005 and 2006. The 2005 summer survey in the Raisin River was conducted to determine if the EC&T drag probe could be used as a large-scale reconnaissance tool to identify deep groundwater seepage in a wide variety of river systems. The 2006 summer survey in the South Nation Watershed covered the Castor River, the East Castor River and the South Nation River as well as some complementary transects at a reach scale level (to the 2005 sampling season) of the Raisin River.

This type of survey is relatively simple and fast; it provides information about potential deep groundwater discharge locations at a relatively large scale. It was done using a kayak or a motor boat to drag an EC&T probe at the water sediment interface while recording GPS coordinates. Additional direct seepage measurements were made and piezometers were installed where unexplained anomalies in the South Nation Watershed were found in order to confirm the presence of groundwater seepage believed to be coming from the buried eskers. EC&T results are presented in Chapter 6. Geochemical analyses were carried out at a number of sites but they yielded little information about the origin of the river water because of incompleteness and also because of the magnitude of the variability. Another technique, stream gauging, was attempted to verify the results from the EC&T drag probe from the Raisin River. The technique had limited success because of the low flow rates in the Raisin River and because of the ensuing large error; the results are presented in Appendix C for completeness.

2. Literature review

The spectrum of surface water – groundwater interactions can be broadly categorized into two types: local and deep groundwater interactions. Groundwater that interacts locally with surface water will be referred to as "local groundwater"; it is usually recharged from precipitations along the shores of rivers and lakes and the near vicinity (up to a few hundred meters from shore); and consequently, it is discharged into the surface water body after a relatively short travel path in the ground, and a relatively short contact time. The short contact time and distance typically results in small concentrations of Total Dissolved Solids (TDS), except in areas of anthropogenic loading. In contrast, groundwater of deeper origin that interacts with surface water, referred to here as "deep groundwater", is in contact with the ground for much longer times and distances resulting in higher levels of TDS than local groundwater and surface water. The longer contact times enables more mineral dissolution and therefore higher TDS levels, which increases electrical conductivity (EC) of the water (Frape and Fritz, 1982). Consequently, areas with higher EC at the sediment-water interface in rivers can be possible deep-groundwater discharge zones, if other electrolyte sources can be ruled out.

Temperature, can also act as a tracer for indicating groundwater discharge into rivers. Groundwater temperatures annually range between 8 and 12°C, while surface water temperatures ranges, during the summer months, between 18 and 22°C. It would therefore be expected that, during the summer months, in areas of high groundwater discharge, the streambed temperature near the surface would resemble that of the colder groundwater (McGuinty, 2007). Therefore, in the summer, cool zones may be indicative of groundwater discharge, local or deep.

Both types of systems, the local and deep groundwater, are important in water budget considerations, but when groundwater systems are mapped at a large scale, we find that local systems are prevalent (USGS, 2007). Local systems have been examined more extensively in the literature compared to deep groundwater discharge systems, which are more difficult to identify and are less understood. Chapter 6 presents the results of both local and deep groundwater systems.

Before elaborating on the site description, field methodology and the data processing, it is useful to review the basics of electrical conductivity measurements.

Electrical Conductivity (EC) is the ability of a solution, such as water, to conduct an electrical current. EC is the reciprocal of the electric resistance. Electrical conductance is the EC of a body or mass of fluid of unit length and unit cross section at a specified temperature (Freeze and Cherry, 1979). System International (SI) units for EC are Siemens per meter (S/m). The data in this project are reported as microsiemens per cm (μS/cm or 10^{-6}S/ 10^{-2}m). EC is dependant on temperature and on the type and concentration of dissolved ions. Specific electrical conductance permits rapid evaluation of the chemical quality of the water sample (i.e. Total dissolved electrolyte content). The higher the dissolved electrolyte content, the higher the EC; distilled water is not conductive since there are no electrolytes in the water to carry the charge. Since the electrical current flow (I) increases with increasing temperature, the EC values are automatically corrected to a standard value of 25°C. Corrected EC values are referred to specific electrical conductivity. EC is only slightly affected by suspended sediments.

At a given temperature, EC is proportional to the electrolyte concentration dissolved in water. EC is often used to estimate the amount of TDS (Freeze and Cherry, 1979):

$$\mathrm{TDS} = A\ \mathbf{C} \qquad \text{Equation 2.1}$$

Where:

TDS is expressed in g/m^3 or in mg/L

C = Conductance (μS/cm)

A = conversion factor (For most groundwater, *A* varies between 0.55 and 0.75 (Freeze and Cherry, 1979)). As a general thumb rule, we can use A=2/3.

The conductance of groundwater ranges from several tens of μS/cm for rainwater, to hundreds of thousands of μS/cm for brines in deep sedimentary basins (Freeze and Cherry, 1979). According to field measurements, during summer, groundwater, in the Raisin Region, has an EC ranging from 450-2000 μS/cm compared to surface water ranging from 450-850 μS/cm. Therefore, only groundwater with EC greater than 850 μS/cm can effectively be discriminated from surface water.

However, it was observed, in the South Nation Watershed, that during the summer, the groundwater has an EC ranging from 900 to 2000 μS/cm (measured from nearby wells during summer 2006) compared to surface water ranging from 450 to 750 μS/cm.

For both regions, the groundwater temperature varies between 8 and 12°C annually, compared to the surface water temperature of around 20°C during the summer months. Therefore, we expect to see a contrast in either electrical conductivity or temperature values, or both.

According to Kingsley (2005), the electrical conductivity of the groundwater is affected by the geology, the size of the catchment area, the anthropogenic pollutants and the evaporation of surface water. When rainfall infiltrates and flows through the ground, the water is being enriched in dissolved minerals, which increases EC. Therefore, the geology or the rock type affects the groundwater EC. For example, groundwater traveling through igneous bedrock has a lower EC compared to water in limestone-rich bedrock since the types of minerals and their solubility are not the same.

The average time required for groundwater to travel through the ground to the discharge zone will be affected by the size of the catchment area. The bigger the catchment area is, the longer it will take (on average) for groundwater to get to the discharge zone. This will typically increase the TDS present in the groundwater, causing higher EC values. Pollutants can also increase EC of the groundwater. Surface water pollutants such as wastewater from sewage treatment plant, septic systems, tile drainage, urban and agricultural runoff can increase the nutrient levels present in water causing an increase of EC, which produces a confounding source of EC in the water. Finally, evaporation of surface water bodies concentrates dissolved solids in the remaining water and also increases the EC.

When high EC values are found using the EC&T drag-probe method at the water-sediment interface they can be explained either by (1) the deep groundwater flow patterns as discussed previously or (2) the anthropogenic loading of electrolytes into the river (pollutants).

The EC method, using a probe dragged behind an embarkation at the water-sediment interface, was first developed in the early 1980's by Dr. Lee. The EC&T probe was used to detect a salty solution injected through the sediment in a lake (Lee & Al., 1980). In 1985, the drag probe was used successfully to detect an artificially created seepage area in soft bottom sediment below 8 m of lake water (Lee, 1985). In 1991, the EC&T method was used to identify a freshwater upwelling zone along a marine coast (Vanek and Lee, 1991). The research demonstrated that the sediment probe was a valuable tool for studying groundwater inputs into large lakes (Harvey et al. 1997). Janet Kingsley (2005) showed the EC&T probe to be useful in detecting groundwater seepage and in pinpointing sources of anthropogenic electrolyte loading into the South Nation River. Consequently, previous study showed that EC&T could potentially identify groundwater seepage areas.

3. Site descriptions

3.1 Raisin River Watershed

3.1.1 Description

The Raisin River Watershed is located North of Cornwall, within the counties of Stormont and Glengarry, in Eastern Ontario. The Raisin River Watershed has a surface area of 546 km^2 and a total tributary stream length of 817 km (Figure 1.1 and 3.1) (Porter 1996; McGuinty 2007). The river system drains into Lake Saint Francis on the Saint Lawrence River near Lancaster, Ontario. The river is composed of three main branches; the North, Middle and South branches; but, for data presentation purposes it was separated into 5 sections: the North Branch, the Middle Branch, the South Branch, the North+Middle Branch[1] and the Main Branch[2] (Figure 3.2).

The North Branch originates near Monkland and merges with the Middle Branch a few hundred meters upstream of Martintown. It is located in a forested area with little development and it provides a good buffer zone for the river. The proximity to forest also provides a high dissolved organic matter content, which imparts a brown color to the water. Of practical consideration for this study, the North Branch is very shallow and rocky during baseflow conditions, which limits kayak access.

The Middle Branch, originates at Dixon Creek, near Lunenburg and flows North-East to Martintown where it meets with the North Branch. The organic-rich Newington Bog headwater of the Middle Raisin River causes the water to be a dark brown color. The Middle Branch passes through a highly agricultural area with little or no buffer zones. This lack of buffer zone may cause increased erosion as evidenced by the increased sediment load in the river. This Branch increases in width from a few meters upstream to approximately 10 m downstream and has a depth varying between 0.5 and 1 m.

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[1] The North+Middle Branch starts at the merging point of the North and Middle Branch and ends where the river meets with the South Branch.

[2] The Main Branch starts at the merging point of the North+Middle Branch with the South Branch and ends at the St-Lawrence River.

The South Branch is markedly different than the other branches in its color, width and land use patterns. The South Raisin River originates at a man-made inlet off of the St-Lawrence River and goes through the city of Cornwall, which may have an impact on the quality of the water. The total amount of suspended solids is very high, causing the river to be a green color. Bank erosion, due to the lack of a buffer zone, is frequent on the South Raisin River. The channel is also narrower and deeper than the other branches, and offers a clay subsurface.

The North+Middle Branch refers to a reach of the river between the confluence of the North and the Middle branches a few hundred meters upstream of Martintown, and the confluence with the South Branch downstream of Williamstown (Figure 3.2). The buffer zones vary greatly along this Branch. The North+Middle Branch is similar to the North and the Middle Branch in terms of land use (farming and residential) and water color (brown). However, this Branch is twice as wide as the middle Branch. A dam in Martintown regulates the flow of the river.

The reach of the river referred to as the Main Branch starts at the confluence of the South Branch with the North+Middle Branch, near Williamstown and ends at the St-Lawrence River. The mixing of the two branches is noticeable during base flow conditions when the greenish color of the South Branch mixes with the brown color of the North+Middle Branch. At the point of confluence, the North+Middle Branch is 3 times wider than the South Branch. During the summer months, the banks of the river have a large amount of macrophytes, which make it difficult to navigate.

3.1.2 Topography

The elevation of the Raisin River Watershed increases gently from 30 m above sea level (a.s.l.), in Lancaster at the East end of the basin, to 120 m at the surface water divide along a ridge in the northwestern part of the watershed (Figure 3.3). The topography varies from flat downstream to undulating and hummocky in the upstream regions of the watershed.

3.1.3 Land Use

Present land use in the Raisin River Watershed is mainly a mixture of forested areas and agricultural fields. Swamps and wetlands are located in parcels throughout the watershed. The city of Cornwall is an urbanized sector, located in the southern section of the basin and hosts the majority of the Raisin Region population. Figure 3.4 gives a breakdown of land use classification throughout the watershed (Data from the Map Library, University of Ottawa, 2005). Extensive artificial drainage is also part of the land use patterns: tile drains are installed in agricultural areas and municipal surface drains are used in urbanized areas. Artificial drainage systems maintain the depth to the water table at or below the tile drain level as infiltrated water is drained into the fields (Porter, 1996). These drainage systems are discharged directly into the Raisin River, which, in agricultural areas, contributes to nutrient loading.

3.1.4 Climate

The area receives on average 960 mm of precipitation annually (RRCA-SNC, 2007). The average annual temperature of the Raisin River Watershed is 6.1°C, with a maximum mean daily temperature of 20.7°C in July and a minimum mean daily of -10.1°C in January (RRCA-SNC, 2007). The average annual actual evapotranspiration is estimated at 583 mm/y, leaving 377 mm/y in water surplus (RRCA-SNC, 2007), available for direct runoff and infiltration.

3.2 South Nation River Watershed

3.2.1 Description

The South Nation Watershed is located North and West of the Raisin River basin in Eastern Ontario, between longitudes 74° 41' and 75°44' W and latitudes 44°38' and 45°34' N (Figure 3.5) (Kingsley, 2005), with a total surface area of 3915 km^2. A highly permeable buried esker system that is believed to cross beneath the area's river systems was identified in the early 1990's by G.A. Gorell (Gorell, 1991). This sand and gravel system travels longitudinally along the townships of Cumberland, Embrun and Maple Ridge (Figure 3.5), and is believed to be hydraulically connected with surface water systems of the area, such as the Castor, the East Castor and the South Nation rivers.

Some of the areas that are believed to be hydraulically connected were examined in this study with the EC&T drag probe; Figure 3.6 shows the extent of the sampling area. The Castor River passes through the city of Embrun, while the East Castor river flows West-East, approximately one kilometer South of the city in a more agricultural area. The two rivers meet downstream of Embrun. The Castor River is approximately 20 m wide and 2 m deep, in the deepest regions, compared to the East Branch that is both narrower (10 m wide) and shallower (no more than 1 m deep). The sediments of the two rivers are clayey except where the esker is believed to cross the river, where it is sandier. The South Nation River runs along the Eastern and Southern edges of the Maple Ridge fan deposit and is thought to be a possible groundwater discharge area for the Maple Ridge aquifer (Cooper, 2007). Only the section where the Maple Ridge Fan Deposit borders the South Nation River (Figure 3.6) was investigated using the EC&T drag probe method. This coincides roughly with the section of the river located between the outskirts of Winchester and Chesterville. This river, which is bigger than the Castor and East Castor Rivers, has a depth of more than 2 m and a width of 15 m or more.

3.2.2 Topography

The South Nation Watershed study area is composed of numerous small river systems with a flat topography (Figure 3.6). The elevation varies between 60 and 90 m (a.s.l.) where the lowest elevations are found along the rivers. Looking longitudinally at the esker that crosses the Castor, East Castor and South Nation Rivers, we notice that the Castor and East Castor are less elevated with respect to the trace of the esker than at the South Nation River. The South Nation River is located near a topographic high in the region (Cooper, 2007)

At mid-way along the Vars-Winchester esker, the low elevation area surrounding the town of Embrun is likely to experience groundwater discharge into the rivers. At the southern end of the esker system, on the other hand, flow from the buried sand and gravel system in the Maple Ridge fan deposit can travel (1) northward to the southern part of the esker and discharge in the lower elevation part of the esker system (Castor and East Castor River) and/or (2) South and discharge in the South Nation River. Therefore, we expect that the probe could possibly detect an anomaly in the rivers at both locations, provided that there is a contrast in EC&T between the surface water and the groundwater.

3.2.3 Land Use

Almost 90% of the South Nation Watershed is agricultural pasture and crop fields, although forested areas (10%) are found in patches throughout the watershed. A major wetland is located at the middle of the study area and several small municipalities are found in the watershed. Figure 3.7 gives the breakdown of land use classification for this watershed.

3.2.4 Climate

The climate in the South Nation Watershed is similar to that of the Raisin Region: The average annual total precipitation is 919 mm and the average annual temperature is 5.8°C, with a maximum mean daily temperature of 20.6°C in July and a minimum mean daily of -10.7°C in January (RRCA-SNC, 2007). The average annual actual evapotranspiration is estimated at 575 mm/y, leaving 344 mm/y in water surplus (RRCA-SNC, 2007), available for direct runoff and infiltration.

4. Geology and regional hydrogeology

This section describes the geology and regional hydrogeology for both study regions: the Raisin River Watershed and the South Nation Watershed.

4.1 Bedrock geology

The bedrock geology of the South Nation Watershed and the Raisin Region consists of Precambrian rocks overlain by a series of Cambrian and Ordovician Rocks from the Paleozoic.

In the South Nation and Raisin River Watersheds, the major geological formations are of Late Cambrian to Late Ordovician (From ~443 and ~500 Ma years before present (B.P.)). The formations are named Nepean-March-Oxford Formation, the Rockliffe Formation and the Ottawa Group and the Billings-Carlsbad-Queenston Formations. The Nepean, March and Oxford Formations were deposited by a marine transgression during the Late Cambrian to early Ordovician Periods (RRCA-SNC, 2007). The sandstones of the Nepean Formation are conformably overlain by the sandstone-dolostones of the March Formation and the dolostones of the Oxford Formation (RRCA-SNC, 2007). These formations are mostly found in the South Nation Watershed (Figure 4.1).

During the Middle to the Late Ordovician, fluctuating sea levels deposited the Rockliffe Formation and the Ottawa Group (Kingsley, 2005). Above the Nepean-March-Oxford Formation are sandstones of the Rockliffe Formation and limestones of the Ottawa group, which include the Gull River Formation (limestone/dolostone/shale), the Bobcaygeon Formation (limeston/shale), the Verulam Formation (limestone/shale) and the Lindsay Formation (limestone/shale) (RRCA-SNC, 2007). These sedimentary rocks were formed on the bottom of ancient seas and are found in both watersheds (Figure 4.1).

Younger rocks from the Late Ordovician that are mostly found in the South Nation Watershed include the Billings Formation, the Carlsbad Formation and the Queenstone Formation (RRCA-SNC, 2007). These formations were deposited in an intercontinental shelf environment and consist of shale, limestone and siltstone. They are found in the South Nation Watershed (Figure 4.1).

According to Chin et al. (1980), the largest bedrock aquifers are the limestone/shale aquifer and the limestone/dolomite aquifer. These include the Ottawa formation and the younger rocks from the Late Ordovician (Billings, Carlsbad and Queenstone Formations). The limestone/dolomite aquifer is the more important because the drilled wells in this aquifer have the potential for higher yields and because it usually contains fresher water than the limestone/shale aquifer.

Exposures of bedrock in the Raisin River and the South Nation Watersheds are not common: According to the RRCA-SNC (2007) water budget conceptual understanding, bedrock is exposed at the surface over less than 1% in the Raisin River and the South Nation Watersheds. However, bedrock is exposed at a few locations in the study areas: in a 1 km reach of the N+M Branch of the Raisin River; and in the Castor River, immediately upstream of the study site at Russell, and immediately downstream, at Embrun (Figure 4.1). The exposures in the Castor River manifest themselves as 500 m long rapids.

Faults act as geologic boundaries between various formations. A set of faults runs East-West through our study area (Figure 4.1). According to the RRCA-SNC (2007) water budget conceptual understanding, the extensive networks of faulting in the region are potential zones of higher transmissivity and play a role in influencing the direction of groundwater flow between formations. Therefore, groundwaters from these faults are potentially a viable source of groundwater supply for homeowners.

4.2 Overburden geology

The surficial geology consists of unconsolidated deposits of Pleistocene age or more recent. These recent deposits include glacial, glaciofluvial and glaciomarine deposits, and deltaic and fluvial deposits (Figure 4.2). Glacial deposits are made of tills and moraines that occur during the advance and retreat of ice sheets. The glaciofluvial deposits are created by sediments depositing from meltwater of the streams escaping from the glacier. Glaciomarine deposits are sand and gravel, and silt and clay sediments from shallow and deep water that was present during the glacial retreat. Deltaic and fluvial deposits are from the early phases of the Ottawa River and recent alluvium, colluvium and organic deposits (RRCA-SNC, 2007). "Till is nonsorted and nonstratified sediment carried out by glaciers and is generally sandy, with variable amount of silt and clay" (American Geological Institute, 1984). Most of the surficial geology of the region consists of till. "Regionally, till deposits generally thicken towards areas of decreased bedrock surface elevations, and thins or sometimes disappears in areas of higher bedrock surface elevation" (RRCA-SNC, 2007)

We would expect higher groundwater discharge in sand and gravel surficial geology than in till. In Eastern Ontario, sand and gravel patches are rare except in our study area, where eskers are an example of sand and gravel features. The North-South oriented Vars-Winchester esker is believed to cross the study area in locations close to the village of Embrun in the South Nation Watershed (Figure 3.5). Eskers, which are glaciofluvial deposits that are found in Eastern Ontario, have been mapped by Gorell (1991). "Eskers are rudely stratified accumulations of gravel, sand, and waterworn stones and are rough fluvial or torrential originates that occur in long tortuous ridges, mounds and hummocks that have in most cases a general direction of drainage" (American Geological Institute, 1984). The eskers of Eastern Ontario are an important groundwater supply for small communities in the surrounding area even though their extent is limited to a small area.

The eskers from Eastern Ontario were deposited during the last glacial retreat 10,000 years ago. After the glaciers retreated, the earth's crust was still depressed from the mass of the ice, 9,000 yrs ago, and then was filled with water from the Atlantic Ocean (SNC-GSC-UO, 2007) creating the Champlain Sea. The deposited clay and silt from the Champlain Sea was laid over the existing esker deposits. Thus the sandy and gravelly esker deposits are surrounded by relatively impermeable materials.

4.3 Regional hydrogeology

4.3.1 <u>Bedrock hydrogeology</u>

Most of the water supply in Eastern Ontario comes from a number of bedrock units. The groundwater supplies in the bedrock aquifers in Eastern Ontario provides adequate quantities of water for domestic uses but is generally inadequate for users requiring higher yields (Kingsley, 2005; Chin et al., 1980). The Nepean-March-Oxford Unit, a limestone/dolomite aquifer, is considered a good water reservoir both in quantity and quality of water whereas the

Ottawa Group Unit, a limestone/shale aquifer has good quantity yields but poor water quality. The Precambrian unit, the Rockcliffe unit and the Billings-Carlsbad-Queenston unit are low yielding aquifers with poor to inferior quality water. It is to be noted however that some faulted areas in the unit mentioned above may have higher water productivity (RRCA-SNC, 2007).

4.3.2 Overburden hydrogeology

The rural region of the South Nation Watershed and the Raisin River watershed is mainly agricultural and residential. Most landowners possess a private well from which their water is drawn. According to the Ministry of the Environment (MOE), 12% of the wells in the Raisin River Watershed and 11% in the South Nation Watershed are overburden wells (WESA, 2006). The overburden water supply is limited due to the reduced thickness and extent of the deposit (sand and/or gravel) (WESA, 2006). These overburden deposit water supplies are limited to few areas of thick cover such as esker deposits (RRCA-SNC, 2007). In fact, most of the wells in the area draw their water from the contact between the overburden and the weathered upper bedrock; zone referred to as the "Contact Zone Aquifer" (RRCA-SNC, 2007).

4.3.3 Groundwater quality

Groundwater in the study area is used by homeowners, for agricultural activities and by many small communities. Therefore, it represents an important asset. Contamination of the groundwater throughout Eastern Ontario is a very important issue when assessing drinking water supply for present and future years as the community will likely grow. The geologic or intrinsic potential for contamination depends on the thickness of the overburden, the vertical hydraulic conductivity of geologic material overlying the aquifer, as well as the direction and the magnitude of the hydraulic gradient (Kingsley, 2005). Diffuse sources of contamination, such agricultural practices, and point sources such as waste water disposal systems, manure sewage disposal and landfill sites are the main processes that can potentially contaminate and affect the water quality of the groundwater (Porter, 1996). As stated earlier, most of the aquifer formations are good suppliers of water. However, the most pressing concern related to groundwater in the basin relates to inadequate quantities from poor hydro-stratigraphic units and to poor quality due to natural processes or to contamination.

5. Methodology

5.1 Electrical Conductivity and Temperature (EC&T) survey

There are two steps involved in evaluating groundwater-surface water interactions using the EC&T probe: gathering the raw data in the field and data processing. Data from an EC&T probe and a GPS were inputted into a GIS database to produce maps for data processing. These maps were used to interpret the EC&T values found in the rivers to determine if deep-groundwater seepage is present.

5.1.1 EC&T probe survey

The probe used to survey the sediment-water interface of rivers is a Reelogger Model 2001 probe from Solinst Canada (Figure 5.1). It records EC, expressed in microsiemens per centimeter (uS/cm or 10^{-6}S/cm) corrected to 25°C, temperature in °C, and time. The EC&T probe was dragged at the sediment water interface (Figure 5.2); and to prevent damage to the EC&T probe and cable, the system was modified with the addition of a Tygon™ plastic tube with holes surrounding the probe and the cable. The EC&T probe was attached to a cable that connects to a data acquisition system. Coordinates of the EC&T probe along the river were recorded by a GPS, which allowed georeferencing of the data. A RoyalTek BlueGPS with a waterproof antenna recorded coordinates and time, at the same time interval as the EC&T probe: every 3 seconds. In addition, a hand held GPS (Magellan eXplorist 210) along with a hand held EC&T probe (Hanna Instrument) were used to note EC and coordinates of tile drains, bridges or any point of interest. These bench marks helped when correlating the Solinst probe with the GPS to produce the maps. When the Raisin River was more than 5 m wide, several passes of the probe were made along the reach to see if a difference between the banks could be observed.

Depending on the conditions, a kayak or a motor boat was used to drag the EC&T probe along the river. The kayak was able to go in shallow areas like the headwaters of the Raisin River. We were able to go at a slow pace (less than 4 km per hour) to ensure that the probe touched the bottom of the river. A single or double kayak was used. The principal task besides kayaking was to verify that the probe and the GPS were recording every 3 seconds. It was also necessary to take note of the coordinates of bridges, tile drains, land use changes or any other variations occurring along the river.

To ensure quality and consistency of the data, we calibrated the EC&T probe using a solution of 0.01 M KCl with an electrical conductivity of 1413 μS/cm at 25°C. The probe was calibrated each sampling morning and we made sure that the Reelogger probe was calibrated at ± 15 μS/cm.

5.1.2 EC&T Data processing

The fact that time was recorded by both the EC&T probe and the GPS allowed us to merge both files into one, and to match EC&T measurements to geographical location. Occasional equipment failure caused data errors on either the probe or the GPS and therefore some sections of the rivers have gaps with missing data showing in graphs and figures from Chapter 6. For example, on Figure 6.8, we can notice a break in the data between distances 17000 and 16000 m.

The EC&T data of the Raisin River was taken over a period of 3 months in 2005. EC values along the basin can change considerably with variations of base flow and extreme events of precipitation. To partially remove this temporal variability of the data, all summer sampling days were corrected to the first day of data collection, July 12th. The EC&T data of the South Nation River and the local studies from 2006 were not temporally corrected because the survey took place over a short period of time. Also, for visual purposes, for the local studies in the Raisin River, interpolation of data along the reach was performed using Inverse Distance Weighting (IDW) in a GIS software.

To carry out this temporal correction in the Raisin River, a section of the river that was done on the previous day was repeated at the beginning of the surveying day. On the first day, July 12th, we kayaked in the headwaters of the main Branch up to St Andrew's. On the second day, a section of the river before St Andrew's was re-sampled to correct for temporal variability. This correction was done with a GIS software using the difference between the mean values of both days as a correction value. An example correction for temporal variability is shown in Appendix A.

5.2 Piezometers and Open Top Seepage Meters (OTSM)

Open top seepage meters (OTSM), provide direct measurements of groundwater discharge/recharge (or seepage/leakage) rates. OTSM's were used in this study to corroborate areas of deep groundwater seepage that were identified at the survey scale. OTSM were therefore installed in the Castor and East Castor Rivers where unexplained EC&T anomaly areas were located; and in the South Nation River, in the sandy areas and at strategic places along the north shore since no anomaly was identified using the drag probe.

Our OTSMs consisted of a PVC pipe (5 cm diameter) that was inserted into the sediment in the river to a depth of approximately 1 m. The water inside the OTSM was connected to the river water by a siphon (made from a polyethylene 3/8-inch tube). As groundwater seeps into the seepage meter, the water inside the OTSM escapes to the river via the siphon tube. A plastic bag attached to the siphon at the river end catches the seepage water, the volume of which can then be measured. The seepage flux across the sediment interface can be measured by recording the change of water volume in the bag (modified from Kingsley 2005; Lee and Cherry 1978; Lee 1977). Before being attached to the siphon, the bag was filled with 500 mL of water (Figure 5.3), in the eventuality that there may be groundwater recharge instead of groundwater discharge. The discharge flux (m^3/m^2/day or m/day) measurements were corrected to take into account the change in the river water level between the time when the seepage bags are attached and detached for measurement. The fluxes were also corrected for the area of each PVC pipe as they were removed at the end of the season (some tubes got partially deformed during the installation process).

An increase in volume in the bag indicates a positive seepage (groundwater discharge) and a loss in water indicates groundwater recharge or negative seepage (Porter, 1996). The groundwater seepage flux, q, is calculated from Darcy's Law:

$$q = \frac{Q}{A} = \frac{\Delta V}{At} \qquad \text{Equation 5.1}$$

Where:

q= Darcy's flux (Units: $m^3\ m^{-2}\ s^{-1}$)

Q= Volumetric flow rate (m^3/day)

A= Cross-sectional Area of the seepage meter (m^2)

(Note: Radius of undamaged PVC pipes were 0.025 m (area of 0.0019 m^2) and damaged PVC had a smaller area with an irregular shape that was measured by tracing the outline of the deformed pipe on millimetric paper. When the pipes were installed, damage could have been caused at the bottom of the pipe due to rocks and hammering into the ground.)

