Groundwater Surface Water Interaction in the Raisin River Watershed, near Cornwall, Ontario

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Abstract

The interaction of groundwater with surface water is an integral part of the hydrologic cycle. Recognition of this relationship is pertinent when assessing the components of an ecosystem, or while examining factors such as water quality or quantity in a watershed.

A field study was conducted in 1994 and 1995 to understand the interaction of groundwater and surface water in the Raisin River watershed, near Cornwall, Ontario. A number of variables were examined to describe the regional groundwater system and to determine the magnitude of the groundwater contribution to the river. The Raisin River lies within an agricultural region which relies heavily on groundwater use. The regional groundwater supply is predominantly from a limestone aquifer underlying various surficial deposits (primarily glacial till). Groundwater movement appears to be in a southeasterly direction, towards the St. Lawrence River.

Seepage meters, mini-piezometers, and a falling head permeameter were used to i) measure the flux of groundwater into (positive seepage) or out (negative seepage) of the Raisin River, and ii) measure the hydraulic conductivity of the Raisin River sediments. Measurements were made at thirteen sites within the watershed. To identify the source of groundwater and study processes of streamflow generation during storm runoff, surface water, groundwater, and rainwater samples were collected for environmental isotopes (oxygen-18 and deuterium). Raisin River discharge data was also analysed for further insight into groundwater and surface water relationships.

Seepage measurements and hydraulic conductivities exhibit significant variability. The coefficients of variation for seepage measurements ranged from 20.3 to 392 %, and for hydraulic conductivity from 0 to 161 %, depending on the site. Seepage flux ranges from 2.23×10^{-6} to $-9.82 \times 10^{-9}\ m^3 m^{-2} s^{-1}$, and hydraulic conductivity ranges from 10^{-6} to $10^{-9}\ ms^{-1}$. Measurements indicate that seepage can be positive or negative, depending on spatial location or time of year. This suggests that few measurements in space or time can misrepresent the flow regime status of the watershed. Environmental isotope analyses indicate that meteoric water is the source of local groundwater with a mean residence time of approximately 4 months. Oxygen-18 and deuterium results also indicate that after a storm event, groundwater composed 63% of total stream discharge. Cross-correlation of Raisin River discharge data and Cornwall area precipitation indicates that the peak response in the river is approximately two days after a storm event. These variables indicate that groundwater/surface water relationships should be taken into account if decisions are made with respect to water quality or quantity.

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Chapter 1.0 Introduction

1.1 Background

Hydrogeological research in the following thesis has contributed, in part, to a larger study called the "Ecosystem Recovery on the St. Lawrence River", being led by the Institute for Research on the Environment and Economy (IREE) at the University of Ottawa. Many different disciplines from academia, various levels and departments of government, and community were involved in this study, which has focused on the City of Cornwall, Ontario, the Mohawk Nation of Akwesasne, and the St. Lawrence River.

1.2 Scope of Work

The area of study chosen for this thesis is the Raisin River watershed, north of Cornwall, which drains into the St. Lawrence River. It was postulated that this basin could be representative of similar, small agricultural watersheds which contribute to the flow of the St. Lawrence River.

Two other studies were undertaken concurrently in the Raisin River watershed: a study of the groundwater geochemistry and potential for groundwater contamination from agricultural sources by Greg Cane, also of the Department of Geology; and a study of the synchronism of hydrological events with agricultural practices and impacts on surface water quality by Anne Watelet, at the Department of Geography (University of Ottawa).

1.3 Objectives of this Study

The first objective of this thesis is to describe the hydrogeology of the Raisin River watershed. This will provide an information base of previous research in the study area and enable us to predict groundwater behavior, such as regional groundwater discharge/recharge zones or flow patterns. In order to describe the hydrogeology of the Raisin River basin, a review of existing geological and hydrogeological literature and maps will be done. This will include the identification of groundwater resources, regional groundwater discharge and recharge zones, and the extent of groundwater exploitation in the region. Digital data (water well records) provided by the Ontario Ministry of the Environment and Energy (OMOEE) and a geographical information system (GIS) called SPANS™ will also be used to meet this objective.

The second main objective is to examine the relationship between groundwater flow and surface water flow; and to identify local zones of groundwater recharge or discharge. The interaction of groundwater with surface water is an important component of the hydrologic cycle. The study of this relationship can be useful in predicting the impacts of surface water or groundwater quality or quantity. With regards to water quality, an example might be contaminated groundwater discharging into a surface water body, or vice versa. In this circumstance, knowledge of the extent of groundwater/surface water interaction would be advantageous. Also, locating local groundwater recharge or discharge zones can be important to water quality, in relation to surrounding land uses or agricultural practices (e.g. landfill sites, manure storage, etc.). In terms of water quantity, concerns have been expressed that artificially drained soils may lower the amount of groundwater storage available for later release to surface water during low flow periods. Understanding the magnitude of the groundwater contribution to streamflow would be practical for such research.

The description of groundwater/surface water interaction and the identification of local groundwater recharge/discharge zones will involve an examination of local water flow paths. In the context of this study, these water flows are investigated using the following variables: a. direct seepage measurements into or out of the Raisin River, b. hydraulic gradients of groundwater, c. hydraulic conductivity of Raisin River sediments, d. the relationship between infiltration, streamflow, and baseflow, e. the origin of local groundwater, f. seasonality of surface water, g. mean residence time of groundwater, h. the contribution of groundwater to streamflow during a storm event, and i. groundwater geochemistry. Investigation of these variables provides the basis for discussion of the magnitude, as well as the temporal and spatial variability, of the groundwater component of the Raisin River. Examination of these variables also provides the means to examine the relationship of groundwater to the individual components of the hydrologic regime in the Raisin River watershed.

To examine variables a. through c., several field methods will be used. A combination of seepage meters and mini-piezometers will be used to measure the groundwater flux into or out of the Raisin River, to measure the hydraulic gradient of groundwater, and to determine the hydraulic conductivity of the river sediments. Slug tests will be performed with a falling head permeameter and mini-piezometers as a second method for measuring hydraulic conductivity in the field. Darcy's Law can be used to estimate the groundwater seepage flux in the Raisin River with the measurements of hydraulic conductivity and hydraulic gradients.

Stream discharge and precipitation data will be used to understand the relationship between infiltration, streamflow, and baseflow (variable d). The magnitude and seasonality of baseflow contributions to the Raisin River will be found through a stream hydrograph analysis. The temporal response of the watershed to storm events will be examined with a cross-correlation analysis of stream discharge and precipitation.

Samples of groundwater (pumped from piezometers), surface water, tile drainage and rainfall will be analysed for the stable isotopes of hydrogen and oxygen and subsequently used for the examination of variables e. to h. These analyses will be used to determine the origin of local groundwater (i.e. whether it is meteoric or from deeper groundwater systems) and show the seasonality of surface water. Stable isotopic data can also be used to estimate a mean residence time for groundwater (i.e. the period of time from groundwater recharge by meteoric waters to groundwater discharge into the Raisin River). Additionally, isotope data can be used in storm hydrograph separation, to determine the contribution of groundwater to streamflow during a storm event.

Finally, the general geochemistry of water samples will be examined and used to determine whether water has been recently recharged or has remained longer in deeper aquifers. Geochemical analyses can also be used to indicate interaction or mixing of water types and if there are any anthropogenic impacts in the watershed.

Chapter 2.0 Study Area and Site Descriptions

2.1 Location

The Raisin River watershed lies within the counties of Stormont and Glengarry, near the City of Cornwall, Ontario (Figure 1). The watershed is approximately 546 km^2 and drains into the St. Lawrence River east of Cornwall at Lancaster, Ontario. The headwaters of the main branch originate in an organic-rich bog as Dixon Creek, near Lunenberg, Ontario. There are also two large tributaries, the North and South Branches, which start near Monkland and Long Sault, Ontario, respectively.

2.2 Topography

The elevation in the region ranges from about 110 m on a ridge that runs southwest to northeast through the centre of Stormont and Glengarry Counties to 50 m above sea level (a.s.l.) around Lancaster. The topography is gently sloping to rolling hills from the northwest to the southeast towards the St. Lawrence River (Figure 2).

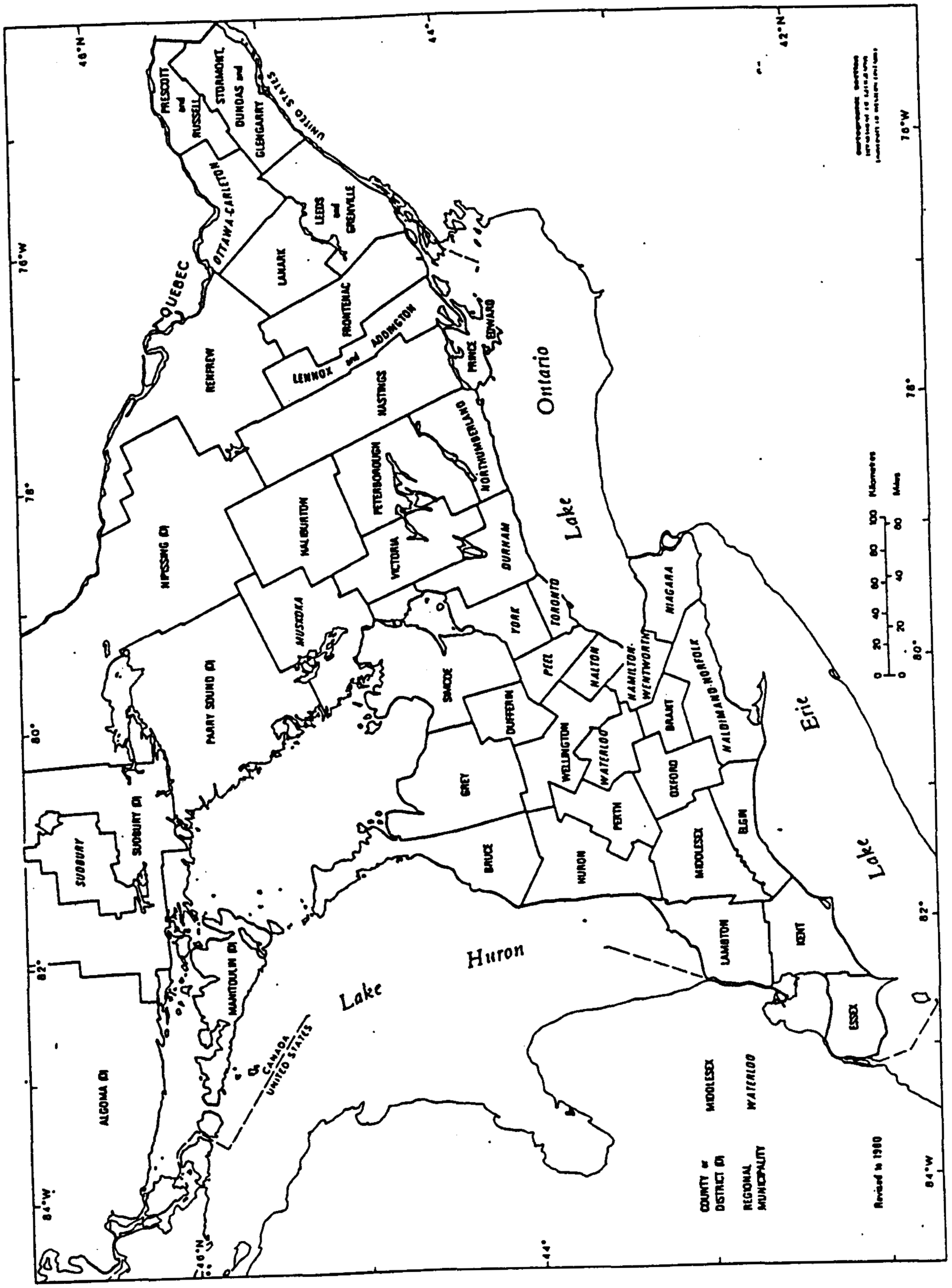
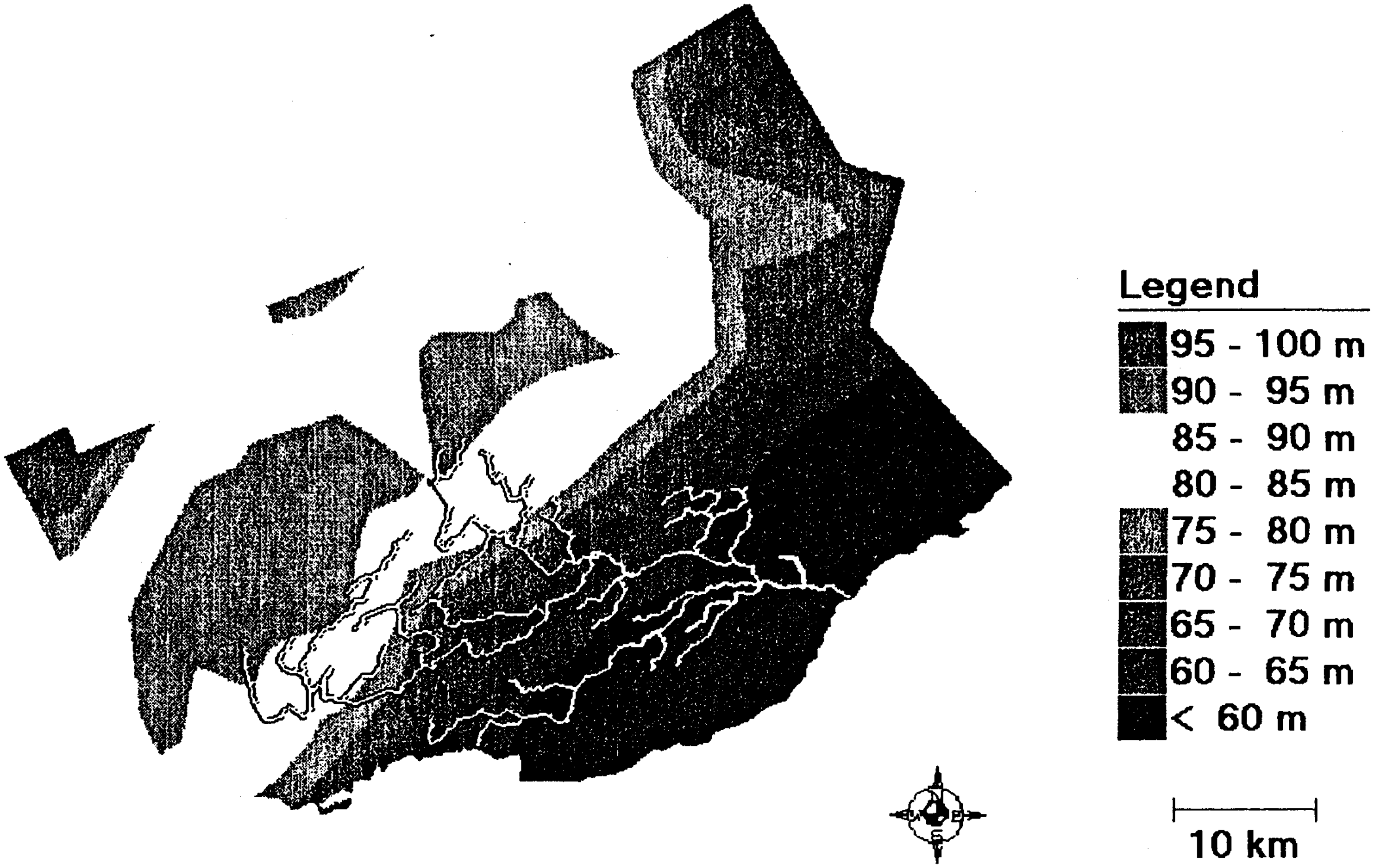

QUEBEC
UNITED STATES
PRESCOTT and RUSSELL
STORMONT, DUNDAS and GLENGARRY
OTTAWA-CARLETON
LEEDS and GRENVILLE
LANARK
FRONTENAC
RENFREW
LENNOX and ADDINGTON
PRINCE EDWARD
HASTINGS
NORTHUMBERLAND
PETERBOROUGH
HALIBURTON
NIPISSING (D)
VICTORIA
DURHAM
Lake Ontario
TORONTO
YORK
MUSKOKA
PARRY SOUND (D)
SIMCOE
PEEL
HALTON
HAMILTON-WENTWORTH
NIAGARA
HALDIMAND-NORFOLK
BRANT
DUFFERIN
WELLINGTON
WATERLOO
GREY
OXFORD
PERTH
BRUCE
HURON
MIDDLESEX
ELGIN
Lake Erie
LAMBTON
KENT
ESSEX
Lake Huron
SUDBURY
SUDBURY (D)
MANITOULIN (D)
ALGOMA (D)
CANADA
UNITED STATES
COUNTY or DISTRICT (D) MIDDLESEX
REGIONAL MUNICIPALITY WATERLOO
Revised to 1980
Kilometres 0 20 40 60 80 100
Miles 0 20 40 60
46°N
44°
42°N
76°W
78°
80°
82°
84°W

Figure 2: Map of Elevation in Stormont and Glengarry Counties



2.3 Landuse

In 1986, the population within the United Counties of Stormont, Dundas, and Glengarry was approximately 55,837 persons (MacViro, 1992). The present land use in these three counties appears to be principally agricultural (crops and numerous dairy cattle operations). In 1981, crop and pasture made up the greatest percentage (57.5 %) of land use in the Raisin River Watershed. Table 1 gives a breakdown of landuse classifications throughout the watershed, in 1981.

Table 1. Land Use Classification in the Raisin River Watershed, 1981

Land Use	Percentage of Watershed
Urban	1.5%
Swamp/Wetlands	6.5%
Forest	34.5%
Crop/Pasture	57.5%

Source: 1981, Maclaren Plansearch (Lavalin).

There is extensive artificial drainage, such as municipal drains and tile drains, throughout the cultivated parts of the watershed. Artificial drainage systems maintain the depth to the water table at or below the tile drain level as infiltrated water is drained off the fields. Water from the drainage system discharges directly into the Raisin River. The Ontario Ministry of Agriculture and Food (OMAF) have generated maps illustrating the artificial drainage network for this area. However, the total areal extent of the tile drainage throughout the counties was not available at the time of this study.

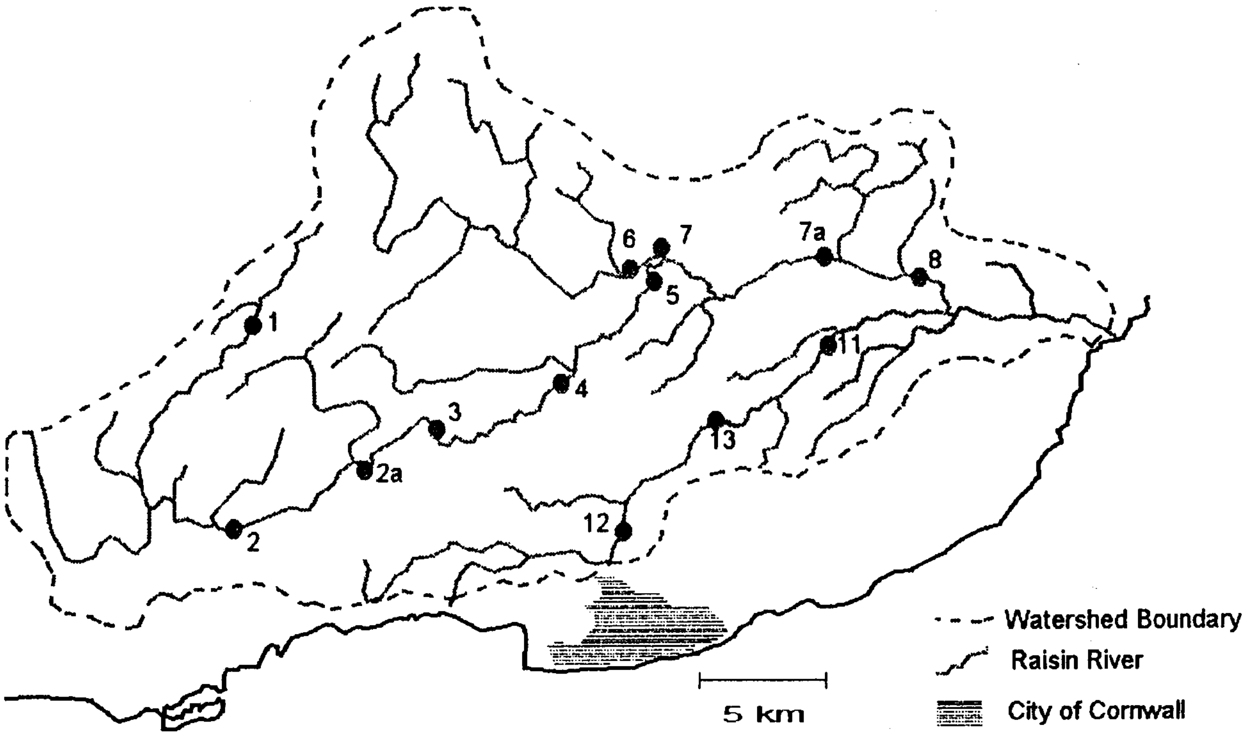
2.4 Climate

In the area, the average annual rainfall and snowfall is approximately 696 mm and 218 mm, respectively (Lavalin, 1981). The average annual temperature in this part of Ontario is 6.6° C, with a maximum mean daily temperature of 21.6° C in July and a minimum mean daily of -9.4°C in January.

2.5 Site Descriptions and Soil Classifications

Field work was carried out at thirteen sites throughout the Raisin River watershed (Figure 3). Three sites were on the South Branch, one on the North Branch and the remaining sites on the Main Branch. Site nos. 1, 2, 3, 5, 6, 7 and 8 were chosen by researchers monitoring surface water quality of the Raisin River (Anne Watelet and Peter Johnson, University of Ottawa) and the rest were chosen by the author. Field descriptions and observations are given in the following paragraphs. Soil classifications, as described by Clayton et al., (1977) and Matthews and Richards (1954), are given in Table 2.

Figure 3: Map of Raisin River Watershed and Study Sites



2.5.1 Stormont County Sites

Site No. 1 - Dixon Creek (Headwaters of Main Branch, Raisin River)

This site lies within a peat bog with very dark coloured, soft organic matter. The bog is drained by a small stream called Dixon Creek which becomes the headwaters of the Raisin River. Leaching of humic substances from the bog is likely the cause of the yellow to brownish appearance of the Creek and the River. Some light coloured silt-sand sediment was observed upstream from the sampling site and occasionally atop the peat onsite (particles carried and deposited during high flows). Site vegetation consists of small brush and phreatophytes. Frequent evidence of beavers along the creek was observed (eg. several dams were constructed close to piezometer installations). Human habitat is not present in the immediate vicinity but there is some agricultural and residential land use within a km of the site. A drainage ditch, which transports water to the creek during high flow periods, is located immediately downstream from the site. The topography is fairly flat.

Site No. 2 - Windfall Road (near Lunenberg), Main Branch Raisin River

The soil on the shoreline appeared dark brown and the sediment was a mixture of gravel and blueish-grey clay. A bright orange precipitate was observed on several occasions on the west bank (during summer months) when the river was low. On the west side of the river there is cultivated land (corn) and a sheep operation. On the east side, a pasture is used for dairy cattle. Cattle have been observed in and very close to the river. A recently built house (August 1994) adjacent to the cattle pasture had a new drinking water well drilled approximately 43 m (140 ft) in limestone. The owner's father noted that while drilling for this well, water was also encountered at approximately 18m (60 ft). He also informed the author that wells of two other homeowners close by were completed around this shallower depth. The area topography is slightly undulating (pasture slopes down to river).

Site No. 2A - Black River Road (beside Raisin Region Conservation Authority Gauging Station) on Main Branch Raisin River

On the north shore, the sediment is very loose, soft material containing some sand. Landuse is residential and agricultural (a cultivated field, corn, slopes downwards to the river). On the opposite side, a considerable amount of sedimentary rock bedding is exposed. The area topography is undulating to rolling hills. Gas bubbles were observed surfacing on the river while field work was performed.

Site No. 3 - Simon Fraser Farm on Main Branch Raisin River

The sediment in the Main Branch at this site is quite rocky with assorted sizes of gravel. This site is low lying and becomes completely submerged by spring flooding. There is some hilly terrain east of the site. Several houses are near the river and cattle have been observed in the river, approximately 1 km upstream from the measurement site.

Site No. 4 - Main Branch Raisin River, upstream of Beaver Creek (downstream from St. Andrews)

The sediment is fairly soft, mixed with variable sized rocks to boulders. A cultivated field on the east bank is drained by tile drain into the river. A paved road runs adjacent to the west bank. A small stream (Beaver Creek), which is part of a municipal drain system, discharges into the Raisin River immediately upstream from the measurement site. Several houses are in the vicinity, along both shorelines.

Site No. 12 - McConnell Avenue & 401, South Branch Raisin River, close to Eamer's Corners

The sediment appears to be a soft, silty clay. There is a farm on the north side and the pasture gently slopes down to the river. The Raisin River runs fairly close to Highway 401 at this site. Aquatic plant growth was quite notable during shallow periods in summer months.

2.5.2 Glengarry County Sites

Site No. 5 - Cemetery Road, Main Branch Raisin River

The sediment is very soft with a clay-like texture. The south side is cultivated and drained artificially with a tile drain and ditch into the river. The farmer (Mr. H. Kinloch), who owns the cultivated property on the south side, has several wells nearby (in both gravel and shale). The north side of the river is pasture land for cattle (which have been observed in the river). Site topography is flat.

Site No. 6 - Cemetery Road, North Branch Raisin River

The sediment is soft and clay-like to stony. Upstream from the site, the river bed is quite rocky and sediment is thin to nonexistent. This site appears to be in a small valley and the land, cultivated with corn on both sides, slopes downwards to the river.

Site No. 7 - Martintown, Main Branch Raisin River

The sediment is soft and loose at this site. Landuse along the shoreline is residential and parkland. Cattle were observed in river upstream from measurement site and sewage-like odour was noticed in the summer. (Note: a similar odour was reported in a study by the OMOEE in 1992). A municipal storm drain contributes to streamflow immediately downstream from the measurement site.

Site No. 7A - Downstream Martintown, beside Environment Canada Gauging Station, Main Branch Raisin River, near McGillvary's Bridge

The sediment is soft and appears to be predominantly clay. There are cultivated fields (corn) on both sides of the river. The site topography fairly flat and the river is wide and calm.

Site No. 8 - Heron Road, Upstream of Williamstown, Main Branch Raisin River

The sediment is soft with a grey, clay-like texture. Landuse around the site is residential and agricultural. There are fairly steep slopes along shorelines of the river. OMAF (1983) Artificial Drainage Maps indicate that tile drainage systems are in the vicinity of this site (although they were not visible to the author).