ΔV= Change in water volume in bags attached to seepage meters (m^3)

t= time (day).

By correcting for water level change in the river, the Darcy's flux becomes:

$$q = \frac{Q}{A} = \frac{\Delta V - \Delta V_w}{At} \qquad \text{Equation 5.2}$$

Where:

ΔV_w= change in volume (m^3) in the seepage bag caused by a change in water level of the river. Because the OTSM are opened to the atmosphere, an increase in water level in the river will cause water to flow from the river into the OTSM, thereby decreasing the volume of water in the seepage bag. The internal volume of the OTSM corresponding to the increase in water level must then be added to the volume in the bag to correct for the change in water level. To calculate ΔV_w, a measure of the water level on both days must be taken. The difference between these two values times the cross-sectional area of the pipe will give us the change in volume of water in the seepage bag caused by a change of level of the river. For a numerical example, refer to Appendix B.2

The PVC pipes can act as piezometers (mini-wells) when they are left with no siphons and bags. The piezometers installed in this manner permit the measurement of the hydraulic gradient and the hydraulic conductivity, when combined with the seepage measurement.

The hydraulic gradient, *i*, is

$$i = \frac{dh}{dx} \qquad \text{Equation 5.3}$$

Where:

dh= difference in water level between the inside of the PVC pipe and the water level of the river (m) (when there is no siphon attached)

dx= depth of penetration in the sediments of the PVC pipe (m).

Hydraulic conductivity, K (m/day), can be derived from Darcy's flux, q, as measured by the seepage meter:

$$q = -K\frac{dh}{dx} \qquad \text{Equation 5.4}$$

Therefore,

$$K = -\frac{q}{i} \qquad \text{Equation 5.5}$$

The sign of q (and i) determines if there is recharge or discharge of groundwater into the river.

6. Results

6.1 Raisin River Watershed

The first Raisin River sampling session covered a 57 km long reach that was surveyed over a three month period during summer 2005. Shallower areas, located in the headwaters, could not be surveyed. The investigated area starts at the St-Lawrence estuary and extends as far in the headwaters as possible (Figure 3.2). The river has 3 branches: the North Branch, the Middle Branch and the South Branch. But for better graphic representation, the river is separated into five sections: the North Branch, the Middle Branch, the South Branch, the North+Middle Branch and the Main Branch (Figure 3.2). To increase the spatial resolution of the data, multiple passes were made along the banks and the middle of the Raisin River. For presentation purposes the EC&T values were plotted as a function of linear distance along the river; distance 0 m is the furthest point downstream of the basin, and is located at the confluence of the Raisin River with the St. Lawrence River. Every data point upstream is labelled according to the distance separating it from that point. In order to reduce noise, the following graphs are 50-points moving averages; and for comparison purposes all EC values were plotted on the same scale.

The North Raisin River was surveyed for a distance of 2.5 km upstream of Martintown (Figure 6.1). Its shallow water level and rocky bottom made it difficult to travel. One transect was made along the North Raisin River. The surficial geology of the investigated area is mainly composed of sand and silt with sandy, silty and clayish patches. No anomalies were apparent in our recorded EC&T data (Figure 6.2 & 6.4). Groundwater EC values (W9-A and W9-B from Table 6.1 and Figure 6.3) from adjacent wells and from the drag-probe in the North Branch were not sufficiently different to produce a clear contrast between groundwater and surface waters. The EC from the North Branch showed constant values ranging from 550 to 600 μS/cm, while EC values from groundwater ranged between 550 and 1000 μS/cm. The decrease in the conductance of the North Branch at distance 18,000 m (Figure 6.2) is caused by the confluence with the Middle Branch. EC values from the Middle Branch are 50 μS/cm lower than the EC values from the North Branch. This contrast is apparent because the Middle Branch is larger and deeper than the North Branch. The temperature from the North Branch varied between 22 and 27°C and showed no apparent anomaly along the reach (Figure 6.4).

The middle Raisin River was surveyed for a distance of 12 km upstream of Martintown (Figure 6.5). The riverbed alternated between riffle and pool zones. Since the river was wider, a pass along both shores was made. In addition, EC values from adjacent wells (W1-A, W1-B and W1-C from Table 6.1) were not significantly different from the EC of the surface waters of the Middle Branch. Both surface and groundwater EC ranged between 450 and 730 µS/cm. Therefore, no anomalies were apparent on either transect of our EC&T recorded data. Surface water ranged between 500 and 550 µS/cm (Figure 6.6) while temperature ranged between 20 and 27°C (Figure 6.7). The EC profile from both shores is slightly different since the adjacent land use is different on each bank.

The 20 km survey of the South Branch started in the Center of Cornwall and was carried out downstream until it met with the other branches, close to Williamstown (Figure 6.8). The South Raisin River had a few obstacles such as fallen trees, beaver dams and tall grasses which made it hard to paddle down the river. The South Branch, as a whole, is expected to be quite different than the other branches because it originates in the St-Lawrence River, upstream of Cornwall, at a man-made structure that is intended to maintain water levels constant in the Raisin River. Although the EC of the St-Lawrence River is less than that of the Raisin River, we expected higher EC values from anthropogenic loading, since the highly developed urban areas of Cornwall surround the first 10 km of the South Branch. We then expected EC to decrease as distance from the urban areas increased. This trend was in fact observed: EC values ranging between 700 and 950 µS/cm covering a 3 km reach (from 21,000 and 18,000 m) are attributed to residential activities of Cornwall (Figure 6.9). The river is directly located in the center part of the city of Cornwall and a golf course is adjacent to the river; pesticides, fertilizers, bridges, septic tanks, and drains increase the mineral and nutrient loading, and consequently, increases EC. Downstream, the South Raisin River showed EC values between 600 and 700 µS/cm. These values are slightly higher than the values observed in the North Branch and in the Middle Branch. Adjacent wells to the South Branch show similar EC values: both the river and the wells have EC ranging between 385 and 950 µS/cm (Table 6.1, W3-B, C and D and Figure 6.9). There was an increase of temperature values for the surface water of the South Branch going downstream, which can be explained, in part, by temporal variability as we sampled downstream locations later in the summer. Values ranged between 14 and 28°C

(Figure 6.10) and were different than the groundwater temperatures of W3-B, C and D (Table 6.1), which ranged between 10.7 and 16.6°C.

The North+Middle (N+M) Branch starts at the confluence of the North and the Middle Branch of the Raisin River and ends downstream at the confluence with the South Branch, downstream of Williamstown (Figure 6.11). In Martintown, which is located on the N+M Branch, the river level is controlled by a dam. The EC values along this reach of the river are plotted in Figure 6.12. A gap in the data, between 17,000 and 16,000 m, was caused by malfunction of the GPS device. The EC values were on average between 500 and 600 μS/cm (Figure 6.12). The high peak of 700 μS/cm with lower temperatures of 19°C (Figure 6.13) found at distances 12,000 m are believed to be an anomaly caused by deep groundwater discharge into the river. This section, called the "Swimming Hole" by local residents, is a deep hole of more than 10 m wide and 2 m deep (compared to an average depth of 0.5 m up- and downstream of the "Swimming Hole"). A private well adjacent to the "Swimming Hole" had EC values ranging between 900 and 1200 μS/cm. The high EC and lower T values found in the "Swimming hole" were studied in more detail; results are presented later in this chapter. Also, at a distance between 6,000 m and 8,000 m from the St. Lawrence River, the N+M Branch of the Raisin River meets with the South Branch (becoming the Main Branch of the Raisin River). The increase in the EC values is caused by input from the South Branch where a food processing plant is located. EC values were close to 700 μS/cm over a distance of 1 km. The probe showed constant temperature values ranging from 22 to 28°C with the exception of the "Swimming Hole". (Figure 6.13).

The main Branch of the Raisin River starts at the confluence of the N+M and the South Branch and extends downstream to the St. Lawrence River, a distance of approximately 8 km (Figure 6.14). Reading passes along the banks were done by kayak while passes in the middle of the river were made by motor boat. EC was expected to decrease closer to the St. Lawrence River, in which EC values are around 350 μS/cm. This is indeed what results indicate, as shown in Figure 6.15. Values start at around 600 μS/cm and decrease to 500 μS/cm close to the St. Lawrence River. The effects of the food processing plant along with the South and the N+M Branch merge that were observed on the previous figures are also noticeable in the Main Branch, between 6,000 and 8,000 m, with high EC values close to 700 μS/cm (Figure 6.15).

Adjacent wells (W2-A, W2-B, W2-C and W2-F from Table 6.1) show groundwater EC values varying over a wide range that encompassed the surface water range: the surface values ranged between 500 and 800 μS/cm while the groundwater values ranged between 400 and 1000 μS/cm, with an additional outlying value of 2090 μS/cm, which is believed to be caused by contamination. The surface water temperature ranged between 20 and 28°C (Figure 6.16) while groundwater temperatures ranged between 9.5 and 14.3°C (Table 6.1, W2-A, B, C and F). Thus the EC&T drag probe could not clearly detect the presence of seepage in this area.

After a large scale survey over the entire watershed in 2005, reach scale surveys were done in 2006. They are described in the next section.

The scale over which deep groundwater discharge takes place in surface water bodies is not intuitive. This has important implications in terms of the resolution of the survey: if deep groundwater discharge takes place over small scales, then a survey of moderate resolution may not be able to detect deep groundwater seepage. Conversely, it may be argued that a "significant enough" deep groundwater discharge site may cause a detectable anomaly irrespective of the actual scale of the seepage area. In order to address this question the survey resolution was increased to the less-than-meter scale in areas where large-scale anomalies suggest deep-groundwater discharge. Large-scale anomalies were selected as opposed to the entire study area because a survey at such a high resolution at the basin scale would have been impractical.

Two sites were selected, the "Swimming Hole" and Site A; both located in the Raisin River. Their location is given in Figure 6.17. The "Swimming Hole" (45°09'18"N, 74°38'47"W) was identified in the large scale survey as a major anomaly in the North+Middle (N+M) Branch of the Raisin River and is believed to be associated with deep groundwater discharge. However, the extent of the seepage was not clear because of the resolution of the survey. Site A is located at coordinates 45°8'6.80"N, 74°34'40"W (Figure 6.17) and at the confluence of the N+M Branch with the South Branch. It was chosen because it shows a large anomaly that is not believed to be the result of deep groundwater discharge, and also because it is highly instrumented as part of other studies in the WERAP (Suchy, 2008, M.Sc. in progress).

High resolution EC&T surveys were carried out in the "Swimming Hole" on August 7th and on September 6th 2006. Results from August 7th (Figure 6.18) show high EC in the middle of the river and along the South bank of the river and the north bank at the Eastern edge of the "Swimming Hole". The EC of the river is approximately 500 µS/cm upstream of the site and the anomalies are as high as 1813 µS/cm. The temperatures taken from the EC&T probe are depicted in Figure 6.19. They showed a steady decrease from 27°C upstream of the Swimming Hole to an average of 24°C. These observations suggest that the temperature differences do not correlate with the high EC zones. In contrast, the results from September 6th did show a clear association of high EC with low temperatures, although the differences were not as pronounced as for the August 7th results. The EC anomaly values are as high as 724 µS/cm compared to 425 µS/cm in the surrounding area, and the temperature was of 17°C compared to the surrounding values of 19°C. These results are presented in Figures 6.20 and 6.21, respectively. The observations made in the field show that the anomaly (Figure 6.20) is in fact located in the deepest section of the "Swimming Hole". Attempts were made to measure seepage directly at this site, but viable seepage meters and piezometers could not be installed because of the stony nature of the sediments in the river.

Site A is located close to the confluence of the North+Middle Branch and the South Branch (Figure 6.17). It showed a large EC&T anomaly at the scale of the basin survey. The survey was repeated at a much higher resolution to see if additional small-scale anomalies could be detected. The results of the high resolution survey are plotted in figures 6.22 and 6.23 for EC and temperature, respectively. The figures show that no groundwater anomaly could be detected, even at high resolution. The likely explanation for the lack of groundwater anomaly is the lack of contrast between groundwater and surface water at this site. EC measurements were made on groundwater from wells in the vicinity of Site A, and are given in Table 6.2. The groundwater EC values ranged between 375 µS/cm and 660µS/cm (Table 6.2) except for one well W2-C, which was around 2000 µS/cm. This well was located in a barn, and the high EC value is an indication of probable contamination. The lack of a clear contrast in EC between surface and groundwater makes it impossible to detect seepage using the EC&T probe, irrespective of the resolution of the survey.

6.2 South Nation Watershed

The South Nation River was surveyed for a reach from Chesterville to Winchester and is depicted in Figure 6.24. To increase spatial resolution of the data since the river is wide and deep (about 5 m deep in the middle), multiple passes were made on the north shore and the middle of the river. On the EC&T graphs (Figure 6.25 and 6.26), distance 0 m is the furthest sampling point downstream on the South Nation River. Every data point upstream is labelled according to the distance separating it from the downstream point.

Between Winchester and Chesterville interactions were expected between the groundwater of the Maple Ridge fan deposit, which constitutes the southern end of the Vars-Winchester buried esker complex, and the surface water in a sandy area (Figure 4.2) of the South Nation River. However, no anomalies were apparent on either shore in our recorded data (Figure 6.25). The groundwater EC measurements made on adjacent wells were not significantly different than the values obtained while dragging the probe in the river (Table 6.3). Both surface and groundwater EC values ranged between 500 and 900 μS/cm. The lack of a clear contrast in EC between groundwater and surface water makes it impossible to detect seepage using the EC&T probe. Similarly, the temperature at the surface water – sediment interface varied between 15 and 17°C and showed no apparent anomaly along the reach (Figure 6.26). This section of the river was surveyed at the end of September, which explains the low temperature values. If the probe had been dragged during the summer, at peak temperatures, a contrast might have been seen. However, temperature contrasts may get dissipated rapidly because of the relatively rapid flow of water in the South Nation River and the large volumetric flow rate of the river.

Since there was no contrast between the groundwater from the well samples and the surface water, open top seepage meters were installed in the sandy area of the South Nation River and at other locations along the shoreline upstream and downstream of the sandy area. This work was carried out in collaboration with Rachel Cooper as part of her Fourth-year project at the University of Ottawa (Cooper, 2007). The results from the seepage meters confirmed the presence of a discharge flux in the silty, sandy area of the South Nation River (MR-1 through MR-4 from Figure 6.27). The small upward flux in the sandy area varies between 0.08 and 0.11 m/day (Figure 6.27). Hydraulic conductivities were measured with both failing-head test and the seepage meters. There is a significant discrepancy between the two techniques and large uncertainty with this data due to the large fluctuations in the river levels at the time of year when the measurements were made, and because of the time lag between measurements (Cooper, 2007). Appendix B tables give the hydraulic conductivities, the hydraulic gradient and fluxes. For more information regarding the failing-head tests, refer to Cooper (2007).

Another location in the South Nation River Watershed where the Vars-Winchester Esker crosses a river is near the Village of Embrun, where the Castor and East Castor Rivers cross the esker at approximately right angles. The two rivers are parallel at Embrun, but at the downstream extremity of the village the two rivers merge to become the Castor River. The East Castor River is narrow and shallow compared to the deeper (1.5 m) and wider Castor River. As mentioned previously, the region near the Village of Embrun is favourable for groundwater discharge of the esker water due to its low elevation relative to the rest of the esker to the North and to the South of the village. Both the Castor River and the East Castor River, were surveyed by kayak for a distance of 3 km each (Figure 6.28). Multiple passes were made over each reach of the river to improve the spatial resolution of the data.

The EC values for the Castor River at the sediment-water interface are plotted in Figure 6.29 and averaged 800 μS/cm. To facilitate the comprehension of this and the following figures, the point of confluence of the two rivers is labelled as distance 0 m. Every data point upstream is labelled according to the distance separating it from the confluence. The high EC peaks found on the Castor River between distances 500 and 1000 m (Figure 6.29) are believed to be anomalies caused by groundwater discharge into the river.

Temperature recorded by the EC&T probe along the same transect ranged between 16 and 17°C (Figure 6.30), and did not show anomalous regions. The difference between surface water temperature and groundwater might not be large enough to notice any changes using the EC&T probe. Thus temperature at the sediment interface does not appear to be a good indicator of groundwater discharge at this location. This is consistent with the observations of Kingsley (2005) over the entire South Nation Basin. However, the work of Conant (2004) indicates that temperature measured *below* the sediment-water interface usually does give a good indication of seepage. It is postulated here that the flow in the river is sufficiently fast to dissipate the thermal gradients that may be present but not fast enough to dissipate the concentration gradients. The EC values obtained from the groundwater in nearby wells ranged between 1200 and more than 2000 μS/cm, (Table 6.4) and are similar to the values obtained in the anomaly region of the Castor River between distance 500 and 1000 m, which supports the discharge hypothesis. As part of Beth Sargent's Fourth-Year thesis work (Sargent, 2007), open-top seepage meters and piezometers were used to confirm and quantify the flux located using EC. The seepage measurements as well as the hydraulic gradient values confirmed the presence of groundwater seepage into the Castor River (Figure 6.31). Appendix B tables give the hydraulic conductivities, the hydraulic gradient and fluxes for the Castor River.

The EC anomaly found in the East Castor River covers a longer distance than in the Castor River. The EC of the East Castor River is normally between 800 and 900 μS/cm except in one anomalous area (Figure 6.32). Similarly, the temperature ranges between 18 and 20°C except in the same area (Figure 6.33). Within this anomalous area, between distance 1,800 and 2,300 m, EC increases up to 2,000 μS/cm and temperature drops as low as 8°C. High EC and low temperature are a very strong indication of possible deep groundwater seepage to the river. The high EC values observed in the river were confirmed to be the result of groundwater seepage into the river rather than anthropogenic loading by measuring groundwater electrical conductivity values from nearby residential wells. Residential wells (Table 6.4) have an EC value similar to the anomaly found in the river. Of interest is the fact that the East Castor River is a much smaller tributary with much lower stream flow and velocity than the Castor River and consequently a temperature anomaly could be detected. Open-top seepage meters installed in the East Castor River confirm the presence of seepage (Figure 6.31) (Sargent, 2007). Refer to Appendix B for more details on the hydraulic conductivities, the hydraulic gradient and fluxes for the East Castor River.

7. **Discussion**

7.1 Raisin River Watershed

Deep groundwater discharge and anthropogenic loading of electrolytes into rivers generally have an impact on the EC and occasionally on temperature at the sediment water interface: Higher EC and lower temperature anomalies are expected in areas of deep groundwater discharge. Except for one location, the Raisin River did not display EC&T anomalies that could be attributed to deep groundwater discharge. The groundwater wells sampled in the Raisin River Watershed were not significantly different than the EC values recorded at the water-sediment interface of the Raisin River, and because of this lack of contrast, it was difficult to identify seepage into the Raisin River. In total, 57 km of river were surveyed in the Raisin Region and one deep-groundwater seepage area was located: the "Swimming Hole". The high EC anomalies identified in the Raisin River were otherwise the result of anthropogenic activities. In particular, the South Raisin Branch flows through the City of Cornwall in a residential area with septic fields and a golf course which increased the EC values to 900 µS/cm. Also, a food processing plant, located at the intersection of the South Branch and the N+M Branch increased EC values up to 800 µS/cm. A 50 µS/cm difference in EC between the North and the South banks of the Middle Raisin River is thought to be caused by different land use patterns and buffer zones, which can influence the EC of the river.

Since the drag-probe at the water-sediment interface did not detect deep groundwater discharge, except in the "Swimming Hole" area, it is postulated that most of the groundwater discharge into the Raisin River comes from local groundwater flow and not deep groundwater discharge. It is possible that the seepage water from the adjacent banks of the Raisin River has not been enriched by electrolytes because it has not traveled in the ground for a long time (Porter, 1996). This provides an explanation as to why discharge was not picked up by the EC&T method, although it proved to be successful in finding electrolyte loading stemming from anthropogenic activities.

When the EC&T probe was dragged over the entire Raisin River Watershed, few large scale anomalies were observed. Two anomalous sites were re-examined at a much higher resolution to see if the higher resolution could provide additional information. For one site, the "Swimming Hole", an anomaly inferred to be the result of deep groundwater seepage was observed at a scale on the order of 20-30 m. Additional anomalies on the river banks were of a seasonal nature and were inferred to be the result of local groundwater discharge. The second anomalous location, Site A, showed the result of mixing surface waters at the confluence of two branches but no deep or shallow groundwater discharge, irrespective of the resolution of the survey. The inability to detect seepage was ascribed to the lack of contrast between the groundwater and the surface water.

Comparing the results of the two survey dates gives an indication of the spatial and temporal variability. The large EC&T anomaly in the center of the "Swimming Hole" was identified on both dates. Groundwater EC measurements made on nearby wells were more than 1000 μS/cm, similar to the magnitude of the center EC anomaly, giving strong evidence of deep groundwater discharge into the river on both days. The bank anomalies observed on August 7th are believed to be the result of shallow groundwater discharge from nearby agricultural fields, at a time when the river level is very low. The lack of bank anomalies and generally lower EC values in September are explained by an increase in water level in the river causing less local seepage into the river from the banks and increased dispersion of the deep groundwater seepage. Deep groundwater interactions with surface water may be less dependent on seasonality in terms of seepage flux into the river but are still subject to the impacts of varying dispersion caused by varying river flow rates. Conversely, local groundwater interactions appear to be highly dependent on seasonality, showing seepage that is not continuous and is more present during summer period. At this particular site the local seepage showed EC levels that were similar to our inferred deep groundwater seepage, which would make it undistinguishable in a large scale survey. These results point to the necessity to carry out EC&T surveys at the highest resolution feasible, and at a number of times during the season. The temperature measurements support these observations and also demonstrate the effects of seasonality on temperatures (with lower temperatures in September compared to August).

Finally, a key observation is that the EC&T method detects possible groundwater seepage areas only when a contrast between the surface water and the groundwater is present. In the absence of such a contrast the hydrologist wanting to estimate groundwater contribution to surface water must rely on punctual measurement techniques such as direct seepage measurements, or temperature gradient measurements in the sediments; or perhaps integrated techniques such as stream gauging and storm hydrograph separation.

One of the difficulties encountered in the field while kayaking the Raisin River Watershed was equipment failure. GPS signal losses occurred a few times especially when a cover of vegetated areas surrounded the Raisin River. A major malfunction event occurred in the Middle Raisin River where the GPS stopped working for 2 km. We also encountered some technical difficulties with the EC probe due to excessive battery drainage and short circuits in the probe. These difficulties were largely inconsequential, however, because of the redundancy in the data gathered.

Results from the EC&T drag probe were verified using techniques such as geochemistry and river discharge. Geochemical analysis were carried out at a number of sites, but yield little information about the origin of the water. The results were incomplete and had a high variability. On the other hand, stream-gauge measurements were attempted to verify EC&T result from the Raisin River. The method also had limited success because the flow of the river was low and because of the large error. Detailed methodology and results are found in appendix C.

7.2 South Nation Watershed

In the South Nation Watershed high electrical conductivity values are believed to be prevalent because anthropogenic loading of electrolytes into the River. In particular, landowners' septic fields and the agricultural fields near the Village of Embrun and the Maple Ridge Fan deposit area produced increases in the EC of the Castor, East Castor and South Nation Rivers. However, for some of the reaches of river surveyed, areas of increased EC were not clearly correlated to specific land use patterns; but they could often be associated with reaches of the river that were sandier than the rest of the river.

The largest anomalies were identified in the East Castor River: High EC's, and low temperatures, were clearly correlated to upward flux measurements and confirm the presence of GW seepage into the East Castor River. The anomaly on the East Castor River (800 m, 2000 μS/cm) shows higher values than the one in the Castor River (400 m, 1200 μS/cm). The presence of groundwater discharge in the Castor River and in the East Castor River can therefore be inferred with reasonable confidence. The temperatures measurements were not as conclusive as the EC measurements. A temperature anomaly may have been detected if the survey had been conducted in warmer temperature (i.e. in July or August rather than late September); however, the higher stream velocity is the likeliest cause of dissipation of the thermal gradient. The EC anomalies found in the Castor and the East Castor Rivers coincide with the highly permeable buried esker crossing the two rivers.

The contrast between the EC of the surface and the groundwater in the South Nation River was not large enough to identify possible discharge areas. Surface water EC values were around 600 μS/cm with lows of 475-500 μS/cm while groundwater varied between 490 and 865 μS/cm. Surface temperatures were also too low to distinguish any difference: surface water varied from 16 to 17°C. Open top seepage meters installed in the sandy area confirmed the presence of a small seepage area into the river. This seepage likely comes from the Maple Ridge fan deposit area, the southern part of the esker. Further investigations done by Rachel Cooper (2007) show that, in fact, the esker interacts with the South Nation River.

8. Conclusion

The purpose of this thesis was to identify deep-groundwater seepage into surface waters of the South Nation Watershed and the Raisin River Watershed, Eastern Ontario. The method used to find seepage areas was a drag-probe with a Reelogger, (Solinst Canada Ltd). The probe was dragged at the water-sediment interface to measure the electrical conductivity and temperature (EC&T) of several reaches of the Raisin River, the South Nation River, the Castor River and the East Castor River.

Amongst the rivers tested, those with low permeability clay streambeds (such as the Raisin River and the South Nation River) had very few locations of significant discharge detected using the EC&T probe. In the Raisin River, three locations of higher EC were noted. One area of more than 10 m wide and 2 m deep, the "Swimming Hole", was identified as a seepage area. Other high EC anomalies were found along the South Raisin River were the results of anthropogenic activities. Site A at the confluence between the South and the N+M Branch of the Raisin River showed an anomaly that was the result of mixing of waters of differing composition. The South Raisin Branch flows through a residential area in the City of Cornwall also showed steadily increasing the EC values. Results from the EC&T probe in the South Nation River showed no anomalies. However, the seepage meters installed in a sandy area confirmed the presence of a small discharge area into the South Nation River. This seepage likely comes from the maple ridge fan deposit area, the southern part of an extensive buried esker system. Further investigations by Rachel Cooper (2007) inferred that the esker likely interacts with the South Nation River. The EC&T probe has identified relatively high flux discharge zones in the Castor and East Castor River (both are tributaries of the South Nation River) at locations where the same highly permeable buried esker system crosses the rivers. The survey identified an approximately 400 m-long reach along the Castor River and an 800 m-long reach along the East Castor River where EC was as high as 2000 μS/cm and temperature as low as 11°C. The results from the direct seepage measurements confirm the interaction of the esker with the surface waters of the Castor and the East Castor River.

8.1 Advantages and Limitations

Overall, the EC&T probe proved to be a useful reconnaissance tool for detecting both groundwater seepage and nutrient loading into the rivers. The advantages and limitations of the method are listed bellow:

Advantages:

1. This method can cover a large territory in a short amount of time. For example, in three months we were able to cover three reaches of river and to do multiple passes.

2. The EC&T drag probe when used with a GPS for georeferencing, is a good reconnaissance tool and a powerful management tool: it can pinpoint areas of interests so that further investigations can be made.

3. Finally, this tool is able to detect groundwater discharge zones like the zones observed in the Castor and East Castor Rivers when these zones are larger than the spatial resolution of the method, which is determined largely by the sampling frequency and the rate of travel, and which in this case was on the order of a few meters.

Limitations:

1. The EC&T probe method does not measure groundwater recharge (or river leakage). It can only see groundwater discharge (or seepage) into rivers.

2. Because of the sampling rate, small scale seepage may go undetected. Since it records once every 3 seconds, small seepage areas of less than a few meters can be omitted using the drag probe method. Similar drawbacks can also be observed with piezometers and open top seepage meters: if these small-scale tools are not installed in the proper location, seepage will again go undetected.

3. The EC probe's ability to detect groundwater discharge may be affected by the following: (1) when surface water and groundwater have similar EC values and (2) when anthropogenic loading occurs. To be able to detect a signal we need a contrast in EC between surface waters and groundwater. Groundwater generally has higher EC

values, due to its contact with the aquifer material. For example, in order to detect groundwater seepage, the contrast of EC between the groundwater and surface water in the East Castor River had to be significant.

4. Finally, seasonality is a limiting factor. Groundwater temperatures are constant throughout the year and vary from 8 to 12°C, whereas surface temperatures are warmer in the summer and colder in the winter. Therefore, sampling should be done in summer were surface water temperatures are the highest. The South Nation River was sampled during the fall when surface temperatures were too close to groundwater temperatures to detect any anomalies.

8.2 Recommendations

Below is a list of recommendations for future work using the EC&T drag probe.