Site No. 11 - County Road 19, South Branch Raisin River

River sediment at this site is very soft and loose with a silty/clay appearance. Cultivated fields (corn and soybean) are drained artificially directly into south side of the river. Tile drains are visible on the south bank, opposite of the site. The property adjacent to the river is owned by Mr. I. Grant and his drinking water well was dug to a depth of approximately 7m.

Site No. 13 - Kinloch Road, (off County Road 19) South Branch Raisin River

The sediment is fairly firm with what appears to be clay. There are cultivated fields on both sides of the river (corn). The south side is artificially drained into river (by tile drains).

Table 2. Soil Classifications within the Raisin River Watershed

Sites	Soil Order[a]	Description[b]
1	Organic	decomposed organic matter (peat bog situated at this site); underlain by various deposits (sand, clay, or till) or bedrock; high water-holding capacity
All Sites	Regosolic	found along river channels; parent materials consist of alluvial deposits; texture and drainage variable
2, 4, 5, 6, 7, 13	Gleysolic	poorly drained soil formed from neutral to slightly alkaline lacustrine clays, generally stonefree
2A, 3, 12	Brunisolic	well drained soil, formed from loamy, calcareous till; moderately stony
7A, 8, 11	Podzolic	soils formed on outwash material, underlain by lacustrine material; sandy and silt loams with imperfect drainage; weakly developed in this region

Table Notes:

[a] Source: Clayton et al., (1977).

[b] Source: Clayton et al., (1977) and Matthews and Richards (1954).

2.6 References

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Habicht, M.H., Cornfield, H.W., (of MacLaren Plansearch), (1982), "Water Management Study of the Raisin River (Main Branch), Report to Raisin Region Conservation Authority, Phase II, Final Report.

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Ontario Ministry of the Environment, (1992), Water Pollution Survey, Community of Martintown.

Maps:

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OMAF, (Dec. 1982, revised Aug. 1992), Artificial Drainage System, County: Stormont, Township: Cornwall, Drawing No. 04-010, Drawn by D.J.B., Scale: 1:25,000.

OMAF, (Oct. 1983, revised Aug. 1992), Artificial Drainage System, County: Stormont, Township: Osnabrook, Drawing No. 04-060, Drawn by W.B., Scale: 1:25,000.

Chapter 3.0 Geology and Regional Hydrogeology

3.1 Bedrock Geology (Paleozoic Era)

Stormont and Glengarry Counties, which encompass the Raisin River watershed, are located within an area designated as the St. Lawrence Lowlands. This area has five major formations from the Ordovician Period (460 million years before present (B.P.)), as described by Williams (1991). These formations are part of the Ottawa Group[1], and are named (from most to least recent): the Lindsay, Verulam, Bobcaygeon, and Gull River Formations. The Rockcliffe Formation [2], near the St. Lawrence River, lies below the Ottawa Group (Figure 4). These sedimentary rock formations, formed on the bottom of ancient seas, consist primarily of fine crystalline limestone, silty dolostone and fine-grained sandstone, with some interbeds of shale and calcarenite. The age of formation increases as the elevation decreases southbound towards the St. Lawrence

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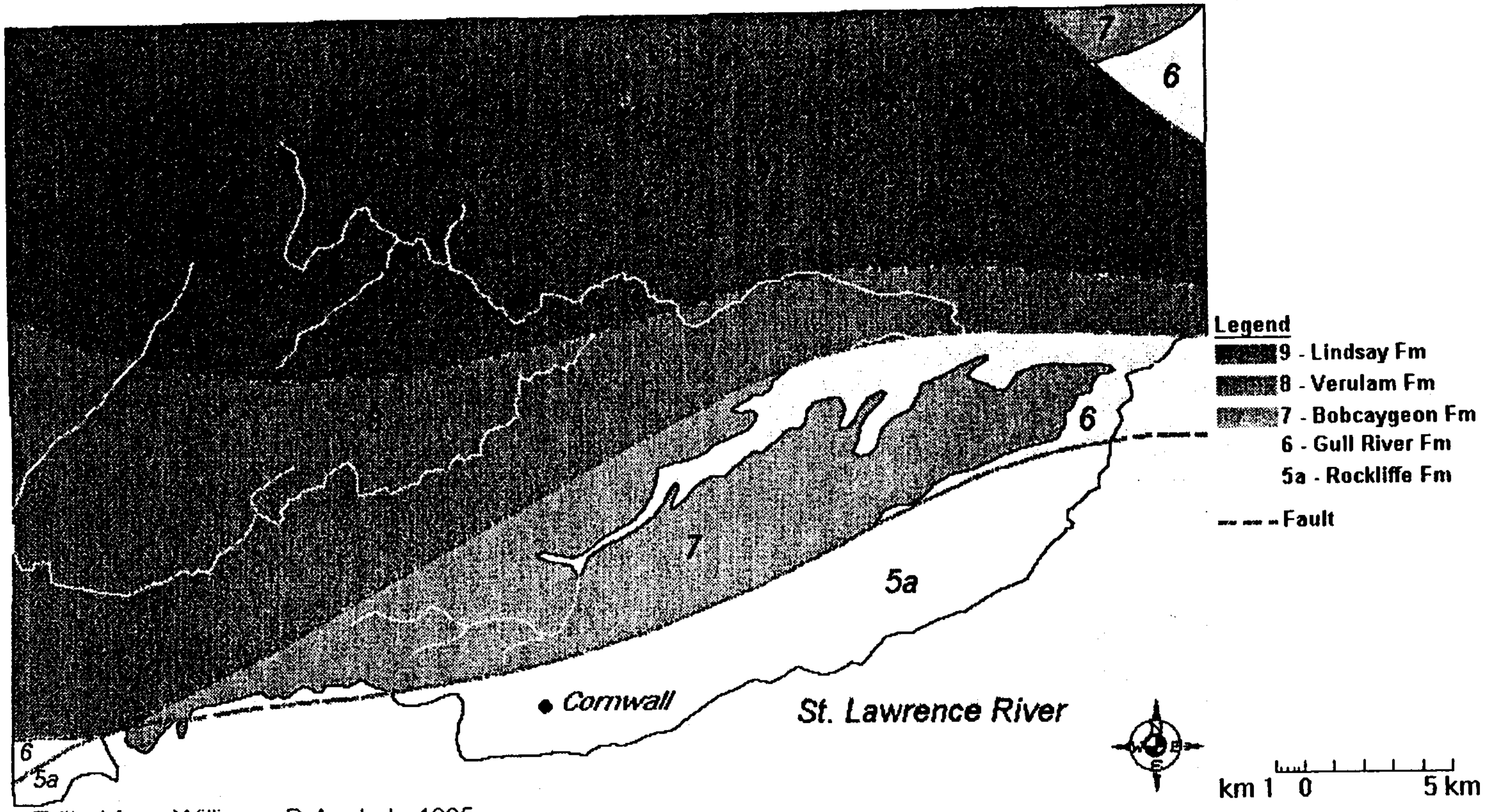
[1] What is referred to as the Ottawa Formation (of the Trenton and Black River Sub-epoch) in previous bedrock geology studies by Wilson (1946), was renamed by Williams (1991) as the Ottawa Group.

[2] Wilson's (1946) St. Martin and Rockcliffe Formations (of the Chazy Sub-epoch) were reclassified by Williams (1991) as the Rockcliffe Formation (with an Upper and Lower Member corresponding to the St. Martin and Rockcliffe Formations, respectively).

Figure 4: Bedrock Geology (Paleozoic) of Raisin River Watershed



Edited from Williams, D.A. et al., 1985

River. Table 3 provides a description of bedrock geology for each site. Outcrops of the Lindsay Formation are visible at Sandfield Mills and southeast of McMillans Corners (both in Cornwall Township) along the north branch of the Raisin River. Outcrops of the Verulam Formation can be seen at Black River (Cornwall Township) and east of McGillvrays Bridge (Charlottenburgh Township), along the shoreline of the Raisin River. An outcrop of the Bobcaygeon Formation can be found along Richmond Road (west of Cornwall Centre, Cornwall Township). The Gull River Formation outcrops along the south branch of the Raisin River near the intersection of South Branch Road and McConnell Ave. (Cornwall Township). An outcrop of the Rockcliffe Formation is visible along Fraser Creek, near Summerstown (Charlottenburgh Township).

3.2 Surficial Geology (Cenozoic Era)

The surficial geology of the Raisin River watershed, as illustrated in Figure 5, consists of two types of deposits: i) Glacial and ii) Post Glacial.

3.2.1 Glacial Deposits

Over the past one million years, glacial ice has covered Ontario at least four times (OMNR, 1984). However, in the Ottawa-St. Lawrence Lowlands, evidence exists mainly for glacial deposition during the Wisconsin Age. Pre-Wisconsin glacial deposits were mostly removed by erosion which is indicated by the unconformity which lies between the Ordovician bedrock

Table 3. Geological Descriptions of Measurement Sites

Site	Bedrock Geology [1]	Surficial Geology [2]	Notes
1	Verulam Fm - interbedded bioclastic limestone, sublithographic to fine crystalline limestone and shale	Peat and Muck - includes poorly drained areas supporting fen, swamp, and marsh vegetation	Dixon Creek - head waters of Raisin R. Fault runs through this site (not visible)
2	Verulam Fm	Glacial Till - Fort Covington Till (sandy, bouldery) and Malone Till (compact, clay till)	Lunenberg - Main Branch Raisin R.
2A	Verulam Fm	Glacial Till	Black River - Main Branch Raisin R., outcrop (horizontal bedding) visible on shoreline - very thin layer of sediment in river
3	Verulam Fm	Champlain Sea Deposits - marine Clay and silt, locally overlain by thin layer of sand	Upstream St. Andrews, Simon Fraser Farm, Main Branch Raisin R.
4	Verulam Fm	Glacial Till	Downstream St. Andrews, near Beaver Ck., Main Branch Raisin R.
5	Lindsay Fm - sublithographic to fine crystalline limestone, nodular in part, with beds of calcarenite and shale (up to 5 cm thick)	Champlain Sea Deposits	Upstream Martintown, Main Branch Raisin R.
6	Lindsay Fm	Glacial Till	Upstream Martintown, North Branch Raisin R.
7	Lindsay Fm	Glacial Till	Martintown - Main Branch Raisin R.
7A	Lindsay Fm	Alluvial Deposits (Post Glacial) - stratified sand and silty clay; thickness at least 1.2 m, commonly underlain by soft marine clay	Upstream Williamstown - east of McGillvrays Bridge, Main Branch Raisin R.; Bedrock visible downstream from site where fault crosses

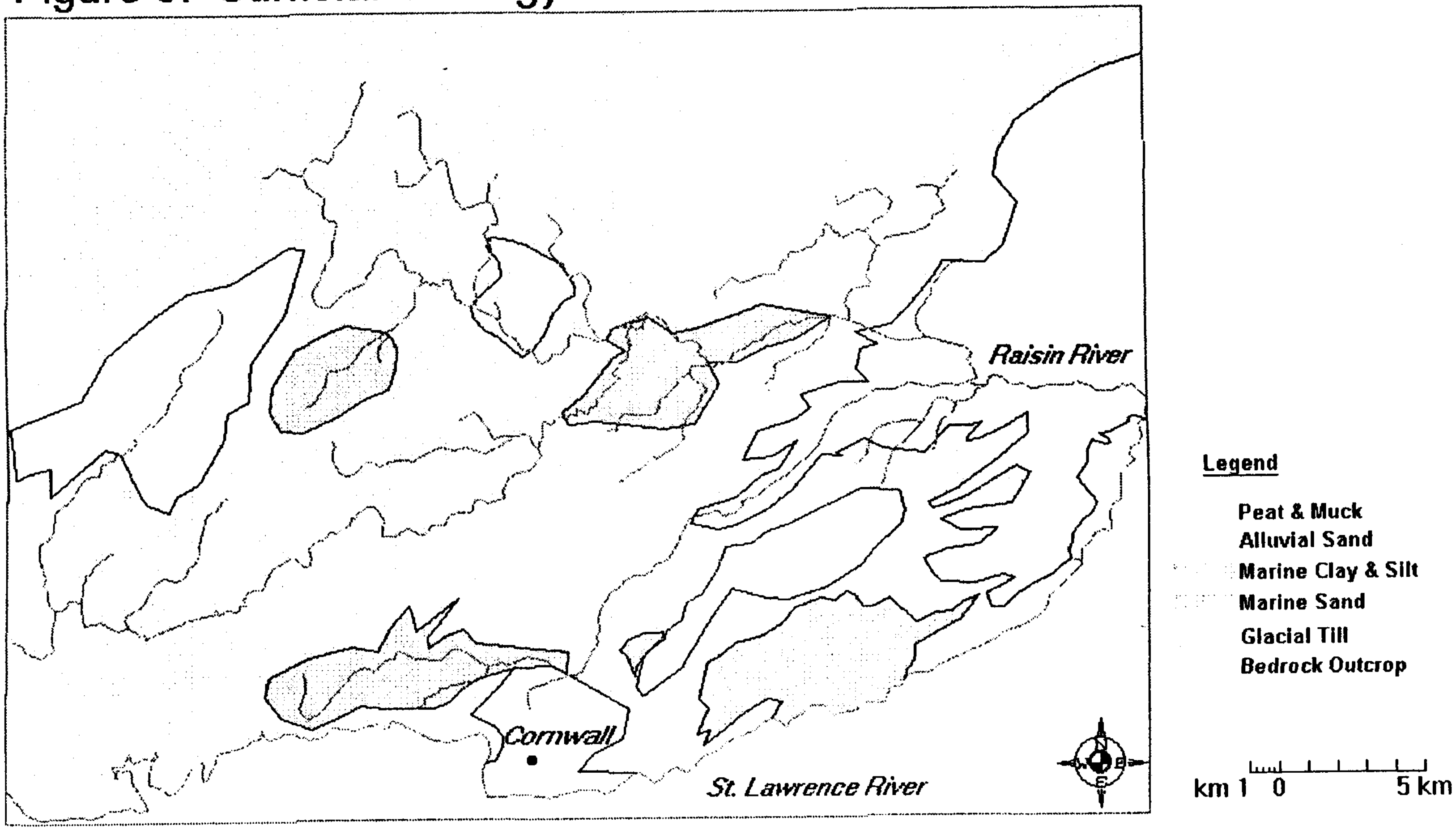
Site	Bedrock Geology [1]	Surficial Geology [2]	Notes
			river
8	Verulam Fm	Alluvial Deposits	Williamstown - Main Branch Raisin R.
12	Bobcaygeon Fm - interbedded calcarenite and sublithographic to fine crystalline limestone	Champlain Sea Deposits	S.E. of Eamers Corners, near 401, South Branch Raisin R.
13	Gull River Fm	Alluvial Deposits	N.E. of Grants Corners, South Branch Raisin R.

References:
1- From Williams, D.A. (1991)
2- Terasmae, J. (1965)

and material deposited by Wisconsin Age glacial activity (Terasmae, 1965). An unconformity generally indicates a period when deposition was negligible and/or a period of erosion, fracturing, and weathering (Freeze & Cherry, 1979).

a) *Glacial Till*: Till deposits from the two most recent glacial advances, the earlier Malone Advance and the later Fort Covington Advance (older than 11,000 years B.P.) form a physiographic region called the Glengarry Till Plain (Chapman and Putnam, 1966). The Glengarry Till Plain extends from Prescott to the Quebec border, north of the St. Lawrence River and includes most of Stormont and Glengarry Counties. MacViro Consultants (1992) report that the thickness of the till around the counties of Stormont, Dundas and Glengarry ranges up to several tens of metres (m). Charron (1978) describes a long, flat

Figure 5: Surficial Geology of Raisin River Watershed



Edited from Terasmae, J., 1965

till ridge between the Ottawa River and the St. Lawrence River, which has an elevation a.s.l. ranging from 76 m at the base to 114 m at the highest point.

The Malone Advance is considered part of the large Wisconsin Ice Sheet which flowed from the northeast. The Malone Till has been described as clayey silt and stony in texture (Gartner Lee, 1982) and as a coarse material with a large, compact, sandy silt component, having a permeability of approximately 10^{-7} m s^{-1} (Proctor and Redfern, 1992) to 4.5×10^{-9} m s^{-1} (MacViro, 1992). Terasmae (1965) notes that 90% of the pebbles in this till are of Paleozoic sedimentary rock origin (such as the local bedrock). The Fort Covington Till, later deposited from an ice sheet flowing from the northwest, has been described as being less compact and less consolidated with a higher sand content than the Malone Till; and as a silty, sand till with stratified sands and gravels (Proctor and Redfern, 1992). Gartner Lee Ltd. (1982) characterize the Fort Covington Till as cobbly to bouldery, sandy silt till. The hydraulic conductivity of the Fort Covington Till has been reported as 10^{-6} m s^{-1} (Gartner Lee, 1982) to 1.9×10^{-8} m s^{-1} (MacViro, 1992). It is also believed to contain a larger proportion of pebbles from igneous rocks (Terasmae, 1965).

b) *Glacio-fluvial/lacustrine Deposits:* Silt, sand and gravel deposits from glacio-fluvial processes, and silt and clay deposits from glacial lakes (abundant throughout the province around 10,000 to 20,000 B.P.) are also found within the counties of Stormont and Glengarry (OMNR, 1984).

3.2.2 Post Glacial Deposits

a) *Champlain Sea Deposits*: After the ice sheets receded, Eastern Ontario was inundated by the Champlain Sea (approx. 12,000 years B.P.). As a result, marine clay deposits as well as smaller beach/shoreline sand deposits are found throughout the region. In the less elevated, southern part of Glengarry County, a physiographic region has been named the Lancaster Flats, for its clay to very fine sand water-laid (both marine and alluvial) deposits (Chapman and Putnam, 1966).

b) *Alluvial and Organic Deposits:* Once the Champlain Sea receded (approximately 10,000 years B.P.), the primary erosional/depositional processes were due to river and stream water movement. Stratified sand, gravel, and silt deposits, as well as the buildup of organic matter in poorly drained areas (marsh/bogs) are found throughout both Stormont and Glengarry Counties. The headwaters of the Raisin River originate in a sizable peat bog. Layers of peat can act as a sponge which will delay *surface runoff* (Ineson and Downing, 1964).

For site descriptions of surficial geology, see Table 3.

3.3 Structural Geology

Four normal faults which generally run west to east through the study area act as borders between the various formations (i.e. they outline the fault blocks) (Figure 4). The faults strike from northeast to southeast and a major junction can be found just west of Long Sault. In the map area, the upward displacement of faults (relative to a datum of zero near Russell, Ontario) ranges from 355 m in the north to 515 m in the south (Williams, 1991). Bedding in the sedimentary rocks is generally flat-lying to gently dipping but in the vicinity of fault zones, can dip steeply. These faults are part of the Ottawa Valley rift zone which extends in a northwesterly direction from the St. Lawrence River to Lake Nipissing. The most notable seismic activity was an earthquake which occurred in the Cornwall-Massena area in 1944 with a magnitude of 5.7 on the Richter scale.

3.4 Regional Hydrogeology

3.4.1 Aquifers

Water bearing zones are often found in the fractured or weathered section of bedrock, commonly associated with unconformities (Freeze & Cherry, 1979). Thus, fractured limestone and dolostone are probably the most reliable source for water supply in this region since an unconformity lies below the glacial deposits. Sandstone, which can have interconnected spaces amongst the rock, also provides a smaller portion of water storage. Furthermore, in fault zones there are typically large number of fractures. Accordingly, zones of high specific capacity (productivity) have been reported by Charron (1978) along the trend of the major east-west fault near Cornwall.

A recent study by Proctor and Redfern, Ltd. (1992) defined two water bearing zones in the Cornwall area, a shallow unconfined aquifer and a deep confined aquifer, separated by an aquitard layer of stiff sandy silt till. The unconfined zone was found to have a hydraulic conductivity of between 3.05 x 10^{-8} and 2.25 x 10^{-6} m s^{-1}. The hydraulic conductivity of the deeper zone ranged from 9.05 x 10^{-8} to 5.40 x 10^{-7} m s^{-1}. These values of hydraulic conductivity are within a typical range for silty sand and glacial till (Freeze & Cherry, 1979).

Water well records provided by the OMOEE show that groundwater is extensively used as a source of drinking water in the area (Figure 6). Well records also indicate that the major water bearing formation in the study area is bedrock (or more likely at the contact between overburden and bedrock) (Table 4 and Figure 7). Figure 7 is a Voronoi[3] map of water well completions which illustrates the extent of bedrock wells in the two counties of Stormont and Glengarry. A drift thickness map, generated by Gwyn, Q.H.J., et al., (1974), indicates that most water wells in the region reach bedrock.

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[3] The Voronoi map (also known as a Thiessen diagram) has been generated in SPANS™ with a Triangulated Irregular Network (TIN) model. The model creates an area surface from a point surface (Bonham-Carter, 1994). See Appendix 1 for methodology.

Figure 6: Water Wells in Stormont and Glengarry Counties

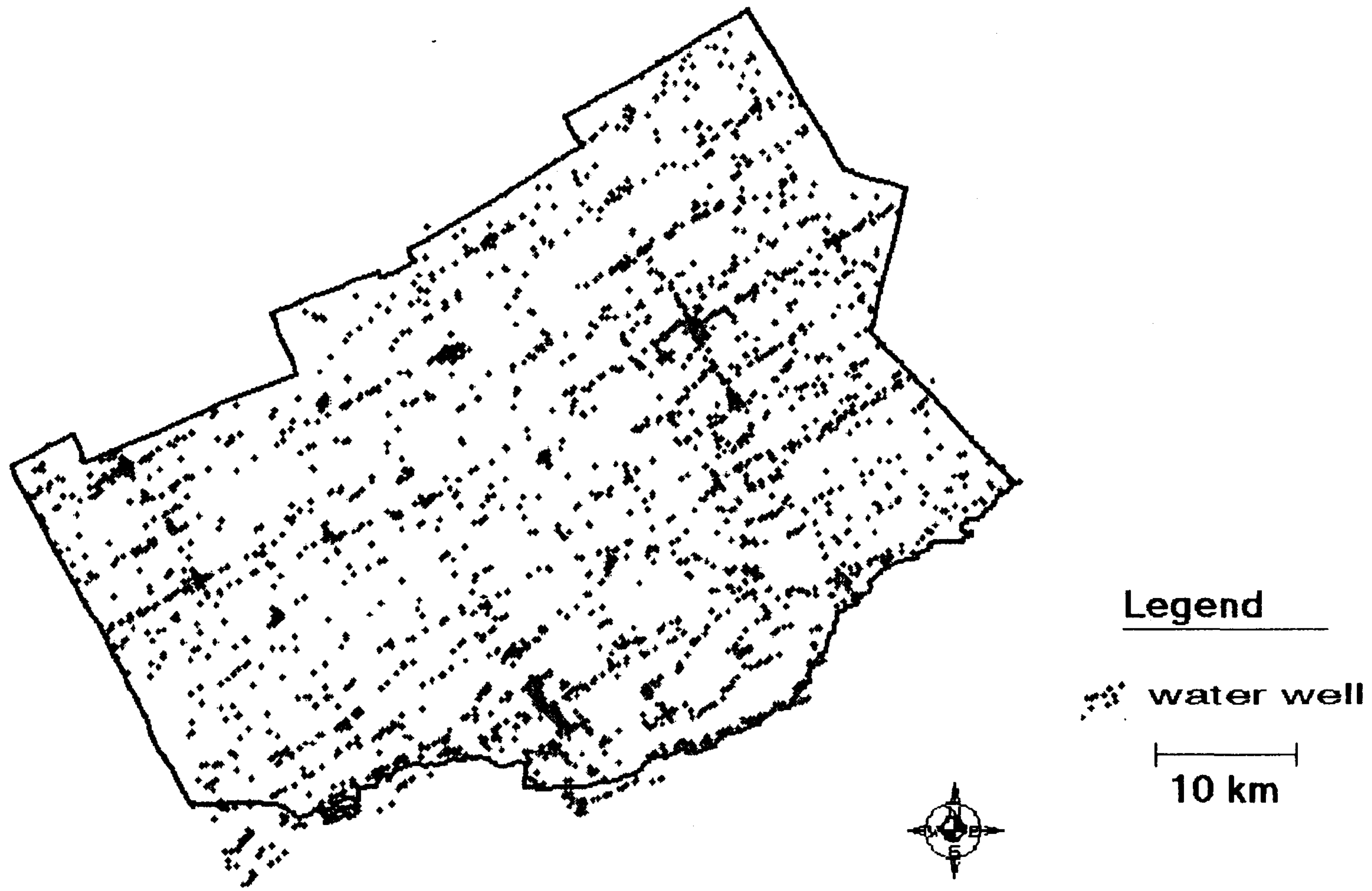


Figure 7: Map of Water Well Completions in Stormont and Glengarry Counties

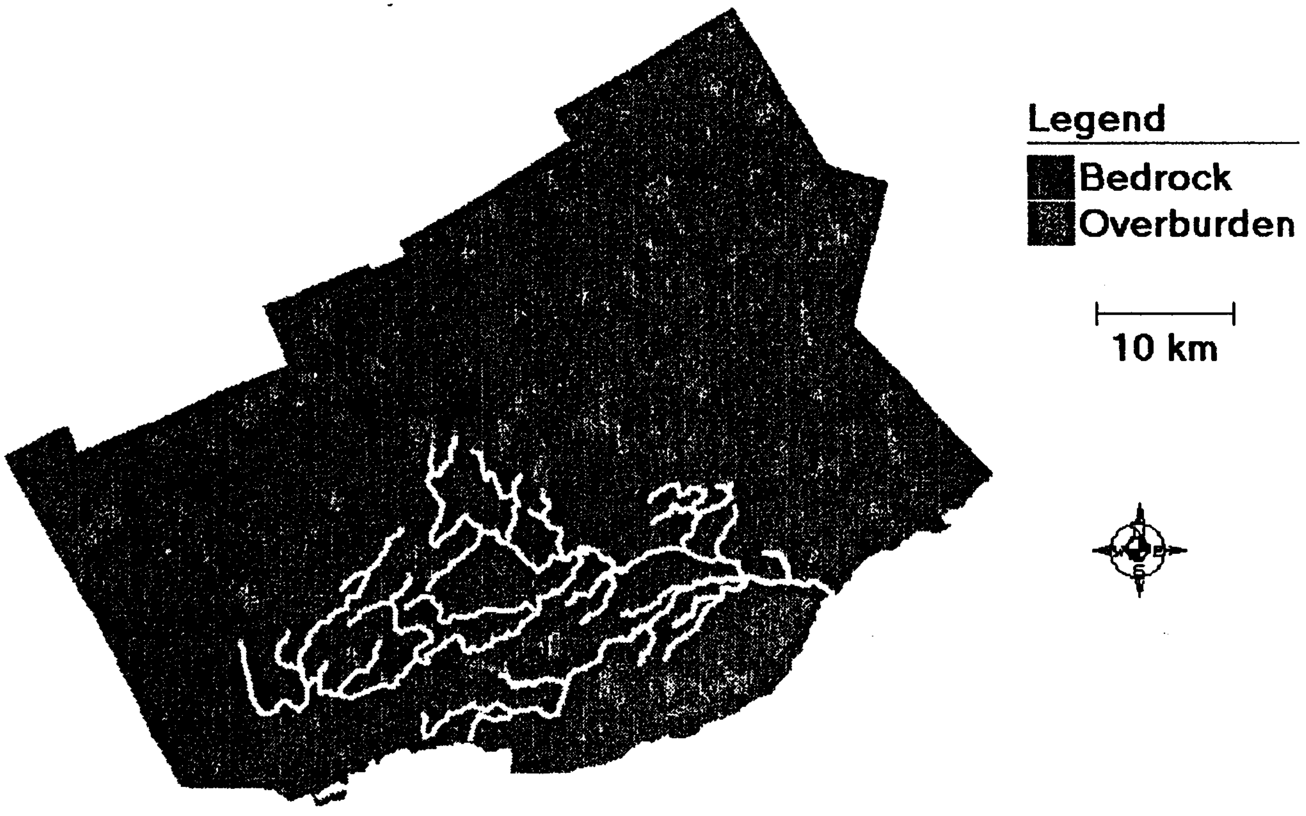


Table 4. Summary of OMOEE Water Well Records in the United Counties of Stormont, Dundas and Glengarry (up to 1984)

Name of County	**No. of Wells Ending in Bedrock**	**No. of Wells Ending in Overburden**
Dundas	2359	199
Stormont	1790	279
Glengarry	1944	506

3.4.2 Groundwater Recharge/Discharge Zones

Although considered semi-permeable, the main area of groundwater recharge for the region is believed to be located in the till plain (Charron, 1978). Bedrock outcrops and areas where depth to bedrock is shallow are potential recharge zones. Charron (1978) reports that recharge areas generally have depths to bedrock of less than 46 m and discharge areas tend to have depths greater than 46 m. In Stormont and Glengarry counties, the mean depth to overburden is 12.6 m and the range is -0.6 to 73.8 m (negative depths indicate outcrops of bedrock). A histogram, whose classes were generated from normal probability plot (Appendix 1, Figure 2), illustrates the distribution of data (Figure 8) and a contour map of overburden depths is shown in Figure 9.

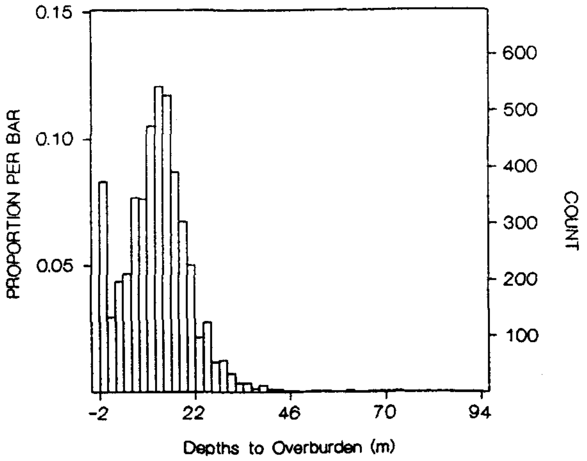
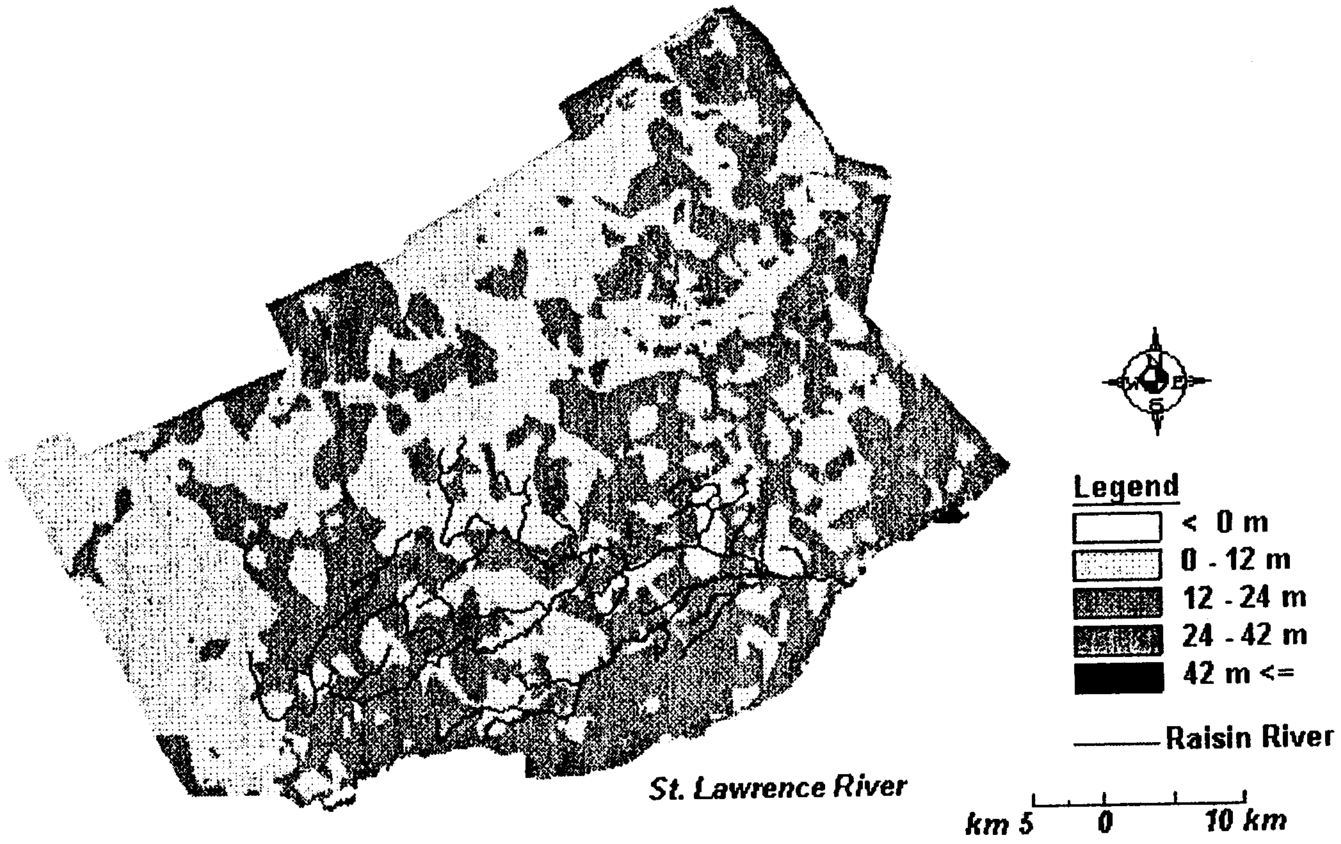


Figure 8. Histogram of Depths to Overburden in Stormont and Glengarry Counties (from OMOEE water well data)

3.4.3 Groundwater Flow

The general direction of regional groundwater flow is southerly to south-easterly from the till plain to the St. Lawrence River. This groundwater flow pattern was determined from a contour map of hydraulic head values for bedrock wells generated by SPANS (Figure 10). The flow direction is believed to follow the bedrock topography, since the fractured zone at the bedrock contact with overburden would be much more permeable than the glacial till (Charron, 1978). Estimates made by Gartner Lee Assoc. Ltd. (1982) indicate that the lateral groundwater flow rate is considerably larger through bedrock than through

Figure 9: Depth of Overburden in Stormont and Glengarry Counties



overburden with flow rates of 30 m per year and less than 1 m per year, respectively. In 1984, the Ontario Ministry of Natural Resources (OMNR) reported for this region greater well yields in bedrock as compared to overburden with well yields between 1 and 4 Ls^{-1} for bedrock and less than 1 Ls^{-1} for overburden.

3.4.4 Regional Groundwater Quality

The main processes that can affect water quality in the study area include diffuse sources of contamination, such as agricultural practices (agro-chemicals and nutrients); and point sources such as milkhouse waste disposal systems, manure piles, sewage disposal (faulty septic systems), and landfill sites (St. Lawrence RAP Team, 1994). Since the area is mostly rural, the main potential sources of contamination are from agriculture.

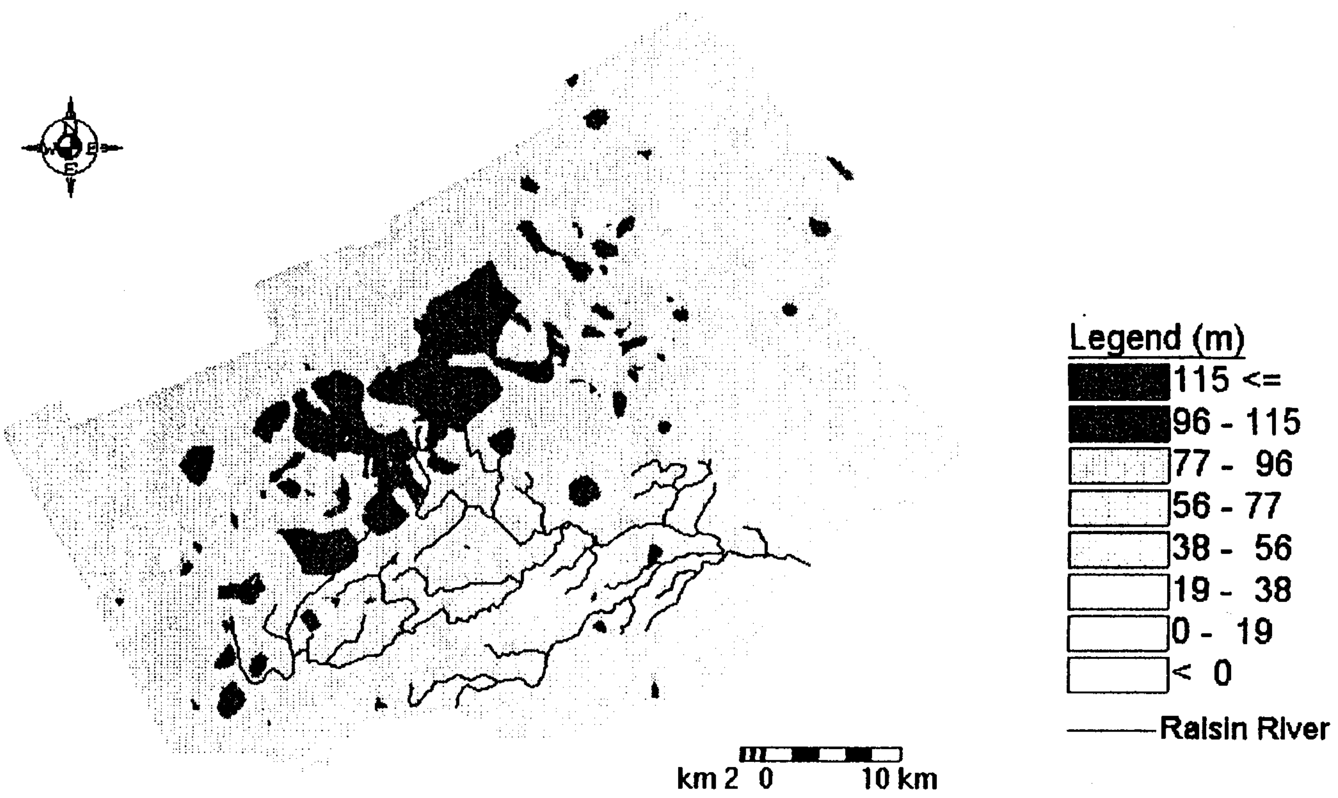
There are 17 landfill sites throughout the United Counties of Stormont, Dundas, and Glengarry. MacViro (1992) recently reported varying degrees of groundwater contamination adjacent to the following landfill sites: Cornwall Township, Charlottenburgh Township - North Site, Finch Township, Lochiel Township - Glen Robertson Site, Osnabrook Township. The study also found that the potential exists for groundwater contamination at eight other landfill sites. Additionally, leachate from the landfills is either discharging (or has the potential to discharge) into surface water and/or wetlands (MacViro, 1992).

A two year study was carried out on the drinking water quality in the community of Martintown in 1990 and 1991 by the Ontario Ministry of the Environment and Energy (OMOEE). Martintown is a small village approximately 15 km north-east of the city of Cornwall with a population close to 300 persons. Drinking water is supplied by wells only, which is typical of rural communities in this region. Wells are either dug or drilled and the water supply is the underlying bedrock aquifer. The study revealed that 34% of the wells sampled over the two years were considered "unsafe" for drinking due to their bacteriological count being greater than 10 per 100 mL (total coliforms). Most of those found "unsafe" were shallow, dug wells with depths that ranged from 2 to 14 m. Residential sewage is generally treated by septic tank systems and leakage into shallow groundwater may be contaminating the wells.

An Ontario farm groundwater quality survey carried out in 1991/1992 by various groups such as the Ontario Soil and Crop Improvement Association (OSCIA) and OMAF found sixteen wells in the counties of Stormont, Dundas and Glengarry that had concentrations of coliform bacteria greater than acceptable drinking water levels. Again, shallow wells (drilled, bored or dug) showed more contamination than deep wells, especially those with depths of less than 18 m (Agriculture Canada, 1993).

Further potential risks of groundwater contamination include fuel and chemical spills. OMOEE records in the Cornwall district lists 30 reported spills that

Figure 10: Potentiometric Surface of Bedrock Wells in Stormont and Glengarry Counties



occurred within the Raisin River watershed, between 1988 and 1989. The spilled materials included transformer oil, diesel fuel, and sulfuric acid (St. Lawrence RAP Team, 1992).

3.5 Discussion

Long established farming communities and small towns within the Raisin River watershed have relied primarily on groundwater for water supply during the past century. As a result, there are many water well records available for analysis. However, data was only available up to 1984 (more recent data was unavailable due to economic constraints) and older records are perhaps not as accurate, e.g. rock types are sometimes referred to in a very general sense as "bedrock".

Contour maps, generated with GIS software, were useful for illustrating the topographic and groundwater flow trends. Water well records indicate that most wells are "in" bedrock or at the contact of bedrock with the overburden (Figure 7). The overburden is highly variable in texture, has fairly low hydraulic conductivities, and it appears that regional groundwater recharge takes place where this layer is thinnest (between 0 and 12 m). This recharge most likely occurs on the ridge which runs through both counties, from the southwest to the northeast. The surficial geology map (Figure 5) indicates a significant bedrock outcrop in the central portion of the watershed, near sites no. 5, 6, and 7, which is apt to be an important regional groundwater recharge zone. Contouring hydraulic head values from water well records (Figure 10) illustrates that regional groundwater flow follows the bedrock topography and surficial drainage, from the northwest to the southeast, towards the St. Lawrence River. In terms of groundwater quality, the Martintown study (OMOEE, 1992) indicates that shallow wells (<18m) are more susceptible to contamination.

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Chapter 4.0 Surface Water/Groundwater Interaction

4.I Introduction

A 1981 watershed study, for the Raisin Region Conservation Authority (RRCA), concluded that an objective of the RRCA should be to maintain "adequate low flow conditions" in the Raisin River. This objective was motivated by poor surface water quality conditions during periods of low flow in the late 1960's. To address low flow concerns, it was recognized that research pertaining to groundwater/surface water interaction was needed. One particular research recommendation was to identify the groundwater recharge and discharge zones in the watershed (Habicht and Cornfield, 1982). This was, presumably, in the interest of preserving (or improving) groundwater discharge (baseflow) conditions to the river. For instance, the Newington Bog, in which the headwaters of the Raisin River originate, is believed to be a substantial groundwater recharge/storage zone that releases water during low flow periods. Consequently, artificial drainage of the bog area has been discouraged (Habicht and Cornfield, 1982).

The extent of artificial drainage in cultivated fields has been increasing within the watershed and there is some concern that the amount of groundwater storage available for later release as baseflow will be decreased, exacerbating low flow conditions (Habicht and Cornfield, 1982). However, based on physical considerations, agricultural drains will not discharge groundwater unless the pore pressure in the soil surrounding the drain is greater than atmospheric pressure (Robin, 1996, pers. com.) This condition occurs only when the water table is above the drain or during a rainfall event large enough to cause the ponding at the ground surface; not during normal periods of low baseflow. Other field research supports these theoretical considerations; studies of artificially drained watersheds by the Long Point Conservation Authority (1978), Eddie (1982), and Irwin and Whiteley (1983) found no evidence or trends that artificial drainage systems were reducing dry season flow rates.

The movement of groundwater is generally controlled by hydraulic gradients, which often follow surface topography. Thus, shallow groundwater typically discharges into surface water bodies, such as streams, rivers and lakes, which are located in low lying topographic areas. This groundwater discharge can contribute a significant portion to the flow of rivers, particularly in dry seasons. The Ontario Ministry of Natural Resources (OMNR) estimates that the contribution of groundwater to streamflow in this region is between 0 and 20 % (OMNR, 1984). The magnitude of the groundwater contribution can vary temporally since it is dependent on precipitation inputs (Ineson and Downing, 1964). Groundwater recharge by precipitation can cause vadose conditions to evolve to phreatic and thus, augment the flux of groundwater to a stream (Buttle, 1994). The amount, intensity, and spatial distribution of precipitation in a watershed can vary considerably over the course of a year. The groundwater component of streamflow can also be spatially variable since it depends on the infiltration potential (governed mostly by the hydraulic conductivity) of surficial deposits in a region (Ineson and Downing, 1964). Since the hydraulic conductivity of surficial deposits (or bedrock formations) can vary by orders of magnitude, we would expect to see large variability in the groundwater component of streamflow (Freeze and Cherry, 1979).

The direction of groundwater flow into or out of a stream can also change, allowing groundwater to be recharged by the same surface water bodies. The direction of groundwater flow into or out of a surface water body depends on the local hydraulic gradient which is related to surface water levels. If surface water levels change rapidly, the direction of flow can also change within short time periods (Wolf et al., 1991). The rate of groundwater discharge or recharge can vary considerably due to the variability in texture of river sediments (Norman et al., 1986).

When considering the transport of contaminants in groundwater, the groundwater/surface water interaction can be important. This interaction can be studied in the field with instruments such as seepage meters and mini-piezometers. Such studies have been carried out by Lee and Hynes (1978), Norman et al., (1986), Cruickshanks (1988), and Morrow (1989).

4.2 Previous Research with Seepage Meters and Mini-piezometers

A seepage meter is an instrument which can be used to measure the flux of groundwater into or out of a river or stream through the sediments. An example of a simple seepage meter design is given by Lee and Cherry (1978). A plastic bag, attached to a cylinder placed in the sediments, is used to measure a change in the volume of water flowing through the sediments over time (Figure 11). A positive seepage flux indicates groundwater discharge to the river and a negative seepage flux indicates groundwater recharge from the river. A mini-piezometer, which consists of a length of polyethylene tubing with a filtered tip on the end, is installed in river sediments to measure the vertical hydraulic gradient across a riverbed (Figure 11). A positive hydraulic gradient (level of water in the piezometer is above the surface of the river) indicates groundwater discharge into the river and a negative hydraulic gradient (water level in piezometer below the surface of the river) indicates groundwater recharge from the river.

Details of the seepage meter and piezometer designs used in this study are given in Appendix 2, along with sample calculations. The hydraulic gradient and seepage flux, q, are related through Darcy's Law:

$$q = \frac{Q}{A} = -\frac{dh}{dl}K$$

where:

q = groundwater seepage flux ($m^3 m^{-2} s^{-1}$)

Q = groundwater flow rate ($m^3 s^{-1}$)

A = area through which seepage occurs (m^2)

$\frac{dh}{dl}$ = hydraulic gradient (hydraulic head (m) /distance (m))

K = hydraulic conductivity ($m\ s^{-1}$)

The minus sign indicates that groundwater flow is in the direction of decreasing h.

Lee and Hynes (1978) used seepage meters and mini-piezometers in a small agricultural watershed and measured only groundwater discharge at 45 measurement sites. A range of seepage flux from $<1 \times 10^{-9}$ to $9 \times 10^{-6}\ m^3 m^{-2} s^{-1}$ was reported. However, after a large rainfall event (38 mm) the head differential in one piezometer reversed (i.e. the stream level was higher than that of the groundwater level) and they believe that groundwater flux reversed during a short time interval. Spatial variability of seepage flux measurements in this study was attributed to errors caused by the effects of stream currents[4] on the measuring bag attached to the seepage meter or the heterogeneity of streambed materials. Another groundwater study conducted by Norman, et al. (1986) used seepage meters *to determine* the rate of groundwater discharge into the Cochato River. Groundwater seepage rates into the river ranged from 2.72×10^{-7} to $4.07 \times 10^{-7}\ m^3 m^{-2} s^{-1}$ and only groundwater discharge conditions were found at the

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[4] Lee and Cherry (1978) recommended that seepage meters not be used where currents were greater than $0.2\ m\ s^{-1}$.

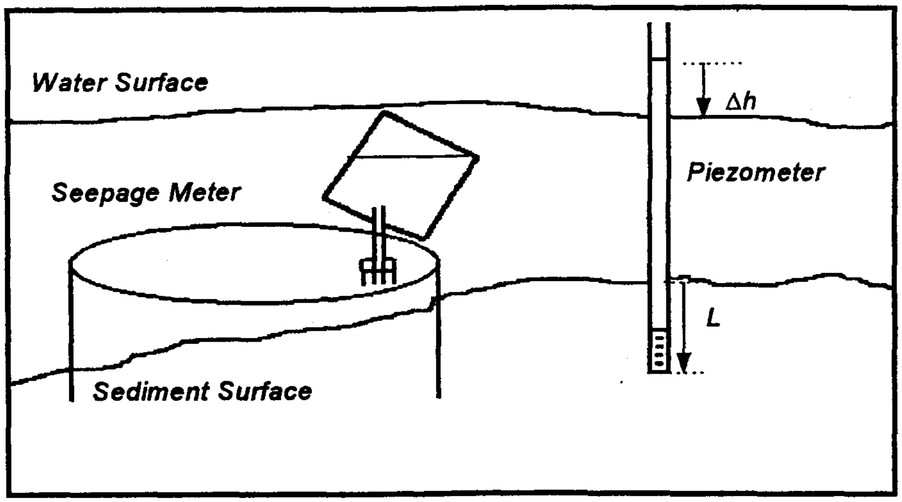

Figure 11. Seepage Meter and Mini-Piezometer Installation

three sites they measured. Cruickshanks et al. (1988) measured only positive groundwater seepage flux rates at 29 locations in a small watershed. The measurements ranged from 0 to 8.9 x 10^{-10} m^3 m^{-2} s^{-1} and were found to increase downstream through the Winter River watershed. However, Cruickshanks et al., (1988) found negative hydraulic gradients in piezometers (installed in the streambed) in an area associated with high pumping rates (municipal groundwater withdrawal). Spatial and temporal variability of seepage flux in this study was explained by natural variation, well pumping, and stream currents. In Morrow's 1989 study of Otego Creek, positive groundwater seepage flux only was measured, between 1.56 x 10^{-6} and 2.50 x 10^{-6} m^3 m^{-2} s^{-1}. A groundwater/lake study by Wills (1992) which employed seepage meters and mini-piezometers, attributed spatial variability in flux measurements to small heterogeneities in sediments. In another groundwater/lake study, conducted by Shaw et al., (1990), direct seepage flux measurements were compared to estimates of seepage flux (from hydraulic gradients and conductivities) and estimates were found to be approximately 25% of direct measurements.

4.3 Present Study

4.3.1 Methodology of Field Measurements

In order to identify groundwater discharge and recharge zones along the Raisin River, seepage meters were installed at 13 selected sites throughout the Raisin River watershed. Seepage meters were installed in the sediment to a depth of 8 to 15 cm. Seepage measurements were made at each of the sites on one to three occasions during the period of May to November 1994 and measurements were made over periods ranging from 2 to > 24 hours (see Appendix 2 for a description of seepage meter design and installation). The change in volume of water in a bag attached to the submerged seepage meter is used to calculate the groundwater seepage flux. An increase in volume indicates a positive seepage (groundwater discharge) and a loss in water indicates groundwater recharge or negative seepage. Generally, five seepage meters were placed at each site, offshore by approximately 100 to 300 cm, and apart by about 300 cm. The groundwater seepage flux, q, is calculated from Darcy's Law:

$$q = \frac{Q}{A} = \frac{\Delta V}{A\,t} \quad \left(\text{with units of cm}^3\text{m}^{-2}\text{s}^{-1}\right)$$

where:

ΔV = change in volume in bag attached to seepage meter (cm^3),

t = time over which seepage was measured in minutes (multiplied by 60 to convert to seconds, see below),

A = surface area of the seepage meter (0.255 m^2)

The final equation is similar to that used by Lee and Cherry (1978):

$$q = \left(\frac{\Delta V}{0.255\text{m}^2}\right)\left(\frac{1}{t\left(\frac{60\,\text{s}}{\text{min}}\right)}\right) = \frac{\Delta V(0.0653)}{t}$$

(Note: In text, flux values are given in SI units, m^3 m^{-2} s^{-1})

Mini-piezometers were installed to depths that ranged from 40 cm to 150 cm below the surface of the sediment, adjacent to each seepage meter (see Appendix 2 for a description of installation and materials). The hydraulic gradient, measured with the piezometer, is given by the difference in elevation between the water level in the piezometer and the water level in the river, divided by the distance, L, between the piezometer tip and the river bed (Figure 11). Hydraulic gradients from piezometers were measured for two purposes, i) to calculate K values for sediments, in conjunction with seepage meter measurements, and ii) to estimate seepage flux, once satisfactory K values were established.

4.3.2 Present Study Results

In the field season of 1994, a positive seepage flux (with hydraulic gradients causing upward groundwater flow into the river) was measured at all sites, ranging from 4.31×10^{-10} to 2.23×10^{-6} $m^3 m^{-2} s^{-1}$. A negative seepage flux (along with negative hydraulic gradients) was measured at sites no. 5 (on two different occasions in the months of July and August) and no. 7A (on three occasions, once in August and twice in September). Negative seepage measurements were within the range of -8.18×10^{-10} to -1.93×10^{-8} $m^3 m^{-2} s^{-1}$. On several occasions at site no. 1 (August/September) and once in October at sites no. 11 and 12 (south branch of the river), negative hydraulic gradients were measured in the piezometers. Conversely, a positive seepage flux was measured at the accompanying seepage meters during the same period. Additionally, a negative seepage flux was measured but a positive hydraulic gradient was found at two sites (no. 7A and 1) on separate occasions. The positive hydraulic gradients might be attributed to air in the piezometer or defective piezometers.