1. A preliminary study should be done prior to any field work. This first step should measure EC&T of different groundwater wells in the watershed along with a few surface water samples. If EC is significantly different, then the survey should proceed; if the EC is too similar, other techniques or approaches should be researched.

2. In future studies, seasonal variation should be examined, and fluxes from an area should be studied for the summer periods and over several field seasons.

3. Surveys should be done during baseflow when surface water temperatures are the highest. Therefore, a temperature signal by the EC&T probe would have more chance to be detected.

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10. Figures

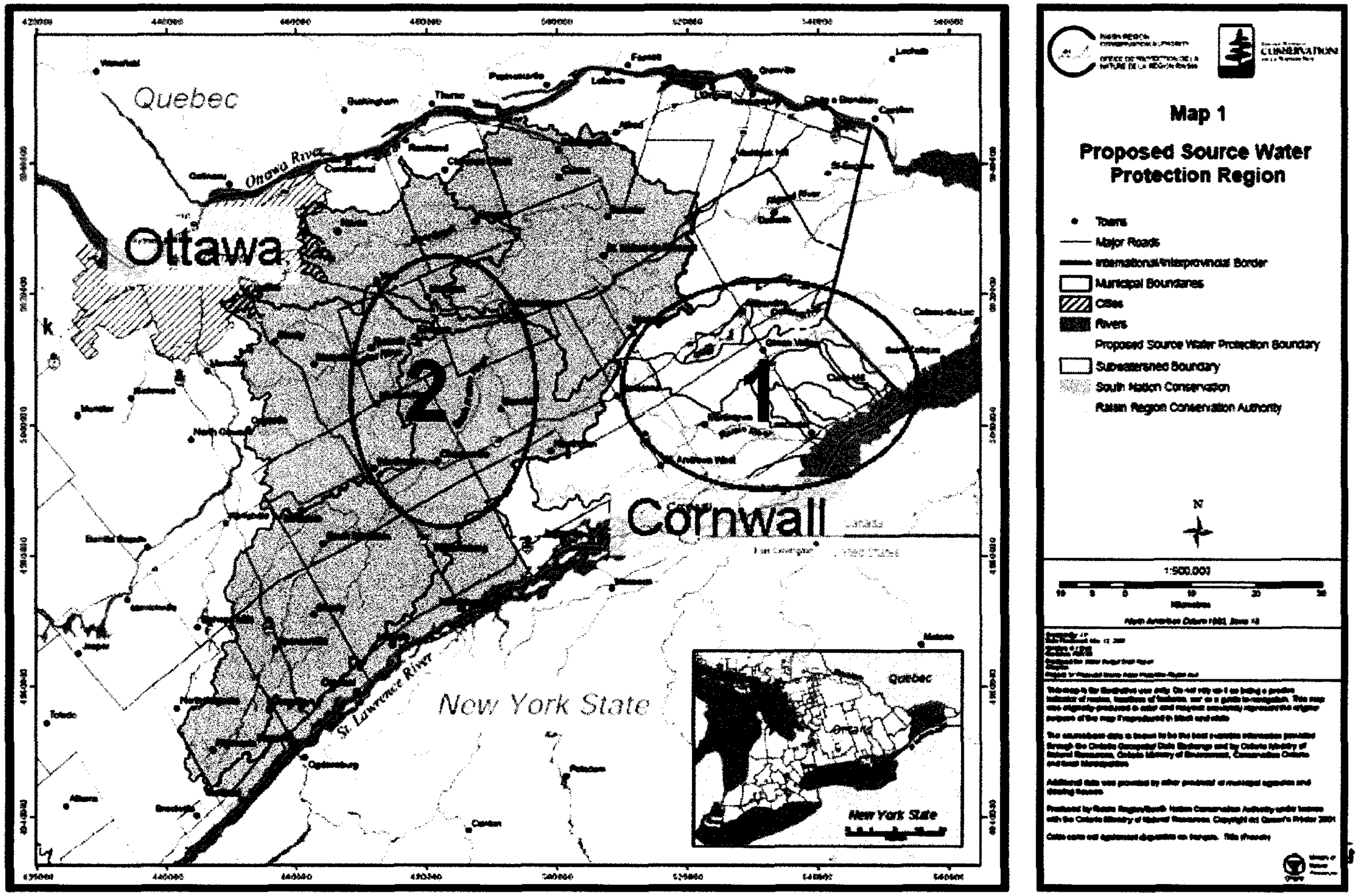


Figure 1. 1: Location map of the South Nation Watershed and the Raisin River Watershed, Eastern Ontario (RRCA-SNC, 2007).

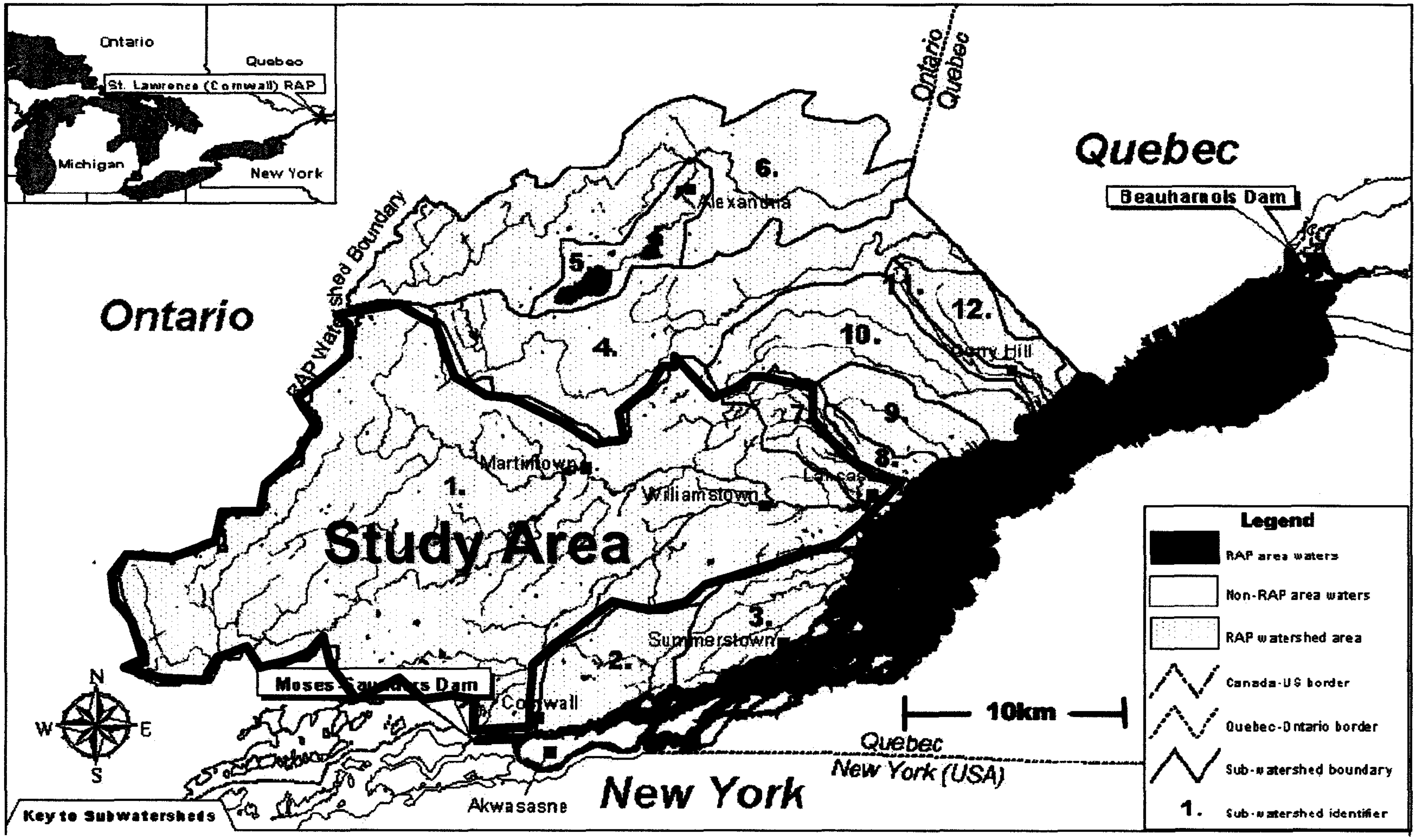


Figure 3. 1: Location map of the Raisin River Watershed, Eastern Ontario.

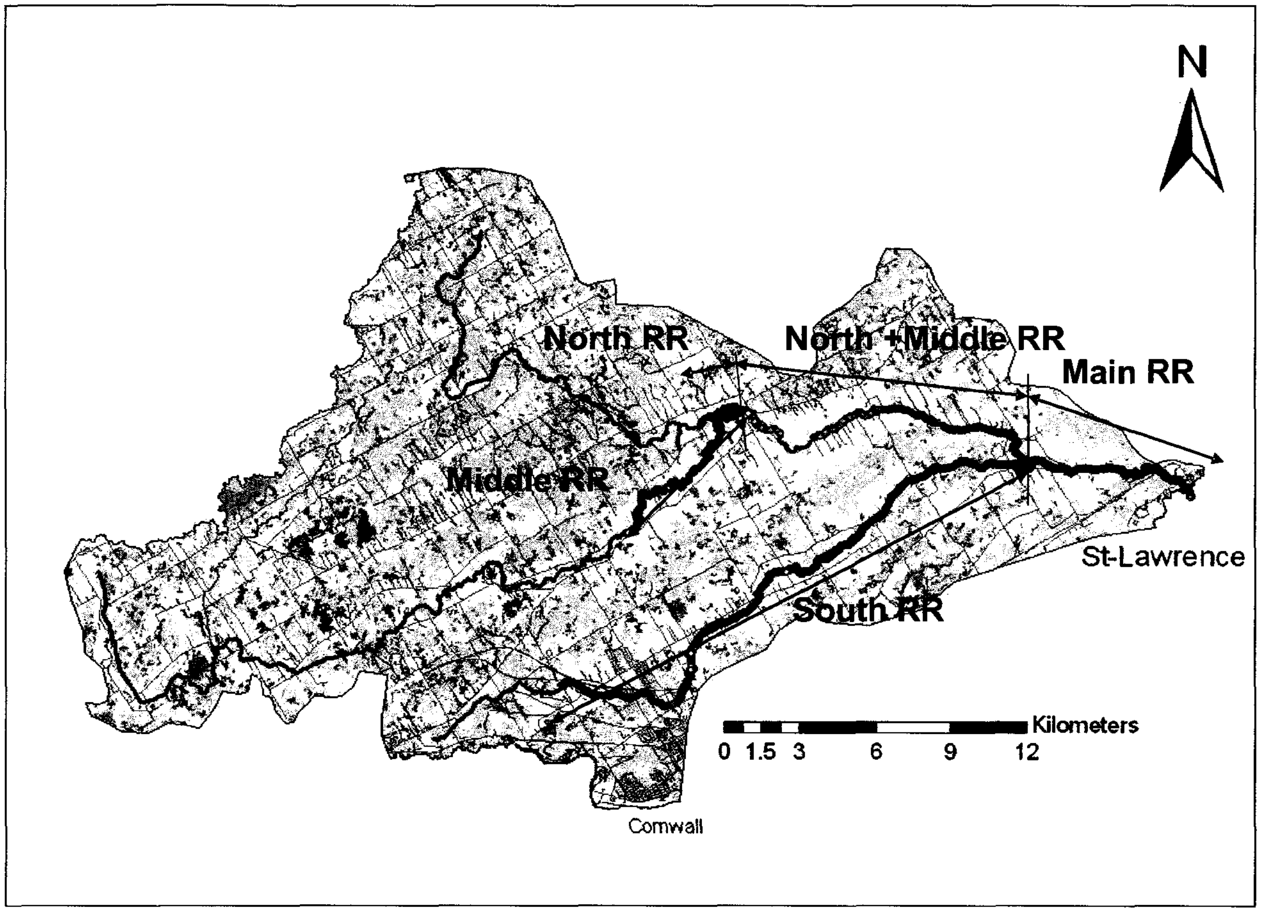


Figure 3. 2: Location map of each branches of the Raisin River. The red arrows represent the survey area of each corresponding Branch reach.

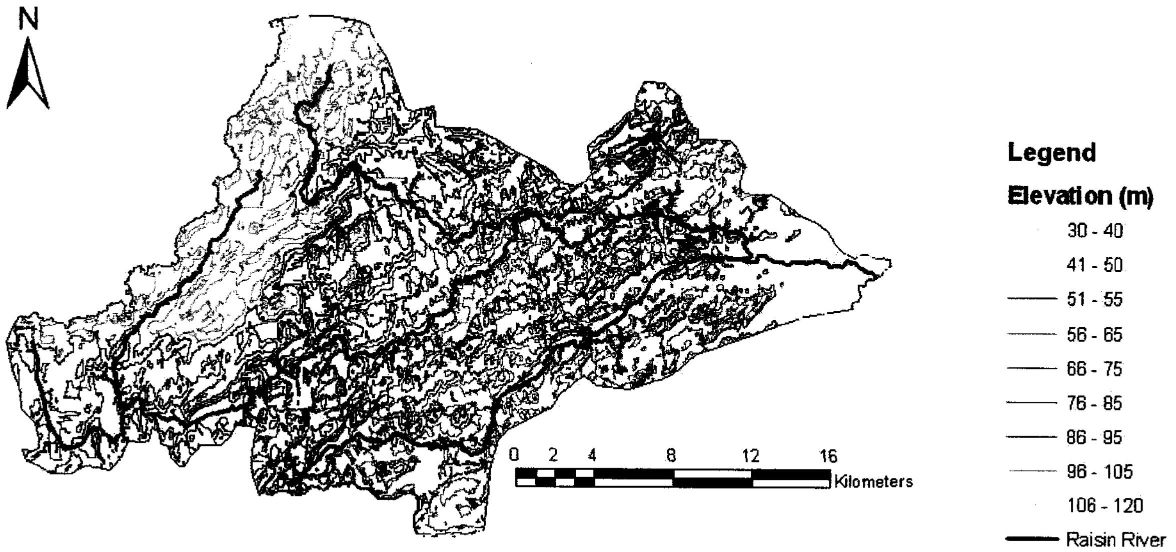
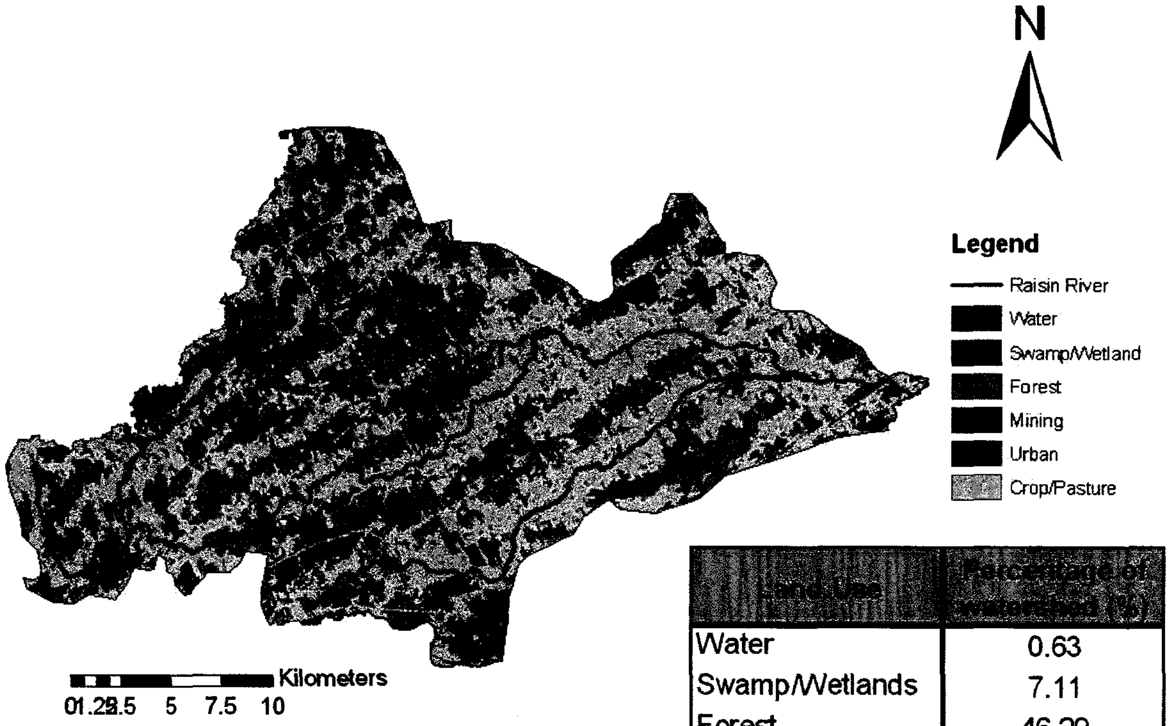


Figure 3. 3: Map of elevation in the Raisin River Watershed.



Land Use	Percentage of watershed (%)
Water	0.63
Swamp/Wetlands	7.11
Forest	46.29
Mining	0.27
Urban	1.29
Crop/Pasture	44.41

Figure 3. 4: Map of Land Use classification in the Raisin River Watershed.

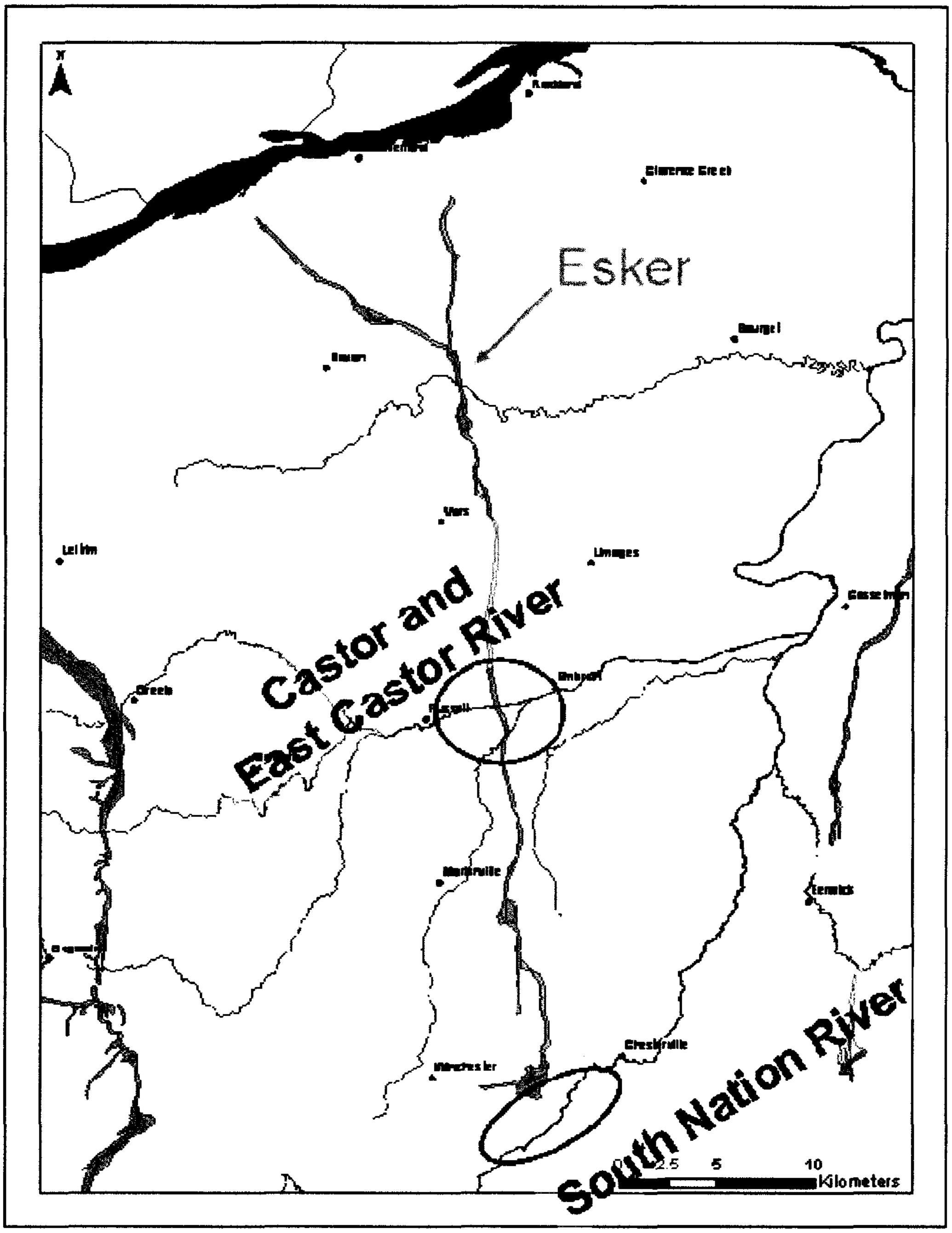


Figure 3. 5: Vars-Winchester esker. The areas of interest are close to Embrun and Winchester (Charland, C, 2007).

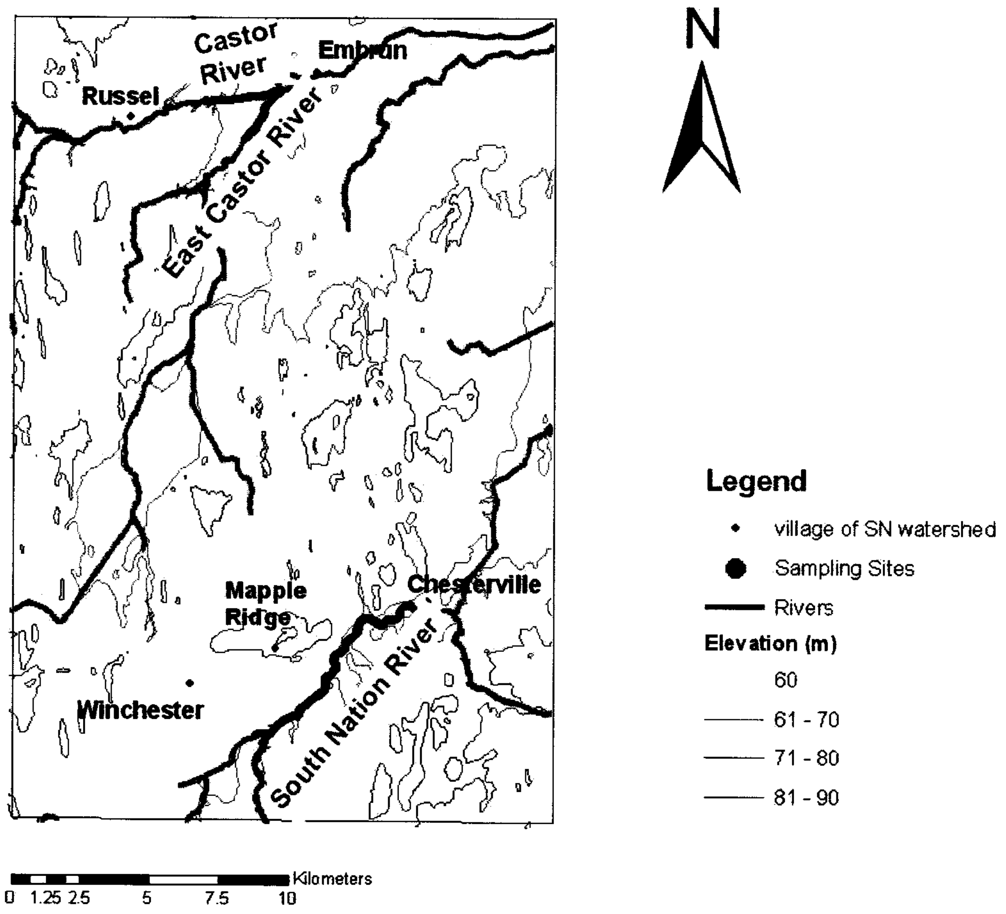
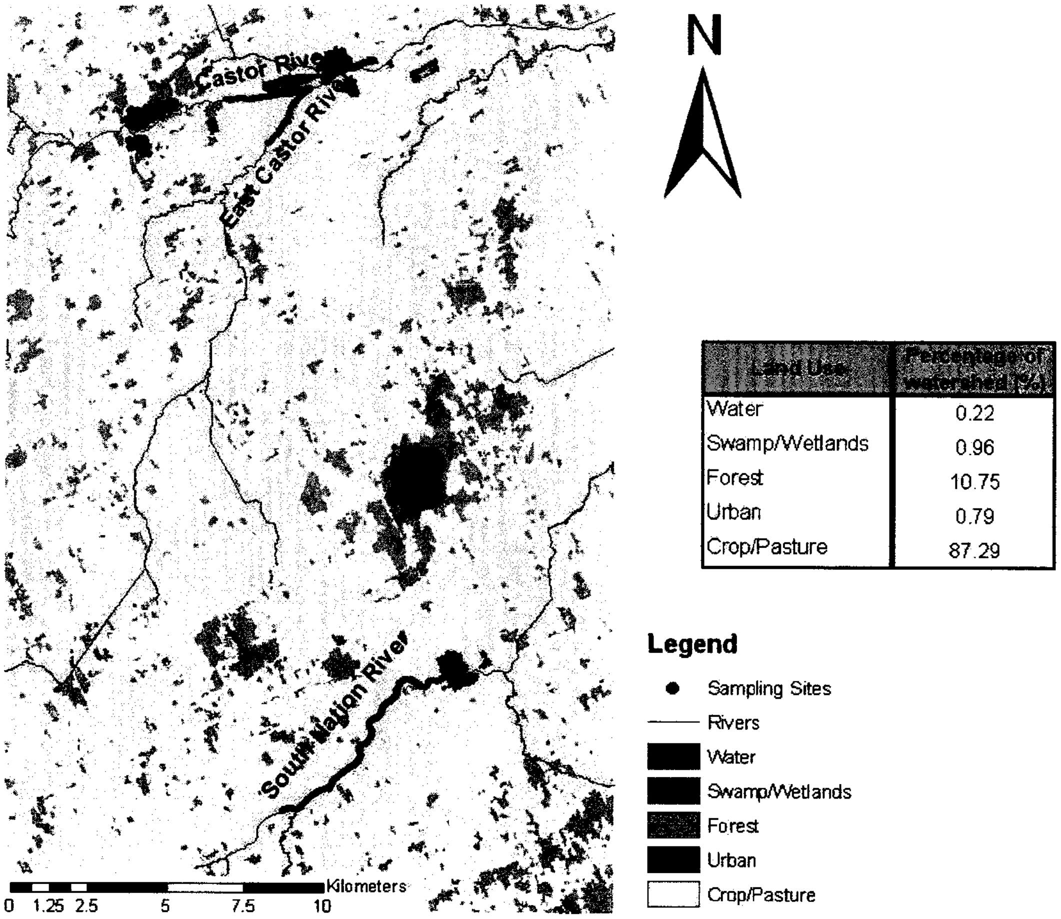
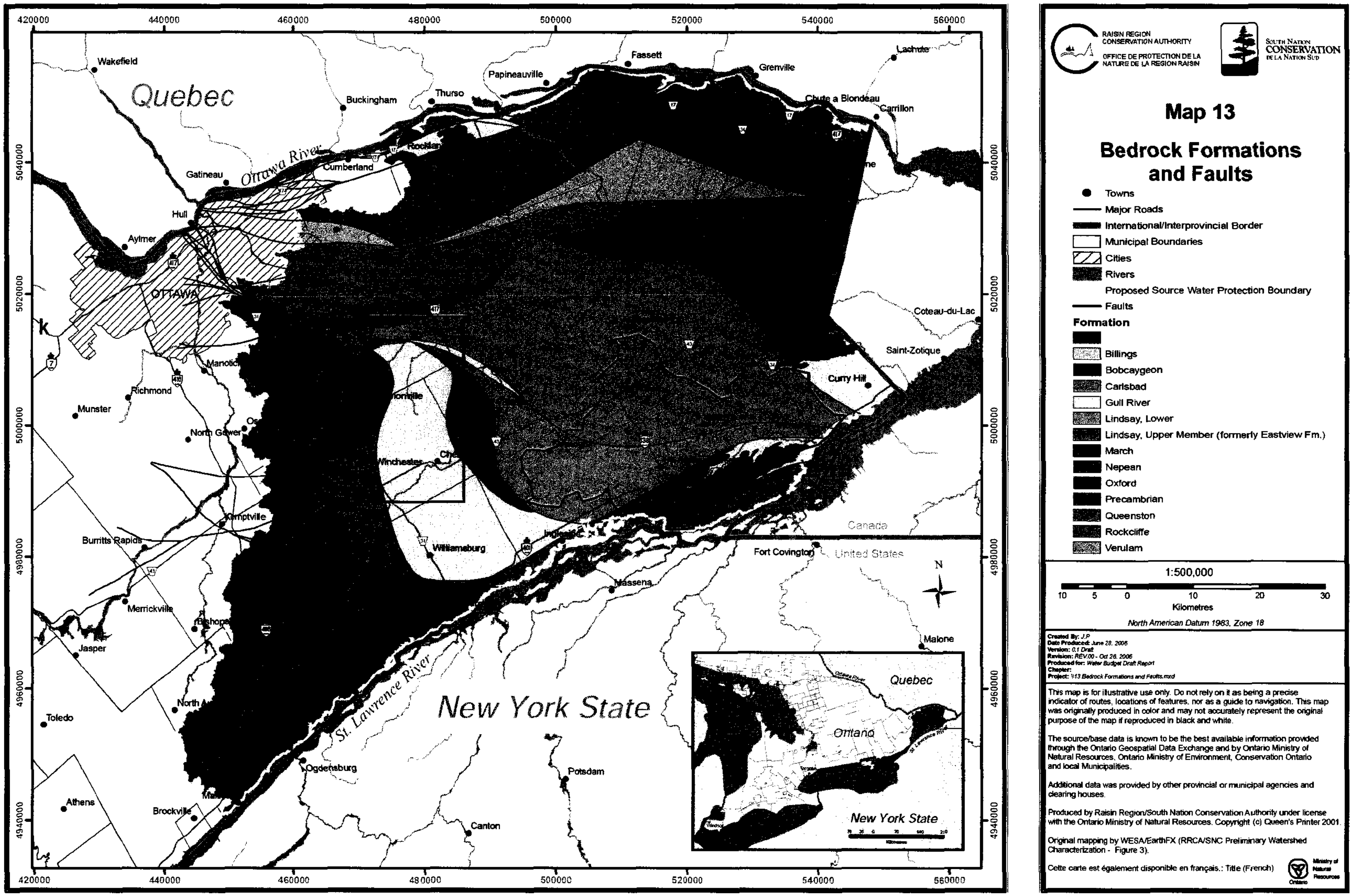


Figure 3. 6: Map of elevation in the South Nation Watershed.