In May 1995, five seepage meters each were placed at sites no. 5 and 7A, and four at site no. 13 for repeated measurements. Daily measurements over five days were made at sites no. 5 and 13, and over eight days at site no. 7A. Again, mini-piezometers were installed beside the seepage meters. A positive seepage flux (with positive hydraulic gradients) was measured at all sites during these time intervals except one occasion where both negative seepage flux and hydraulic gradient were observed at site no. 5 (in one seepage meter only). However, negative hydraulic gradients were found on several occasions along side positive seepage measurements at sites no. 5, 7A, and 13. This might be due to defective equipment. The total range of seepage measurements for all three sites was -2.3×10^{-9} to 1.04×10^{-7} $m^3 m^{-2} s^{-1}$. A comparison of the means of seepage estimates and measurements exhibit some differences at several sites but they are generally around the same order of magnitude. One must take into account that some *comparisons* are 1994 measurements and 1995 seepage estimates, thus some temporal variability might be expected. The range of groundwater seepage flux measurements for 1994 and 1995 and the coefficients of variabilility ($CV = \frac{s}{\bar{X}}$) are given in Table 5.

Table 5. 1994 - 1995 Groundwater Seepage Flux Measurements and Estimates, Raisin River Watershed

Year	**Site no.**	**Seepage Flux Range ($m^3 m^{-2} s^{-1}$)**		**Mean Seepage ($m^3 m^{-2} s^{-1}$)**	**C.V. (%)** [b]	**No. of Meas.**
1994	1	Max: Min:	2.23×10^{-6} 4.31×10^{-10}	1.25×10^{-6}	50.1	32
1995	1[a]	Max: Min:	1.40×10^{-6} 4.65×10^{-7}	9.73×10^{-7}	3.1	22
1994	2	Max: Min:	8.63×10^{-7} 4.47×10^{-10}	9.31×10^{-8}	247.7	5
1995	2[a]	Max: Min:	9.76×10^{-9} -4.73×10^{-9}	3.24×10^{-9}	918.3	45
1994	2A	Max: Min:	1.08×10^{-6} 4.70×10^{-9}	1.88×10^{-7}	194.0	4
1994	3	Max: Min:	7.62×10^{-7} 2.45×10^{-9}	1.84×10^{-7}	155.72	4
1995	3[a]	Max: Min:	1.37×10^{-6} 5.48×10^{-8}	4.86×10^{-7}	20.6	23
1994	4	Max: Min:	9.19×10^{-7} 2.37×10^{-9}	1.47×10^{-7}	191.9	5

Year	Site no.	Seepage Flux Range (m^3 m^{-2} s^{-1})		Mean Seepage (m^3 m^{-2} s^{-1})	C.V. (%) [b]	No. of Meas.
1994	5	Max:	1.03×10^{-7}	9.19×10^{-9}	393.6	3
		Min:	-1.93×10^{-8}			
1995	5 - Set 1	Max:	1.36×10^{-7}	5.81×10^{-9}	66.9	24
		Min:	-2.30×10^{-9}			
1995	5 - Set 1[a]	Max:	1.38×10^{-7}	1.45×10^{-8}	NA	92
		Min:	-1.38×10^{-7}			
1995	Set 2[a]	Max:	2.40×10^{-7}	-3.75×10^{-8}	-46.4	166
		Min:	-5.44×10^{-7}			
1995	Set 3[a]	Max:	1.44×10^{-7}	-4.90×10^{-8}	-38.9	143
		Min:	-6.27×10^{-7}			
1994	6	Max:	7.90×10^{-8}	4.24×10^{-8}	66.8	4
		Min:	2.44×10^{-9}			
1994	7	Max:	8.34×10^{-9}	6.22×10^{-9}	25.4	5
		Min:	4.66×10^{-9}			
1995	7[a]	Max:	9.60×10^{-8}	1.98×10^{-8}	13.2	22
		Min:	-7.17×10^{-9}			
1994	7A	Max:	1.52×10^{-8}	-1.34×10^{-9}	-463.5	5
		Min:	-9.82×10^{-9}			
1995	7A - Set 1[a]	Max:	1.92×10^{-8}	-9.55×10^{-10}	-173.0	134
		Min:	-4.53×10^{-8}			
1995	Set 2	Max:	1.55×10^{-8}	5.98×10^{-9}	47.2	25
		Min:	1.39×10^{-9}			
1995	Set 2[a]	Max:	2.01×10^{-8}	6.44×10^{-10}	370.5	161
		Min:	-3.88×10^{-8}			
1995	7A - Set 3[a]	Max:	3.42×10^{-8}	2.80×10^{-10}	95.2	128
		Min:	-5.18×10^{-8}			
1994	8	Max:	2.16×10^{-8}	4.51×10^{-9}	164.4	8
		Min:	7.26×10^{-10}			
1995	8[a]	Max:	5.00×10^{-9}	1.92×10^{-9}	116.5	24
		Min:	-2.39×10^{-9}			
1994	11	Max:	3.01×10^{-9}	2.36×10^{-9}	49.1	3
		Min:	1.72×10^{-9}			
1995	11[a]	Max:	1.10×10^{-7}	1.09×10^{-8}	24.3	17
		Min:	-3.94×10^{-9}			
1994	12	Max:	9.90×10^{-9}	6.51×10^{-9}	41.9	4
		Min:	2.59×10^{-9}			
1995	12[a]	Max:	2.46×10^{-8}	8.48×10^{-9}	10.5	22
		Min:	-1.97×10^{-8}			
1995	13	Max:	1.04×10^{-7}	3.35×10^{-8}	72.0	16
		Min:	8.60×10^{-9}			
1995	13[a]	Max:	7.72×10^{-7}	1.04×10^{-7}	16.0	84
		Min:	-2.74×10^{-7}			

Table 5 Notes:

[a] Seepage flux was estimated from hydraulic gradient (I) measurements and hydraulic conductivity (*K*) calculations.

[b] The C.V. includes seasonal variability.

The variability between seepage flux measurements at individual seepage meters at a particular site gives an estimate of the error of seepage measurements. For estimates of seepage flux, the variance (s^2) was calculated from an equation developed by Leaver and Thomas (1974):

$$s^2_{Qest} = I^2 s^2_K + K^2 s^2_I$$

Standard deviation ($\sqrt{s^2_{Qest}}$ or s) values from the above equation were used in the calculation of the C.V. For seepage flux measurements, s was calculated directly with Excel 5.0™ software. The C.V.'s for seepage flux estimates ranged from 3 to 371% and from 25 to 464% for seepage flux measurements (Table 5). The C.V.'s for seepage flux measurements are generally greater than those for seepage flux estimates. However, the C.V. values include both temporal and spatial variability for groundwater seepage flux and therefore, need to be interpreted with caution. The effects of temporal and spatial variability can be removed with ANalyses Of Variances (ANOVA). The details are presented in the following sections.

4.3.3 Error Estimation

As was shown in the previous section, the total variability of seepage measurements can be quite high, when it includes the effects of temporal and spatial variability. Thus, the total variability is a poor indication of the error on an individual seepage measurement. In order to assess the magnitude of the error on seepage measurements, a series of measurements were made with several seepage meters at three sites, over several days. These results were then analysed with an Analysis of Variance (ANOVA). The ANOVA results produced the error, expressed as variance, 3.72×10^{-5} with 40 degrees of freedom. This is an estimate of the error on seepage measurements which excludes the effects of site variability and time variability. See ANOVA results in Appendix 2 (Section 2.7).

4.4 Hydraulic Gradient Measurements

A number of mini-piezometers were installed in the Raisin River sediments to measuring the hydraulic gradient of groundwater. At sites no. 5 and 7A, a total of thirty piezometers were installed (three sets of five at both sites). The individual piezometers were approximately 300 cm apart and the sets were 10 - 15 m apart. The piezometer tips were located at depths below the river bed ranging from 80 to 171 cm. Daily measurements, taken over the Spring, Summer and Fall, were used to investigate the spatial or temporal variability of the hydraulic gradients.

4.4.1 Spatial Variability of Hydraulic Gradient Measurements

ANOVAs were performed in Systat™ to compare the variability in hydraulic gradient measurements produced by the different sets at a given site, and by repeating measurements over a short period of time. The variability between sites is large and the ANOVA's were therefore performed separately for each site. A total of 379 data points for site no. 5 and 471 for site no. 7A [5] were used. In the ANOVA, the dependent variable is the hydraulic gradient and the independent, categorical variable is the "set" number (i.e. 1, 2, 3). Since measures were repeated on the individual piezometers, they were treated as "repeated" measures in Systat™. The results for each site are as follows:

Site no. 5 Hydraulic Gradient Measurements: For site no. 5 a first ANOVA showed that there was a significant difference between sets ($p = 1.0 \times 10^{-4}$ = the probability of committing an error when declaring the difference significant or loosely defined, p represents the probability of there being no significant difference). A Post Hoc, Pairwise Mean Differences test, indicated that the 1st set of site no. 5 is significantly different from the 2nd or 3rd set[6]. Measurements

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[5] Measurements were made in Summer 1994 and Spring 1995

[6] The first three piezometers from the first set were vandalized in the field and therefore, had less data.

from the last two piezometers of the first set were questionable since the hydraulic head values did not change very much (when others at the same site did). Therefore, it was reasonable to discard data from the first set altogether. Data from the second and third sets were also deleted on the same physical grounds.

Once data from the first set (piezometers no.'s 25 to 29), second set (piezometer no. 30, 31) and 3rd set (piezometer no. 37) were discarded (a total of 180 values deleted), a second ANOVA was performed on the data set of 199 values. The second ANOVA showed that the hydraulic gradient measurements in set no. 2 were insignificantly different from set no. 3 ($p = 0.53$). That is, the variability over time was larger than the variability between sets of piezometers. The details of the statistical analyses are given in Appendix 3.

Site no. 7A Hydraulic Gradient Measurements: An ANOVA showed a *significant* difference between sets ($p = 6.5 \times 10^{-5}$) with $n = 471$ data. A Pairwise Comparison indicated that set no. 2 was significantly different from set no. 1 and no. 3. After re-examining the data, several piezometers (no. 50, no. 51 from set no. 1 and no. 53, no. 56 from set no. 2) were dropped from the data set because of suspicious measurements. A second ANOVA test was carried out on a data set of $n = 298$. The second test produced a non-significant difference ($p = 0.46$). Therefore, one can conclude that hydraulic gradient values showed less variability between sets than the variability over time. Statistical test results are given in Appendix 3.

4.4.2 Comparison By Piezometer - ANOVA Results

Site no. 13 Hydraulic Gradient Measurements: At total of 97 hydraulic gradient measurements were taken at this site. An ANOVA showed that the hydraulic gradient measurements are insignificantly different ($p = 0.27$) from other piezometers at the same site. Statistical test results are given in Appendix 3.

4.5 Estimates of Groundwater Seepage Flux, 1995

In addition to the piezometers installed at sites no. 5, 7A and 13, single piezometers were installed at the following sites: no. 1, 3, 4, 6, 7, 8, 11, 12. In the Fall of 1995, hydraulic gradient, h/L, measurements were taken at all sites (10 sites, 38 piezometers). These gradient measurements (along with a weighted mean hydraulic conductivity of stream sediments for each site - see Chapter 5) were used to estimate groundwater seepage flux into or out of the river. Most estimates of seepage flux were positive (indicating groundwater seepage into the river), though negative seepage flux estimates were found at a number of sites (no.'s 2, 5, 7, 7A, 8, 11, 12, and 13). The range of seepage flux estimates for all sites was -7.17×10^{-9} to 1.40×10^{-6} $m^3 m^{-2} s^{-1}$.

4.5.1 Temporal Variability of Seepage Flux Estimates - All Sites

To investigate the variability of seepage flux estimates over time, two groups of hydraulic gradient measurements were made at all sites in October 1995 (Group 1: October 1 to 4[7] and Group 2: October 16 to 20[8]. These groups consist of measurements made before and after notable storm event which occurred on October 5th and 6th, 1995[9]. Seepage flux estimates taken several days after the storm event appear to be similar to pre-storm estimates (Figure 12). The seepage flux estimates from the first group were found to be significantly different from that of the second group using an ANOVA ($p << 5 \times 10^{-4}$) and the variability with respect to piezometer location was larger. When data from some piezometer sites were removed (9 piezometers were discarded because of dubious gradient measurements), a second ANOVA was run which again generated a significant difference between the two groups of days ($p << 5 \times 10^{-4}$). Statistical results are given in Appendix 3 (Section 2). However, when seepage estimates for each piezometer were analysed on an individual basis using F

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[7] Dates correspond to Julian Days 639 to 643 on Figure 12.

[8] Dates correspond to Julian Days 654 to 658 on Figure 12.

[9] Julian Days 644 to 645. This storm was Hurricane Opal, during which, 61.4 mm of rain fell over the course of two days.

tests[10] in Excel 5.0™ (and thus, not taking into account the significant variability due to piezometer location), 76 % of the seepage estimates for the first group were insignificantly different that those of the second group. Out of 29 piezometers, 22 have p values ≥ 0.015. Statistical results are given in Appendix 3, Section 2.0. They indicate that groundwater seepage flux does not vary significantly over short time (several days) intervals but storm events have a visible impact on the seepage flux along the Raisin River bed.

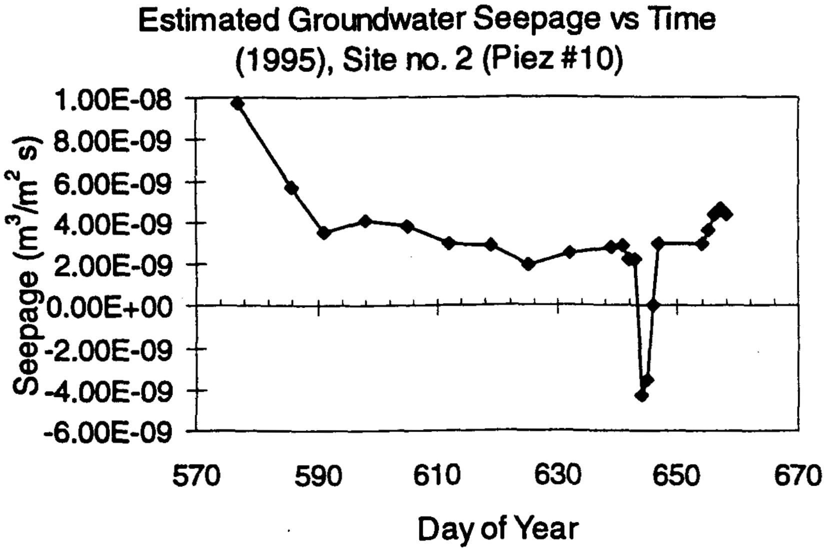

Figure 12. Example of Seepage Flux vs. Time

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[10] An Excel 5.0 F Test returns the one-tailed probability (p) that the variances in the two groups are not significantly different. If p was less than 0.01, one could reject a null hypothesis, H_o: $\sigma_1^2 = \sigma_2^2$, with a 99 % confidence level, i.e. the variability of seepage flux estimates for the first group of days would be significantly different than the second group of days.)

4.5.2 Temporal Variability of Groundwater Seepage Flux Estimates - Single Site

An ANOVA was used on two groups of daily seepage flux estimates at site no. 7A only. Hydraulic gradient measurements were used to estimate seepage flux on the following two time groups in May/June 1995: Group 1: May 23 to May 26 and Group 2: May 29 to June 2, 1995. The test revealed no significant difference ($p = 0.16$) when comparing seepage flux estimates for all fifteen piezometers from the first group to the second group. Again this illustrates that there is little variability of seepage flux over short time intervals. Statistical results are given in Appendix 3, Section 2.0.

4.5.3 Spatial Variability of Groundwater Seepage Flux Estimates - Single Site

To examine the variability between three sets of piezometers at site no. 7A during these same measurement periods in May/June, an ANOVA was used. This ANOVA indicated that seepage flux estimates are not significantly different for the two time periods ($p = 0.22$) but we can be mildly confident that some variability between the three sets of piezometers exists ($p = 8.4 \times 10^{-3}$). After some data was discarded due to questionable gradient measurements, a second ANOVA showed that seepage flux estimates for the three different sets at site no. 7A can be considered insignificantly different ($p = 0.28$ for the two different time periods and $p = 4.50 \times 10^{-2}$ for the three sets). Thus, one can conclude that spatial variability over short distances is insignificant. However, spatial variability throughout the watershed would probably be significant, since different areas have different values of hydraulic conductivity. Statistical results are given in Appendix 3.

4.5.4 Comparison of Direct to Estimated Seepage Flux Measurements

Seepage flux was measured directly (with seepage meters); and estimated using hydraulic conductivities from permeameters and hydraulic gradients in May 1995. The two methods (estimated or direct measurement) were compared at three sites: 5, 7A, and 13, using a factorial random block design ANOVA. In this design, two principal factors were considered: the effects of the type of seepage number (estimated vs. directly measured); and the effects of the day (DAY) on which the measurements were made. The effects of DAY are undesirable but potentially significant in the comparison of methods, and they can be removed using the random-block design.

At all three sites, the ANOVA results show that there was no significant difference between the measurement methods ($p = 0.99$ for site 5, 0.71 for site 7A, and 0.36 for site 13). More correctly stated, the variability produced by the method was less than that produced by making measurements on different days with one method, or that produced by making measurements on different days with different methods. Also, the previous section showed that dh/dl measurements from one set (at sites 5 and 7A) where actual seepage flux measurements were taken, were not significantly different from other sets with seepage estimates only. Therefore, one can expect that estimates of seepage flux would not be significantly different from a direct measurement. Thus, for practical purposes, calculating seepage flux from K and dh/dl produces accurate estimates of seepage considering the day-to-day variability in the seepage measurements. See Appendix 2 (Section 2.6) for statistical results.

4.6 References

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Chapter 5.0 Hydraulic Conductivity of Raisin River Sediments

5.1 Introduction

The hydraulic conductivity, *K*, is a parameter that describes the ease with which water is transmitted through a porous medium. This property remains essentially constant for a uniformly saturated soil or porous medium (Brady, 1990). However, since *K* is dependent on the size and configuration of pores, its spatial variability can be large. In surficial deposits or bedrock, *K* can be homogeneous if grain sizes and pores are similar in size (e.g. sand), or heterogeneous if grain sizes (or fractures, in bedrock) are variable. Freeze and Cherry (1979) and Brassington, (1988) report a wide range of values for typical surficial deposits and these are listed in Table 6.

5.2 Field Measurements

In the 1994/95 field season, the hydraulic conductivity, *K*, of the Raisin River sediments was measured at 12 sites throughout the watershed. Two methods of measurement were used: i) a combination of seepage meters and mini-piezometers which generates a vertical *K* ; and ii) a falling head test in mini-piezometers, which gives a horizontal *K* in the area is adjacent to the piezometer tip.

Table 6. Range of Hydraulic Conductivity Values for Unconsolidated Deposits (with references)

Unconsolidated Deposit	***K*** **(cm/s)**	**Reference**
Gravel	10^{2} to 10^{-1}	Freeze & Cherry (1979)
Gravel	3×10^{0} to 3×10^{-2}	Domenico and Schwartz (1990)
Alluvial Gravels	10 to 10^{-1}	Brassington (1988)
Clean Sand	1 to 10^{-4}	Freeze & Cherry (1979)
Coarse Sand	6×10^{-1} to 9×10^{-5}	Domenico and Schwartz (1990)
Medium Sand	5×10^{-2} to 9×10^{-5}	Domenico and Schwartz (1990)
Fine Sand	2×10^{-2} to 2×10^{-5}	Domenico and Schwartz (1990)
Alluvial Sands	10^{-1} to 10^{-3}	Brassington (1988)
Silty Sand	10^{-1} to 10^{-5}	Freeze & Cherry (1979)
Silt, Loess	10^{-3} to 10^{-7}	Freeze & Cherry (1979)
Silt, Loess	2×10^{-3} to 1×10^{-7}	Domenico and Schwartz (1990)
Silt	10^{-3} to 10^{-5}	Brassington (1988)
Glacial Till	10^{-4} to 10^{-10}	Freeze & Cherry (1979)
Till	2×10^{-4} to 1×10^{-10}	Domenico and Schwartz (1990)
Unweathered Marine Clay	10^{-7} to 10^{-10}	Freeze & Cherry (1979)
Unweathered Marine Clay	2×10^{-7} to 8×10^{-11}	Domenico and Schwartz (1990)
Clay	4.7×10^{-7} to 1×10^{-9}	Domenico and Schwartz (1990)
Clay	10^{-5}	Brassington (1988)

The first method uses Darcy's Law to calculate K from values of seepage flux, q, (from seepage meters) and vertical hydraulic gradients (measured in the adjacent mini-piezometer) (equation given in Chapter 4, page 48).

The second method of K measurement uses a falling head permeameter. A falling head permeameter was brought to each site and used to perform a slug test in the mini-piezometer. A detailed description of the method and a number of assumptions that accompany this method, as described by Lee and Cherry (1978) and originally by Hvorslev (1951), are outlined in Appendix 4.

5.3 Variability of K Measurements

There are several factors that may influence K in this study. The first, and perhaps most obvious, is spatial variability. It is well known that K can vary over several orders of magnitude, even within a single aquifer (eg. Robin et al., 1991). In this study, we would expect considerable variability between sites, and perhaps between the different locations at a given site. Another important source of variability in K values is caused by differences in the measurement method, and error for a given method. This section presents results of ANOVA's used to estimate the magnitude of these sources of variability. Since it is well established that K is log-normally distributed, the natural log of K was used in all statistical analyses.

Since the variability between sites is very large, and the degree of heterogeneity at each site is expected to be different, a separate ANOVA was performed for each site. The ANOVA design included the effects of "Method" and "piezometer location" on the ln (K) value. The ANOVA model was: $\ln K = \mu +$ "Method" + "Piez" + ϵ. Piezometer location was treated as a random block variate and the error included the effects of measurement error and the interaction between method and piezometer location. The two different measurement methods of K considered in the above design are: Method 1, based on seepage meter measurements; and Method 2 from slug tests (with a falling head permeameter).

The results showed that there was significant spatial variability between piezometers ($p = 10^{-15}$), but that there was no significant difference between the two methods ($p = 0.707$). The details of the analysis are given in Appendix 4.

Since the statistical test results show that the two different methods yield K measurements that are insignificantly different, a weighted mean K was calculated for each site using values from both methods. The weight used for this calculation was the number of measurements. A sample calculation is given in Appendix 4. Table 7 lists the mean weighted K for each site. These mean K values, in conjunction with hydraulic gradient values, can subsequently be used in predicting groundwater seepage.

The coefficient of variability (C.V. = $\frac{s}{\bar{x}}$) is calculated for each of the sites, for both methods (Table 8). C.V.'s range from 20 to 196% for Method 1, and 0 (indicating all measurements were equal) to 148 % for Method 1. Weighted mean K values ranged from 1.30 x 10^{-5} ms^{-1} (for organic-rich bog) to 6.40 x 10^{-8} ms^{-1} (for fine textured sediment).

Table 7. Mean K Results (Field Measurements with Seepage Meters/Mini-piezometers and Falling Head Permeameter/Mini-piezometers)

Site	**Method 1 Mean K (ms^{-1})**	**No. of Meas.**	**C.V. (%)**	**Method 2 Mean K (ms^{-1})**	**No. of Meas.**	**C.V. (%)**	**Weighted Mean K (ms^{-1})**
1	4.96 x 10^{-7}	14	125	4.81 x 10^{-5}	5	17	1.30 x 10^{-5}
2	9.41 x 10^{-8}	5	148	1.38 x 10^{-9}	3	0	6.40 x 10^{-8}
2A	7.05 x 10^{-7}	4	133	na	na	na	na
3	6.14 x 10^{-7}	4	85	3.23 x 10^{-6}	14	148	7.78 x 10^{-6}
4	1.40 x 10^{-7}	5	173	7.10 x 10^{-7}	3	7	3.54 x 10^{-7}
5	1.19 x 10^{-6}	25	196	4.83 x 10^{-6}	10	124	3.19 x 10^{-6}
6	1.24 x 10^{-6}	4	100	7.91 x 10^{-6}	3	33	4.24 x 10^{-6}
7	4.21 x 10^{-7}	5	59	2.49 x 10^{-6}	5	29	1.49 x 10^{-6}
7A	2.17 x 10^{-7}	45	129	4.25 x 10^{-8}	8	109	1.98 x 10^{-7}
8	6.98 x 10^{-8}	5	78	2.28 x 10^{-8}	3	0	5.22 x 10^{-8}
11	7.04 x 10^{-7}	3	20	9.69 x 10^{-7}	3	77	4.10 x 10^{-7}
12	4.66 x 10^{-7}	3	42	2.65 x 10^{-8}	3	0	2.46 x 10^{-7}
13	2.17 x 10^{-6}	3	114	4.56 x 10^{-6}	5	85	4.40 x 10^{-6}

5.4 References

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Chapter 6.0 Raisin River Discharge and Precipitation Data Analyses

6.1 Baseflow Contributions from Stream Hydrographs

Previous studies of groundwater contributions to rivers, such as those by Meyboom, (1961); Farvolden (1963), and Ineson and Downing, (1964), identify the groundwater component of streamflow (also known as baseflow) by analysing stream hydrographs. A stream hydrograph is a plot of river discharge (m^3/s), on a logarithmic scale, versus time. The negative sloping, straight-line part of the graph represents the groundwater discharge into a river (also termed groundwater recession since it represents groundwater removal from storage), and can be expressed with the following equation (Barnes, 1939):

$$Q_t = Q_o K_r^t$$

where:

Q_t = river discharge, t time units after Q_o ($m^3\ s^{-1}$)

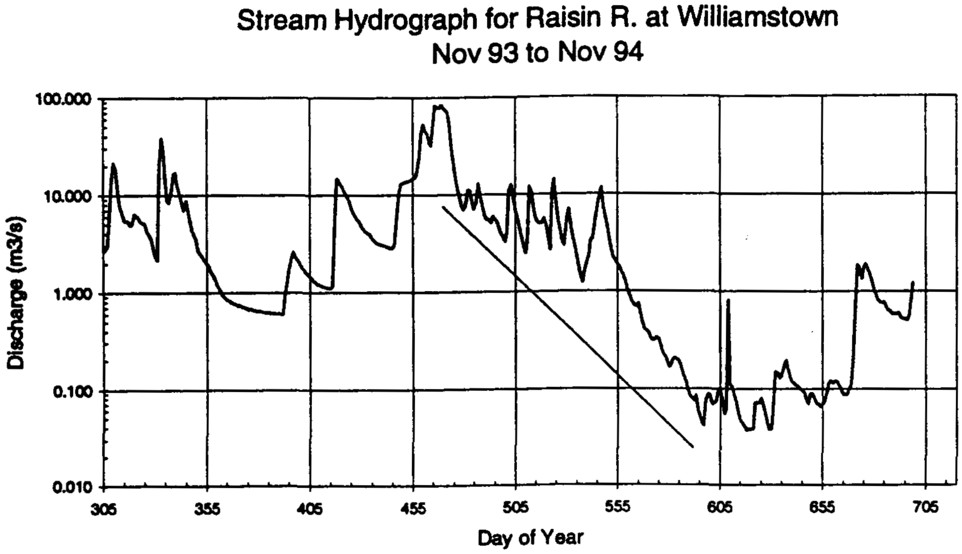
Q_o = river discharge at any given time ($m^3\ s^{-1}$), ($Q_t = Q_o$ at start of recession)

K_r = recession constant

t = time (sec)

Analysing stream hydrographs can give a rough estimate of the magnitude of baseflow contributions to a river. For instance, Ineson and Downing (1964) estimated that the groundwater component of many streams in Britain can exceed 75% of the total river flow. The measure of baseflow to a river can give an indication as to the permeability and storage capacity of aquifers in a watershed (Meyboom, 1961). The shape of the stream hydrograph has been studied by Farvolden (1963) and he theorized that the slope of the recession curve can be characteristic of the geology of the basin. Domenico and Schwartz (1990) summarized Farvolden's (1963) supposition that flat recession curves are common in limestone regions and steep recession curves are indicative of low permeability *(such as granite) regions.*

During the period of this study, November 1993 to October 1995, the longest periods of baseflow recession, as calculated from stream hydrographs at Williamstown, began in April and lasted until mid to late summer. The recession periods were 115 days in 1994 and 96 days in 1995 (a sample calculation is given in Appendix 5). The baseflow recession, or the amount of baseflow to a river, is estimated from the linear, negative-sloping portion of a semi-logarithmic plot of stream discharge (Figures 13 and 14). The baseflow is calculated from the beginning of the recession ($t = 0$) to one log cycle. The amount of groundwater discharge into the Raisin River during a recession, estimated from the stream hydrograph during the period of study ranged from 10^6 to 10^7 m^3 (Table 8). The rate of baseflow contributions ranged from 0.62 to 1.37 $m^3 s^{-1}$ (Table 9). The slopes of the recession curves appear quite steep which may indicate some degree of impermeability and low storage (Figures 13 and 14).


Stream Hydrograph for Raisin R. at Williamstown
Nov 93 to Nov 94

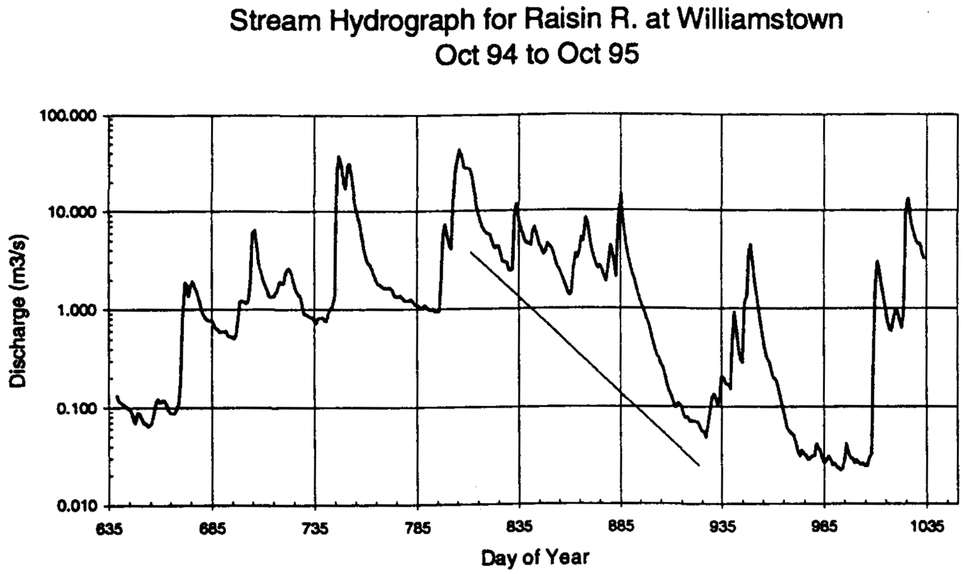

Stream Hydrograph for Raisin R. at Williamstown
Oct 94 to Oct 95

Figure 13 and Figure 14. Stream Hydrographs for the Raisin River, from Stream Discharge Data provided by Environment Canada, 1993 to 1995 (provisional and unpublished).

Table 8. Groundwater Recession Data, calculated from Stream Hydrographs of the Raisin River, at Williamstown (1993 to 1995)

Start of Recession	End of Recession	Duration of Recession (days)	Actual Groundwater Discharge (m^3)	Groundwater Recharge between Recession (m^3)
25 Apr 94	18 Aug 94	115	1.359×10^7	na
11 Apr 95	14 Jul 95	96	5.157×10^6	1.357×10^7

The magnitude of groundwater contribution to streamflow during low flow conditions is outlined in Table 9. Sample calculations are given in Appendix 5.0. During the baseflow recession of 1994, groundwater was estimated to make up 35% of the Raisin River discharge, whereas in the recession of 1995, the groundwater contributions were estimated at 22% (Table 9).

Table 9. Groundwater Contributions to Streamflow, as calculated from Stream Hydrographs

Period of Recession	**Mean River Discharge Rate (m^3s^{-1})**	**Groundwater Contribution (m^3s^{-1})**	**Groundwater Contribution (%)**
25 Apr - 18 Aug 1994	3.91	1.37	35.0
11 Apr - 16 July 1995	2.89	0.62	21.5

To approximate the amount of groundwater seepage along the entire riverbed of the main branch (from Dixon Creek to Williamstown) with the above baseflow calculations, the total area of the riverbed was roughly estimated to be 1.05 x 10^6 m^2. For each recession, the actual groundwater contribution to river discharge (m^3) over the period of the recession was divided by the area of river bed (m^2) and the duration of the recession (seconds) to generate a groundwater seepage flux with units of $m^3\,m^{-2}\,s^{-1}$. A sample calculation is given in Appendix 6. Results are given in Table 10. These values of seepage flux are the same order of magnitude of values found with seepage meters.

Table 10. Estimates of Groundwater Seepage Flux for the Main Branch of the Raisin R.

Duration of Recession (Days)	Estimated Groundwater Discharge to river ($m^3m^{-2}s^{-1}$)
115 (1994)	1.30 x 10^{-6}
96 (1995)	5.92 x 10^{-7}

6.2 Precipitation and Stream Discharge

The response time of a river to storm events is defined here as the time it takes for the greater part of a storm event to generate a peak in discharge. The response time of a river and the magnitude of storm runoff are dependent on several variables such as the magnitude or duration of the storm, the degree of wetness of the soil, and the permeability of the surface cover (outcrops and surficial deposits). The magnitude of storm runoff can vary from season to season. Serrano et al., (1985) found that storm runoff was high in the spring, decreased to a minimum in summer and elevated again in the fall.

In 1981, the response time of the Raisin River at Williamstown, was reported as 18-20 hours (MacLaren, 1981). In this study, the examination of rainfall and stream discharge data revealed that the response time of the Raisin River to storm events[11] (greater than 10 mm) was up to 48 hours during the spring months (April to June for both 1994 and 1995) (Figure 15). However, during the period of July to September (1994 and 1995), increases in stream discharge after a storm event were generally not observed (Figure 16). Additional Raisin River discharge and precipitation graphs are located in Appendix 5.

Daily stream discharge and rainfall data were examined together with a cross-correlation. Cross-correlation, as a function of lag time, is the correlation of two time series offset by the lag time. The resultant cross-correlogram shows the strongest correlation at a negative lag of two days, indicating that the Raisin River discharge is correlated to values of rainfall that occurred two days earlier (Figure 17).

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[11] Daily rainfall data, collected by Environmental Services, for the City of Cornwall was used for analysis since the city is directly adjacent to the watershed. It is possible that different amounts of rain could have fallen within the watershed on the same day.

The autocorrelation of the Raisin River discharge data is given in Figure 18. The autocorrelation function (ACF) is the cross-correlation of a time series with itself. The ACF can be used to estimate a correlation scale, which is an indicator of the time over which measurements are correlated and can be used to find out how quickly a signal in river discharge would die off in the stream. The autocorrelogram for the Raisin River discharge drops to and stays near zero after about 20 days indicating that after about twenty days, the Raisin River discharge becomes random. A periodicity of about one year could be identified

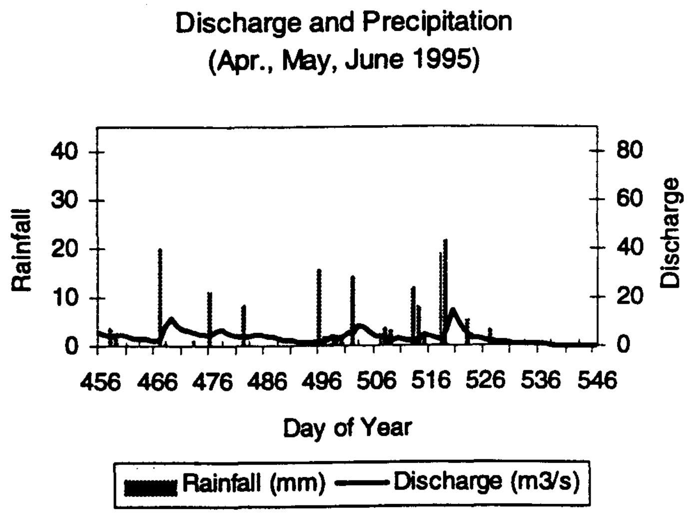

Figure 15. Raisin R. Discharge (at Williamstown) and Cornwall Area Precipitation

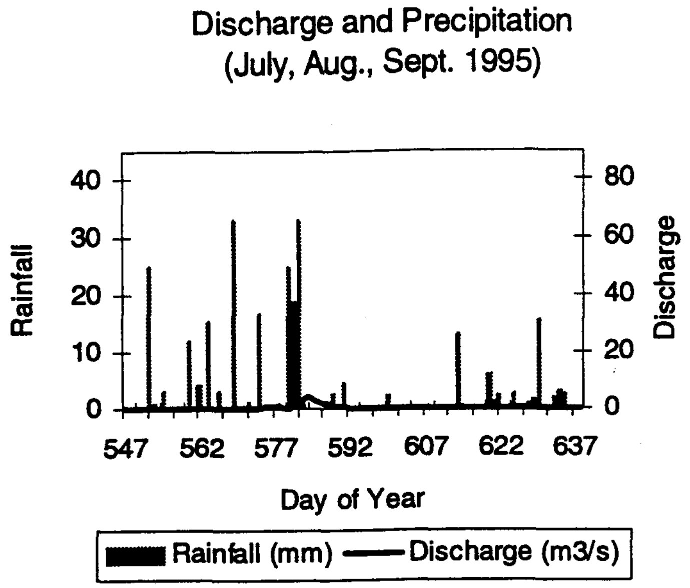

Figure 16. Raisin R. Discharge (at Williamstown) and Cornwall Area Precipitation

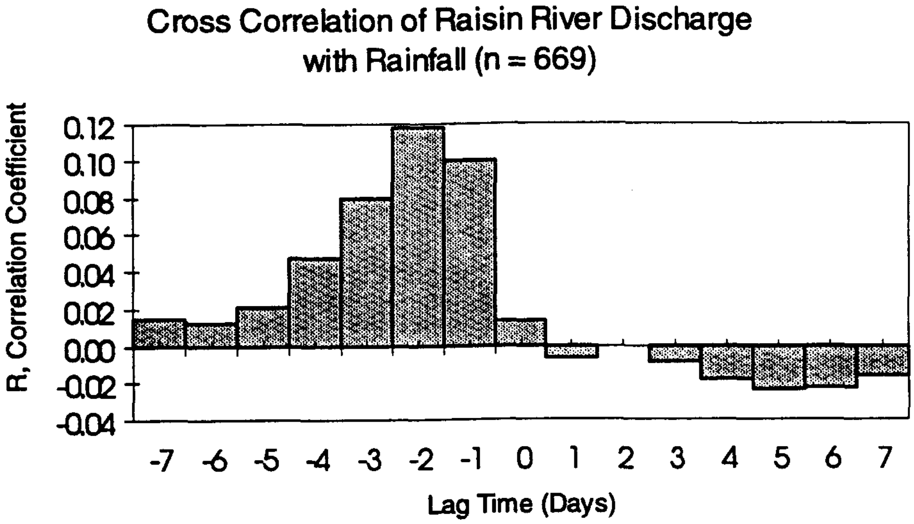

Figure 17. Histogram of Cross-Correlation Coefficients for Raisin R. Discharge and Rainfall (at Cornwall)

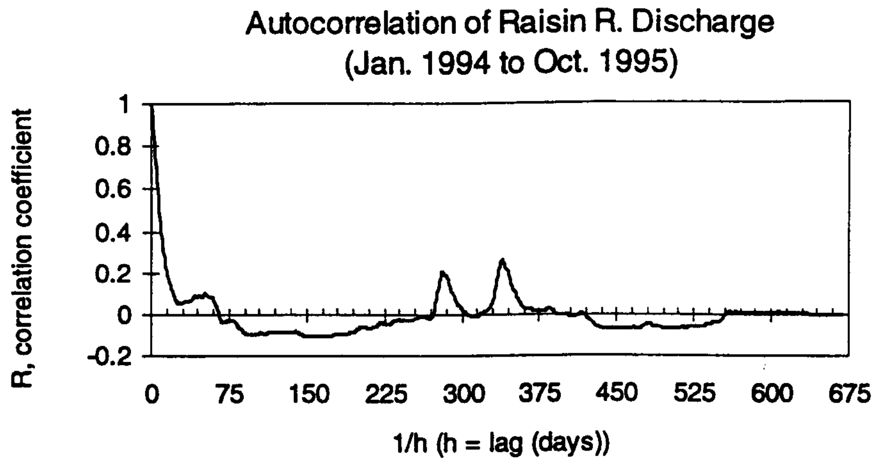

Figure 18. Autocorrelation of Raisin R. Discharge

in the data, which appears as a sinusoidal waveform in the ACF. The large peaks in the ACF at lags 285 and 345 days are due to two large rainfall events (and therefore large discharges) on days 581 (56.6 mm over three days) and 643 (61.4 mm over two days). The two large discharge events may also be responsible for masking periodicities in the ACF.

6.3 Precipitation and Groundwater Relationships

Infiltration of precipitation to groundwater usually occurs (but is not limited to) when soil moisture is low or when rainfall exceeds evaporation. In general, groundwater recharge will be higher when soils are "wet" (Ineson and Downing, 1964). There is a lag between the time groundwater is recharged by precipitation and the time groundwater discharges as baseflow into a river. The residence time in a shallow aquifer can range from days, weeks, to months and as a result, baseflow contributions are less variable than surface runoff contributions (Ineson and Downing, 1964). Farvolden (1963) found that because of high soil moisture deficiencies in summer periods, the magnitude of baseflow can be unaffected by storm events. However, large storm events, which cause water levels to increase in rivers may actually slow down or reverse groundwater discharge to a stream (Domenico and Schwartz, 1990). Therefore, when water levels in the river rise (after a precipitation event) and the hydraulic head value becomes higher than the adjacent groundwater, the hydraulic gradient will reverse. On the other hand, capillary fringe research by Gillham (1984) has shown that the response of shallow water tables to precipitation can be fast and large. Thus, a watertable rise would lead to increased groundwater discharge to a river.

During the course of this study, a large storm event (61.4 mm) from Hurricane Opal occurred on October 5th and 6th, 1995 (Days 643 and 644) at Cornwall, which caused significant increases in the Raisin River stage (measured at Williamstown). The estimated groundwater seepage flux was plotted with stage level, at Site no. 7A near Williamstown in Figure 19. The figure shows that the estimated groundwater seepage flux reverses during the increase in river stage. A less positive hydraulic gradient or a reversal (from positive to negative) of the hydraulic gradient, measured at piezometers installed in the river sediments, were found at all sites after this unusually large storm event. Seepage plots for other piezometers are given in Appendix 5.

One other notable rainfall event occurred on May 28 and 29, 1995 (Days 513 and 514), (total of 20.0 mm). This rainfall event also caused an increase in stage (at Williamstown) and caused a decrease or reversal in gradients at Site no. 7A (Figure 20).

Thus, the flux of groundwater to the Raisin River can be variable on short time intervals, especially with respect to storm events in the watershed.

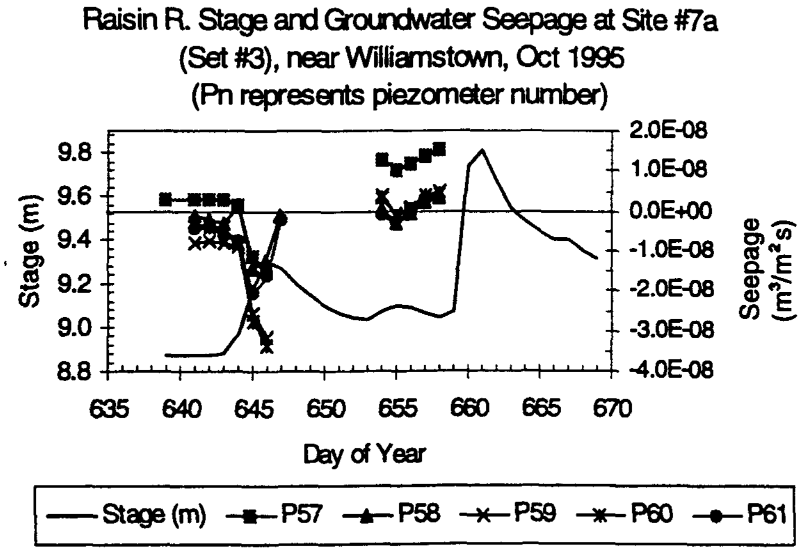

Figure 19. Decline in Seepage Estimates after Storm Event on October 5-6, 1995 (Days 643-644)

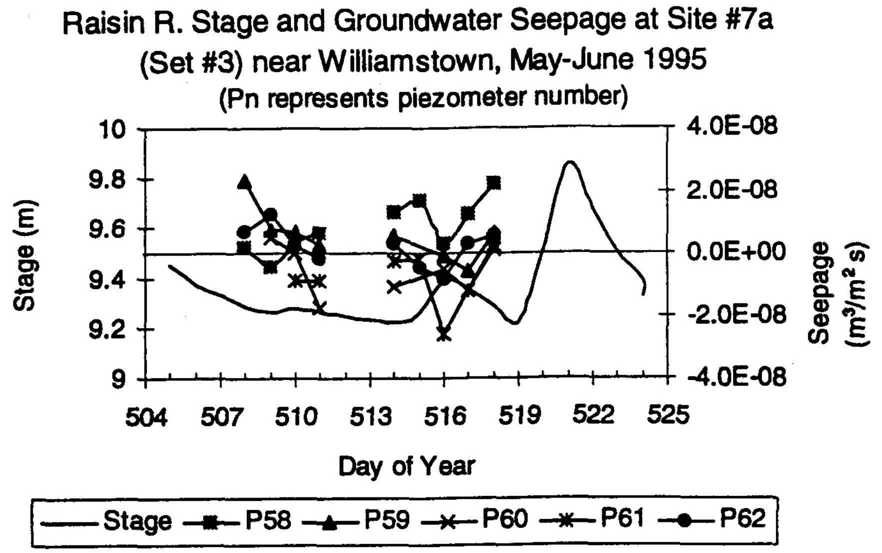

Figure 20. Decline in Groundwater Seepage Estimates after Storm Event on May 28-20 (Days 513 and 514)

6.4 Comparison of Discharge Volume vs Storm Volume

Stream discharge after a storm, Q_t (m^3/s), is believed to be comprised of "event", Q_e, water (rainfall and direct runoff and an increased groundwater flow component) and "pre-event" water (groundwater) Q_P. The steady-state mass balance equation for stream discharge as used by Sklash and Farvolden (1979) is:

$$Q_e = Q_t - Q_p$$

Q_t and Q_P are obtained directly from the hydrograph and Q_e is obtained by difference. The event component of discharge of the Raisin River, Q_e, can then be integrated with respect to time, to give a volume of river water which can be attributed to the storm event. To get an idea of the extent of rainfall infiltration or groundwater recharge, the volume of water which manifests itself in the Raisin River after a storm event was compared to the volume of rainfall estimated to have fallen on the watershed from the actual storm (calculated from area and "height" of rainfall). The storm event chosen for this comparison occurred on September 13 and 14, 1994. A total of 11.4 mm fell on these two days.

The volume of river water attributed to the storm event (V_e, Event Discharge Volume) was found by first, plotting $Q_e\ (t)$ vs time, t, for the period of the peak discharge. (Q_p is assumed to be constant over this period.) Secondly, the area underneath the curve in Figure 21 was calculated with the following equation:

$$V_e = \text{Event Discharged Volume (m}^3\text{)} = \int Q_e\, dt = \sum_n (Q_e)_n\, (\Delta t)$$

The event discharged volume was found to be 6.38×10^3 m^3. The detailed calculation is shown in Appendix 5.

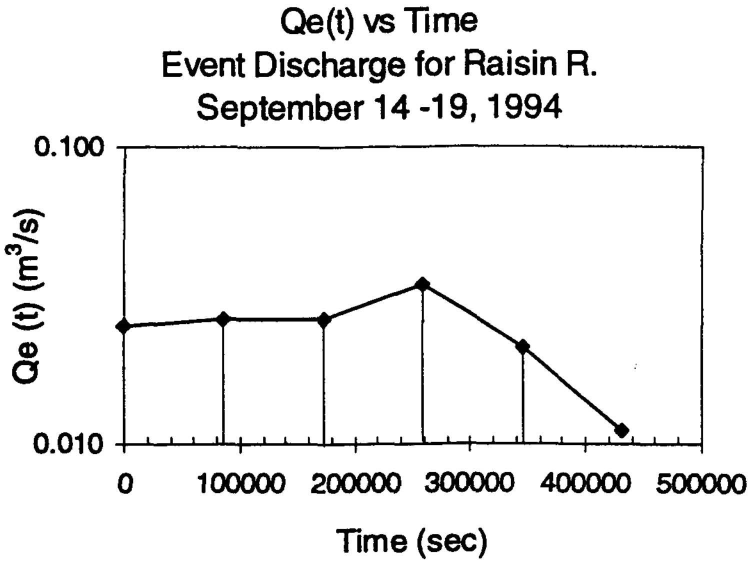

Figure 21. Area Under Curve used to find Event Discharge Volume

An estimate of the volume of the water that may have fallen on the watershed was calculated by multiplying the area of the Raisin River watershed (546 km^2) by the height of precipitation received during the storm event (11.4 mm):

$$\textit{Storm Volume}\ (m^3) = \left[546\ km^2 \times \left(1000\frac{m}{km}\right)^2\right] \times \left[\frac{11.4\,mm}{1000\dfrac{mm}{m}}\right] = 6.22 \times 10^6\ m^3$$

The difference between storm volume and event discharge volume is 6.20 x 10^6 m^3. This indicates that most of the precipitation from a storm event recharges the phreatic aquifers or contributes to evapotranspiration rather than contributing to streamflow. Assuming that evapotranspiration is negligible, and that the porosity of surficial aquifers is approximately 30%, then a rainfall event of approximately 10 mm would produce a 30 mm rise in the water table. A rise in the water table level can lead to an increase in seepage flux into the river since hydraulic gradients will be greater along the river.

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Chapter 7.0 Stable Isotopes

7.1 Introduction

An isotope of an element is one that has the same number of protons but different number of neutrons. A stable isotope is one which does not exhibit radioactive decay. Stable isotopes of oxygen and hydrogen, specifically oxygen-18 or O^{18} and deuterium or D, are used for finger printing water and to understand the processes water may have been exposed to (Drever, 1982). Oxygen and hydrogen isotopes in water are fairly conservative and thus maintain their original compositional signature (as meteoric water) until mixing with other waters or until evaporation occurs (Kendall et al., 1995). Oxygen-18 and deuterium concentrations in water are customarily reported as enriched or depleted relative to a standard of known composition, usually Standard Mean Ocean Water (SMOW) as determined by Craig (1961). The concentrations are expressed in delta (δ) notation with units of parts per thousand (‰ or per mil) and is calculated as:

$$\delta = \left(\frac{R_{sample}}{R_{standard}} - 1 \right) * 1000$$

where R = the ratio of heavy to light isotopes (Kendall et al., 1995). The value of δ will be positive if the sample is enriched relative to the standard and negative if depleted. Delta oxygen-18 and deuterium values are usually plotted against one another and values of precipitation from around the world plot on a straight line, called the Global Meteoric Water Line (GMWL) with the following equation, originally developed by Craig (1961) and more recently by Gat (1980) :

$$\delta D = 8.17\ (\pm 0.08)\delta^{18}\mathrm{O} + 10.56\ (\pm 0.64)$$

Stable isotope values can also be compared to a Local Meteoric Water Lines (LMWL) if precipitation data has been collected for a certain area. The International Atomic Energy Agency (IAEA) has collected such data for Ottawa, Ontario. Fritz et al., (1987) report that the mean annual LMWL for Ottawa is:

$$\delta D = 7.63\delta^{18}\mathrm{O} + 6.53$$

This LMWL will be used in this study because of the close proximity of Ottawa to the study site. Isotopes in precipitation can be quite variable throughout a year since they vary with temperature, but they tend to have an overall seasonal signature which remains fairly constant from one year to the next (Kendall et al., 1995). Winter precipitation (snow) generally has more depleted oxygen-18 values than summer precipitation (Sklash, et al., 1976). The isotopic signature of groundwater tends to reflect an annual average of precipitation values if no mixing with "older" waters occurs (Fritz, 1981). In river systems where surface runoff of precipitation dominates, the isotopic signature of the surface water will reflect the seasonality of the precipitation. However, if the source of water is mainly groundwater, there will not be as much variation in the isotopic signature of the surface water (Fritz, 1981). The isotopic results of groundwater, surface water and precipitation can be plotted alongside the LMWL to determine the source of the water, i.e. if the results plot close to the line, then one can conclude that the water is meteoric (Drever, 1982).

7.2 Isotopic Composition of Waters in the Raisin River Watershed

The analytical procedures for stable isotope analysis of water samples are outlined in Appendix 6. Isotope analyses were performed on rainfall, surface water, tile drainage waters, and groundwater samples. The variability of the isotopic concentrations over time and space were examined with ANOVAs.

7.2.1 Rainfall

Isotopic analyses of rainwater samples (collected in the basin) plot closely to the LMWL, as expected but have the highest coefficient of variability (C.V.) for delta oxygen-18 values (-0.35%) and deuterium values (-0.45%) (Figure 22). Although only a small number of samples were collected ($n = 19$) between July and November, 1994, rain samples are more enriched, in both oxygen-18 and deuterium, than groundwater, surface water and tile drainage water (Table 12). A regression analysis indicates there is no significant relationship with either isotope over time ($p = 0.49$ for deuterium and $p = 0.34$ for oxygen-18). Data and statistical results are given in Appendix 7.