Land Use	Percentage of watershed (%)
Water	0.22
Swamp/Wetlands	0.96
Forest	10.75
Urban	0.79
Crop/Pasture	87.29

Figure 3. 7: Map of Land Use classification in the South Nation Watershed.



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Original mapping by WESA/EarthFX (RRCA/SNC Preliminary Watershed Characterization - Figure 3).

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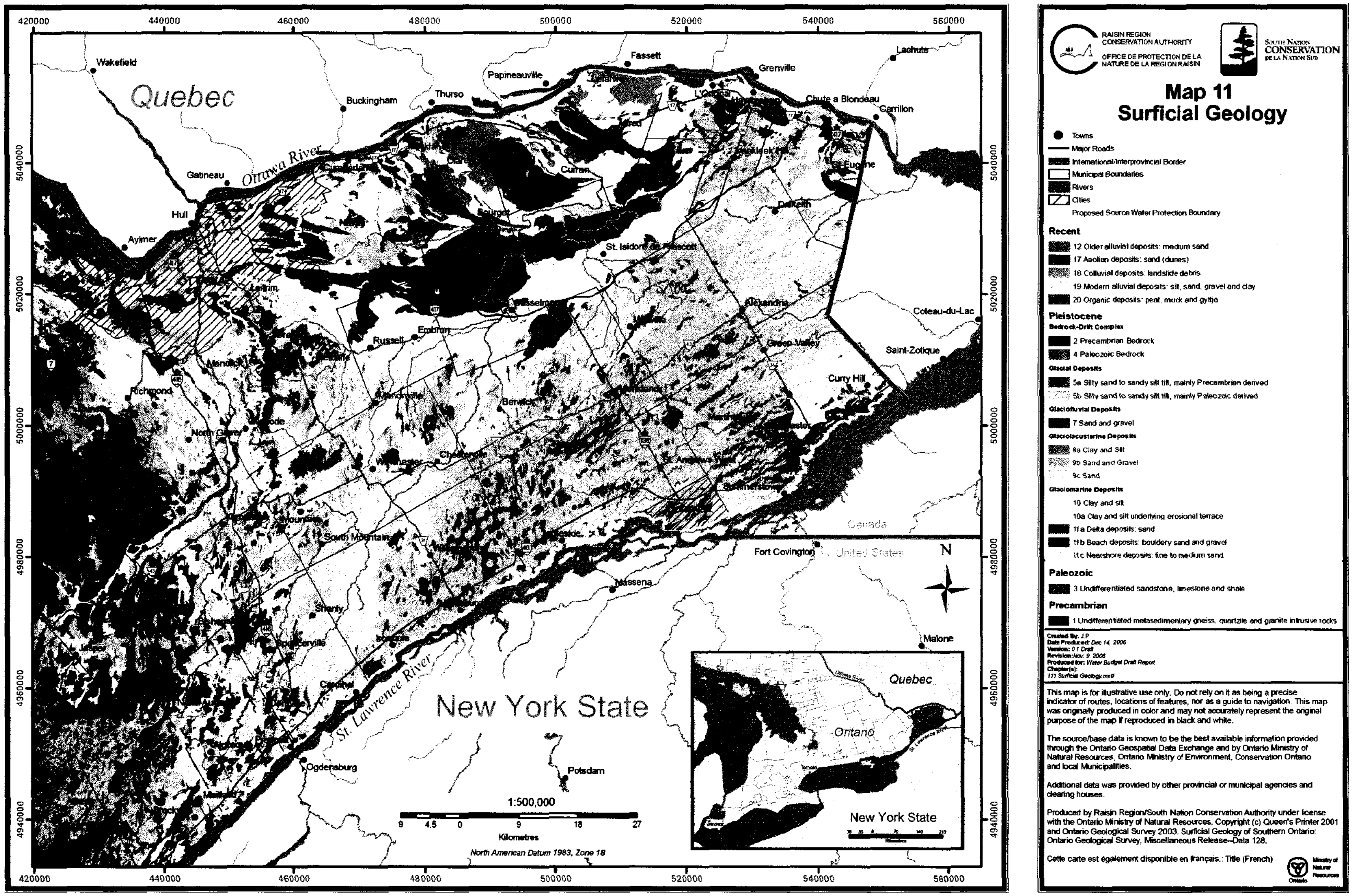
Figure 4. 1: Bedrock Formation and Faults (modified from the RRCA-SNC, 2007).



Created By: J.P
Date Produced: Dec 14, 2006
Version: 0.1 Draft
Revision: Nov. 9. 2006
Produced for: Water Budget Draft Report
Chapter(s):
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Figure 4. 2: Surficial geology (modified from the RRCA-SNC, 2007).

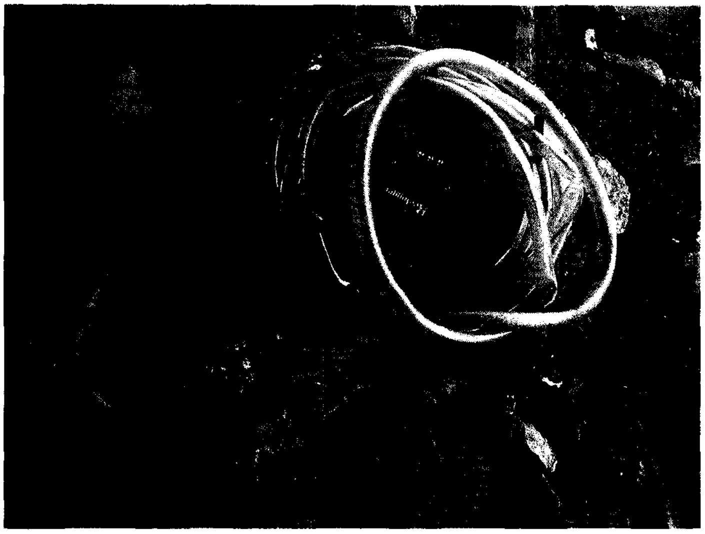


Figure 5. 1: Reelogger Model 2001 probe from Solinst Canada Ltd that records EC&T at the water-sediment interface.

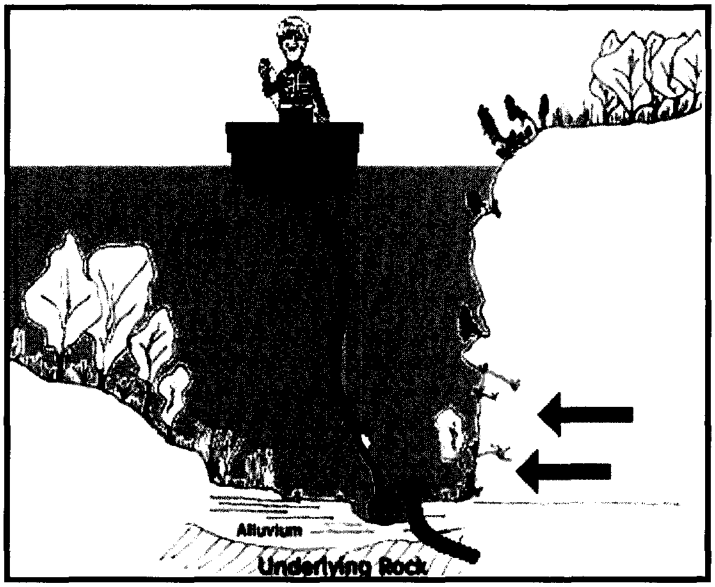


Figure 5. 2: EC&T probe dragged at the sediment-water interface.

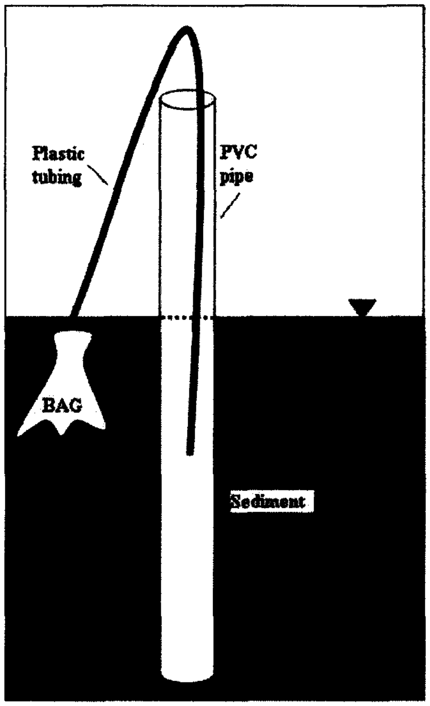


Figure 5. 3: Open Top Seepage meter (OTSM) to measures direct measurements of flux (m/day).

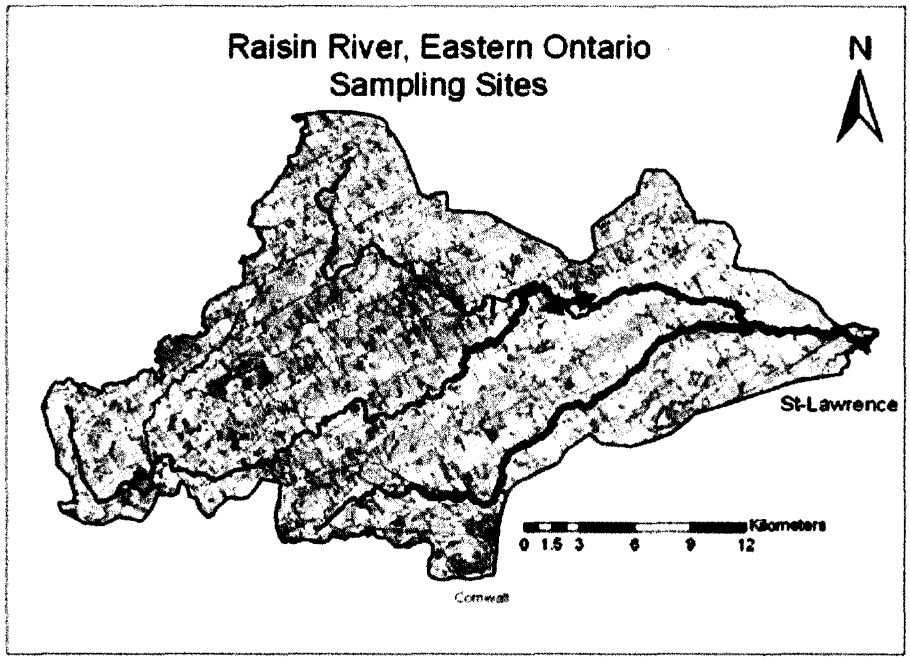


Figure 6. 1: North Branch sampling area.

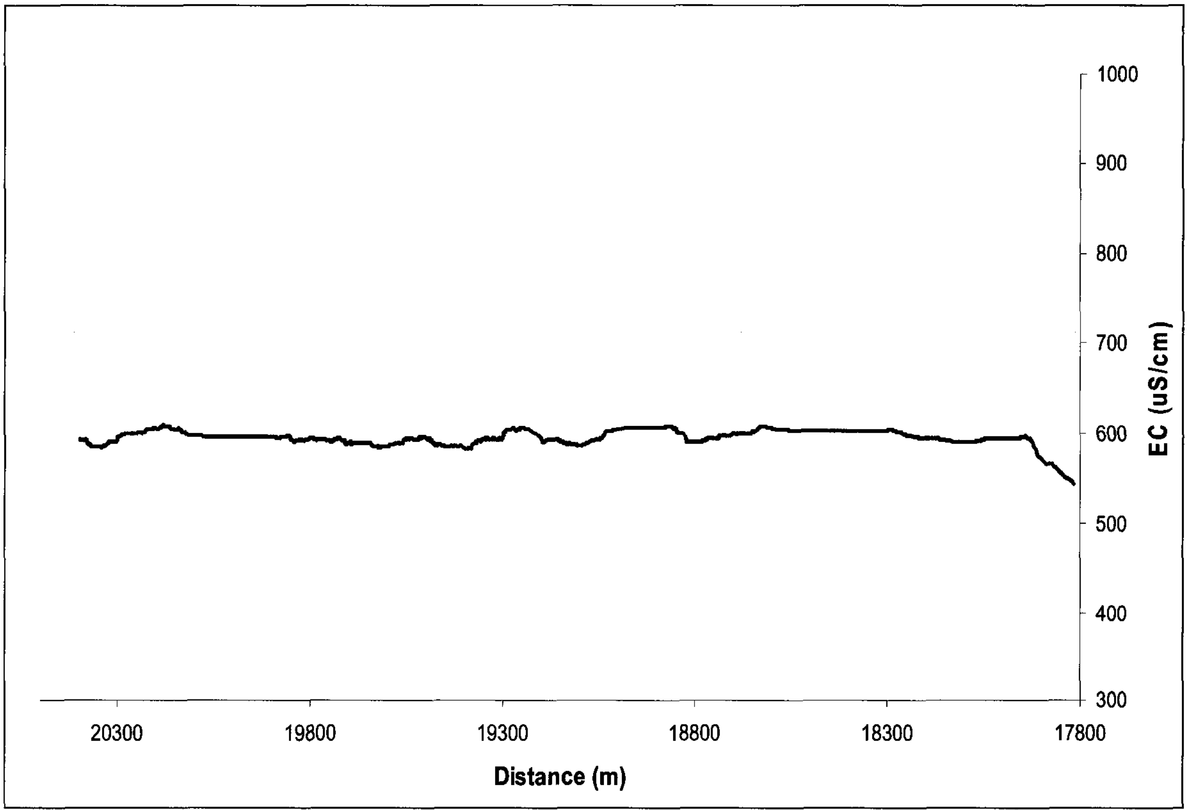


Figure 6. 2: EC profile of the North Branch of the Raisin River. Data acquired on the 28th of July 2005. For a location of this river reach, refer to Figure 3.2.

Table 6. 1: Table of EC&T of groundwater collected in wells in the Raisin Region from June to September 2005. The well labels are named according to the nomenclature of the WERAP project. W1 refers to the area whereas A, B, etc. are adjacent well in the corresponding area. Figure 6.2 shows the location of the wells.

ID	Northing	Easting	Zone	June 2005		July 2005		August 2005		September 2005	
				EC (µS/cm)	Temperature (°C)	EC (µS/cm)	Temperature (°C)	EC (µS/cm)	Temperature (°C)	EC (µS/cm)	Temperature (°C)
W1-A	5000070	530421	Nad 83 zone 18N	455.0	11.0	525.0	10.1	683.0	13.1	590.0	11.6
W1-B	4999561	530851	Nad 83 zone 18N	560.0	11.4	554.0	9.9	715.0	9.7	722.0	9.9
W1-C	4999522	530618	Nad 83 zone 18N	441.0	15.2	485.0	11.4	591.0	12.1	596.0	10.8
W2-A	4998715	532299	Nad 83 zone 18N	442.0	11.0	567.0	11.2	653.0	15.0	660.0	12.3
W2-B	4998056	533014	Nad 83 zone 18N	512.0	10.0	525.0	14.3	633.0	11.2	563.0	10.3
W2-C	4998625	532285	Nad 83 zone 18N	2010.0	11.0	2090.0	9.7	1770.0	11.8	1700.0	9.5
W2-F	4998092	532361	Nad 83 zone 18N	399.0	10.5	465.0	10.7	556.0	10.8	556.0	10.9
W3-B	4992858	523724	Nad 83 zone 18N	387.0	10.7	453.0	11.0	550.0	11.7	500.0	10.7
W3-C	4994055	524003	Nad 83 zone 18N	572.0	12.0	719.0	14.6	767.0	16.6	744.0	14.3
W3-D	4994105	523888	Nad 83 zone 18N	-	-	813.0	14.1	946.0	10.7	798.0	10.9
W9-A	4997613	513823	Nad 83 zone 18N	689.0	10.0	855.0	12.0	963.0	13.6	990.0	12.4
W9-B	4997620	513820	Nad 83 zone 18N	561.0	11.0	601.0	10.9	728.0	12.4	674.0	12.6

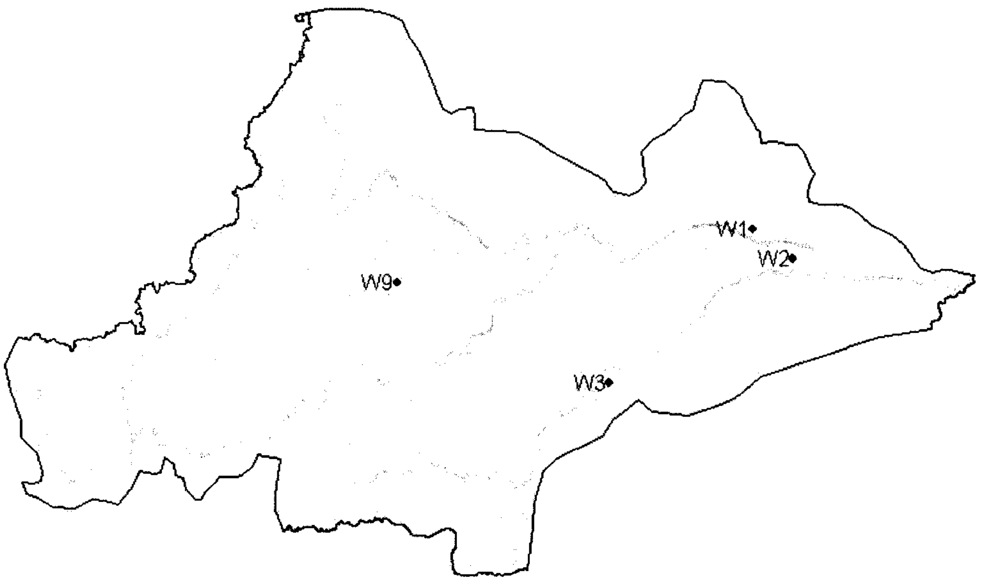


Figure 6. 3: Location map of the wells.

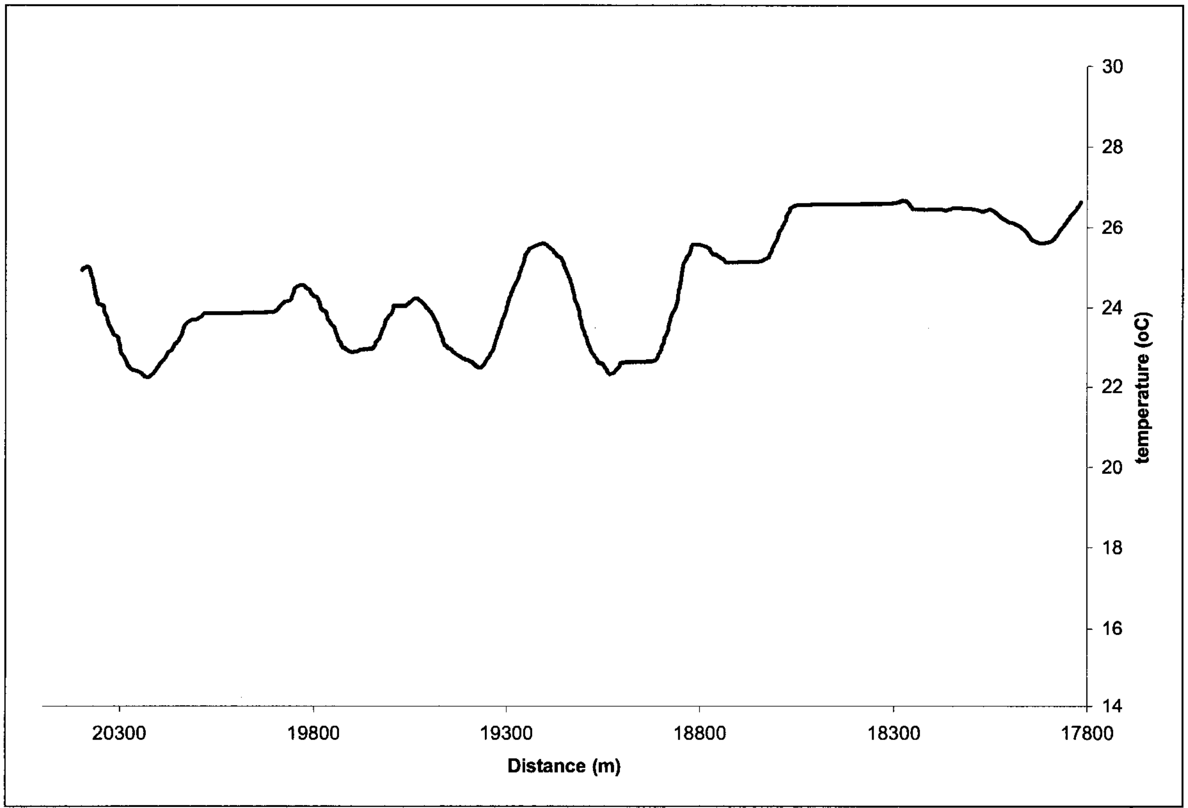


Figure 6. 4: Temperature profile of the North Branch of the Raisin River. Data acquired on the 28th of July 2005. For a location of this river reach, refer to Figure 3.2.

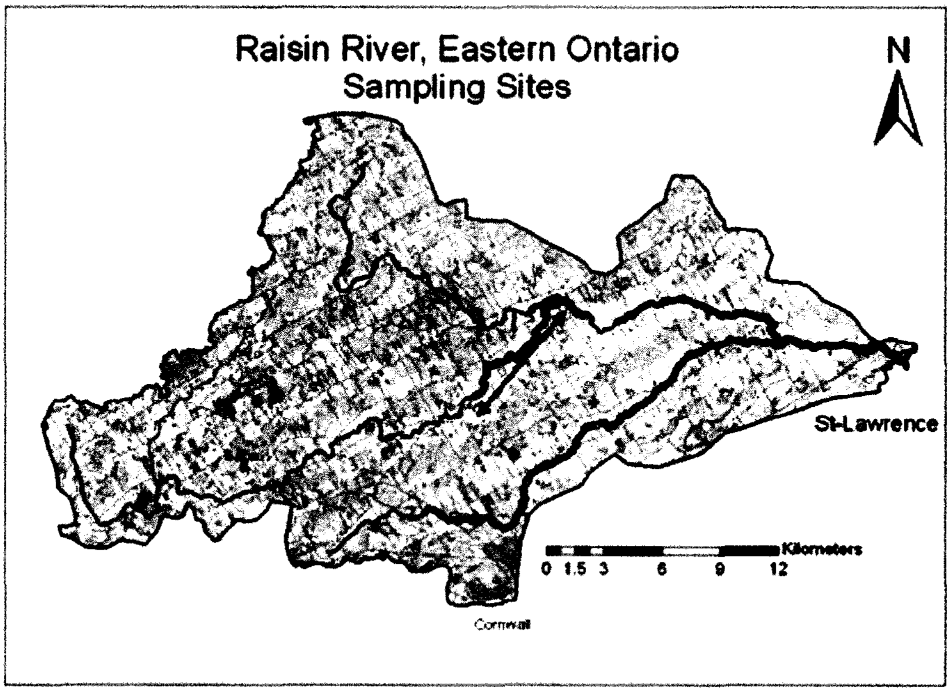


Figure 6. 5: Middle Branch sampling area.

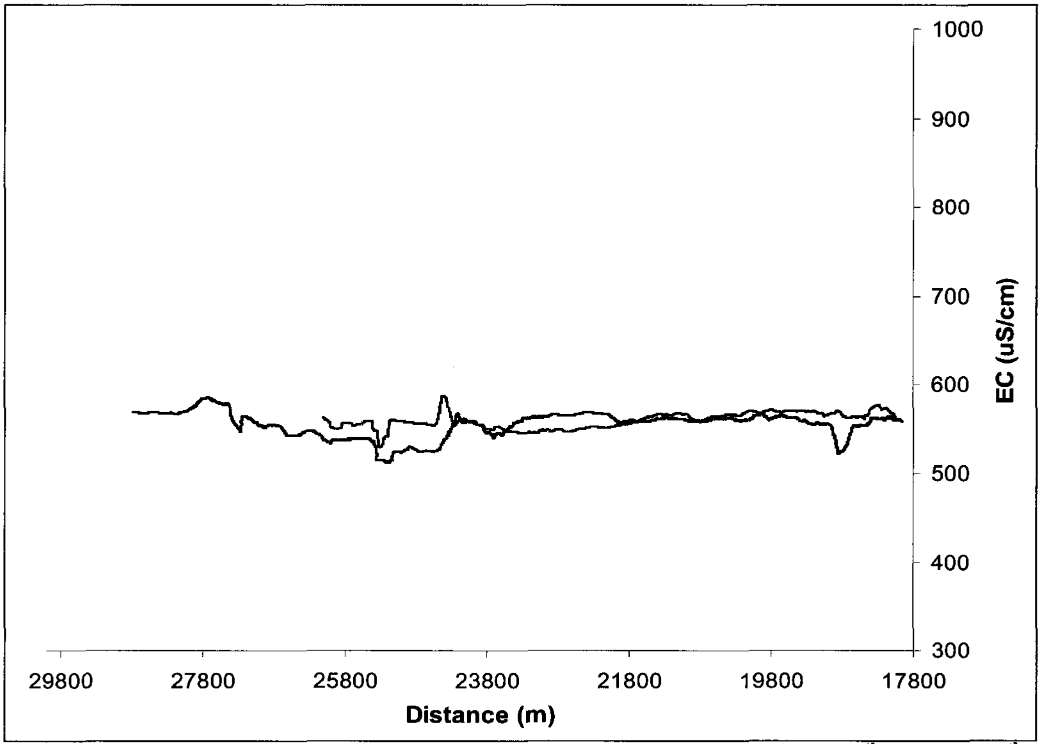


Figure 6. 6: EC profile of the Middle Raisin River. Data acquired on the 14th and the 15th of July 2005. For a location of this river reach, refer to Figure 3.2. Each line represents a different bank along the river.