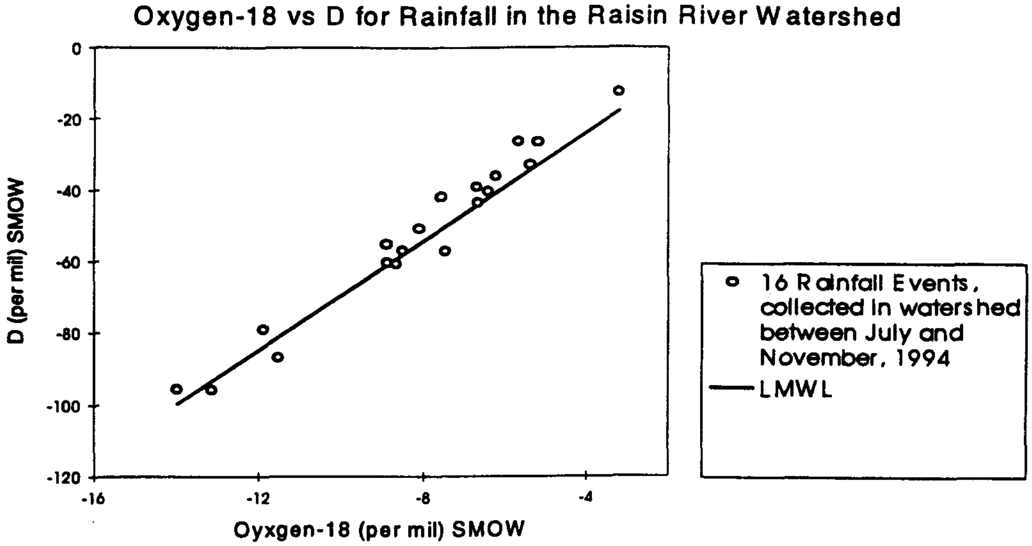


Figure 22. Delta Oxygen-18 and Deuterium Graph for Rainfall

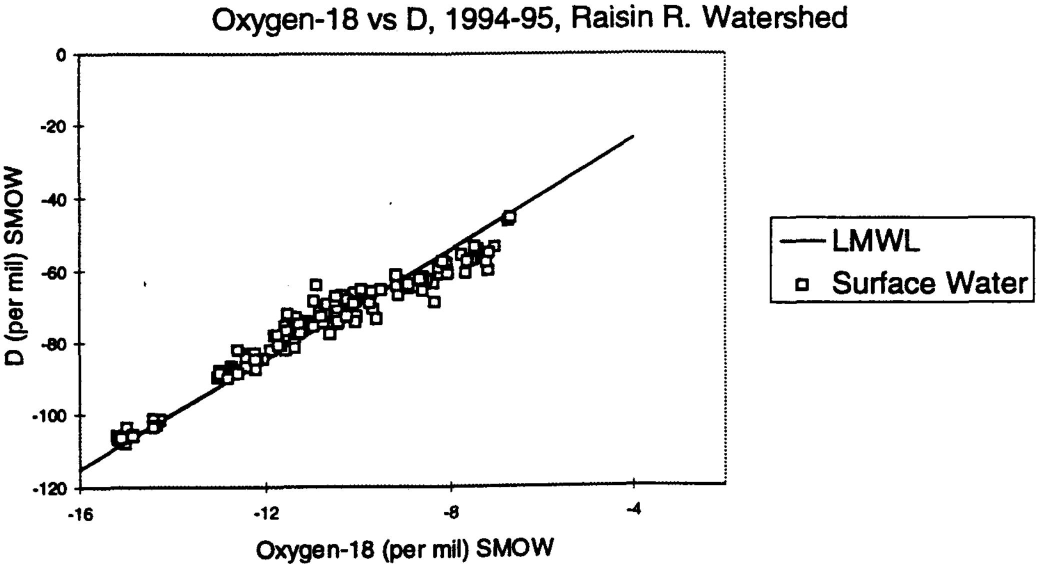


Figure 23. Delta Oxygen-18 and Deuterium Graph for Surface Water

7.2.2 Surface Water

Of all the waters collected, the stable isotopes in Raisin River water samples were the most depleted in both oxygen-18 and deuterium (Table 11). The stable isotopes for surface water plot closely to the LMWL, which suggests that meteoric water comprises a large component of the river (Figure 23).

Table 11. Results from Mass Spectrometric Analysis - Delta Oxygen-18 and Deuterium

	$\delta^{18}O$			δD			
Water Type	**Max**	**Min**	**C.V.**	**Max**	**Min**	**C.V.**	**n**
Groundwater [a]	-9.1	-11.8	-0.05	-60.2	-80.8	-0.05	97
Surface [b]	-7.0	-15.2	-0.17	-53.4	-108.0	-0.17	159
Rain [c]	-3.2	-14.0	-0.35	-12.5	-95.8	-0.45	19
Tile Drain [d]	-9.0	-12.3	-0.07	-58.3	-84.4	-0.09	19

Table Notes:

a. Water collected from piezometers during June to November, 1994 and May 1995.

b. Collected during April 1994 to May 1995. Many samples provided by Anne Watelet, graduate student, Dept. Of Geography, University of Ottawa.

c. Samples collected during April to December, 1994 and April, May 1995.

d. Samples collected during July and November 1994.

Compared to groundwater collected over the same time period of June to November 1994, surface water samples have a larger range of values. Surface water samples have the second highest C.V. (0.17%) for both delta oxygen-18 and deuterium, and groundwater samples have the lowest C.V. for both with 0.05%. This indicates that stable isotopes of surface water have more variability than groundwater, which is a reflection of the seasonality of precipitation. When the isotopes in surface water are plotted against time, there appears to be a seasonal trend, i.e. samples are more depleted around the time of snow melt. This can be seen around Day 100 (April 10, 1994), and Day 420 (Feb. 24, 1995) on Figures 24 and 25. Analyses of variance on the isotope data revealed that there was no significant differences between sites for both oxygen-18 ($p = 0.21$) and D ($p = 0.48$) and no effect due to the time of year for both oxygen-18 ($p = 0.21$) and D ($p = 0.16$). Data and statistical results are shown in Appendix 7.

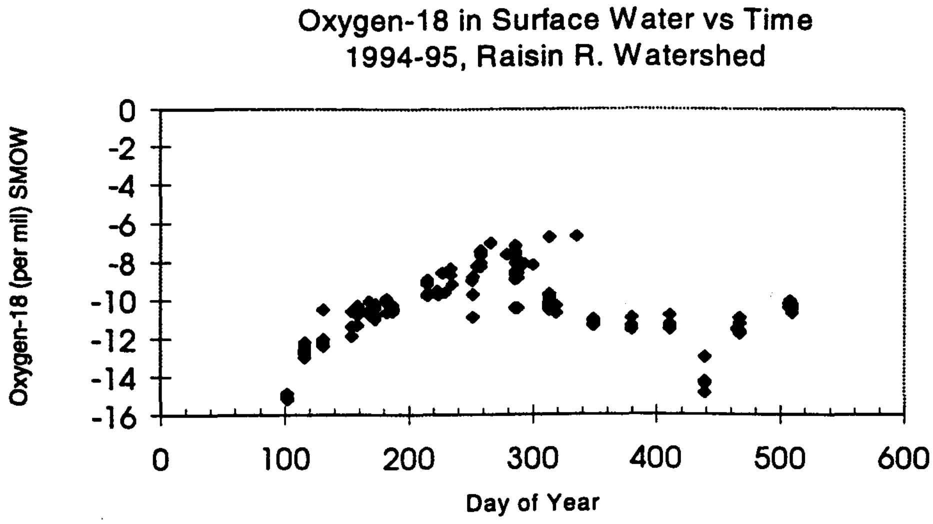


Figure 24. Delta Oxygen-18 vs Time for Surface Water in the Raisin River Watershed (8 sampling sites)

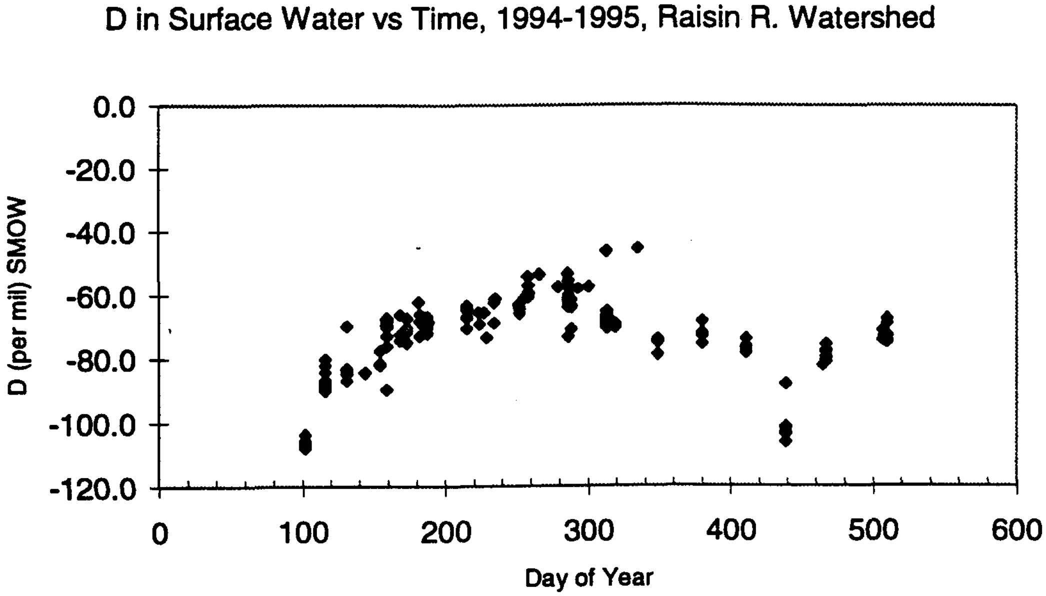


Figure 25. Delta Deuterium vs Time for Surface Water in the Raisin River Watershed (8 sites)

7.2.3 Groundwater

Groundwater isotope values also plot close to the LMWL, which indicates that the water is meteoric in origin and that this water is from a phreatic aquifer (Figure 26). As mentioned earlier, one would expect that the isotopic values of groundwater would show a subdued seasonal trend, however an insufficient number of samples were collected to prove or disprove this hypothesis. High flow periods (during spring runoff) and winter freeze over of the river made it impossible to install piezometers in the sediment during these times. ANOVA results revealed that there was no significant differences in the isotopic composition of groundwater due to sampling time for oxygen-18 ($p = 0.30$) or for D ($p = 0.36$). The ANOVA indicated that there was a significant difference in the isotopic content from site to site ($p = 4.5 \times 10^{-5}$ for deuterium and 3.9×10^{-3} for oxygen). This might be due to the variability of groundwater residence time in the watershed or quality of drainage. If drainage is poor, there may be more evaporation in some areas than others. ANOVA results are given in Appendix 7

In order to compare the stable isotope concentration in groundwater (water samples from piezometers) with that in water samples collected from the river on the same day, an ANOVA was performed on a data set of $n = 92$. The results showed that for both isotopes the piezometer waters were significantly different from the river waters ($p = 8.4 \times 10^{-12}$ for ^{18}O and $p = 1.7 \times 10^{-12}$ for D). Data and statistical analyses are shown in Appendix 7 (Section 6).

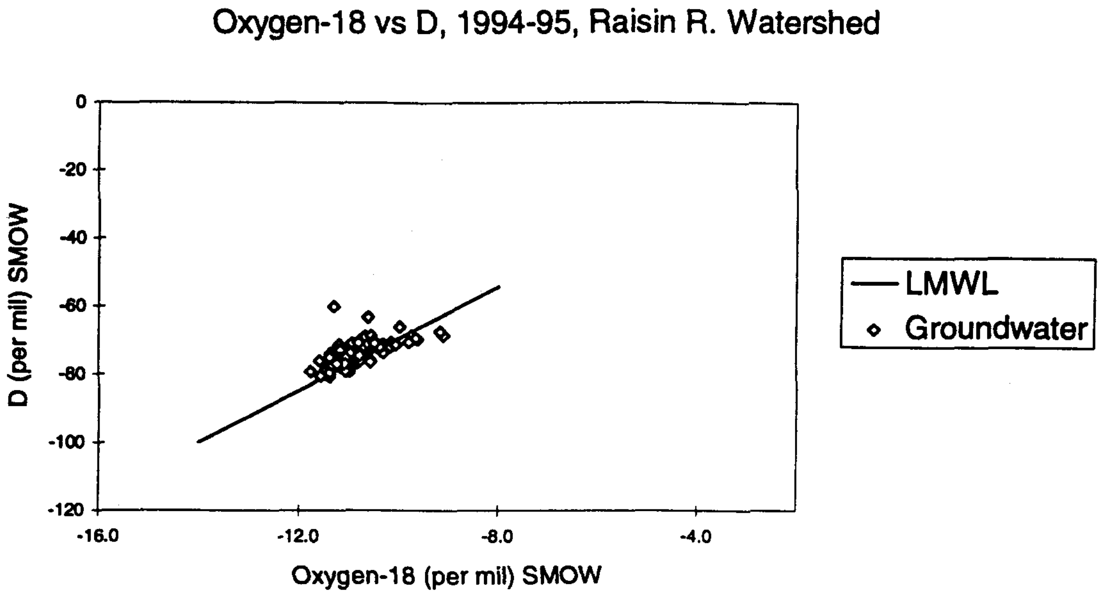


Figure 26. Delta Oxygen-18 and Deuterium Graph for Groundwater (samples from piezometers)

7.2.4 Tile Drainage

A small number of water samples (n = 19) were collected from outlets of tile drains at three sites throughout the watershed, sites no. 4, 5 and 13 over the period of April to December, 1994 and again in April and May, 1995. The C.V. is the second lowest of all the water types (Table 11). One might expect more variability in the tile drainage waters since the isotopic content of rainfall events can be quite variable (Drever, 1982, Kendall, et al., 1995). However, water collected from discharging tile drains may be a mixture of recent rainfall and water that has resided in the soil for some time. The mixing of the two water types may then result in less variability. ANOVAs revealed no significant effect of time on delta oxygen-18 values (p=0.416) or on deuterium (p = 0.530). The oxygen-18 content in tile drainage waters appears to remain fairly constant over time (Figure 27). However, a significant difference in oxygen-18 values between sites was found ($p = 10^{-6}$). This might indicate mixing of precipitation and waters that have resided in the soil for some time. In fact, all three sites from which tile drainage samples were collected are classified as having "poor" drainage. Delta oxygen-18 and deuterium values for tile drainage samples plot along side the LMWL as would be expected since the water collected is precipitation which has infiltrated and drained (or displaced soil water) (Figure 28). Data and statistical results are shown in Appendix 7.

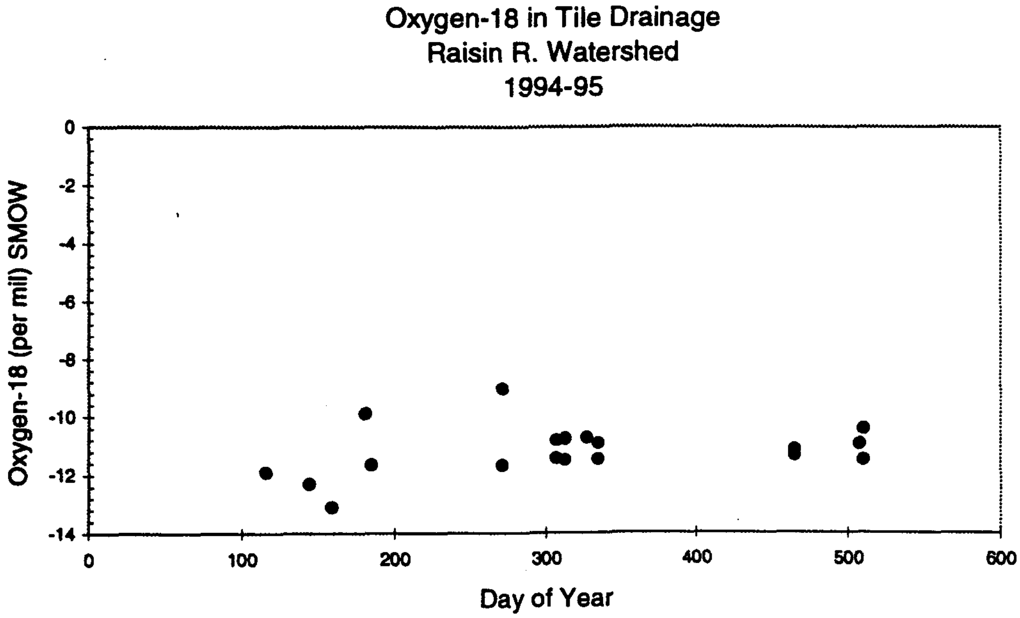


Figure 27. Delta Oxygen-18 vs Time in Tile Drainage Waters

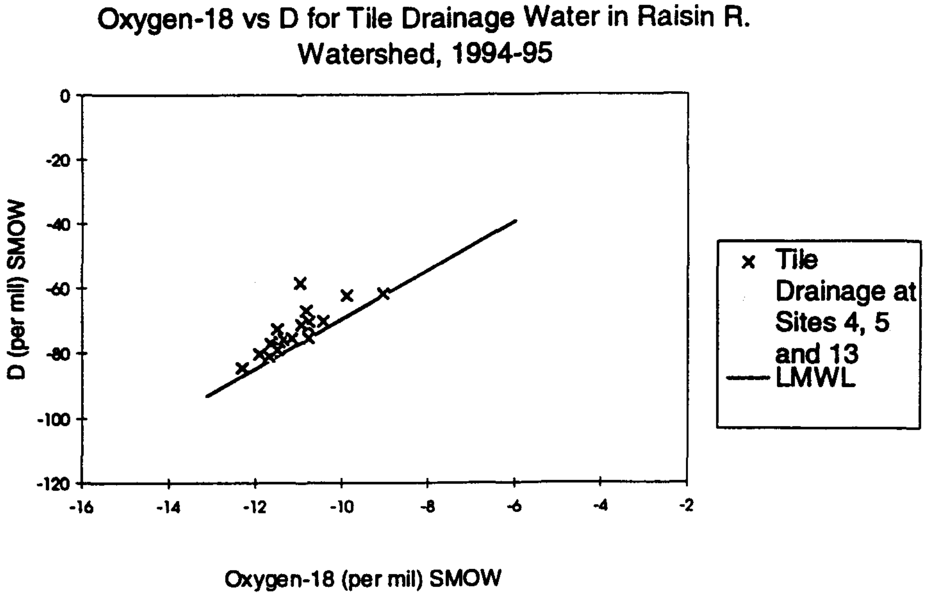


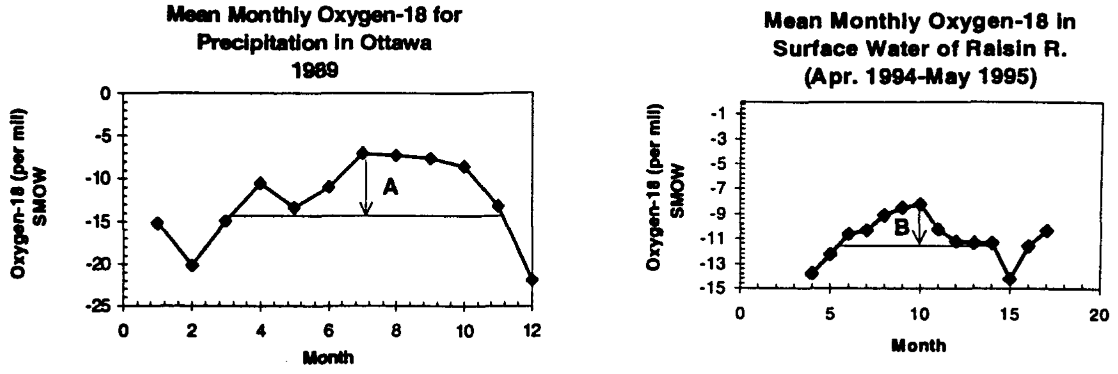
Figure 28. Delta Oxygen-18 and Deuterium Graph for Tile Drainage Waters

7.3 Mean Residence Time of Meteoric Water in Watershed

The mean monthly oxygen-18 content of precipitation (collected in Ottawa during the period of 1989 to 1994, for IAEA) was used to approximate the *mean residence time* of meteoric water in the Raisin River watershed. The IAEA database is far more extensive, and provides a better estimation of the mean isotopic composition of rainfall than the data collected in the watershed over the period of study. The assumption was made that the stable isotopic content of precipitation in Ottawa and Cornwall would not be significantly different. The oxygen-18 content of precipitation from Ottawa was compared with the oxygen-18 content of surface water collected from the Raisin River. Surface water data consisted of monthly, mean oxygen-18 values (calculated from seven sampling sites throughout the Raisin River watershed), between April 1994 and May 1995 (inclusive).

Pearce, et al. (1986) and Burgman, et al. (1987) describe an exponential model used to calculate a *mean residence time* of meteoric water in a watershed. The model has been applied to catchments with glacial tills, weathered conglomerate, and clay soils, both forested and cultivated. The *mean residence time* is basically the duration of time from when rainfall recharges a shallow aquifer to the time it discharges into a river. The stable isotopic content of precipitation is largely affected by temperature and thus, when plotted against time, the result can be similar to a simple harmonic curve (sinusoidal) which reflects the different seasons (Clark and Fritz, unpublished). The ratio of the amplitudes of surface water oxygen-18 plot to that of the precipitation is termed the *amplitude damping* and is used in calculating the *mean residence time.* The amplitudes are defined here as half the distance between the crest and trough of curves on a oxygen-18 content vs. time graph. *Mean residence time* , *T*, in years can be calculated with the following equation from Pearce et al. (1986):

$$T = w^{-1} \left[\left(A/B \right)^2 - 1 \right]^{1/2}$$



Mean Monthly Oxygen-18 for Precipitation in Ottawa 1989

Mean Monthly Oxygen-18 in Surface Water of Raisin R. (Apr. 1994-May 1995)

Figure 29. and Figure 30. Amplitudes of Delta Oxygen-18 Curves for Precipitation (A) and Surface Water (B)

where A/B = amplitude damping, A is the amplitude of oxygen-18 precipitation values and B is the amplitude of oxygen-18 in river values and *w* = period of 2π per year (Figures 29 and 30). A sample calculation is shown in Appendix 8. The *mean residence time* of meteoric water in the Raisin River watershed (~546 km^2) was estimated to be 4.06 ± 0.02 months (the error calculation is given in Appendix 8). This is similar to results found by Burgman et al., (1987) where the residence time of meteoric water in a catchment of 800 km^2 was found to be 4 months.

7.4 Isotopic Separation of a Storm Hydrograph

Stable isotopes of oxygen and deuterium are commonly used to study the components of streamflow during storm runoff (Freeze and Cherry, 1979). A study by Fritz et al. (1976) noted that oxygen-18 in shallow groundwater and baseflow is fairly uniform but considerably variable in rainfall. As a result, the isotopic content of rainfall can be used as a tracer for water that falls on a basin during a storm event. Thus, a storm hydrograph can be separated into pre-event water (groundwater, vadose water, and surface storage) and event water (precipitation or direct runoff). Freeze (1972,1974) theorized that precipitation activates the release of groundwater, and as a result, groundwater can constitute a large portion of peak discharge after a storm event. This theory is supported by the work of Sklash and Farvolden (1979) and Gilham (1984). A previous study by Sklash et al. (1976) found that storm discharge was composed of more than 50% groundwater in four watersheds using stable isotopes for storm hydrograph separation. In another study, Sklash and Farvolden (1979) found that groundwater comprised up to 65% of peak discharge after a storm event. Separating a storm hydrograph into its various components can be done using the steady state mass balance equations describing water fluxes and tracer isotopes (such as oxygen-18) in the stream combined to give the following equation (Sklash, et al. 1976):

$$C_t Q_t = C_p Q_p + C_e Q_e$$

where:

Q = stream discharge (m^3s^{-1})

C = isotopic tracer concentration ($\delta^{18}O$, δ^2H - per mil SMOW)

t = total stream component

p = pre-event component

e = event component

since $Q_t = Q_e + Q_p$, we obtain:

$$Q_p = Q_t\left(\frac{C_t - C_e}{C_p - C_e}\right)$$

Sklash and Farvolden (1979) recommend that the following criteria be met when using isotopic compositions to separate storm events:

1. The isotopic content (^{18}O, ^{2}H) of the event component should be significantly different from that of the pre-event component.
2. The isotopic content of the precipitation event remains constant.
3. The groundwater and vadose water are isotopically equivalent or vadose water contributions to runoff are negligible due to hydrogeologic constraints.
4. Surface storage contributes minimally to the runoff event.

Event Water:

In the course of this study, a storm event took place on September 13 -14, 1994 which was 11.4 mm in magnitude. The isotopic concentrations of the rainfall collected on September 14 from Site no.1, (C_e), were the following: δD = -26.4‰ SMOW and $\delta^{18}O$ = - 5.68‰ SMOW. (For comparison, a rainfall sample was collected during a storm event on September 16, 1994, (6.4 mm in magnitude) which yielded isotopic results of δD = -26.6‰ SMOW and $\delta^{18}O$ = -5.20‰ SMOW.) The event component of discharge, Q_e, is unknown.

Pre-Event Water:

Two surface water samples were collected on September 12, 1994 from sites no. 1 and 4. (Note: there was no precipitation event within two days prior to sample collection and the magnitude of the last event, three days prior, was small (0.5 mm). The average isotopic concentration (C_p) for these two samples was: $\delta D = -65.1‰$ SMOW and $\delta^{18}O = -8.98‰$ SMOW. In accordance with the first criterion listed above, the difference between ^{18}O for event water and pre-event is 3.3‰, which indicates that the concentrations are significantly different. The pre-event component of discharge, Q_p, is unknown.

Post Event Water (at peak discharge):

Three surface water samples were collected on September 15, 1994 at Site no.5, Site no.6, and Site no.7a, when discharge $Q = 0.071\ m^3s^{-1}$ (Q_t). The day of peak discharge was actually two days later, on September 17, 1995, where $Q = 0.079\ m^3s^{-1}$, but a water sample was not collected that day. Since discharge values for September 15 are similar to September 17 (a small difference of 0.008 $m^3\,s^{-1}$), this data was used for the calculations. The mean of isotopic results for the three water samples (C_t), is the following: $\delta D = -58.1‰$ SMOW and $\delta^{18}O = -7.77‰$ SMOW.

Calculations produced an estimate that the pre-event component, Q_p, of total stream discharge resulting from the September 13 -14 storm was 0.045 (± 0.001) m^3s^{-1}. Therefore, the fraction of the total stream discharge that was composed of pre-storm water (groundwater) is 63%. A sample calculation is shown in Appendix 8. This is in accordance with previously mentioned studies which found the groundwater component to be 50% or greater.

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Chapter 8.0 Geochemistry of Water Samples

8.1 Introduction

The chemical analysis of water samples can aid in identifying the sources from which water is derived or if the water is subject to anthropogenic contamination. The major ions analysed in this study are Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, HCO_3^{-}, NO_3^{-}, and Fe^{2+}. The concentrations of the first seven are typically used to find a charge balance (in meq/L) for an indicator of the analytical accuracy (Freeze and Cherry, 1979). The concentration of various ions has been used to predict the direction of groundwater flow, such as the chemical sequence developed by Chebotarev (1955). Chebotarev (1955) theorized that water evolves chemically along a path from the point of recharge to the point of discharge. Near the point of groundwater recharge, the most notable component of a water sample is HCO_3^{-} (Freeze and Cherry, 1979). At the point of discharge, Cl^{-} and SO_4^{2-} become more prominent in groundwater. For an extensive look at the geochemistry of groundwater in the region between the Ottawa River and the St. Lawrence River, the author refers readers to Charron's study (1978).

Geochemical data plotted on a "Piper" diagram can be used to distinguish different water types or possible mixing of water types. Morgan and Winner (1962) and Back (1966) developed a method to classify water from such diagrams, based on hydrochemical facies (Freeze and Cherry, 1979). This method is used to classify natural waters as a certain "type" based on the dominant ions, eg. a bicarbonate or chloride type.

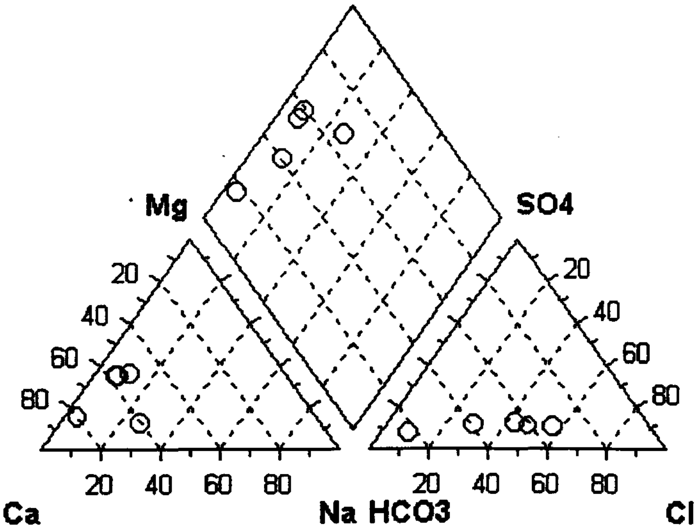
8.2 Method of Analysis

Water samples were analysed at the Geochemistry Laboratory of the Dept. of Geology, University of Ottawa. Ion Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES) was used to analyse the cations and a Dionex DX-100 Ion Chromatograph was used to analyse the anions (except for HCO_3^-). HCO_3^- concentrations were measured with a Hach Digital Titrator. 50 mL samples were titrated with sulphuric acid and Bromcresol Green indicator. Sample size collected for all other ions was 30 mL and those collected for cation analysis were filtered and acidified with nitric acid.

8.3 Results

A small number of groundwater (collected from piezometers), surface water, tile drainage water samples as well as a few rainfall samples were analysed for major ions (data given in Appendix 9). Summary statistics of the water analyses are also given in Appendix 9). The charge balances ranged from 0 to 18.9 % indicating that most of the major ions were identified. The mean charge balance was 7.2%, and 22 of the 50 samples have less than 6% which indicates some analytical error. A charge balance of less than 5% is usually considered "acceptable" for analytical results (Freeze and Cherry, 1979). Some experimental error might be attributed to the method of bicarbonate (HCO_3^-) measurement since there was considerable variability in the analysis of three HCO_3^- standard solutions. Five titrations, performed on each of the standard solutions, generated C.V.'s of 4.1, 8.7, and 7.0% for the measured concentration (data given in Appendix 9). Piper plots of surface water and groundwater indicate that most samples can be classified as a bicarbonate type according to Morgan and Winner's (1962) method (Figures 31 and 32).

Chebotarev's sequence indicates that the groundwater samples are from shallow aquifer (or groundwaters that have recently been recharged) since they have high concentrations of HCO_3^- (generally > 250 mg/L) and generally low percentages of Cl^- (Appendix 9). The Piper diagram for surface waters illustrates a discernible sulphate group for samples collected from the south branch of the Raisin River (site nos. 11, 12, and 13) (Figure 31). Several groundwater samples (site no. 12) are distinguishable as a chloride group (Figure 32). This might be an indication of discharge conditions or more likely some contamination from leaky septic systems. The Piper diagrams for tile drainage indicates considerable variability amongst the results (Figure 33). This is probably because the samples are from four different sites throughout the watershed. A small number of rainfall samples were plotted on a Piper diagram



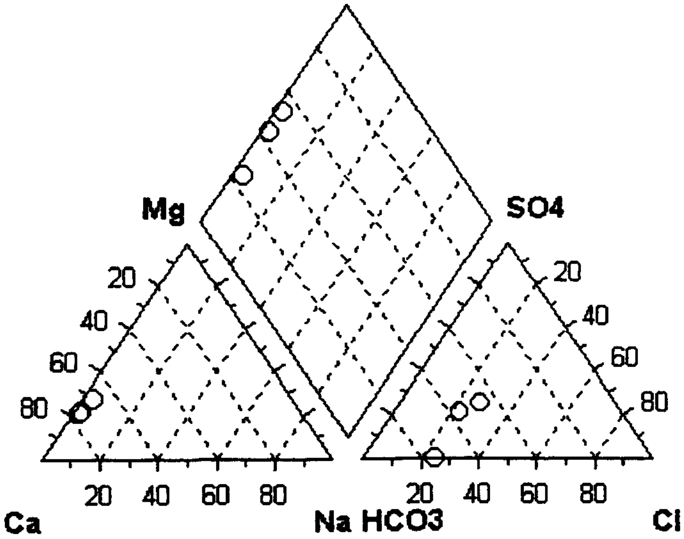


Figure 33. and Figure 34. Piper Plots of Geochemical Data from Tile Drainage (top) and Rain Water Samples (bottom)

and results are similar. However, so few samples reveals little information. A more detailed discussion of several ions is given in the following paragraphs.

8.2.1 Chloride

Most sites have Cl^- concentrations ranging between 5 and 60 mg/L. One exception is site no. 12 on the south branch of the Raisin River (mentioned above). Two groundwater samples from this site, collected about 2 weeks apart, in the Fall of 1994 were considerably higher in Cl^- (231, 253 mg/L). Potential sources for these high concentrations might be septic systems (or rather water softeners, since salt (NaCl) is a by-product of these systems); inorganic fertilizers; road salt; or a natural source of Cl^-, halite dissolution. These concentrations are close to the OMOEE (1993) aesthetic objective for chloride in potable water, which is 250 mg/L. Cl^- concentrations were typically higher in groundwater samples (mean = 44.09 mg/ L) than surface waters (mean = 23.92 mg/L). However, four tile drainage samples (two at site no. 5 on the main branch, and two at site no. 13, on the south branch), had Cl^- concentrations >100 mg/L. On November 9, 1994 samples from groundwater, surface water and tile drainage were collected at site no. 13. Tile drainage and surface water were very similar (72.9 and 79.5 mg/L Cl^-, respectively) and groundwater had a much lower concentration of 15.5 mg/L. This indicates that the source of Cl^- in the tile drains and surface water is probably inorganic fertilizers. This suggests that tile drains provide a short circuit path for rainfall to reach the Raisin River.

8.2.2 Nitrate

The maximum acceptable concentration (MAC) of nitrate in potable water is 10 mg/L (OMOEE, 1993). All samples were below this limit, with the exception of two tile drainage samples which were 27.8 and 67.2 mg/L at site no. 4. The tile drainage leads directly to the river so this may have an impact on aquatic life (nitrates can cause prolific weed growth) (CCREM, 1984). Surface water quality is also relevant for cattle consumption since some farmers allow their livestock to drink directly from the Raisin River. The Canadian Water Quality Guidelines recommends nitrogen (expressed as nitrate plus nitrite) concentration in water to not exceed 100 mg/L for livestock watering (CCREM,1984). This finding also supports the observation that tile drains provide a short circuit for rainfall to reach the Raisin River. The low nitrate concentrations in the river water may simply be an indication of rapid uptake of NO_3^- by plants, and perhaps rapid denitrification. Possible sources of nitrates include fertilizers and organic wastes (eg. manure).

8.2.3 Sulphate

The range of SO_4^{2-} in groundwater is from 0 to 56 mg/L. The range is much greater for surface water, as concentrations were found as high as 114.9 mg/L. The highest values of SO_4^{2-} are found in surface water, particularly along the south branch of the Raisin River, at sites no. 11, 12, and 13. This may be indicative of different bedrock geology, for eg. the dissolution of gypsum ($CaSO_4 \cdot 2H_2O$) or anhydrite ($CaSO_4$). The Canadian Council of Resource and Environment Ministers (CCREM),(1984) recommend that the limit for livestock watering is 1000 mg/L and the objective of the provincial government (1993) is 500 mg/L for potable water.

8.2.4 Iron

An aesthetic objective for potable water of the OMOEE is 0.30 mg/L (OMOEE, 1993). This happens to also be the CCREM guideline recommended for freshwater aquatic life (CCREM, 1984). All samples that exceed this limit are found in groundwater (total of 12 samples). The range of iron concentration in groundwater is 0.01 to 20.63 mg/L. All concentrations for surface water and tile drainage are below 0.15 mg/L. Since iron oxides are a very common element in soils, the iron may be leaching from the subsurface into the groundwater.

8.2.5 Sodium

The OMOEE aesthetic objective for sodium concentration in potable water is 200 mg/L (OMOEE, 1993). All samples are far below this level but the highest levels are in found in groundwater and tile drainage water. Site no.12 is notable with two groundwater samples at 92.8 and 102.2 mg/L. This would suggest water softeners from septic systems, as previously mentioned with chloride. Natural sources of sodium include halite dissolution.

8.3 Influence of Bedrock

The concentrations of calcium, magnesium, and sulphate in both groundwater and surface water samples seem to indicate the dissolution of carbonate (limestone, $CaCO_3$) or dolomite ($CaMg(CO_3)_2$) sedimentary rocks. The geochemical analyses also suggests the dissolution of other minerals such as halite (NaCl) and anhydrite (CaSO4).

8.4 Conclusion

Overall, the geochemical analyses of water samples watershed indicate that tile drains and groundwater can have higher levels of nitrate, sodium, and chloride ions than the adjacent river and, as a result, are potential sources of surface water contamination.

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Chapter 9.0 Summary and Conclusions

Seepage flux measurements with seepage meters showed that groundwater discharge and recharge can be found simultaneously along the Raisin River. Depending on the time of year, a given site could display discharge or recharge. Groundwater seepage flux rates ranged from -9.82 x 10^{-9} m^3 m^{-2} s^{-1}(groundwater recharge from the river) to 2.23 x 10^{-6} m^3 m^{-2} s^{-1} (groundwater discharge into the river). Some sites showed large variations of seepage flux with time. Thus, one can conclude that groundwater discharge or recharge conditions depend on the time of year. Due to the variability of groundwater seepage flux measurements with time and space, it can be concluded that a single measurement cannot give the full status of a groundwater vs surface water balance.

Groundwater seepage flux (estimated from the gradient and mean K values) did not vary significantly when comparing two time periods several days apart. Thus, seepage flux (or groundwater discharge) remains fairly constant over short periods of time but is variable over longer periods of time. This is evident when comparing seepage flux measurements made during 1994 and 1995, the range is considerably different. Statistical tests revealed that seepage flux estimated from the gradient and mean K, were not significantly different than direct seepage flux measurements. The precision of seepage flux estimates (expressed as a coefficient of variability) is on the order of 10 to 100 %.

There is a noticeable relationship between groundwater discharge and the stage of the Raisin River. This surface water/groundwater interaction was particularly noticeable after a significant rainfall event (October 5,6, 1995 - a storm associated with Hurricane Opal), which caused surface water levels to rise fairly quickly. The sites that had negative gradients prior to the storm became more negative. Some sites, which had positive gradients, became less positive, and some sites actually reversed gradients (i.e. went from positive to negative) after the storm. This indicates that the response of the stream to the storm was quicker than that of the groundwater.

Hydraulic gradient measurements, in conjunction with seepage flux measurements, were used to calculate hydraulic conductivity values for the sediments. Previous studies give hydraulic conductivity values in the surficial deposits ranging from 10^{-6} to 10^{-9} m s^{-1} in this region. Two different types of field measurements of K generated similar results for each site. Hydraulic conductivity values of Raisin River sediments generally fell within the reported range (most values are between 10^{-6} to 10^{-8} m s^{-1}). The only significant difference was the peat bog at the Raisin River headwaters which had a higher conductivity of 10^{-5} m s^{-1}, which would be expected for this spongy, organic material.

The period in which baseflow (groundwater) appears to sustain the flow of the Raisin River, was observed from mid-April to late-July in 1995 and from mid-April to mid-August in 1994. This is when the river was at low stage levels and surface runoff was low. Calculated baseflow contribution rates during these periods for 1994 and 1995 were similar for both years, 35% and 22% (respectively). The slopes of the baseflow recessions are quite steep, and according to Farvolden (1963), this is indicative of regions with low permeability and storativity. The low permeability of the glacial till in this watershed might account for such slopes.

A cross-correlation between river discharge and precipitation found the highest correlation at a negative lag of 2 days, when analysing daily data from January 1994 to October 1995. This indicates that it generally takes about two days for surface runoff and groundwater contributions to reach the river after a storm event. However, the response time to storm events in the Raisin River varies with the time of year which is illustrated in plots of precipitation and discharge. The magnitude of groundwater contributions after storm events and the response of the Raisin River during "wet periods" indicate that tile drainage systems may provide a short circuit for rainwater to reach the streams, thereby potentially carrying pesticides and fertilizers before they have a chance to degrade. A cross-correlation analysis of rainfall and river discharge should be conducted on "historical" data to see if there has been a significant change in the temporal response of the Raisin River to storm events. This might help to assess affects of tile drainage on water quality in the watershed.

Stable isotope analyses revealed that the groundwater that is contributing to streamflow in the Raisin River is part of a shallow system, i.e. recently recharged groundwater. Stable isotope values for surface water indicate a seasonality of recharge waters, i.e. water is less enriched in oxygen-18 and deuterium in winter and more enriched in summer. However, the isotopic concentrations of groundwater have less variability than surface water, which indicates that precipitation water circulates from the point of recharge (as precipitation) to the point of discharge (as groundwater) into the Raisin River thereby dampening seasonal variability. Isotopic values of surface water and precipitation from Ottawa were used to calculate a mean residence time of about 4 months for groundwater in the watershed. This is a rough estimate, based on only one year of surface water data and six years of precipitation data. Nevertheless, results were similar to Burgman et al., (1987) for an 800 km^2 catchment. The determination of mean residence time might be more reliable if samples of surface water for stable isotopes were collected for a longer period of time. Additionally, the storm hydrograph separation exercise should have been planned in advance so that water samples were collected on the relevant days.

The stable isotope data was also used to estimate the magnitude of the contribution of groundwater to streamflow after a storm event. The isotopic signatures of rainfall, and surface water before and after an event were compared for this analysis. It was estimated that the groundwater contributed approximately 63 % to post-storm streamflow. This is similar to other studies which found between 50 and 65 % (Sklash et al., 1976), and Sklash and Farvolden, 1979). Thus, groundwater quality hould be taken into consideration when assessing surface water quality.

The geochemistry of several surface water and groundwater samples collected during the same time period were analysed for comparison and for determination of the relative "age" of the water with respect to Chebotarev's chemical evolution sequence. Since most groundwater and surface water samples are have noticeably high concentrations of HCO_3^-, they can be considered fairly young waters, i.e. they have recently been recharged with meteoric waters. Water samples from sites on the south branch of the Raisin River indicate interaction with different bedrock or surficial deposits. Two samples showed high chloride concentrations perhaps due to septic system contamination. There are also several surface water samples with distinctly higher sulphate concentrations at locations along the south branch of the river. These results are interesting because the bedrock geology underlying the sites on the south branch is different from all other measurement sites. The Gull River Formation underlies sites no. 11 and 13 and the Bobcaygeon Formation underlies site no. 12. All other sites are underlain by the Lindsay and Verulam Formations. This may account for the different geochemical groups of the groundwater and surface water. The influence of limestone or dolomite bedrock on the geochemical makeup of both water types is shown by the predominant concentrations of calcium, magnesium and sulphate.

Appendix 1

This Appendix contains the methodology used to generate maps presented in Chapters 2 and 3, which were created with Geographic Information System (GIS) software: SPANS™, SPANS Explorer™, SPANS Map™, and Tydig™.

A1.1 Basemap

A basemap of Stormont and Glengarry Counties was created by digitizing the area from a 1:250,000 topographic map (EMR, 1980) with a software called Tydig™. Tydig™ creates vector files (.VEC/.VEH) which are imported into SPANS™ and transformed into a map with *Transform / Vectors to Polygon / Polygon to Map.*

A1.2 Elevation Map

An elevation contour map was created in SPANS™ with digital elevation data imported from a CD-ROM (National Environment Satellite Data and Information Service, 1987) using the path *Transform /Data Types / Points to Map /Contouring.*

A1.3 Water Well Data

Ontario Ministry of Environment and Energy (MOEE) water well data was used to generate several maps. The raw data contained 2060 and 2448 wells for Stormont and Glengarry Counties, respectively. The data set, originally in ASCII, System Data File (SDF) format, was first imported into Dbase IV™, manipulated in Excel™, and then imported into SPANS Map™. SPANS Map™ creates files with a .TBB extension which can be imported into SPANS™ using the path *Transform / Import / Points.*

A1.3.1 Water Well Completion

A water well completion map was generated in SPANS™ using well data that had been separated into two classes, bedrock and overburden. When the depth to a geologic formation was found to be equal to (or within 1.5 m of) the depth at which water was found during drilling, the formation at that depth was treated as a water bearing formation (i.e. an aquifer). This depth was also presumed to be the depth at which the water wells were completed. A data set of such wells (4468 for both Stormont and Glengarry counties) was transformed into a Voronoi map with a total of 15 different water bearing formation materials using *Transform / Points to Map / Voronoi.* A Voronoi map is a diagram made up of a network of Thiessen polygons. The size of the polygons are inversely related to point density (Bonham-Carter, G., 1994). *Model / Points / Append Class* was used to append the generated map classes from the Voronoi diagram onto the original data. *Model / Reclassification / Make Template* was used to make a reclassification template, which was edited with an OS/2 text editor, so that the 15 different classes could now be designated as either bedrock (class 1) or overburden (class 2). The final Voronoi map, which contains only these two classes, was generated using *Model / Reclassification / Build Map / Interactively / Reclassification Template.*

A1.3.2 Potentiometric Surface

A potentiometric surface of wells (a contour map of hydraulic head) was also created from the OMOEE water well data. The map was generated by subtracting the static water level from the elevation (above sea level) of each well (see Figure 1 below). This point data was then contoured in SPANS™ using the path *Transform /Data Types / Points to Map /Contouring.* The data set was organized into eight equal classifications because of the large number of values. The data set was also separated into overburden and bedrock wells by comparing with above data set. The final plot was a potentiometric surface of bedrock wells exclusively (total number of bedrock wells in Stormont and Glengarry: 3486).

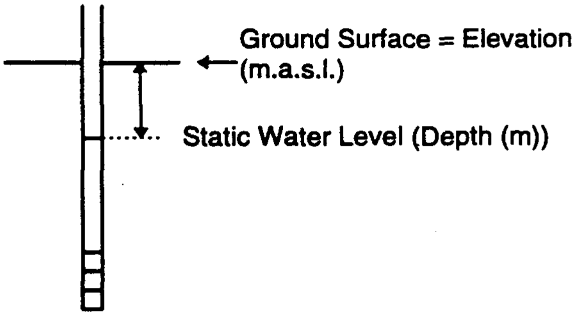

Figure 1. Definition of Surface Elevation and Static Water Level at a Water Well Location

A1.3.3 Depth of Overburden

A third map developed from water well records was a depth of overburden map for Stormont and Glengarry counties (4486 data points). Data points were contoured in

SPANS™ with a classification scheme of 5 unequal classes and annotated with SPANS Explorer™. The classes used to generate this map were defined by a *Normal Probability Plot* (plotted with statitistical software, SPSS™) (Figure 2). The classes were defined by the changes in slope throughout the distribution of data.

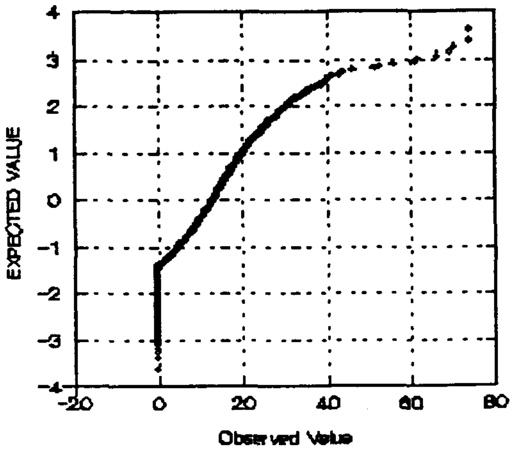

Figure 2. Normal Probability Plot for Overburden Depths (m)

A1.4 Bedrock geology and Surficial Geology Maps

These were created by digitizing original maps produced by Williams (1985) and Terasmae (1965) with Tydig and importing into SPANS™. The maps were annotated with SPANS Explorer™.

A1.5 References

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Appendix 2

This Appendix contains descriptions of seepage meters and mini-piezometers used in the collection of data for this thesis. A sample calculation is given of seepage flux, q. Raw data including groundwater seepage flux measurements, hydraulic gradient measurements, and estimates of groundwater seepage flux is included. Graphs showing seepage flux estimates over time for individual piezometers (all sites) are also included. Also contained in this Appendix is ANOVA results for the estimation of error in seepage flux measurements and the comparison of seepage flux measurements to estimates.

A2.1 Seepage Meter

Hydraulic Conductivities of river sediments were estimated using the method described by Lee and Cherry (1978), using seepage meters and mini-piezometers in the sediment of the Raisin River. Seepage meters were constructed with the end section of a 0.203 m^3 steel drum and installed in the sediments to depths of 8 - 13 cm. A rubber stopper, holding a polyethylene tube (10 to 15 cm in length) was inserted in a hole at the top of the drum. A plastic bag (~ 8 L), with the open edge sealed with a bag sealer (except for a 2 to 3 cm space), containing a known volume of water (between 800 and 1000 mL), is attached to the tube with a rubber band under the surface of the river.

The installation of seepage meters in the sediments was generally problem-free with the exception of a few sites. At several sites, stones below the surface of the sediment hindered or prevented installation. Because of the high clay content at many sites, the duration of seepage meter tests were generally over 24 hour periods. This limited the number of tests that could be done.

A2.2 Sample Calculation of Groundwater Seepage Flux, *q*

$$q = \frac{\Delta V}{\Delta t\, A} = \left[\frac{(200\ \text{mL})}{(1610\ \text{min})(0.255\ \text{m}^2)}\right]\left[\frac{1\ \text{min}}{60\,\text{s}}\right]\left[\frac{\text{m}^3}{10^6\text{mL}}\right] = 8.11 \times 10^{-9}\ \text{m}^3\text{m}^{-2}\text{s}^{-1}$$

where:

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

ΔV = change in volume, in plastic bag = 200 mL

A = Area of streambed covered by seepage meter = 0.255 m^2

Δt = time elapsed = 1610 min.

A2.3 Mini-piezometers

Mini-piezometers were installed in the river sediments beside the seepage meters up to depths of 100 cm below the river bed. The piezometers were constructed from polyethylene tubing having an outer diameter of 14.5 mm and inner diameter of 10 mm. The perforated piezometer tips were also made of polyethylene tubing and were 15 cm in length with a 10 mm outer diameter, an inner diameter of 6.5 mm. The tips were sealed at the end with silicone and screened with a 10 cm wide piece of 100 µm nylon material (Nytex©) that was wrapped about 5 times around the polyethylene tubing.

The piezometers were installed with a steel pipe of diameter slightly larger than the outer diameter of the piezometer. A bolt was put on the end of the pipe (to prevent the pipe from being filled with sediment) and the pipe was hammered into place. The piezometer was placed in the pipe and held in position while the pipe was removed.

Installation of mini-piezometers, along side seepage meters or standing alone, would occasionally be impeded by subsurface rocks but generally went well. Again, because of the high clay content, it was discovered that quick removal of the installation pipe was required, otherwise the clay would adhere to the pipe, causing great difficulties in removing the pipe.