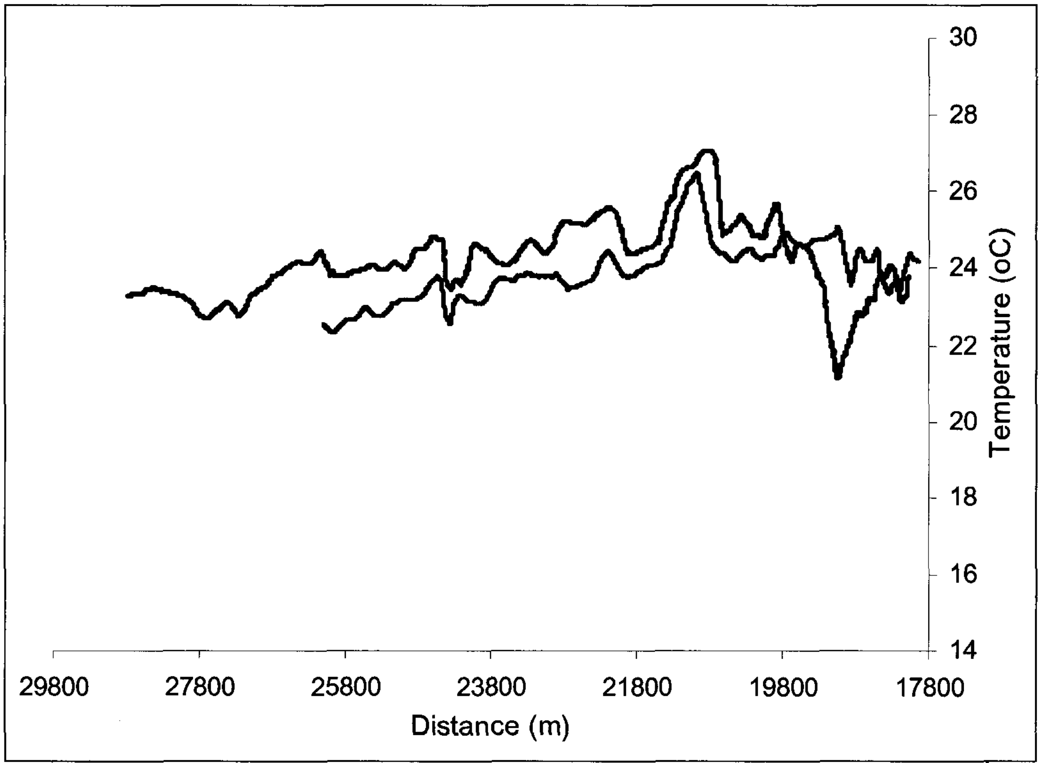


Figure 6. 7: Temperature profile of the Middle Raisin River. Data acquired on the 14th and the 15th of July 2005. For a location of this river reach, refer to Figure 3.2. Each line represents a different transect along the river.

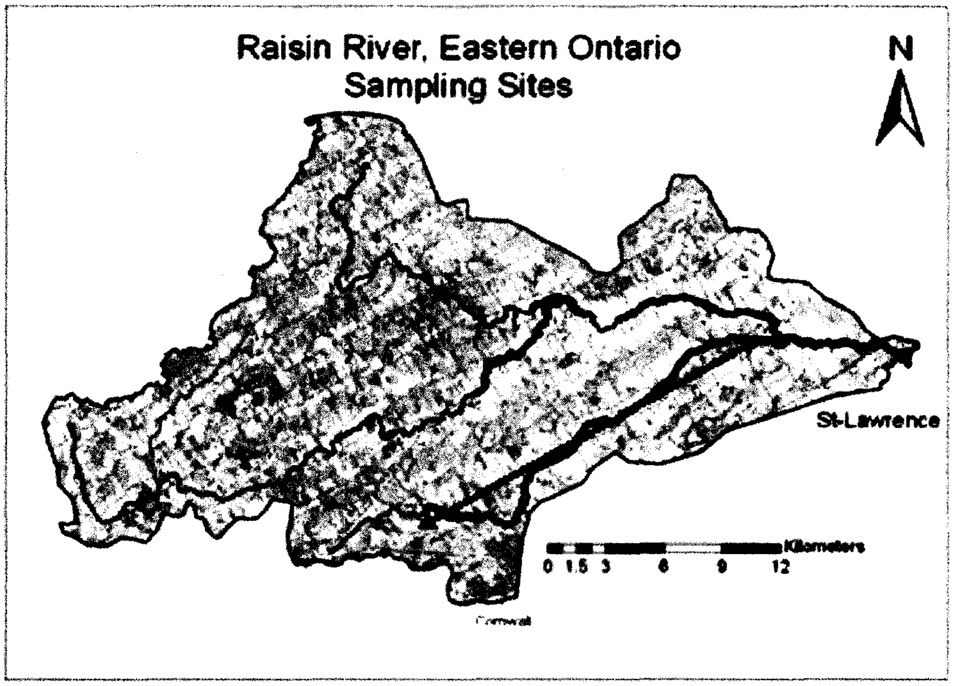


Figure 6. 8: South Branch sampling area.

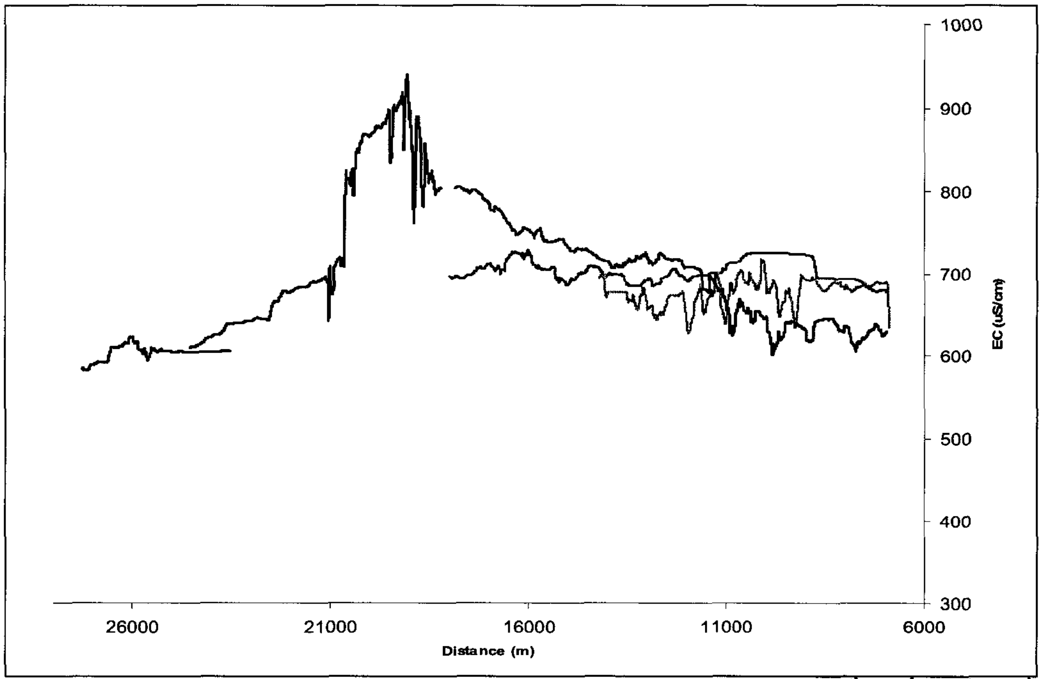


Figure 6. 9: EC profile of the South Raisin River. Data acquired on the 12th, 20th, 21st, 22nd, 26th of July and on the 5th of August 2005. For a location of this river reach, refer to Figure 3.2. When the lines, overlap, they represent a different transect of the river. Otherwise, the center of the river was surveyed.

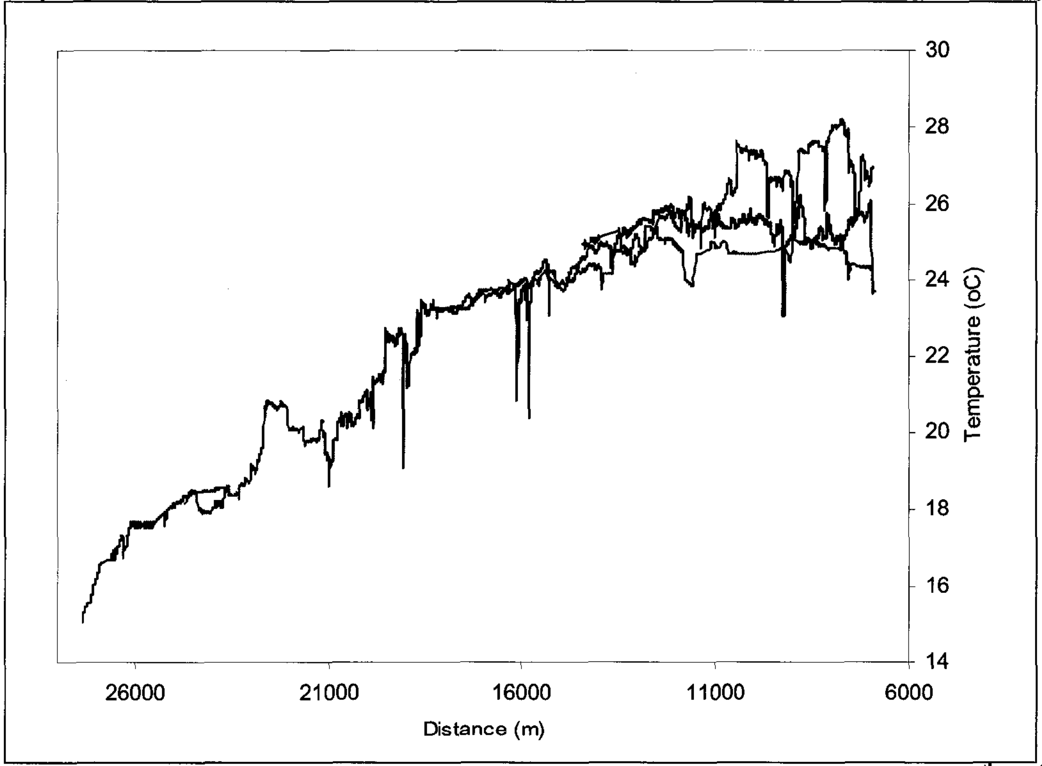


Figure 6. 10: Temperature profile of the South Raisin River. Data acquired on the 12th, 20th, 21st, 22nd, 26th of July and on the 5th of August 2005. For a location of this river reach, refer to Figure 3.2. When the lines, overlap, they represent a different transect of the river. Otherwise, the center of the river was surveyed.

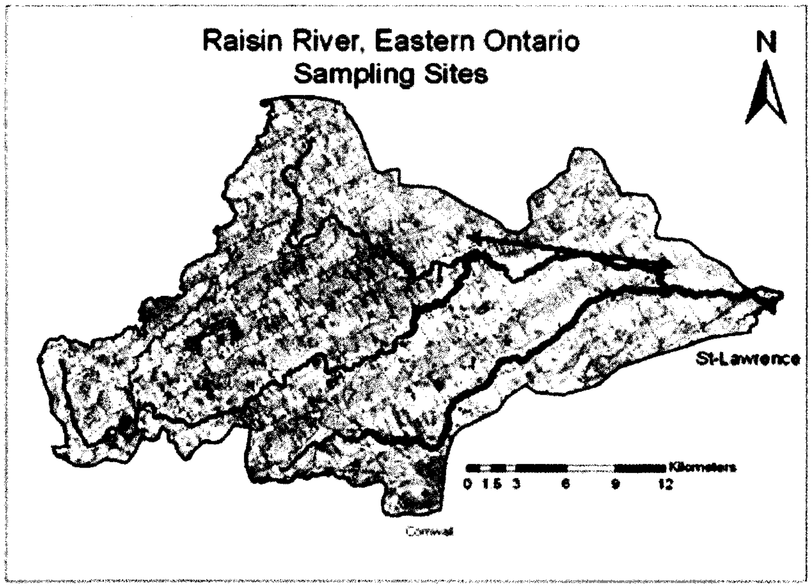


Figure 6. 11: North+Middle Branch sampling area.

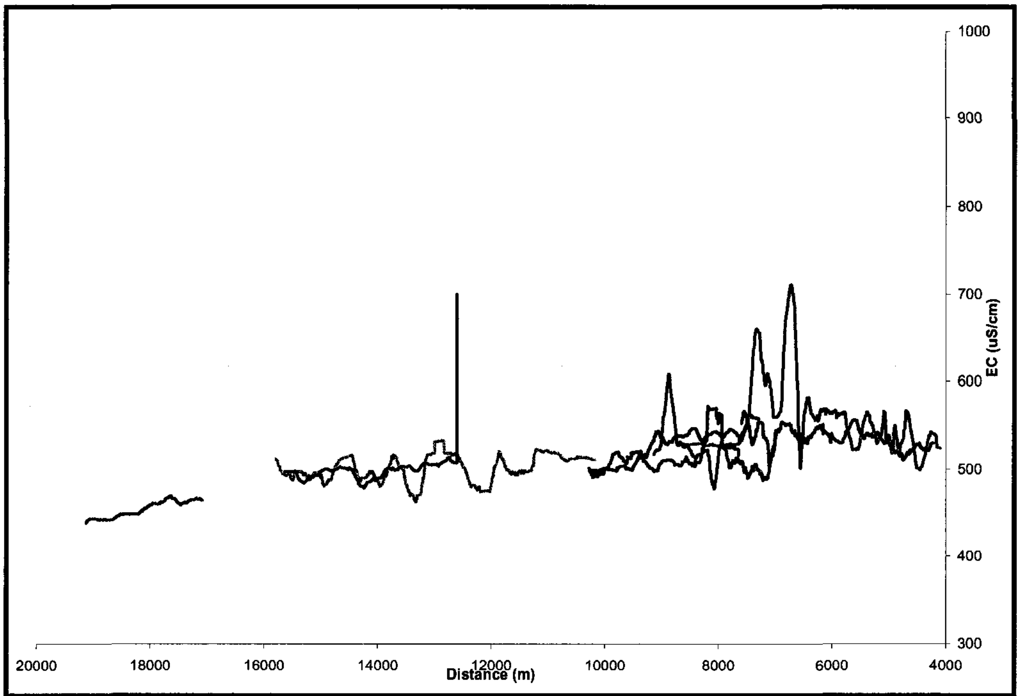


Figure 6. 12: EC profile of the N+M Raisin River. Data acquired on the 25th and the 29th of July and the 3rd and 4th of August 2005. For a location of this river reach, refer to Figure 3.2. When the lines, overlap, they represent a different transect of the river. Otherwise, the center of the river was surveyed.

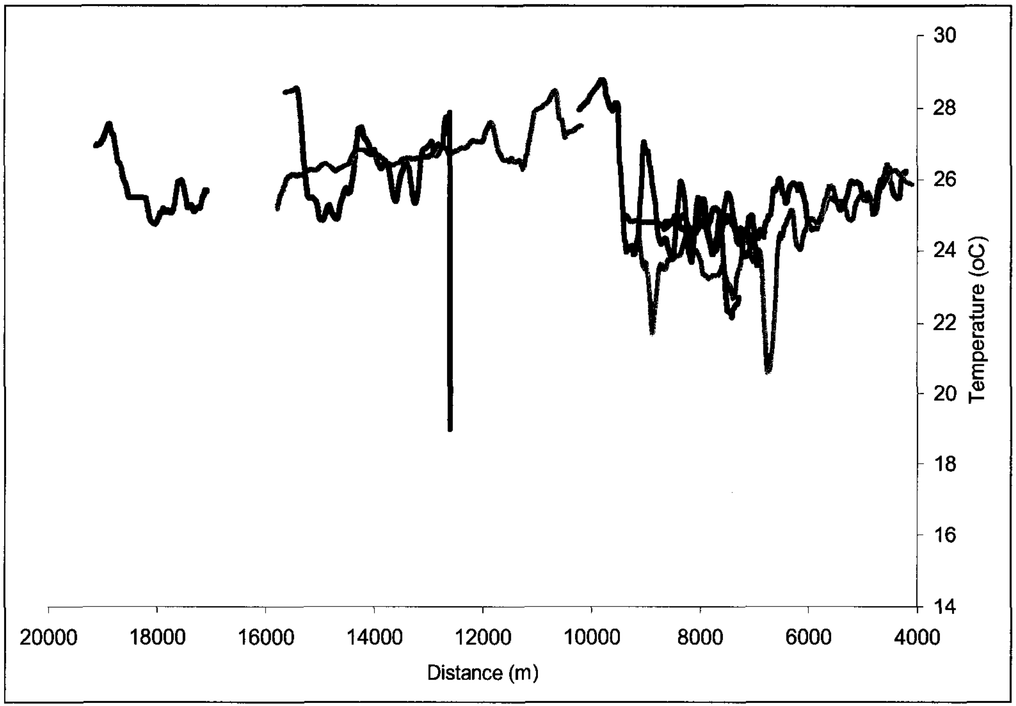


Figure 6. 13: Temperature profile of the N+M Raisin River. Data acquired on the 25th and the 29th of July and the 3rd and 4th of August 2005. For a location of this river reach, refer to Figure 3.2. When the lines, overlap, they represent a different transect of the river. Otherwise, the center of the river was surveyed.

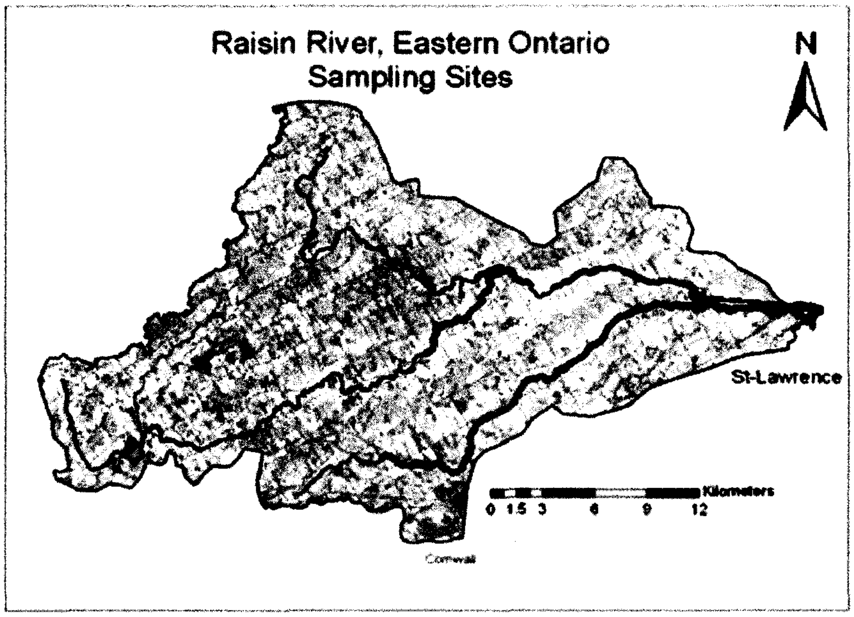


Figure 6. 14: Main Branch sampling area.

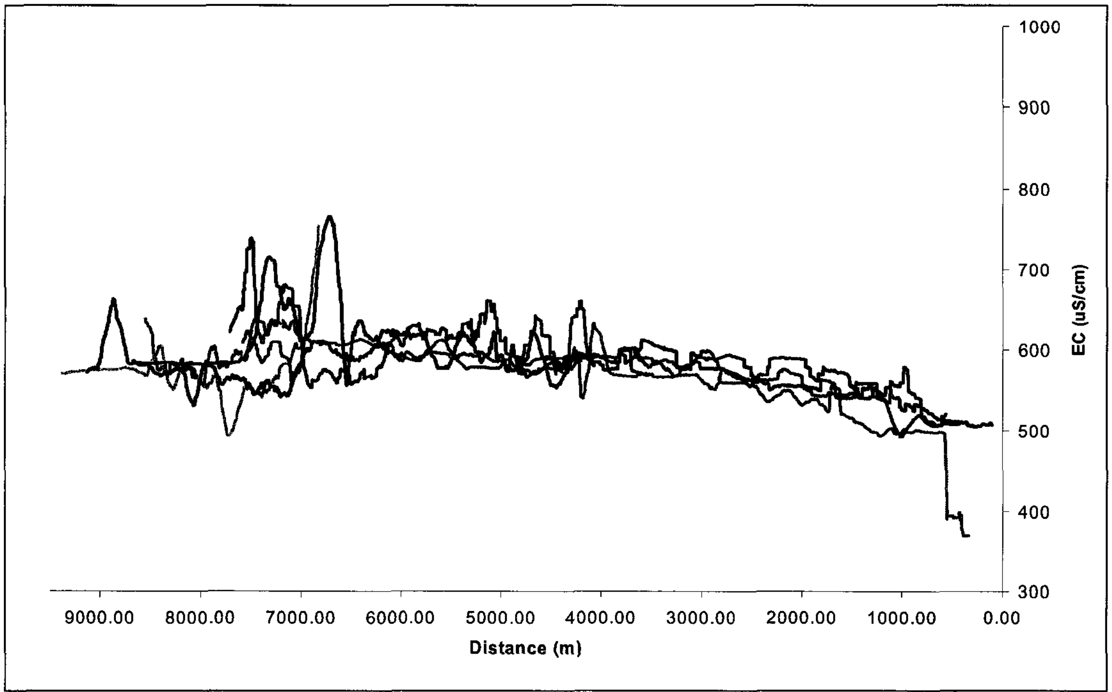


Figure 6. 15: EC profile of the Main Raisin River. Data acquired on the 1st and 4th of August 2005. For a location of this river reach, refer to Figure 3.2. When the lines, overlap, they represent a different transect of the river. Otherwise, the center of the river was surveyed.

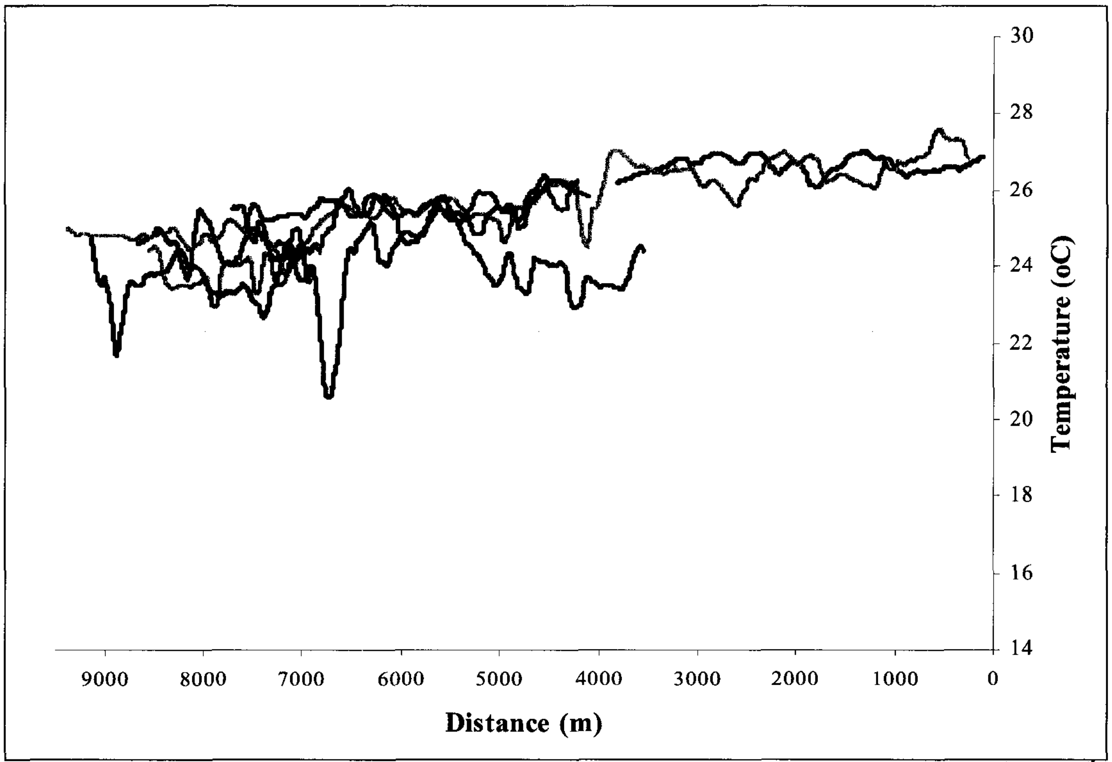


Figure 6. 16: Temperature profile of the Main Raisin River. Data acquired on the 1st and 4th of August 2005. For a location of this river reach, refer to Figure 2.2. When the lines, overlap, they represent a different transect of the river. Otherwise, the center of the river was surveyed.

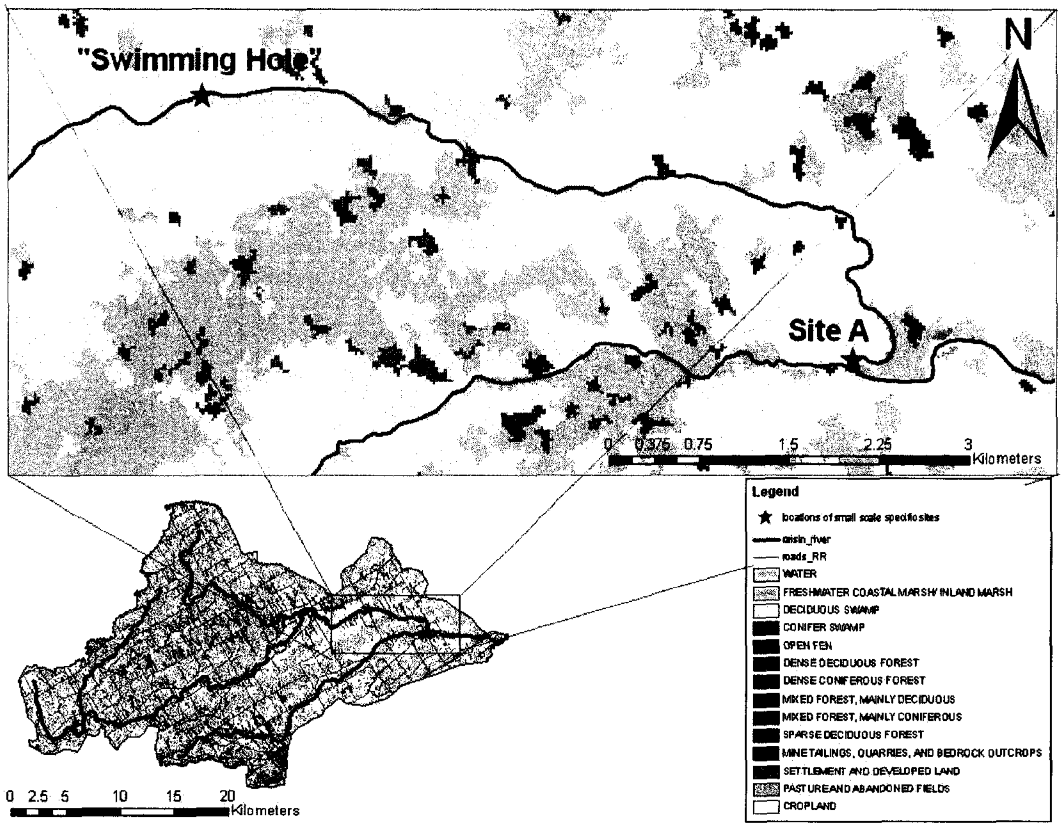


Figure 6. 17: Location map of the "Swimming Hole" and Site A. Both sites are located on the North+Middle Branch of the Raisin River.

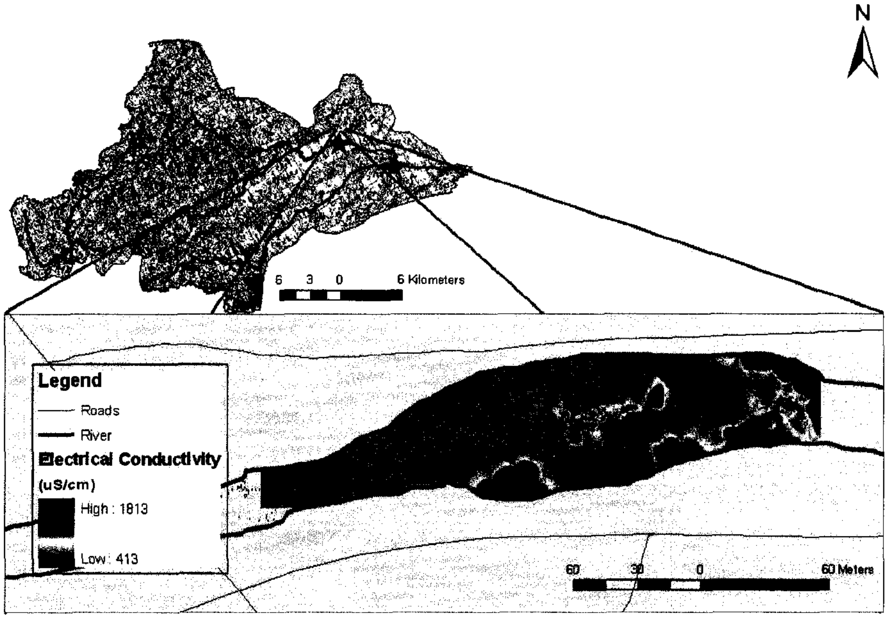


Figure 6. 18: Map of the Electrical Conductivity of the "Swimming Hole" in August 7th.2006.

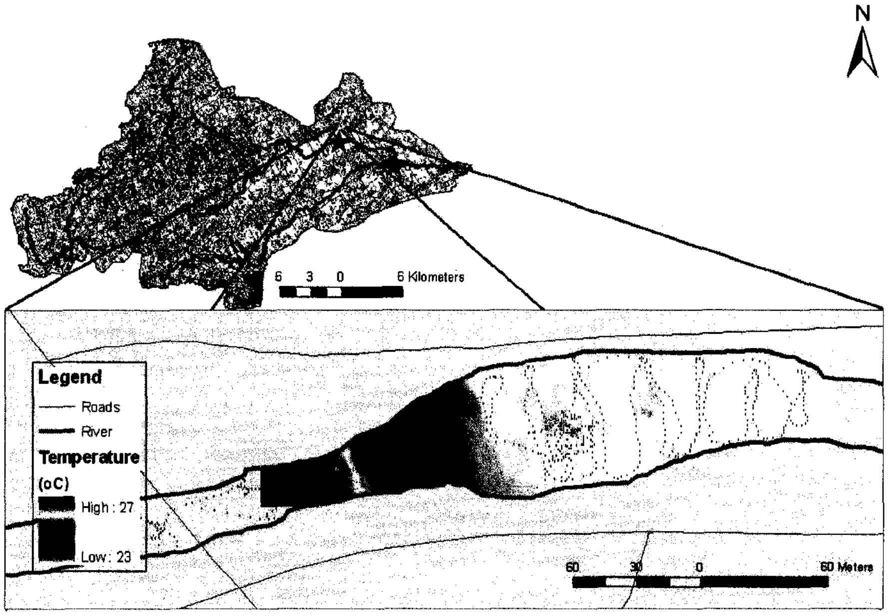


Figure 6. 19: Map of the Temperature of the "Swimming Hole" in August 7th 2006.

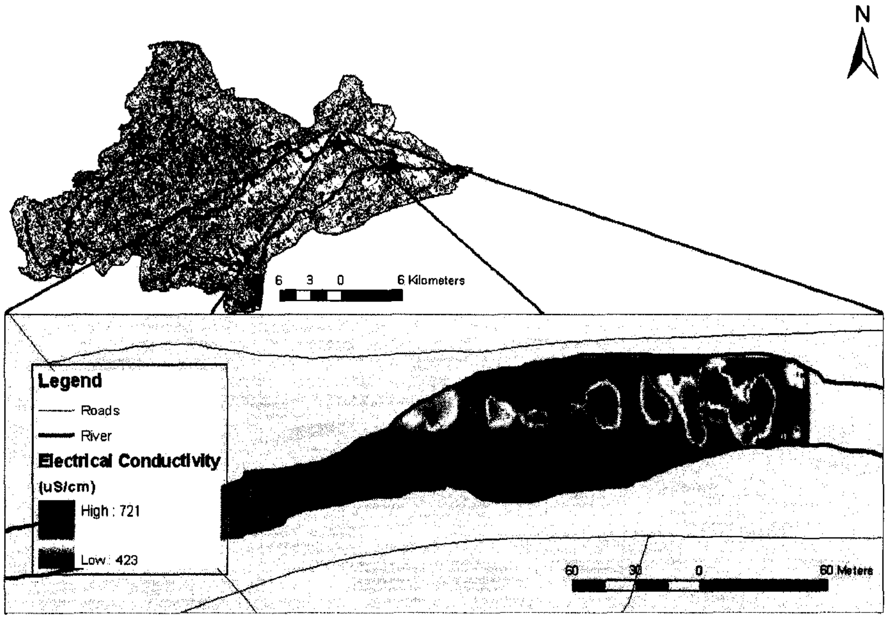


Figure 6. 20: Map of the Electrical Conductivity of the "Swimming Hole" in September 6th 2006.

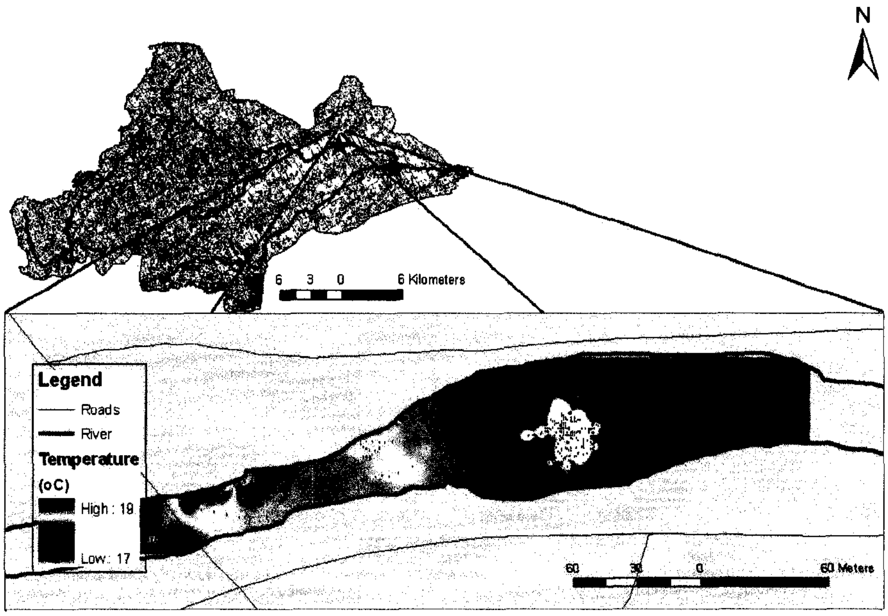


Figure 6. 21: Map of the Temperature of the "Swimming Hole" in September 6th 2006.

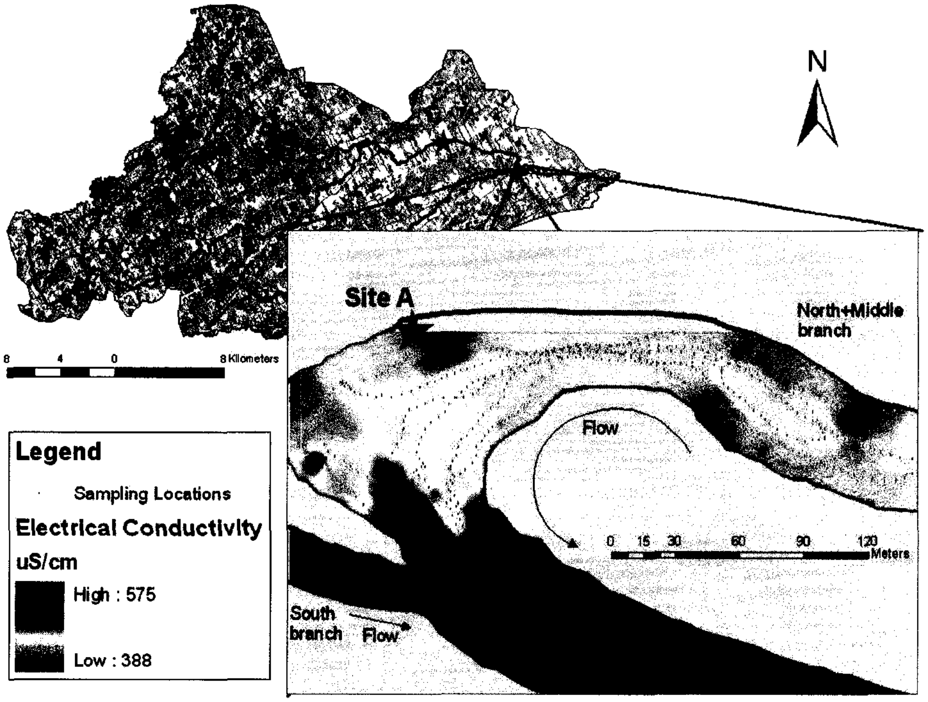


Figure 6. 22: Electrical Conductivity map of Site A on September 6th 2006.

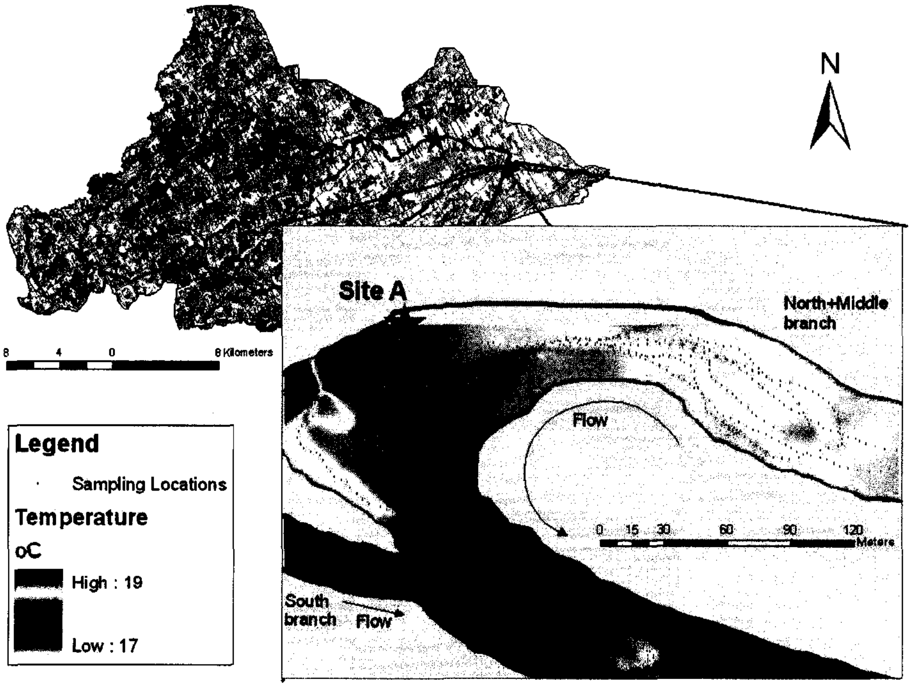


Figure 6. 23: Temperature map of Site A on September 6th 2006.

Table 6. 2: EC&T table from adjacent wells near Site A.

ID	June		July		August		September	
	EC (µS/cm)	Temperature (°C)	EC (µS/cm)	Temperature (°C)	EC (µS/cm)	Temperature (°C)	EC (µS/cm)	Temperature (°C)
W2-A	442	11.0	567.000	11.2	653	15.0	660	12.3
W2-B	512	10.0	525	14.3	633	11.2	563	10.3
W2-C	2010	11.0	2090	9.7	1770	11.8	1700	9.5
W2-F	399	10.5	465	10.7	556	10.8	556	10.9

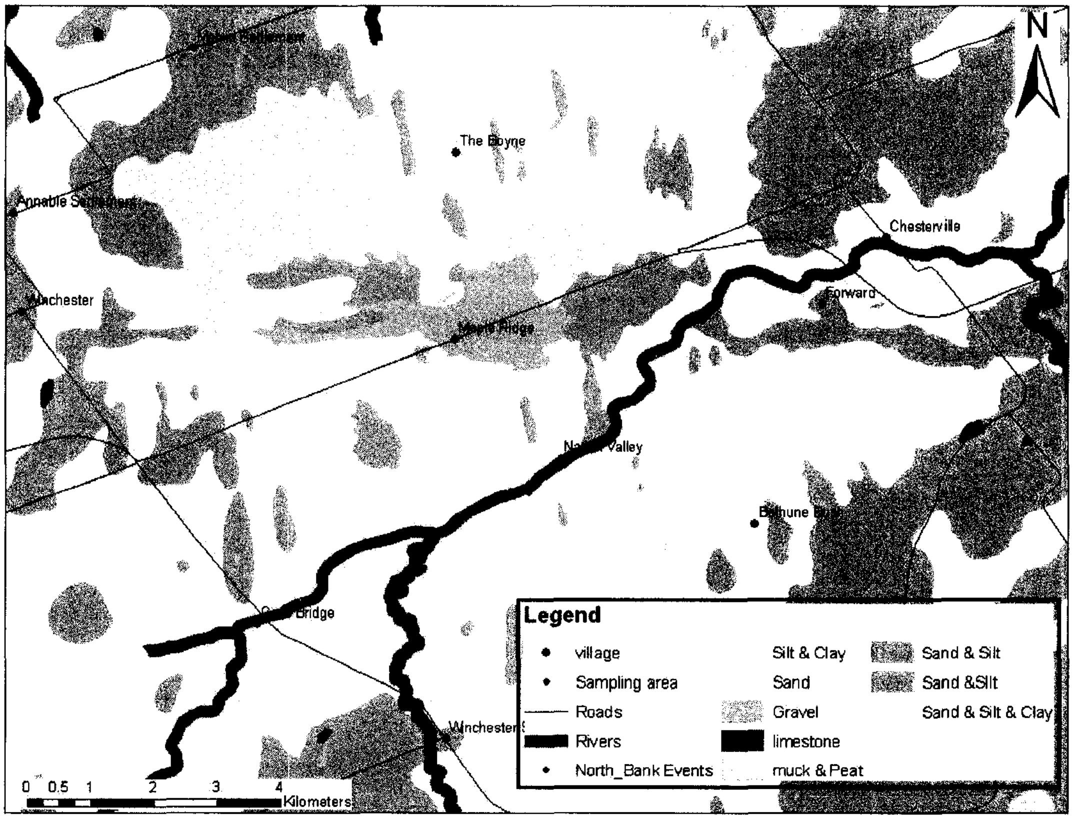


Figure 6. 24: Sampled area for the South Nation River between Winchester and Chesterville, South of the Maple Ridge fan deposit. The Maple Ridge Fan Deposit is roughly located in the gravel area in Maple Ridge.

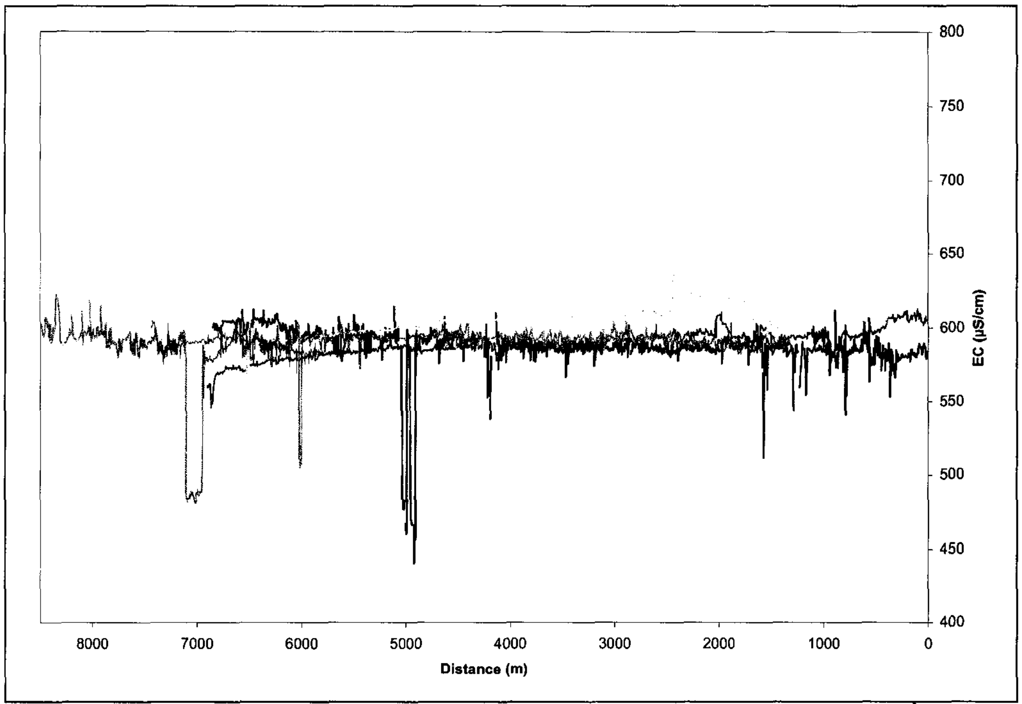


Figure 6. 25: EC profile of the South Nation River. Data acquired on the 18th of September 2006. Each coloured line corresponds to a different pass of the EC&T probe in the river during that day. The blue lines are passes made along the north shores whereas the red lines are passes made in the middle of the river.

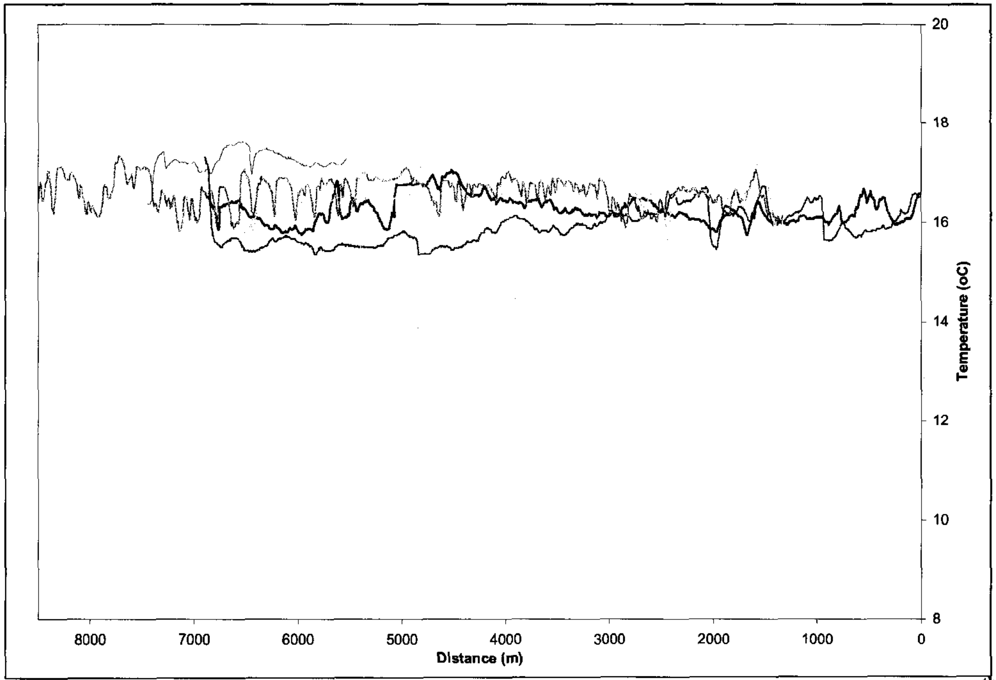
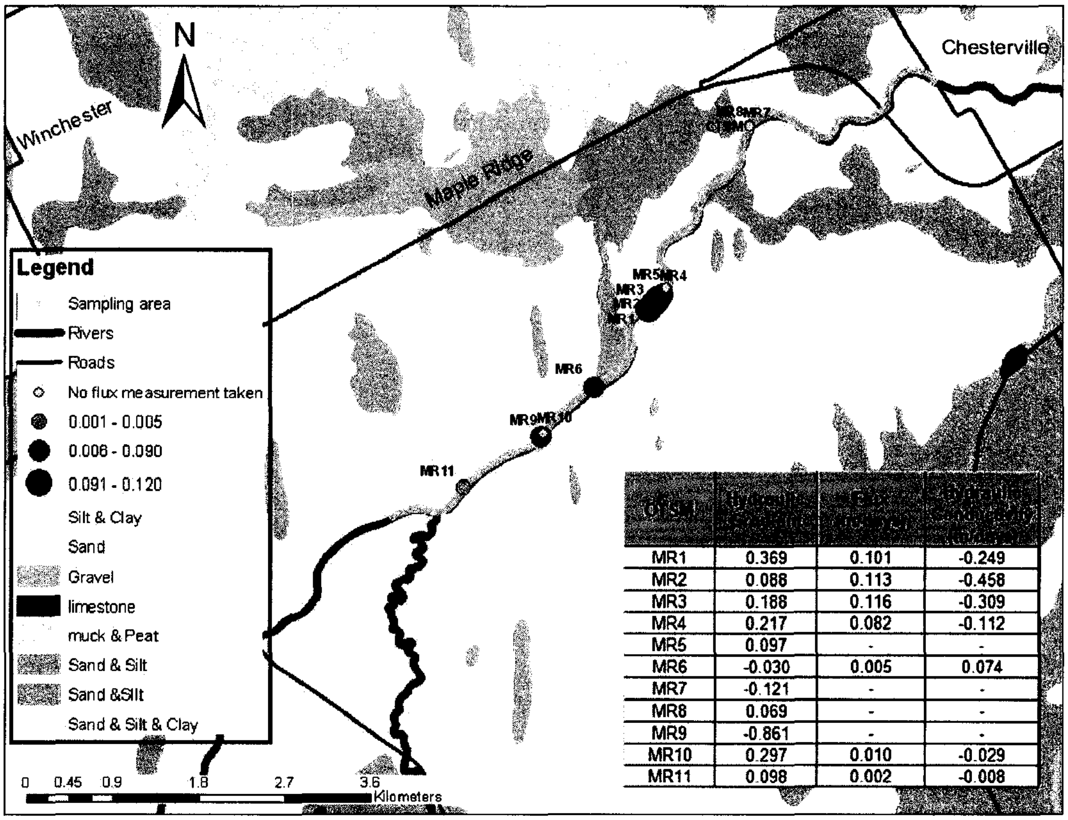


Figure 6. 26: Temperature profile of the South Nation River. Data acquired on the 18th of September 2006. Each coloured line corresponds to a different pass of the EC&T probe in the river during that day. The blue lines are passes made along the north shores whereas the red lines are passes made in the middle of the river.

Table 6. 3: Table of EC&T of groundwater collected in wells in the South Nation River area in October.

Date	Town/ Village	Well #	Well Depth (m)	Water table depth (m)	Type of well	Water Temperature (°C)	Water E.C. (µS/cm)	Notes
16-Oct-06	Chesterville	Maple Ridge Senior Public School	44.2	38.1	private	14.8	525	Drilled well
23-Oct-06	Chesterville	5	12.2	-	municipal	15	550	in Maple Ridge Fan deposit
23-Oct-06	Chesterville	6	9.3	-	municipal	12.6	710	in Maple Ridge Fan deposit--well 6 ~ 100 m away from well 5
23-Oct-06	Winchester	1	45.72	18	municipal	12	865	possibly salt deposit near by, in bedrock
23-Oct-06	Winchester	5	19.8	-	municipal	12	980	possibly salt deposit near by, in bedrock
23-Oct-06	Winchester	6	13.4	-	municipal	11.6	790	in bedrock
23-Oct-06	Winchester	7a	24.5	6-6.5	municipal	14.9	490	Located in Morewood Esker (gravel)--50ft away from 7b
23-Oct-06	Winchester	7b	24.5	6-6.5	municipal	12.6	630	Located in Morewood Esker (gravel)



OTSM	Hydraulic [illegible]	Flux [illegible]	Hydraulic Conductivity [illegible]
MR1	0.369	0.101	-0.249
MR2	0.086	0.113	-0.458
MR3	0.188	0.116	-0.309
MR4	0.217	0.082	-0.112
MR5	0.097	-	-
MR6	-0.030	0.005	0.074
MR7	-0.121	-	-
MR8	0.069	-	-
MR9	-0.861	-	-
MR10	0.297	0.010	-0.029
MR11	0.098	0.002	-0.008

Figure 6. 27: OTSM locations in the South Nation River with a table of the hydraulic gradient, the flux measurements and hydraulic conductivity measurements for each site.

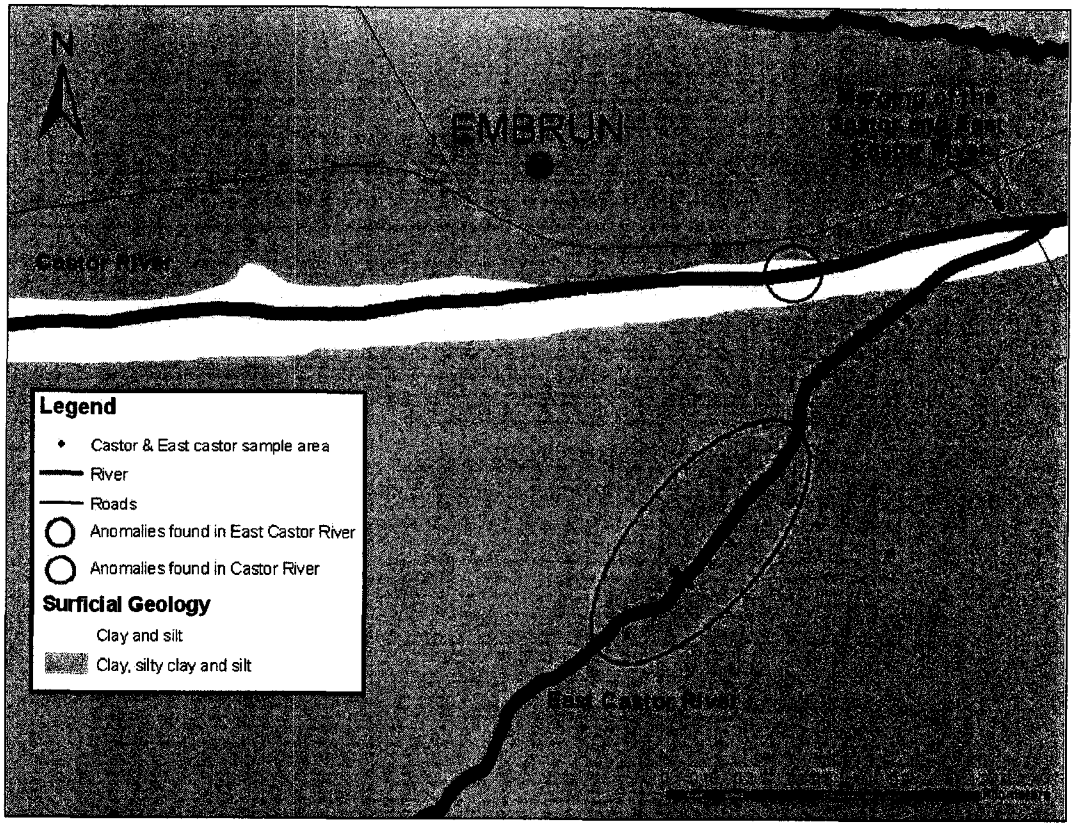


Figure 6. 28: Sampled area for the Castor and the East Castor. Circled areas are anomalies believed to be the result of the interaction with the esker along the 2 branches of the Castor River. Flow of the rivers is from West to East.

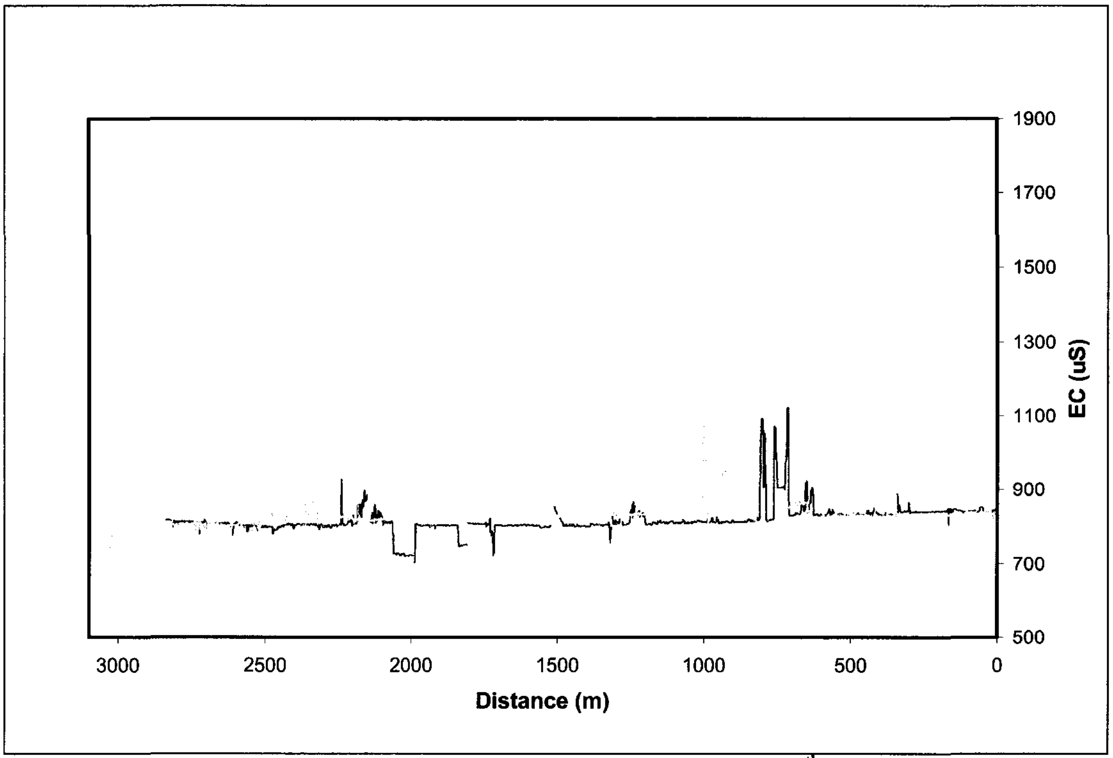


Figure 6. 29: EC profile of the Castor River. Data acquired on the 19th of September 2006. Each coloured line corresponds to a different pass (along each bank) of the EC&T probe in the river during that day.

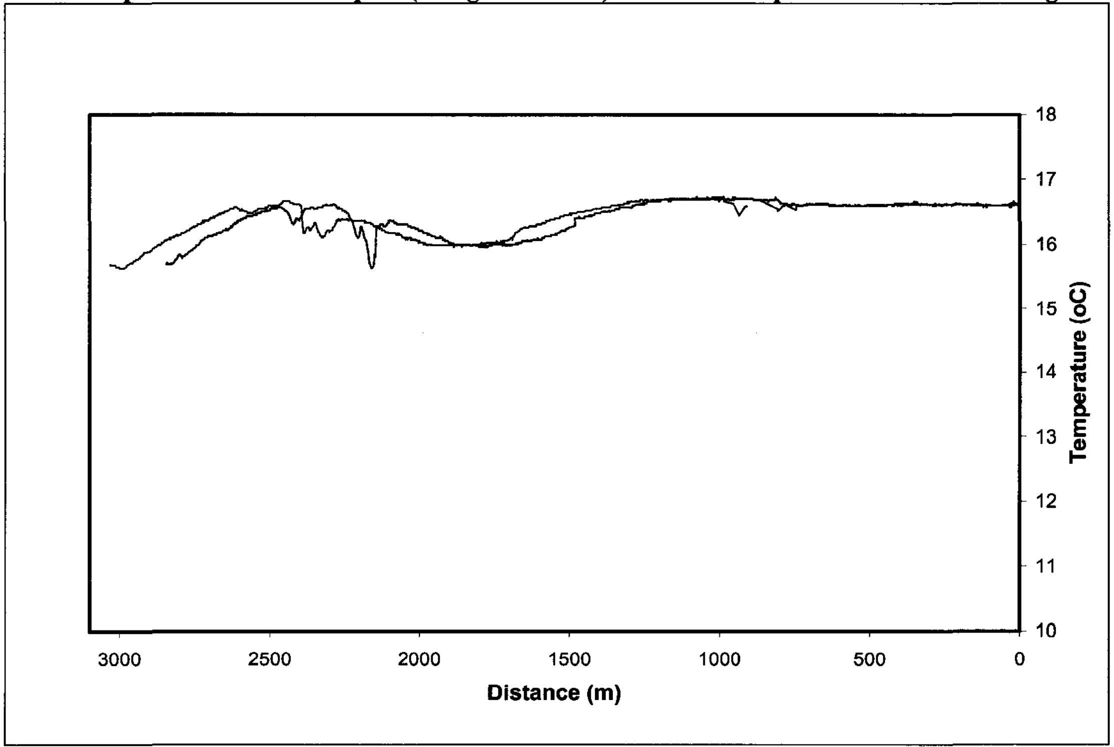
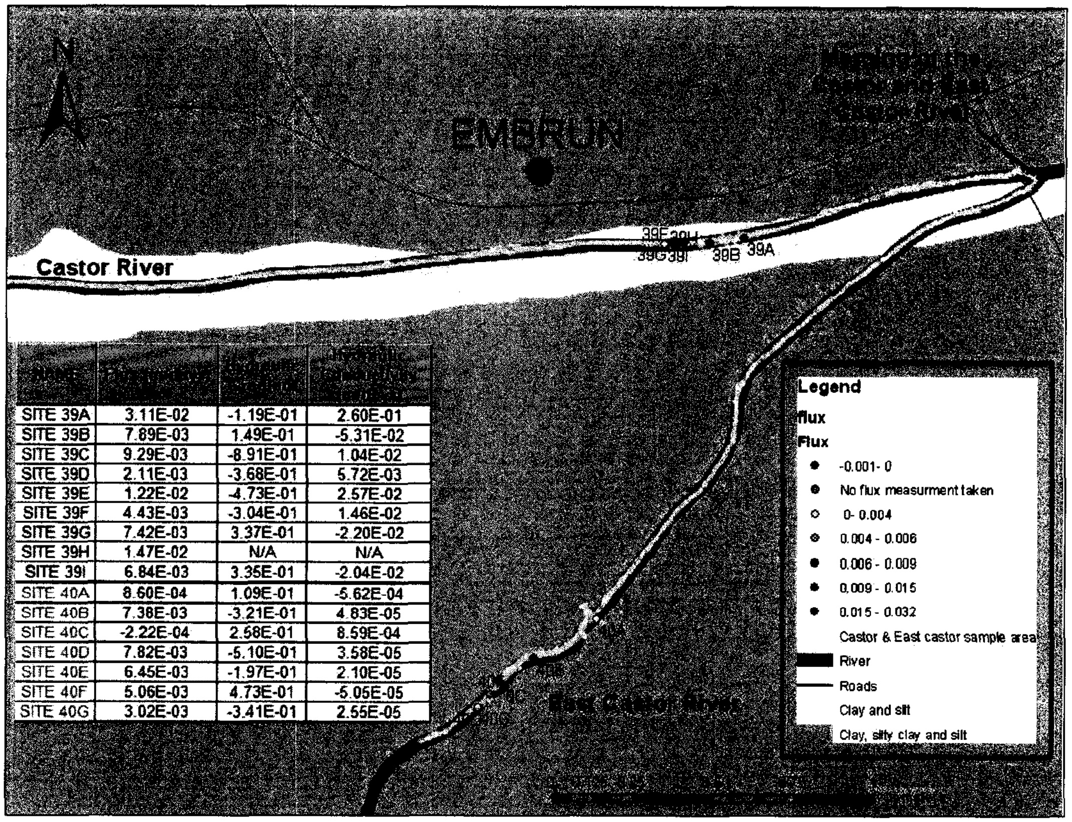


Figure 6. 30: Temperature profile of the Castor River. Data acquired on the 19th of September 2006. Each coloured line corresponds to a different pass (along each bank) of the EC&T probe in the river during that day.

Table 6. 4: Table of EC of groundwater collected in wells from the city of Embrun located in the surrounding area of the Castor and East Castor River.

River	Well Depth (m)	Water depth (m)	Type of well	Water EC (µS/cm)	Comments
East Castor	19.8	13.7	Private	1255	Water sample taken before softener
East Castor	26	-	Private	1871	From kitchen tap, after softener /
East Castor	26	-	Private	-	-
East Castor	19.8	-	Private	4000**	Hard water/ added bleach to water / water taken after softener
East Castor	19.8	-	Private	1677-1666	Water taken after softener



[illegible]	[illegible]	[illegible]	[illegible]
SITE 39A	3.11E-02	-1.19E-01	2.60E-01
SITE 39B	7.89E-03	1.49E-01	-5.31E-02
SITE 39C	9.29E-03	-8.91E-01	1.04E-02
SITE 39D	2.11E-03	-3.68E-01	5.72E-03
SITE 39E	1.22E-02	-4.73E-01	2.57E-02
SITE 39F	4.43E-03	-3.04E-01	1.46E-02
SITE 39G	7.42E-03	3.37E-01	-2.20E-02
SITE 39H	1.47E-02	N/A	N/A
SITE 39I	6.84E-03	3.35E-01	-2.04E-02
SITE 40A	8.60E-04	1.09E-01	-5.62E-04
SITE 40B	7.38E-03	-3.21E-01	4.83E-05
SITE 40C	-2.22E-04	2.58E-01	8.59E-04
SITE 40D	7.82E-03	-5.10E-01	3.58E-05
SITE 40E	6.45E-03	-1.97E-01	2.10E-05
SITE 40F	5.06E-03	4.73E-01	-5.05E-05
SITE 40G	3.02E-03	-3.41E-01	2.55E-05

Figure 6. 31: OTSM locations in the Castor and East Castor Rivers along with a table of fluxes, hydraulic gradients and hydraulic conductivity measurements. Sites 39 are located in the Castor River and Sites 40 in the East Castor River.

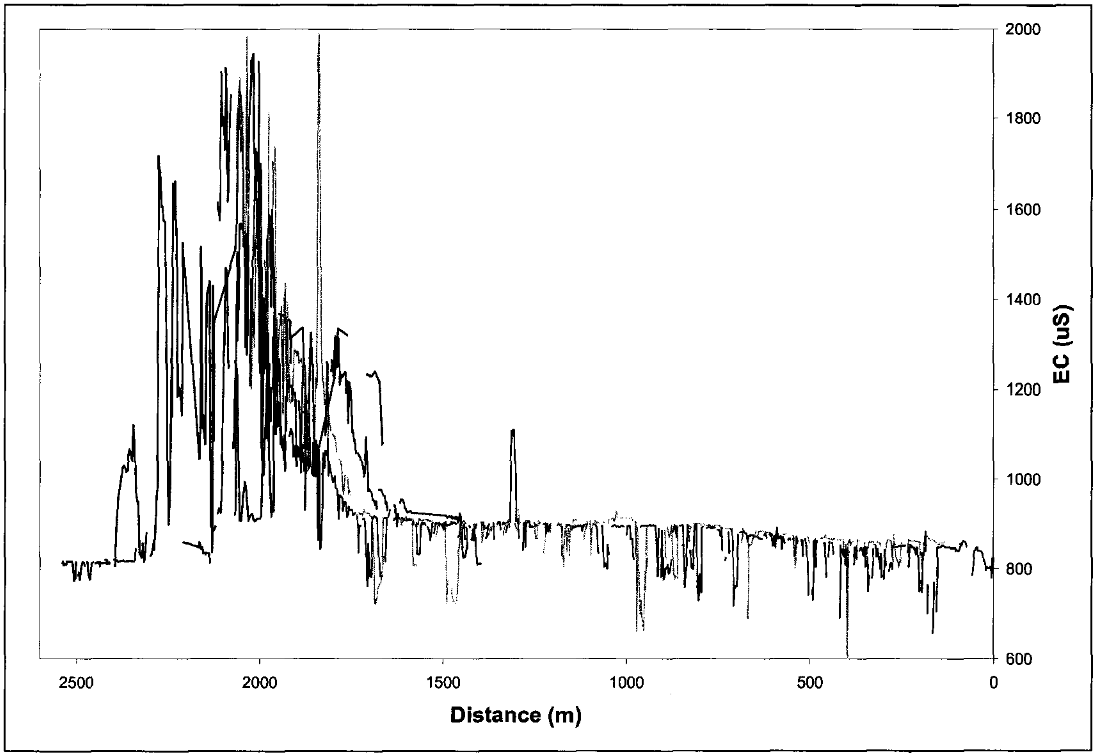


Figure 6. 32: EC profile of the East Castor River. Data acquired on the 19th of September 2006. Each coloured line corresponds to a different pass of the EC&T probe in the river during that day.

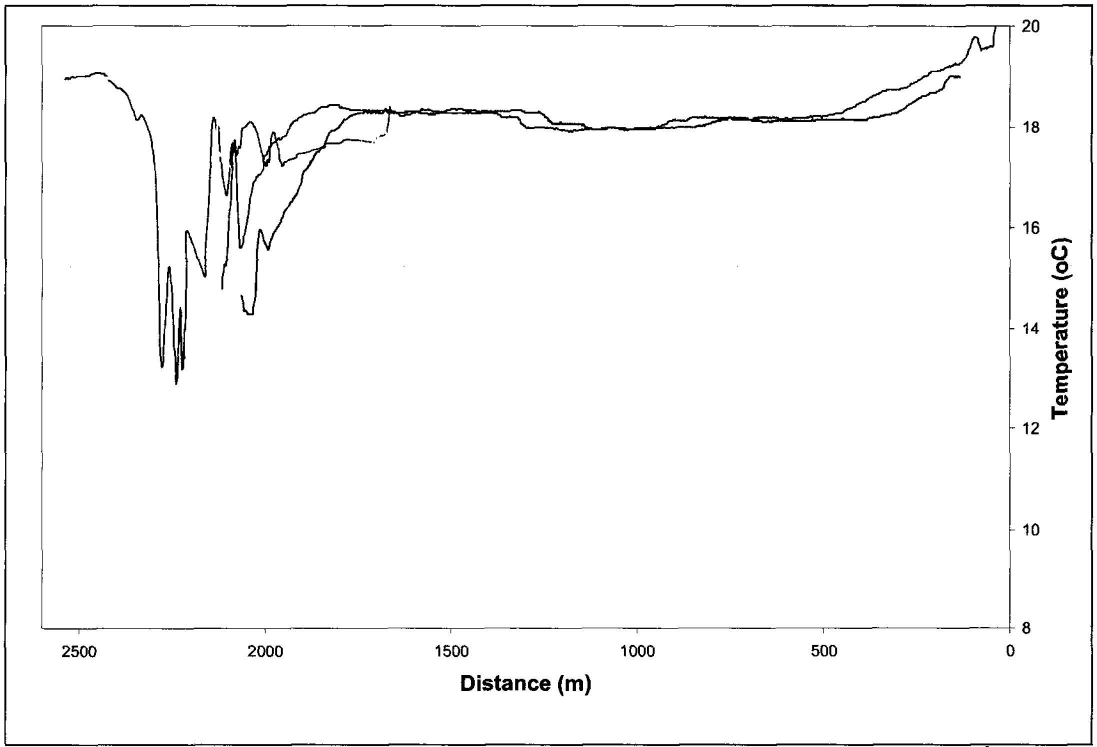


Figure 6. 33: Temperature profile of the East Castor River. Data acquired on the 19th of September 2006. Each coloured line corresponds to a different pass of the EC&T probe in the river during that day.

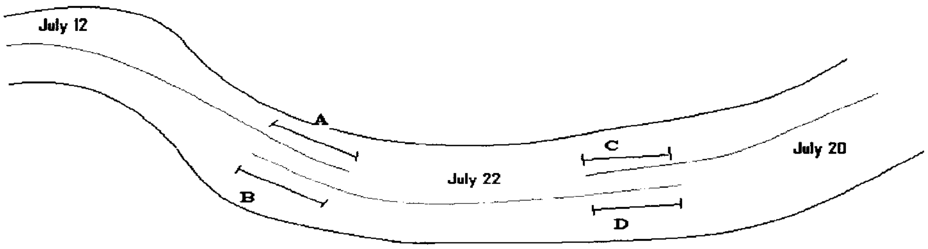
Appendix A: Correcting for temporal variability

The electrical conductivity of river water changes day-to-day depending on rainfall events and other inputs to the river. This temporal variation will produce discontinuities in the spatial distribution of EC&T values at positions that correspond to the beginning and end of each surveying day. The EC&T discontinuities may be large, particularly when surveying dates are not contiguous and/or are separated by precipitation events. If left uncorrected, the discontinuities can be large enough to be misinterpreted as anomalies, when in fact they are simply the result of normal, but unaccounted for, temporal variability.

To partially correct for this temporal variability in the EC&T, we can overlap sections of the survey by re-surveying a section of the river that was done on a previous surveying day. For instance, on the first sampling day, July 12th, 2005, we kayaked the main Branch of the Raisin River downstream to the Village of St Andrew's. On another surveying day, July 22nd, 2005, a contiguous reach of the river downstream of St Andrew's was to be sampled and so a section of the river was resampled upstream of St Andrew's for temporal correction. The difference in average EC&T for the two overlapped segments of the river was used to correct the EC&T values of the second day. This process was repeated every day and so, all measurements of the EC&T probe from the summer 2005 from the Raisin River were corrected to EC&T values of the "standard day", July 12th, 2005. This correction was done using a GIS software. This temporal variation correction is only partial because the same portion of the river was not re-sampled every day (only a portion of a previous day's survey). It would have been impractical to do so, given the large aerial extent of the Raisin River Basin. Alternatively, data logging devices could have been installed at key locations in the watershed to measure EC variability over time. A numerical example of how temporal variability was corrected over the summer is presented below.

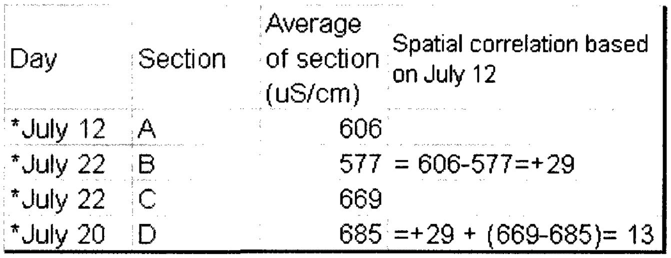
Example

In Figure A.1, the river reach surveyed on July 12th overlaps the reach of July 22nd. By taking the average of the sections done on the 12th and the 22nd, we can then add or subtract the difference to correct for the temporal variation. And so, on the 22nd of July we added a constant 29 μS/cm to all EC values measured on that day. On the 20th of July, the next segment downstream, we added 29 (to account for the previous day) and -16 (to account for this current day) to all EC values of the 20th adding in total a constant 13 μS/cm to all EC measures.



Section Average:
July 12, section A = 606 uS/cm
July 22, section B = 577 uS/cm

July 22, section C = 669 uS/cm
July 20, section D = 685 uS/cm



Day	Section	Average of section (uS/cm)	Spatial correlation based on July 12
*July 12	A	606	
*July 22	B	577	= 606-577=+29
*July 22	C	669	
*July 20	D	685	=+29 + (669-685)= 13

Figure A.1: Correction example of temporal variability using July 12th as the standard day. By using the average section of the overlapping segment, we can correct for temporal variability.

In some other cases, 2 days of sampling were done exactly along the same stretch of the Raisin River. If the variation between those two days was less than 100 μS/cm, it was considered as no change in the EC values and we did not correct for the temporal variability along those reaches. It is important to realize that this correction technique produces error that is systematic from one day to another but that it is partially self-correcting over a long period of time (such as the sampling season), since the corrections are sometimes positive and sometime negative.

Appendix B: OTSM Calculations

This appendix contains results from direct seepage meters and piezometers. The data was gathered in collaboration with 4th year students Rachel Cooper (2007) and Beth Sargent (2007), and is summarized from their thesis here. The raw data from piezometers and direct seepage meters are given in the tables along with the hydraulic gradients, the Darcy flux and the hydraulic conductivity. Sample calculations are included.

B.1. Hydraulic Gradient Calculations

PVC pipes used for open-top seepage meters can act as slow-response time piezometers (mini-wells) when they are left with no siphons or bags. Piezometers installed in this manner can be used to measure hydraulic gradients provided that the water levels in the river and the piezometers are relatively stable. The hydraulic gradient is the driving force in Darcy's Law for discharge or recharge of the aquifer.

The hydraulic gradient, i, is

$$i = \frac{dh}{dx} \qquad \text{Equation B.1}$$

Where:

dh= water level inside of the PVC pipe (piezometers) minus the water level of the river (m)

dx= minus the depth of penetration in the sediments of the PVC pipe (m) = elevation of the open end of the piezometer in the sediment minus the elevation of the sediment-water interface. When discharge of groundwater occurs, the water level inside the PVC pipe is higher compared to the river water level and when recharge groundwater is present, the water level inside of the PVC is lower compared to the river water level. The sign of the gradient (and thence of the flux) depends on the direction of the hydraulic head drop relative to the coordinate system. Keeping track of the sign can be confusing and the sign in Darcy's Law is often ignored in practice in favor of the simple rule of flow taking place in the direction of decreasing hydraulic head. In the following tables, B.1 to B.3, a positive hydraulic gradient indicates a downward flux (groundwater is being recharged) and a negative hydraulic gradient indicates an upward driving force (groundwater is being discharged into surface waters).

Example

Sample calculation for the hydraulic gradient using Data from MR-1on October 30, 2006: (Note: water level measurements were made from the top of the PVC pipe to the water, either inside or outside of the PVC pipe; consequently the coordinate system is positive downward.)

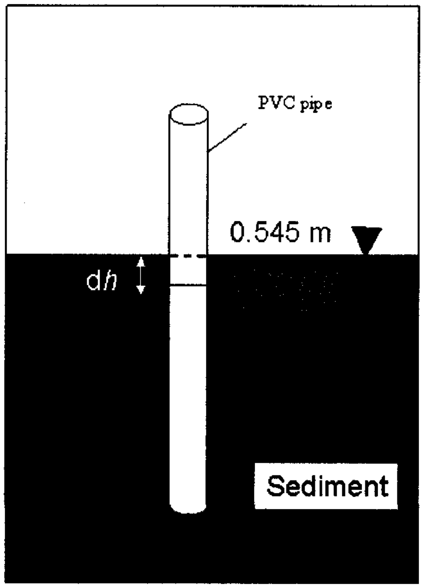


Figure B.1: Hydraulic gradient example.

$$i = \frac{dh}{dx} = \frac{0.545 - 0.57m}{-0.605m} = 0.041$$

This result gives a gradient indicating a downward force: groundwater is being recharge into the aquifer with a hydraulic gradient of 0.041.

Tables B.1 to B.3 present the hydraulic gradient results for the South Nation River, the Castor River and the East Castor River (positive values indicate downward flow and negative values, upward flow).

Table B.1: Hydraulic Gradient Calculations for all OTSM for the South Nation River (Note: water levels are measured from the top of the PVC pipe)

South Nation	Date	d*x* (m)	Water level river (m)	Water level pipe (m)	d*h* (m)	**Hydraulic gradient (*i*)**	Average gradient
MR1	10/30/2006	-0.605	0.545	0.57	-0.025	**0.041**	0.369
	11/13/2006	-0.605	0.660	0.930	-0.270	**0.446**	
	11/14/2006	-0.605	0.540	0.915	-0.375	**0.620**	
MR2	10/30/2006	-0.512	0.705	0.68	+0.025	**-0.049**	0.088
	11/13/2006	-0.512	0.795	0.910	-0.115	**0.225**	
MR3	10/30/2006	-0.68	0.665	0.63	+0.035	**-0.051**	0.188
	11/13/2006	-0.68	0.755	1.045	-0.290	**0.426**	
MR4	10/30/2006	-0.565	0.55	0.505	+0.045	**-0.080**	0.217
	11/13/2006	-0.565	0.625	0.915	-0.290	**0.513**	
MR5	11/03/2006	-0.585	0.99	0.99	0.000	**0.000**	0.097
	11/05/2006	-0.585	1.010	0.990	+0.020	**-0.034**	
	11/07/2006	-0.585	1.025	0.995	+0.030	**-0.051**	
	11/09/2006	-0.585	0.950	0.990	-0.040	**0.068**	
	11/13/2006	-0.585	0.670	0.965	-0.295	**0.504**	
MR6	10/30/2006	-0.41	0.82	0.81	+0.010	**-0.024**	-0.030
	11/13/2006	-0.41	0.915	0.900	+0.015	**-0.037**	
MR7	11/03/2006	-0.403	1.530	1.415	+0.115	**-0.285**	-0.121
	11/07/2006	-0.403	1.550	1.415	+0.135	**-0.335**	
	11/09/2006	-0.403	1.480	1.400	+0.080	**-0.199**	
	11/13/2006	-0.403	1.270	1.405	-0.135	**0.335**	
MR8	11/03/2006	-0.29	1.415	1.56	-0.145	**0.500**	0.069
	11/07/2006	-0.29	1.7	1.495	+0.205	**-0.707**	
	11/09/2006	-0.29	1.53	1.52	+0.010	**-0.034**	
	11/13/2006	-0.29	1.315	1.465	-0.150	**0.517**	
MR9	11/03/2006	-0.445	1.18	0.86	+0.320	**-0.719**	-0.861
	11/05/2006	-0.445	1.26	0.85	+0.410	**-0.921**	
	11/07/2006	-0.445	1.23	0.86	+0.370	**-0.831**	
	11/09/2006	-0.445	1.65	0.845	+0.805	**-1.809**	
	11/13/2006	-0.445	0.845	0.835	+0.010	**-0.022**	
MR10	11/03/2006	-0.64	1.22	0.9	+0.320	**-0.500**	0.297
	11/13/2006	-0.64	0.88	1.205	-0.325	**0.508**	
	11/14/2006	-0.64	0.64	1.205	-0.565	**0.883**	
MR11	11/03/2006	-0.305	1.36	1.065	+0.295	**-0.967**	0.098
	11/13/2006	-0.31	1.01	1.365	-0.355	**1.164**	

Table B.2: Hydraulic Gradient Calculations for all OTSM for the Castor River (Note: water levels are measured from the top of the PVC pipe)

Castor River	Date	d*x* (m)	Water level river (m)	Water level pipe (m)	d*h* (m)	**Hydraulic gradient (*i*)**	Average gradient
39 A	09/18-/006	-1.51	1.800	1.210	0.590	**-0.391**	-0.119
	20/10/2006	-1.51	0.610	0.680	-0.070	**0.046**	
	27/10/2006	-1.51	0.830	0.830	-0.000	**0.000**	
	07/11/2006	-1.51	0.937	0.585	0.352	**-0.233**	
	13/11/2006	-1.51	0.030	0.000	0.030	**-0.020**	
39 B	0918/2006	-1.29	1.100	1.160	-0.060	**0.047**	0.149
	20/10/2006	-1.29	0.550	0.760	-0.210	**0.163**	
	13-11-2006	-1.29	0.500	0.805	-0.305	**0.236**	
39 C	07/11/2006	-0.70	0.850	0.053	0.798	**-1.139**	-0.891
	13/11/2006	-0.70	0.495	0.045	0.450	**-0.643**	
39 D	09/18/2006	-0.87	0.940	0.950	-0.010	**0.011**	-0.368
	20/10/2006	-0.87	0.360	0.030	0.330	**-0.379**	
	07/11/2006	-0.87	0.705	0.065	0.640	**-0.736**	
	13/11/2006	-0.87	0.360	0.040	0.320	**-0.368**	
39 E	09/18/2006	-0.88	1.090	1.090	-0.000	**0.000**	-0.473
	07/11/2006	-0.88	0.870	0.080	0.790	**-0.898**	
	13/11/2006	-0.88	0.505	0.045	0.460	**-0.523**	
39 F	09/18/2006	-0.85	1.050	1.000	0.050	**-0.059**	-0.304
	20/10/2006	-0.85	0.510	0.710	-0.200	**0.235**	
	07/11/2006	-0.85	0.835	0.070	0.765	**-0.900**	
	13/11/2006	-0.85	0.470	0.050	0.420	**-0.494**	
39 G	13/11/2006	-0.83	0.315	0.595	-0.280	**0.337**	0.337
39 H	09/18/2006	-1.61	0.910	0.910	-0.000	**0.000**	0.000
39 I	09/18/2006	-1.26	0.920	1.390	-0.470	**0.373**	0.335
	1311/2006	-1.26	0.350	0.725	-0.375	**0.298**	

Table B.3: Hydraulic Gradient Calculations for all OTSM for the East Castor River (Note: water levels are measured from the top of the PVC pipe)

East Castor River	Date	dx (m)	Water level river (m)	Water level pipe (m)	dh (m)	**Hydraulic gradient (*i*)**	Average gradient
40 A	27/09/2006	-1.22	0.960	0.890	0.070	**-0.057**	0.109
	13/11/2006	-1.22	0.320	0.655	-0.335	**0.275**	
40 B	27/09/2006	-1.34	1.060	1.040	0.020	**-0.015**	-0.321
	20/10/2006	-1.34	0.430	0.010	0.420	**-0.313**	
	03/11/2006	-1.34	0.690	0.075	0.615	**-0.459**	
	07/11/2006	-1.34	0.850	0.085	0.765	**-0.571**	
	13/11/2006	-1.34	0.390	0.060	0.330	**-0.246**	
40 C	13/11/2006	-1.26	0.305	0.630	-0.325	**0.258**	0.258
40 D	27/09/2006	-0.37	0.860	0.960	-0.100	**0.270**	-0.510
	20/10/2006	-0.40	0.220	0.010	0.210	**-0.525**	
	07/11/2006	-0.40	0.615	0.105	0.510	**-1.275**	
40 E	27/09/2006	-1.17	0.780	0.680	0.100	**-0.085**	-0.197
	07/11/2006	-1.17	0.505	0.065	0.440	**-0.376**	
	13/11/2006	-1.17	0.150	0.000	0.150	**-0.128**	
40 F	27/09/2006	-1.03	1.060	1.630	-0.570	**0.553**	0.473
	13/11/2006	-1.03	0.355	0.760	-0.405	**0.393**	
40 G	27/09/2006	-1.11	1.060	0.860	0.200	**-0.180**	-0.341
	20/10/2006	-1.11	0.400	0.095	0.305	**-0.275**	
	07/11/2006	-1.11	0.850	0.113	0.738	**-0.664**	
	13/11/2006	-1.11	0.360	0.090	0.270	**-0.243**	

B.2. Flux Calculations

Open top seepage meters provide direct measurements of groundwater discharge/recharge (or seepage/leakage) rates. The groundwater seepage flux or Darcy Flux, q, is calculated from Darcy's Law:

$$q = \frac{Q}{A} = \frac{\Delta V}{At}$$

Equation B.2

Where:

q= Darcy flux ($m^3\ m^{-2}\ s^{-1}$)

Q= Volumetric flow rate (m^3/day)

A= Cross-sectional Area of the seepage meter (m^2) that is open to the sediments

(Note: When the PVC pipes were installed, damage could have been caused at the bottom of the pipe due to rocks and hammering into the ground. This damage could be assessed only upon removal of the pipe at the end of the season. The radius of undamaged PVC pipes was 0.025m (area of $0.0019m^2$) and damaged PVC had a smaller cross-sectional area at the down-hole end that was measured by tracing the irregular shape of the damaged end of the PVC pipe onto millimetric paper.

ΔV= Change in water volume in bags attached to seepage meters (m^3)

t= time (day).

The change in volume in the seepage bag had to be corrected for fluctuations of the water level in the river, giving a Darcy flux:

$$q = \frac{Q}{A} = \frac{\Delta V - \Delta V_w}{At} \qquad \text{Equation B.3}$$

where: ΔV_w= volume correction in the seepage bag = change in volume (m^3) in the seepage bag caused by a change in water level of the river. Because the OTSM are opened to the atmosphere, an increase in water level in the river over the period when the seepage bag is attached to the siphon will cause water to flow from the river into the OTSM, thereby decreasing the volume of water in the seepage bag. The internal volume of the OTSM corresponding to the increase in water level in the river is a volume of water removed unduly from the seepage bag, which must then be added to the volume in the bag to correct the seepage volume. Likewise, a decrease in water level in the river will induce a negative correction to the seepage volume. To calculate $\Delta V_{w,}$ a measure of the river water level must be taken on both the day when the seepage bag is installed and the day when it is removed.

Note 1: A negative change in water level in the river means that the water went down, so the water level in the pipe would have gone down as well. So, we need to add that much more to the inside volume of the bag/pipe.

Note 2: A positive flux (q) value indicates groundwater discharge (seepage) into the river.

Example

Samples Calculation Using Data from MR-1 from Nov 5th to Nov 7th, 2006 from the South Nation River:

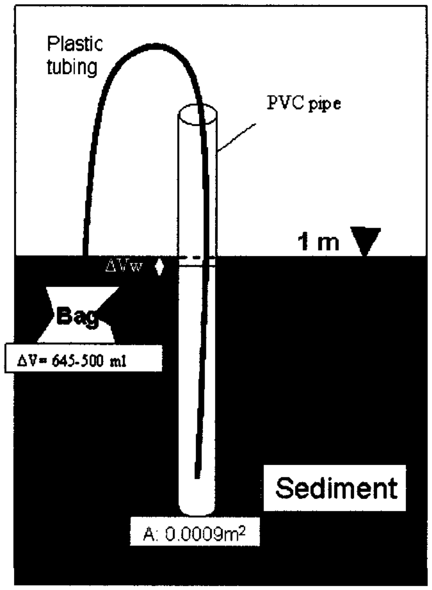


Figure B.2: Flux calculation example.

$$q=\frac{Q}{A}=\frac{\Delta V-\Delta Vw}{At}=\frac{[(645-500)ml\frac{1m^3}{1000000ml}]-[(1-1.01)m*\pi*(0.025)^2m^2]}{0.0009m^2*2.006day}$$

$$q=0.091m^3/m^2/day=0.091m/day$$

Note that the cross-sectional area available to flow in the sediments is A=0.0009 m^2, in this case, which is much less than the cross sectional area of the pipe = 0.0019 m^2. These results show that groundwater is seeping into the river at a flux of 0.091 m/days.

Table B.4: Flux Calculations for OTSM for the South Nation River (Note: water levels were measured from the top of the PVC pipe; positive fluxes are upward)

South Nation	DISCHARGE	initial volume (ml)	final volume (ml)	Area (m^2)	Initial time	final time	delta time (day)	Water Level initial (m)	Water Level final (m)	Darcy flux (m^3/m^3/day or m/day)
MR1	1	500	645	0.0009	5-Nov-06, 8:16am	7-Nov-06, 8:22am	2.006	1.01	1	0.091
	2	500	600	0.0009	7-Nov-06, 8:22am	9-Nov-06, 12:38pm	2.176	1	0.94	0.111
MR2	1	500	640	0.000525	5-Nov-06, 8:23am	7-Nov-06, 8:33am	2.007	1.14	1.145	0.123
	2	500	480	0.000525	7-Nov-06, 8:33am	9-Nov-06, 12:45pm	2.175	1.145	1.075	0.103
MR3	1	500	550	0.0002	5-Nov-06, 8:41am	7-Nov-06, 8:37am	1.997	1.1	1.105	0.101
	2	500	420	0.0002	7-Nov-06, 8:40am	9-Nov-06, 1:00pm	2.181	1.105	1.035	0.132
MR4	1	500	625	0.00054	5-Nov-06, 8:52am	7-Nov-06, 8:44am	1.994	0.975	0.98	0.107
	2	500	430	0.00054	7-Nov-06, 8:48am	9-Nov-06, 12:50pm	2.168	0.98	0.91	0.058
MR6	1	500	670	0.0003325 *	5-Nov-06, 9:25am	7-Nov-06, 9:05am	1.986	1.24	1.3	0.08
	2	500	480	0.0003325 *	7-Nov-06, 9:09am	9-Nov-06, 12:30pm	2.140	1.3	1.28	0.03
MR10	1	500	540	0.0003775 *	3-Nov-06, 1:45pm	5-Nov-06, 9:44am	1.833	1.22	1.295	-0.16
	2	500	680	0.0003775 *	5-Nov-06, 9:50am	7-Nov-06, 9:21am	1.980	1.295	1.27	0.31
	3	500	500	0.0003775	7-Nov-06, 9:24am	9-Nov-06, 12:17pm	2.120	1.27	1.21	0.015
MR11	1	500	650	0.0003475	3-Nov-06, 2:07pm	5-Nov-06, 10:00am	1.828	1.36	1.48	-0.013
	2	500	470	0.0003475	5-Nov-06,10:06am	7-Nov-06, 9:32am	1.976	1.48	1.43	0.010
	3	500	440	0.003475	7-Nov-06, 9:36am	9-Nov-06, 12:12pm	2.108	1.43	1.365	0.009

*Date from Cooper (2007). The area was greater of an order of magnitude than the cross-sectional of an undamaged PVC. They were therefore corrected and assumed that a 0 was missing. Flux measurements were changed accordingly.

Table B.5: Flux Calculations for OTSM for the Castor River (Note: in this table, "water level" indicates the distance from the top of the OTSM to the water in the river; positive fluxes are upward)

Castor River	DISCHARGE	initial volume (ml)	final volume (ml)	Area (m^2)	Initial time	final time	delta time (days)	Water Level initial (m)	Water Level final (m)	Darcy flux (m^3/m^3/days or m/days)
39A	1	500	520	0.001963	9/18/06 10:02 AM	9/27/06 9:50 AM	8.992	1.8	1.16	0.072
	2	500	450	0.001963	9/27/06 10:02 AM	10/6/06 9:25 AM	8.974	1.16	1.08	0.006
	3	500	290	0.001963	10/6/06 10:35 AM	10/13/06 8:57 AM	6.932	1.08	0.87	0.015
39B	1	500	520	0.001963	9/18/06 10:02 AM	9/27/06 9:50 AM	8.949	1.1	1.06	0.006
	2	500	450	0.001963	9/27/06 10:02 AM	10/6/06 9:25 AM	8.970	1.06	0.98	0.006
	3	500	290	0.001963	10/6/06 10:35 AM	10/13/06 8:57 AM	6.938	0.98	0.79	0.012
39C	1	500	415	0.001963	9/27/06 10:12 AM	10/6/06 9:28 AM	8.969	1.05	0.95	0.006
	2	500	235	0.001963	10/6/06 10:30 AM	10/13/06 9:07 AM	6.942	0.95	0.73	0.012
39D	1	500	570	0.001963	9/18/06 11:14 AM	9/27/06 10:15 AM	8.959	0.94	0.88	0.011
	2	500	425	0.001963	9/27/06 10:17 AM	10/6/06 9:30 AM	8.967	0.88	0.81	0.004
	3	500	235	0.001963	10/6/06 10:25 AM	10/13/06 9:14 AM	6.951	0.81	0.73	-0.008
39E	1	500	400	0.001963	9/18/06 11:10 AM	9/27/06 10:21 AM	8.966	1.09	1.06	-0.002
	2	500	400	0.001963	9/27/06 10:23 AM	10/6/06 9:32 AM	8.965	1.06	0.77	0.027
39F	1	500	570	0.001963	9/18/06 11:07 AM	9/27/06 10:28 AM	8.973	1.05	1.07	0.002
	2	500	355	0.001963	9/27/06 10:30 AM	10/6/06 9:35 AM	8.962	1.07	0.93	0.007
	3	500	125	0.001963	10/6/06 10:22 AM	10/13/06 9:25 AM	6.960	0.93	0.71	0.004
39G	1	500	465	0.001963	9/27/06 10:34 AM	10/6/06 9:36 AM	8.9602	0.87	0.78	0.008
	2	500	200	0.001963	10/6/06 10:17 AM	10/13/06 9:27 AM	6.965	0.78	0.58	0.007
39H	1	500	270	0.001963	10/6/06 10:11 AM	10/13/06 9:34 AM	6.974	0.79	0.57	0.015
39I	1	500	505	0.001963	9/18/06 11:00 AM	9/27/06 10:44 AM	8.989	0.92	0.88	0.005
	2	500	230	0.001963	10/6/06 10:09 AM	10/13/06 9:39 AM	6.979	0.8	0.6	0.009

Table B.6: Flux Calculations for OTSM for the East Castor River (Note: in this table, "water level" indicates the distance from the top of the OTSM to the water in the river; positive fluxes are upward)

East Castor River	DISCHARGE	initial volume (ml)	final volume (ml)	Area (m^2)	Initial time	final time	delta time (days)	Water Level initial (m)	Water Level final (m)	Darcy flux (m^3/m^3/days or m/days)
40A	1	500	365	0.001963	9/27/06 1:29 PM	10/6/06 11:05 AM	8.9	0.96	0.88	0.001
	2	500	35	0.001963	10/6/06 11:05 AM	10/13/06 10:14 AM	6.966	0.88	0.64	4.562E-3
40 B	1	500	405	0.001963	9/27/06 1:24 PM	10/6/06 11:09 AM	8.906	1.06	0.95	0.007
	2	500	195	0.001963	10/6/06 11:13 AM	10/13/06 10:20 AM	6.963	0.95	0.74	0.008
40 C	1	500	65	0.001963	10/6/06 11:18 AM	10/13/06 10:25 AM	6.963	0.87	0.65	-0.222E-3
40 D	1	500	480	0.001963	9/27/06 1:18 PM	10/6/06 11:20 AM	8.918	0.86	0.77	0.009
	2	500	140	0.001963	10/6/06 11:23 AM	10/13/06 10:30 AM	6.963	0.77	0.54	0.007
40 E	1	500	385	0.001963	9/27/06 1:15 PM	10/6/06 11:25 AM	8.924	0.78	0.63	0.010
	2	500	65	0.001963	10/6/06 11:28 AM	10/13/06 10:35 AM	6.963	0.63	0.39	0.003
40 F	1	500	345	0.001963	9/27/06 1:13 PM	10/6/06 11:30 AM	8.928	1.06	0.96	0.002
	2	500	135	0.001963	10/6/06 11:33 AM	10/13/06 10:42 AM	6.965	0.96	0.72	0.008
40 G	1	500	375	0.001963	9/27/06 1:08 PM	10/6/06 11:36 AM	8.936	1.06	0.96	0.004
	2	500	60	0.001963	10/6/06 11:39 AM	10/13/06 10:48 AM	13.188	0.96	0.71	0.002

B.3. Hydraulic Conductivity Calculations

Hydraulic conductivity, K (m/day), can be derived from Darcy's Law:

$$q = -K\frac{dh}{dx} = -Ki$$

Equation B.4

Therefore,

$$K = -\frac{q}{i}$$

Equation B.5

The sign indicates that flow takes place in the direction of decreasing hydraulic head. In this study, a positive value of seepage flux indicates upward flow, or groundwater discharge whereas a negative value indicates downward flux or recharge of the groundwater.

Example

Sample Calculation Using Data from MR-1 for the South Nation River:

$$K = -\frac{q}{i} = \frac{0.111198}{0.446} = -0.249 m/day$$

Note that conductivities calculated with this method can occasionally give nonsensical negative values. These arise from the fact that the flux and the gradient are obtained from the same instrument, necessarily at different times. For instance the flux could be measured over a period of several days and the gradient at an all together different time. The impact would be negligible if the water levels did not fluctuate; but this was not the case at all times in these rivers, and consequently nonsensical negative conductivities could sometimes be observed. The problem could be solved with the installation of a pressure logging device in a piezometer in proximity to the seepage meter. Pressure transducers were not available for this study.

Table B.7: Conductivity Calculations for OTSM of the South Nation River

South Nation	*DATE Darcy flux (q)*	*Darcy flux (q)* (m/day)	*DATE Hydraulic gradient (i)*	*Hydraulic gradient (i)*	Hydraulic Conductivity (K) (m/day)
MR1	Nov 7-9	0.111	Nov-13	0.446	-0.249
MR2	Nov 7-9	0.103	Nov-13	0.225	-0.458
MR3	Nov 7-9	0.131	Nov-13	0.426	-0.309
MR4	Nov 7-9	0.058	Nov-13	0.513	-0.112
MR6	Nov 7-9	0.003	Nov-13	-0.037	+0.074
MR10	Nov 7-9	0.015	Nov-13	0.508	-0.029
MR11	Nov 7-9	0.009	Nov-13	1.164	-0.008

Table B.8: Hydraulic Conductivity calculations for OTSM of the Castor River

Castor River	*Darcy flux (q)* (m/day)	*Hydraulic gradient (i)*	Hydraulic Conductivity (K) (m/day)
39A	0.03	-0.17	0.18
39B	0.01	0.10	-0.06
39C	0.03		0.78**
39D	0.00	-0.18	0.01
39E	0.00		-0.10**
39F	0.00	0.09	-0.05
39G	0.02		0.29**
39H	0.01	-0.21	0.03
39I	0.00	**0.37**	0.00

** Average *i* of adjacent OTSM was used to measure K.

Table B.9: Hydraulic Conductivity calculations for OTSM of the East Castor River

East Castor River	*Darcy flux (q)* * (m/day)	*Hydraulic gradient (i)* *	Hydraulic Conductivity (K) (m/day)
40A	-0.01	-0.06	-0.14
40B	0.01	-0.16	0.04
40C	0.00	-0.25	0.01
40D	0.01	-0.15	0.05
40E	0.02	-0.09	0.21
40F	0.01	0.09	-0.14
40G	0.00	-0.23	0.01

* Average of flux and hydraulic gradient measurements weighted by the reciprocal mean square error on the measurement (Sargent, 2007).

Appendix C: Stream Gauging

C.1. Objectives and study area

This Appendix presents an attempt to use another approach to look at surface water–groundwater interactions in the Raisin River. This approach uses stream gauging measurements to estimate water gains and losses into the river along a given reach (Hinton, 1995). Water addition into the Raisin River can be either from surface water by means of tributaries, drains, surface runoff or by groundwater discharge. Conversely, some of the river flow may be lost due to evaporation, groundwater recharge (also called leakage) or human activities and consumption. The method is based upon the fact that a difference in flow rate between an upstream and a downstream location must be explained by the sum of gains and losses in the river reach between the two locations. Thus, if river flow remains constant between the two locations, water gained is equal to water lost within the reach. If the gauging measurements from a downstream location are higher than upstream, it is expected that water discharged into the river reach exceeds the water losses; conversely, if the upstream flow is higher than the downstream flow there is a net loss of water within the reach. In this study, this exercise was carried out for 7 reaches of the three branches of the Raisin River, shown in Figure C.1, in an attempt to better understand the hydrodynamics of the Raisin River Watershed.

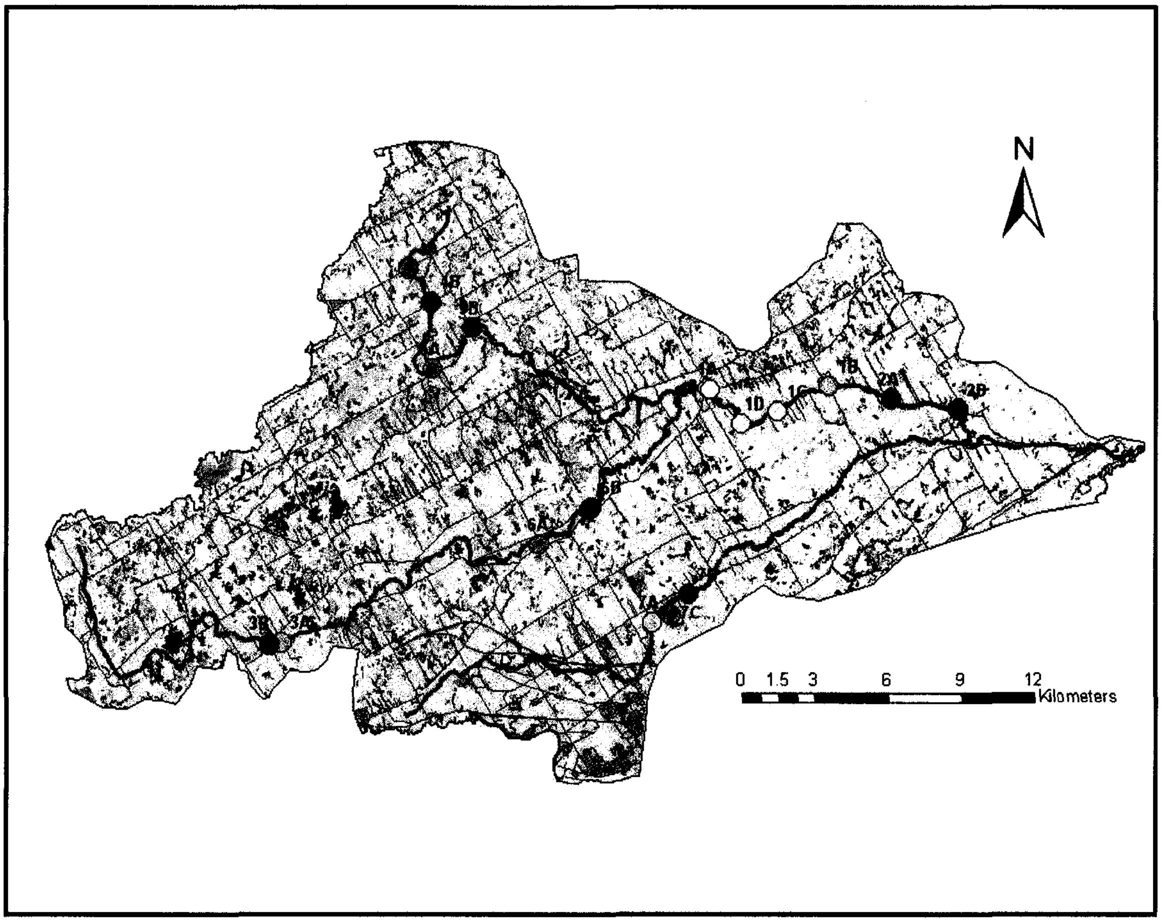


Figure C.1: Stream flow gauge locations in the Raisin River Watershed.

C.2. Methodology

A total of seven reaches of the Raisin River were examined, each bounded by an upstream and a downstream riffle zone. Measurements for a given reach were carried out on the same day to reduce temporal variation. The fourteen riffle zones were selected based on their similar width and depth, to make comparison easier. At each riffle zone, two or three transects perpendicular to the river flow were made when possible: upstream, middle and downstream of the riffle zone itself. The transects were labelled with a three digit system: the first, ranging 1 to 7 refers to the reach; the second, A or B, corresponds to adjacent riffle zones up- or downstream of the reach, respectively; and the last, 1, 2, or 3 corresponds to the upstream, middle and downstream portion of the riffle zone within the reach, respectively.

At a given transect, the depth and width of the river were measured; and at least 15 measurements were made of water velocity. Water velocity measurements were made using the Swoffer 2100 Current Meter (borrowed from the Department of Biology, University of Ottawa). Velocity was measured twice at each emplacement to reduce error. Where depth was less than a meter, a measure at 60% of the height (from the bottom) was made and when the depth was greater than 1m, measurements at 30% and 70% of the height were made; according to the procedure described by Dingman (1994). River discharge at a given transect was estimated using field measurements and the following equation:

$$Q = \Sigma q_i = \Sigma(A_i V_i) \qquad \text{Equation C.1}$$

Where,

Q = River discharge at a given transect (m^3/s)
q_i = Discharge measurements along the transect (m^3/s)
A_i = cross-sectional area of the transect for which the measurement applies (m^2)
V_i =Velocity measurement along the transect (m/s)
i = measurements along the transect

Normally, the total error in the velocity-area measurements using flow meters averages approximately 10 % of the total discharge (Hinton, 1995). This value was found to underestimate measurement error in our case. The main sources of error were: (1) turbulent flow, (2) instrument error and (3) vertical spacing. Turbulent flow is known to cause incorrect readings in the flow meter, which assumes laminar flow; and a number of our sites were mildly turbulent. The instrument error for the Swoffer 2100, as stipulated by the manufacturer (Swoffer Instrument, Inc.) is approximately 1 %, which can contribute significantly to the overall error. It was also noticed that the Swoffer 2100 could not measure low velocities near the banks of the river even though flow was perceptible visually. Vertical spacing between measurements can cause an additional source of error. Text books (e.g. Dingman, 1994) recommend using vertical spacings such that 5% of the total discharge occurs within each vertical spacing. In our case, in the Raisin River, more than 5% of the total discharge was measured in each vertical spacing because of practical considerations. The various sources of error contrive to produce an overall error on the measurements that can be estimated by replication of the entire transect measurements. However, because of time constraints, transect measurements could not be repeated, resulting in mean velocities with a relatively large standard error. Error can be improved in future work by including repetition of transect measurements.

C.3. Results and Discussion

Results for the 7 reaches of the Raisin River are presented in Table C.1. Included in the table are average flow rate estimates for each riffle zone, flow rate differences , standard error estimates on the averages, significance levels (p-values) of the average flow, and the p-values comparing the downstream transects (transect C in the table C.1) of the upstream and downstream riffle zones (assuming a 10% error). From Table C.1, it can be observed that reaches 1, 3 and 7 (p=0.18, p=0.24 and p=0.12) showed gains that were marginally or non-significant. Gains varied from 17 % to 78 % of river flow. Agricultural drains were present on reach 1 and 7: the drains from reach 1 were not flowing and the drain from reach 7 was flowing adding water to the Raisin River. Reach 2 and 4 were reaches where losses were observed; loss from reach 2 was significant (p=0.04) and loss from reach 4 (p=0.86) was not. The losses varied between 6 % and 34 % of water flow. Reach 5 and 6 had no change in water volume. Transects had different cross-sectional areas and flow rates varied considerably within each riffle zone, giving poor statistical resolution when comparing the average riffle zone flow upstream of a reach with the average riffle zone flow downstream. Therefore, comparisons were made of similar parts of riffle zones upstream and downstream of the reaches. The last column of Table C.1, is a comparison of the transects (C) that were downstream of each riffle zone. Since there was no replication, a 10 % error was assumed in the statistical comparisons of flows upstream vs downstream of the reach. Reach 1 and 7 (p=8.06E-08 and p=3.57E-04) had a significant flow gain and reach 2 (p=4.09E-02) had a significant flow loss. The "Swimming Hole" is located between reach 1 and 2; no riffle zones downstream of the "Swimming Hole" were present to quantify the groundwater discharge component.

Since flow was measured during the same clear-sky day, the addition or the lost can only be from (1) groundwater recharge/discharge or by (2) agricultural drains or tributary; all other components being negligible. The flow rate measurements do not permit inference as to the origin of the water along the reach where gain was observed due to the high variability in the values. The variability in the riffle itself (between the upstream, midstream and downstream transect at a given riffle zone) is high for reaches 1,2 and 7. Repetition of a transect (either upstream or downstream of the riffle) measurements would lower the error in the measurements. In the Raisin River Watershed, stream gauge results varied considerably. Some area had a water gain while others lost water. We can conclude that it is essential to make multiple measures in various locations of the river to have a better understanding of the studied area.

Table C.1: River discharge measurements from Sites in the Raisin River Watershed. Site A are found upstream of Site B. As for location, 1 is upstream, 2 midstream, 3 downstream of the riffle zone.

Branch	Reach	Location	Cross-Sectional Area (m2)	Flow (m3/sec)	Average Flow rate (m3/sec)	Gain (m3/sec)	% gain	Standard deviation from flow	Variance from flow	s	t	p-value	comparisons of # 3 transects measurement error (CV) known = 10%			
										(flow)			std deviation	std error	z	p-value
N+ M	1	1A-1	72.53	0.75	0.50	0.39	**78.00**	0.22	0.05							
		1A-2	34.06	0.33												
		1A-3	33.55	0.41						0.24	1.62	0.18	0.04	0.11	5.37	8.06E-08
N+ M	1	1B-1	38.02	0.50	0.89			0.35	0.13							
		1B-2	38.48	1.19												
		1B-3	145.43	0.98									0.10			
N+ M	1 (drain)	-		0.00	0.00											
N+ M	1 (Drain)	-		0.00	0.00											
N+M	2	2A-1	44.18	2.75	2.63	- 0.90	**-34.22**	0.17	0.03							
		2A-3	58.93	2.51						0.18	4.98	0.04	0.25	0.31	2.04	4.09E-02
N+M	2	2B-1	69.12	1.60	1.73			0.19	0.04							
		2B-3	54.34	1.87									0.19			
Middle	3	3A-1	20.56	0.08	0.11	0.03	**27.27**	0.03	0.00							
		3A-2	11.03	0.14												
		3A-3	19.72	0.11						0.02	1.37	0.24	0.01	0.02	1.17	2.40E-01
Middle	3	3B-1	7.07	0.17	0.14			0.02	0.00							
		3B-2	5.35	0.13												
		3B-3	6.51	0.13									0.01			
Middle	4	4A-1	4.81	0.18	0.16	- 0.01	**-6.25**	0.08	0.01							
		4A-2	7.28	0.07												
		4A-3	5.08	0.23						0.05	0.19	0.86	0.02	0.03	0.98	3.25E-01
Middle	4	4B-1	6.67	0.12	0.15			0.04	0.00							
		4B-2	6.54	0.13												
		4B-3	6.60	0.20									0.02			
North	5	5A-1	1.93	0.01	0.01	0.00	**0.00**	0.00	0.00							
		5A-2	1.19	0.01												
		5A-3	3.67	0.01						0.00	0.00	1.00	0.00	0.00	4.47	
North	5	5B-1	2.74	0.01	0.01			0.01	0.00							
		5B-2	4.13	0.01												
		5B-3	1.72	0.02									0.00			
North	6	6A-1	16.68	0.03	0.02	0.00	**0.00**	0.01	0.00							

Branch	Reach	Location	Cross-Sectional Area (m2)	Flow (m3/sec)	Average Flow rate (m3/sec)	Gain (m3/sec)	% gain	Standard deviation from flow	Variance from flow	s	t	p-value	comparisons of # 3 transects measurement error (CV) known = 10%			
										(flow)			std deviation	std error	z	p-value
		6A-2	27.04	0.03												
		6A-3	36.21	0.02						0.00	0.00	1.00	0.00	0.00	0.00	1.00E+00
North	6	6B-1	21.77	0.02	0.02			0.00	0.00							
		6B-2	24.50	0.02												
		6B-3	26.95	0.02									0.00			
South	7	7A-1	8.36	0.18	0.18	0.17	**222.22**	0.01	0.00							
		7A-3	9.54	0.17						0.07	2.61	0.12	0.02	0.03	3.57	3.57E-04
South	7	7B-1	11.06	0.42	0.35			0.09	0.01							
		7B-3	10.16	0.29									0.03			
South	7 (Drain)	-		0.05	0.05											

C.5. Summary and Conclusions

Stream flow measurements up- and downstream of seven reaches indicated that 3 of the 7 reaches were gaining water, 2 were losing and the other 2 had no change in flow rate; reach 2 was loosing significantly based on the average flow of the reach (p-value= 0.04). Reach 2 is also loosing significantly by comparing the downstream transects of the riffle zones upstream and downstream of the reach (p-value=0.04). Using this method, reach 1 and 7 are gaining water significantly. The only identifiable sources of water over the gaining reaches were the agricultural drain in reach 7. Variability is observed over the entire watershed, in the riffle zone and along the transect. The variability in the watershed indicated that specific areas, gain water while others loose water. These results are consistent with those of Porter (1996). The method does not distinguish between local groundwater and deep groundwater, and consequently the results serve to complete, in an integrated way, the results presented in the previous section. Most likely, the results suggest that much of the water in the Raisin River is of local groundwater origin, and based on the results from Chapter 6, this local groundwater must be of similar EC as the river water.