A2.4 1994 and 1994 Groundwater Seepage Flux Measurements, Hydraulic Gradient Measurments, and Estimates of Groundwater Seepage Flux

Table 1. 1994 Groundwater Seepage Flux Measurements

Day	Site #	Piez #	Head (cm)	Gradient	Direct Seepage (m^3/m^2 s)	Total Time of Meas. (min)
147	1	1	8.50	0.085	2.06E-06	105
159	1	1	11.30	0.133	1.19E-06	111
160	1	1	8.00	0.094	NA	NA
227	1	1	1.50	0.014	8.93E-08	180
241	1	1	-0.80	-0.007	1.37E-09	1403
251	1	1	-4.00	-0.036	9.76E-09	1449
252	1	1	-1.00	-0.009	NA	NA
264	1	1	9.30	0.143	6.05E-08	308
265	1	1	7.20	0.111	NA	NA
271	1	1	6.25	0.096	2.79E-08	1496
147	1	2	13.00	0.091	5.22E-10	165
159	1	2	14.80	0.116	2.28E-07	113
160	1	2	16.58	0.130	NA	NA
174	1	2	12.00	0.116	NA	NA
227	1	2	1.20	0.010	-3.65E-08	176
241	1	2	-0.80	-0.007	1.19E-08	1402
251	1	2	-3.80	-0.032	8.89E-09	1447
252	1	2	-7.00	-0.058	NA	NA
264	1	2	14.30	0.152	1.04E-07	290
265	1	2	15.00	0.160	NA	NA
271	1	2	12.15	0.129	3.87E-09	1494
147	1	3	NA	NA	7.81E-07	135
159	1	3	14.70	0.103	5.70E-07	115
160	1	3	30.50	0.213	NA	NA
174	1	3	11.70	0.103	8.83E-09	182
241	1	3	0.90	0.008	5.09E-09	1390
251	1	3	-1.50	-0.013	2.22E-09	1447
252	1	3	-3.00	-0.026	NA	NA
264	1	3	3.40	0.068	2.96E-08	282
265	1	3	3.00	0.060	NA	NA
271	1	3	3.35	0.067	8.60E-10	1495
147	1	4	NA	NA	2.23E-06	135
159	1	4	NA	NA	7.35E-07	112
160	1	4	23.00	0.223	NA	NA
227	1	4	2.00	0.018	NA	NA
241	1	4	1.00	0.008	NA	NA
251	1	4	0.90	0.008	2.22E-08	1450
252	1	4	-1.00	-0.008	NA	NA
264	1	4	12.40	0.166	5.89E-08	273
265	1	4	12.50	0.168	NA	NA
271	1	4	9.35	0.126	4.31E-10	1492
147	1	5	NA	NA	1.30E-07	109
159	1	5	NA	NA	1.47E-06	114
160	1	5	17.00	0.168	NA	NA

Day	Site #	Piez #	Head (cm)	Gradient	Direct Seepage (m^3/m^2 s)	Total Time of Meas. (min)
241	1	5	3.00	0.027	5.09E-09	1390
251	1	5	4.50	0.040	1.69E-08	1447
252	1	5	0.50	0.004	NA	NA
264	1	5	14.60	0.187	1.47E-08	263
265	1	5	15.00	0.192	NA	NA
271	1	5	12.30	0.158	4.31E-10	1492
160	2	6	NA	NA	5.41E-08	285
174	2	6	5.50	0.043	NA	NA
178	2	6	1.60	0.013	NA	NA
181	2	6	2.00	0.016	NA	NA
185	2	6	3.20	0.025	NA	NA
235	2	6	54.20	0.427	NA	NA
236	2	6	54.50	0.429	1.77E-09	1453
159	2	7	NA	NA	5.37E-08	1077
160	2	7	NA	NA	5.79E-09	333
179	2	7	3.20	0.028	NA	NA
181	2	7	2.00	0.018	NA	NA
185	2	7	2.90	0.025	NA	NA
235	2	7	2.60	0.023	NA	NA
236	2	7	2.60	0.023	6.80E-10	1418
159	2	8	NA	NA	3.27E-08	1080
160	2	8	NA	NA	2.70E-08	333
178	2	8	1.00	0.009	NA	NA
181	2	8	1.10	0.010	NA	NA
185	2	8	1.70	0.015	NA	NA
235	2	8	0.50	0.004	NA	NA
236	2	8	0.50	0.004	2.90E-09	1443
160	2	9	NA	NA	9.71E-09	331
179	2	9	2.00	0.016	NA	NA
181	2	9	8.20	0.064	NA	NA
185	2	9	28.90	0.224	NA	NA
235	2	9	2.00	0.016	NA	NA
236	2	9	2.50	0.019	1.80E-09	1429
159	2	10	NA	NA	2.47E-07	1080
160	2	10	NA	NA	8.63E-07	328
172	2	10	-3.00	-0.024	NA	NA
179	2	10	NA	NA	3.16E-09	305
181	2	10	7.00	0.056	NA	NA
185	2	10	6.20	0.050	NA	NA
235	2	10	27.70	0.223	NA	NA
236	2	10	28.50	0.230	4.47E-10	1437
171	2.1	11	NA	NA	1.08E-06	167
172	2.1	11	0.60	0.020	NA	NA
188	2.1	11	1.00	0.033	NA	NA
235	2.1	11	0.50	0.017	NA	NA
236	2.1	11	0.50	0.017	3.73E-08	1172
171	2.1	12	NA	NA	1.18E-07	164
172	2.1	12	1.00	0.029	NA	NA
235	2.1	12	0.50	0.015	NA	NA
236	2.1	12	1.00	0.029	6.03E-09	1172
171	2.1	13	NA	NA	8.46E-08	152
188	2.1	13	1.40	0.050	NA	NA
235	2.1	13	1.20	0.043	NA	NA
236	2.1	13	1.00	0.036	9.08E-09	1169

Day	Site #	Piez #	Head (cm)	Gradient	Direct Seepage (m^3/m^2 s)	Total Time of Meas. (min)
171	2.1	14	NA	NA	1.66E-07	128
188	2.1	14	2.30	0.092	NA	NA
235	2.1	14	2.10	0.084	NA	NA
236	2.1	14	2.00	0.080	4.70E-09	1163
172	3	16	NA	NA	5.41E-08	202
174	3	16	1.30	0.016	NA	NA
223	3	16	0.45	0.005	7.35E-09	1312
224	3	16	0.40	0.005	NA	NA
172	3	17	NA	NA	5.33E-08	205
174	3	17	5.40	0.063	NA	NA
223	3	17	1.00	0.012	2.45E-09	1313
224	3	17	1.00	0.012	NA	NA
172	3	18	NA	NA	5.29E-08	211
179	3	18	NA	NA	7.62E-07	179
223	3	18	1.00	0.013	9.28E-09	1317
224	3	18	1.50	0.019	NA	NA
172	3	19	NA	NA	2.29E-07	216
181	3	19	NA	NA	6.60E-07	230
223	3	19	2.60	0.033	9.35E-09	1307
224	3	19	2.50	0.032	NA	NA
179	4	20	NA	NA	9.65E-08	120
188	4	20	137.50	1.447	NA	NA
223	4	20	41.00	0.432	1.13E-08	1486
224	4	20	42.50	0.447	NA	NA
179	4	21	NA	NA	2.16E-08	119
188	4	21	98.50	1.187	NA	NA
223	4	21	35.00	0.422	2.37E-09	1490
224	4	21	36.00	0.434	NA	NA
179	4	22	NA	NA	1.73E-07	115
185	4	22	32.50	0.378	NA	NA
188	4	22	32.30	0.376	NA	NA
223	4	22	20.00	0.233	1.55E-08	1491
224	4	22	19.40	0.226	NA	NA
179	4	23	NA	NA	9.19E-07	112
185	4	23	54.80	0.589	NA	NA
188	4	23	63.50	0.683	NA	NA
223	4	23	45.00	0.484	1.38E-08	1490
224	4	23	43.50	0.468	NA	NA
179	4	24	NA	NA	2.10E-07	110
185	4	24	4.00	0.049	NA	NA
188	4	24	6.80	0.084	NA	NA
223	4	24	0.60	0.007	3.88E-09	1490
224	4	24	0.50	0.006	NA	NA
216	5	25	-1.50	-0.015	NA	NA
217	5	25	-1.20	-0.012	NA	NA
186	5	26	NA	NA	-1.93E-08	167
187	5	26	NA	NA	4.83E-09	798
188	5	26	11.00	0.112	NA	NA
215	5	26	-3.00	-0.029	NA	NA
216	5	26	-2.50	-0.026	-3.10E-09	1653
217	5	26	-1.20	-0.013	NA	NA
186	5	27	NA	NA	-4.02E-09	160
188	5	27	9.50	0.113	NA	NA
215	5	27	-3.50	-0.035	NA	NA

Day	Site #	Piez #	Head (cm)	Gradient	Direct Seepage (m^3/m^2 s)	Total Time of Meas. (min)
187	5	28	8.00	0.099	7.81E-10	823
188	5	28	0.70	0.007	NA	NA
215	5	28	-0.50	-0.006	NA	NA
216	5	28	-0.20	-0.002	-3.90E-10	1649
217	5	28	-1.00	-0.010	NA	NA
186	5	29	NA	NA	1.03E-07	125
215	5	29	-0.70	-0.009	NA	NA
216	5	29	0.00	0.000	-8.21E-09	1644
217	5	29	-0.50	-0.005	NA	NA
188	6	40	NA	NA	2.15E-08	239
215	6	40	1.20	0.017	2.44E-09	1315
216	6	40	1.50	0.021	NA	NA
221	6	40	1.50	0.021	4.67E-09	2471
223	6	40	1.80	0.025	NA	NA
188	6	41	NA	NA	4.90E-08	236
215	6	41	1.60	0.020	5.39E-08	1301
216	6	41	2.00	0.025	NA	NA
188	6	42	NA	NA	7.90E-08	232
216	6	42	1.50	0.023	NA	NA
217	6	42	1.40	0.021	4.84E-08	1661
223	7	43	1.20	0.014	4.68E-09	1649
224	7	43	0.50	0.006	NA	NA
223	7	44	2.90	0.027	6.99E-09	1655
224	7	44	2.00	0.018	NA	NA
223	7	45	1.20	0.010	8.34E-09	1657
224	7	45	1.10	0.009	NA	NA
223	7	46	1.60	0.014	4.66E-09	1657
224	7	46	2.00	0.018	NA	NA
223	7	47	2.70	0.024	6.42E-09	1653
224	7	47	2.80	0.025	NA	NA
242	7.5	48	2.50	0.019	-1.01E-09	1592
243	7.5	48	2.60	0.020	NA	NA
266	7.5	48	-2.60	-0.027	-5.72E-09	1350
267	7.5	48	-4.10	-0.042	NA	NA
271	7.5	48	-2.90	-0.030	-9.82E-09	1570
272	7.5	48	-1.20	-0.012	NA	NA
242	7.5	49	1.50	0.012	-1.01E-09	1590
243	7.5	49	1.50	0.012	NA	NA
266	7.5	49	-1.10	-0.010	1.50E-08	1353
267	7.5	49	-2.40	-0.022	NA	NA
271	7.5	49	-0.70	-0.006	-1.64E-09	1570
272	7.5	49	-0.90	-0.008	NA	NA
242	7.5	50	0.50	0.004	4.45E-09	1588
243	7.5	50	0.40	0.003	NA	NA
266	7.5	50	-3.00	-0.028	-1.43E-09	1352
267	7.5	50	-2.30	-0.022	NA	NA
271	7.5	50	-2.50	-0.024	-6.13E-10	1573
272	7.5	50	-1.00	-0.009	NA	NA
242	7.5	51	0.50	0.004	-2.03E-09	1584
243	7.5	51	0.60	0.005	NA	NA
266	7.5	51	-1.50	-0.012	3.10E-09	1349
267	7.5	51	-2.00	-0.015	NA	NA
271	7.5	51	-0.90	-0.007	-8.18E-10	1573
272	7.5	51	-0.50	-0.004	NA	NA

Day	Site #	Piez #	Head (cm)	Gradient	Direct Seepage ($m^3/m^2 s$)	Total Time of Meas. (min)
242	7.5	52	1.00	0.007	-8.14E-10	1580
243	7.5	52	1.00	0.007	NA	NA
266	7.5	52	-8.50	-0.077	-8.14E-10	1349
267	7.5	52	-2.40	-0.022	NA	NA
271	7.5	52	-0.70	-0.006	-9.81E-09	1573
272	7.5	52	-0.50	-0.005	NA	NA
243	8	63	7.50	0.068	1.08E-09	1191
244	8	63	8.80	0.080	NA	NA
251	8	63	8.40	0.076	7.26E-10	1449
252	8	63	7.50	0.068	NA	NA
243	8	64	8.50	0.061	2.16E-08	1191
244	8	64	9.00	0.065	NA	NA
251	8	64	8.50	0.061	8.72E-09	1447
252	8	64	7.50	0.054	NA	NA
243	8	65	1.20	0.009	NA	NA
244	8	65	2.00	0.015	NA	NA
251	8	65	3.00	0.022	7.27E-10	1447
252	8	65	3.00	0.022	NA	NA
243	8	66	2.70	0.021	1.08E-09	1194
244	8	66	2.20	0.017	NA	NA
251	8	66	1.60	0.012	1.46E-09	1450
252	8	66	1.50	0.012	NA	NA
243	8	67	4.00	0.031	NA	NA
244	8	67	4.50	0.036	NA	NA
251	8	67	3.40	0.027	7.29E-13	1447
252	8	67	3.00	0.024	NA	NA
293	11	68	NA	NA	1.72E-09	1498
293	11	70	-1.70	-0.014	2.58E-09	1497
294	11	70	0.50	0.004	NA	NA
293	11	71	-1.50	-0.013	2.15E-09	1494
294	11	71	0.40	0.003	NA	NA
293	11	72	-1.30	-0.011	3.01E-09	1496
293	12	72	-1.00	-0.009	7.99E-09	1610
294	12	72	0.40	0.003	NA	NA
294	12	72	1.10	0.010	NA	NA
293	12	73	NA	NA	2.59E-09	1616
293	12	74	-0.20	-0.002	9.90E-09	1623
294	12	74	1.70	0.015	NA	NA
293	12	75	-3.00	-0.026	5.74E-09	1623
294	12	75	2.50	0.022	NA	NA
293	12	76	-0.70	-0.007	6.33E-09	1625
294	12	76	1.40	0.013	NA	NA

Table 2. 1995 Hydraulic Gradient Measurements and Seepage Flux Estimates

Day	Site #	Piez #	Head	Gradient (I)	Mean K* ($m\ s^{-1}$)	Estimated Seepage ($m^3\ m^{-2}\ s^{-1}$)	Direct Seepage ($m^3\ m^{-2}\ s^{-1}$)	Total Time of Meas. (min)
577	1	1	13.0	0.093	1.30E-05	1.21E-06	NA	NA
586	1	1	15.0	0.107		1.40E-06	NA	NA
591	1	1	13.0	0.093		1.21E-06	NA	NA
598	1	1	11.5	0.082		1.07E-06	NA	NA
605	1	1	12.4	0.089		1.15E-06	NA	NA
612	1	1	8.5	0.061		7.91E-07	NA	NA
619	1	1	8.5	0.061		7.91E-07	NA	NA
625	1	1	8.0	0.057		7.44E-07	NA	NA
632	1	1	8.5	0.061		7.91E-07	NA	NA
639	1	1	8.0	0.057		7.44E-07	NA	NA
641	1	1	8.2	0.059		7.63E-07	NA	NA
642	1	1	7.5	0.054		6.98E-07	NA	NA
643	1	1	8.1	0.058		7.53E-07	NA	NA
644	1	1	5.0	0.036		4.65E-07	NA	NA
645	1	1	10.5	0.075		9.77E-07	NA	NA
646	1	1	12.5	0.089		1.16E-06	NA	NA
647	1	1	7.0	0.050		6.51E-07	NA	NA
654	1	1	12.5	0.089		1.16E-06	NA	NA
655	1	1	13.0	0.093		1.21E-06	NA	NA
656	1	1	13.0	0.093		1.21E-06	NA	NA
657	1	1	13.5	0.096		1.26E-06	NA	NA
658	1	1	13.0	0.093		1.21E-06	NA	NA
531	2	10	0.5	0.004	6.40E-08	2.71E-10	NA	NA
577	2	10	18.0	0.153		9.76E-09	NA	NA
586	2	10	10.5	0.089		5.69E-09	NA	NA
591	2	10	6.5	0.055		3.52E-09	NA	NA
598	2	10	7.5	0.064		4.07E-09	NA	NA
605	2	10	7.0	0.059		3.80E-09	NA	NA
612	2	10	5.5	0.047		2.98E-09	NA	NA
619	2	10	5.2	0.044		2.82E-09	NA	NA
625	2	10	3.5	0.030		1.90E-09	NA	NA
632	2	10	4.5	0.038		2.44E-09	NA	NA
639	2	10	5.0	0.042		2.71E-09	NA	NA
641	2	10	5.2	0.044		2.82E-09	NA	NA
642	2	10	4.0	0.034		2.17E-09	NA	NA
643	2	10	4.0	0.034		2.17E-09	NA	NA
644	2	10	-8.0	-0.068		-4.34E-09	NA	NA
645	2	10	-6.5	-0.055		-3.52E-09	NA	NA
646	2	10	0.0	0.000		0.00E+00	NA	NA
647	2	10	5.5	0.047		2.98E-09	NA	NA
654	2	10	5.5	0.047		2.98E-09	NA	NA
655	2	10	6.6	0.056		3.58E-09	NA	NA
656	2	10	8.0	0.068		4.34E-09	NA	NA
657	2	10	8.5	0.072		4.61E-09	NA	NA
658	2	10	8.0	0.068		4.34E-09	NA	NA
577	2	10.5	13.5	0.091		5.84E-09	NA	NA
587	2	10.5	17.5	0.118		7.57E-09	NA	NA
591	2	10.5	13.5	0.091		5.84E-09	NA	NA
598	2	10.5	15.6	0.105		6.74E-09	NA	NA

Day	Site #	Piez #	Head	Gradient (I)	Mean K* $(m\ s^{-1})$	Estimated Seepage $(m^3\ m^{-2}\ s^{-1})$	Direct Seepage $(m^3\ m^{-2}\ s^{-1})$	Total Time of Meas. (min)
605	2	10.5	14.5	0.098		6.27E-09	NA	NA
612	2	10.5	13.0	0.088		5.62E-09	NA	NA
619	2	10.5	12.0	0.081		5.19E-09	NA	NA
625	2	10.5	10.0	0.068		4.32E-09	NA	NA
632	2	10.5	9.5	0.064		4.11E-09	NA	NA
639	2	10.5	8.5	0.057		3.67E-09	NA	NA
641	2	10.5	9.3	0.063		4.02E-09	NA	NA
642	2	10.5	9.0	0.061		3.89E-09	NA	NA
643	2	10.5	9.0	0.061		3.89E-09	NA	NA
644	2	10.5	-5.0	-0.034		-2.16E-09	NA	NA
645	2	10.5	-11.0	-0.074		-4.76E-09	NA	NA
646	2	10.5	-7.0	-0.047		-3.03E-09	NA	NA
647	2	10.5	1.4	0.009		6.05E-10	NA	NA
654	2	10.5	9.8	0.066		4.24E-09	NA	NA
655	2	10.5	10.5	0.071		4.54E-09	NA	NA
656	2	10.5	13.2	0.089		5.71E-09	NA	NA
657	2	10.5	13.8	0.093		5.97E-09	NA	NA
658	2	10.5	13.2	0.089		5.71E-09	NA	NA
528	3	15	3.1	0.044	7.78E-06	3.40E-07	NA	NA
577	3	15	2.0	0.028		2.19E-07	NA	NA
586	3	15	6.5	0.092		7.12E-07	NA	NA
591	3	15	1.8	0.025		1.97E-07	NA	NA
598	3	15	1.0	0.014		1.10E-07	NA	NA
605	3	15	0.5	0.007		5.48E-08	NA	NA
612	3	15	1.0	0.014		1.10E-07	NA	NA
619	3	15	0.5	0.007		5.48E-08	NA	NA
625	3	15	2.5	0.035		2.74E-07	NA	NA
632	3	15	1.0	0.014		1.10E-07	NA	NA
639	3	15	0.5	0.007		5.48E-08	NA	NA
641	3	15	0.5	0.007		5.48E-08	NA	NA
642	3	15	1.5	0.021		1.64E-07	NA	NA
643	3	15	4.5	0.063		4.93E-07	NA	NA
644	3	15	5.2	0.073		5.70E-07	NA	NA
645	3	15	5.0	0.070		5.48E-07	NA	NA
646	3	15	8.5	0.120		9.31E-07	NA	NA
647	3	15	12.5	0.176		1.37E-06	NA	NA
654	3	15	5.4	0.076		5.92E-07	NA	NA
655	3	15	5.5	0.077		6.03E-07	NA	NA
656	3	15	10.6	0.149		1.16E-06	NA	NA
657	3	15	10.5	0.148		1.15E-06	NA	NA
658	3	15	11.9	0.168		1.30E-06	NA	NA
510	5	25	0.8	0.008	3.19E-06	2.66E-08	1.23E-08	1563
514	5	25	-1.0	-0.010		-3.32E-08	6.72E-09	1530
515	5	25	-1.0	-0.010		-3.32E-08	1.36E-08	1367
516	5	25	1.0	0.010		3.32E-08	1.19E-08	1406
517	5	25	1.7	0.018		5.64E-08	NA	NA
518	5	25	0.5	0.005		1.66E-08	NA	NA
528	5	25	2.5	0.026		8.30E-08	NA	NA
577	5	25	-0.5	-0.005		-1.66E-08	NA	NA
586	5	25	0.7	0.007		2.32E-08	NA	NA
591	5	25	-1.5	-0.016		-4.98E-08	NA	NA
598	5	25	0.5	0.005		1.66E-08	NA	NA
605	5	25	0.0	0.000		0.00E+00	NA	NA
510	5	26	0.6	0.005		1.69E-08	4.52E-09	1565
514	5	26	-2.8	-0.026		-8.43E-08	3.35E-09	1536

Day	Site #	Piez #	Head	Gradient (i)	Mean K* (m s^{-1})	Estimated Seepage (m^3 m^{-2} s^{-1})	Direct Seepage (m^3 m^{-2} s^{-1})	Total Time of Meas. (min)
515	5	26	-4.5	-0.043		-1.38E-07	6.11E-09	1368
516	5	26	-1.0	-0.010		-3.06E-08	6.86E-09	1407
517	5	26	3.0	0.029		9.19E-08	7.72E-09	1333
518	5	26	3.0	0.029		9.19E-08	NA	NA
525	5	26	4.5	0.043		1.38E-07	NA	NA
577	5	26	0.5	0.005		1.53E-08	NA	NA
586	5	26	0.4	0.004		1.23E-08	NA	NA
591	5	26	1.6	0.015		4.90E-08	NA	NA
598	5	26	3.0	0.029		9.19E-08	NA	NA
510	5	27	-0.1	-0.001		-1.73E-09	6.38E-09	1563
514	5	27	-0.5	-0.005		-1.73E-08	3.76E-09	1539
515	5	27	-2.0	-0.022		-6.93E-08	7.52E-09	1368
516	5	27	1.5	0.016		5.20E-08	8.23E-09	1406
517	5	27	3.0	0.033		1.04E-07	1.07E-08	1328
518	5	27	2.0	0.022		6.93E-08	NA	NA
524	5	27	2.3	0.025		7.97E-08	NA	NA
525	5	27	2.9	0.032		1.00E-07	NA	NA
577	5	27	0.5	0.005		1.73E-08	NA	NA
586	5	27	1.0	0.011		3.46E-08	NA	NA
591	5	27	0.5	0.005		1.73E-08	NA	NA
598	5	27	1.0	0.011		3.46E-08	NA	NA
510	5	28	1.1	0.011		3.56E-08	2.06E-09	1560
514	5	28	-0.5	-0.005		-1.70E-08	-2.30E-09	1538
515	5	28	-2.0	-0.021		-6.78E-08	3.29E-09	1369
516	5	28	3.0	0.032		1.02E-07	2.29E-09	1407
517	5	28	3.0	0.032		1.02E-07	8.76E-09	1321
518	5	28	2.0	0.021		6.78E-08	NA	NA
577	5	28	2.5	0.027		8.48E-08	NA	NA
586	5	28	0.6	0.006		2.03E-08	NA	NA
591	5	28	0.6	0.006		2.03E-08	NA	NA
598	5	28	0.0	0.000		0.00E+00	NA	NA
605	5	28	-1.0	-0.011		-3.39E-08	NA	NA
612	5	28	-1.2	-0.013		-4.07E-08	NA	NA
619	5	28	0.0	0.000		0.00E+00	NA	NA
625	5	28	-0.5	-0.005		-1.70E-08	NA	NA
632	5	28	0.0	0.000		0.00E+00	NA	NA
639	5	28	-0.5	-0.005		-1.70E-08	NA	NA
641	5	28	-0.2	-0.002		-6.78E-09	NA	NA
642	5	28	0.0	0.000		0.00E+00	NA	NA
643	5	28	-0.5	-0.005		-1.70E-08	NA	NA
644	5	28	-2.5	-0.027		-8.48E-08	NA	NA
645	5	28	-1.5	-0.016		-5.09E-08	NA	NA
646	5	28	-0.5	-0.005		-1.70E-08	NA	NA
647	5	28	1.0	0.011		3.39E-08	NA	NA
654	5	28	0.5	0.005		1.70E-08	NA	NA
655	5	28	1.0	0.011		3.39E-08	NA	NA
656	5	28	0.5	0.005		1.70E-08	NA	NA
657	5	28	0.5	0.005		1.70E-08	NA	NA
658	5	28	0.5	0.005		1.70E-08	NA	NA
510	5	29	0.2	0.002		5.90E-09	2.89E-09	1558
514	5	29	0.5	0.005		1.48E-08	8.36E-10	1539
515	5	29	0.5	0.005		1.48E-08	2.81E-09	1371
516	5	29	0.5	0.005		1.48E-08	3.19E-09	1409
517	5	29	0.5	0.005		1.48E-08	5.86E-09	1317
518	5	29	0.5	0.005		1.48E-08	NA	NA

Day	Site #	Piez #	Head	Gradient (I)	Mean K* (m s^{-1})	Estimated Seepage (m^3 m^{-2} s^{-1})	Direct Seepage (m^3 m^{-2} s^{-1})	Total Time of Meas. (min)
525	5	29	0.2	0.002		5.90E-09	NA	NA
577	5	29	0.5	0.005		1.48E-08	NA	NA
586	5	29	0.5	0.005		1.48E-08	NA	NA
591	5	29	0.5	0.005		1.48E-08	NA	NA
598	5	29	2.0	0.019		5.90E-08	NA	NA
605	5	29	0.5	0.005		1.48E-08	NA	NA
612	5	29	0.5	0.005		1.48E-08	NA	NA
619	5	29	0.3	0.003		8.85E-09	NA	NA
625	5	29	0.5	0.005		1.48E-08	NA	NA
632	5	29	0.0	0.000		0.00E+00	NA	NA
639	5	29	-0.5	-0.005		-1.48E-08	NA	NA
641	5	29	0.5	0.005		1.48E-08	NA	NA
642	5	29	0.5	0.005		1.48E-08	NA	NA
643	5	29	0.5	0.005		1.48E-08	NA	NA
644	5	29	-1.0	-0.009		-2.95E-08	NA	NA
645	5	29	-1.8	-0.017		-5.31E-08	NA	NA
646	5	29	0.5	0.005		1.48E-08	NA	NA
647	5	29	0.5	0.005		1.48E-08	NA	NA
654	5	29	1.0	0.009		2.95E-08	NA	NA
655	5	29	0.5	0.005		1.48E-08	NA	NA
656	5	29	0.5	0.005		1.48E-08	NA	NA
657	5	29	0.5	0.005		1.48E-08	NA	NA
658	5	29	1.5	0.014		4.43E-08	NA	NA
511	5	30	1.0	0.009		2.92E-08	NA	NA
514	5	30	0.5	0.005		1.46E-08	NA	NA
515	5	30	1.0	0.009		2.92E-08	NA	NA
516	5	30	2.0	0.018		5.85E-08	NA	NA
517	5	30	1.5	0.014		4.39E-08	NA	NA
518	5	30	1.5	0.014		4.39E-08	NA	NA
577	5	30	0.5	0.005		1.46E-08	NA	NA
586	5	30	1.2	0.011		3.51E-08	NA	NA
591	5	30	0.6	0.006		1.75E-08	NA	NA
598	5	30	0.3	0.003		8.77E-09	NA	NA
605	5	30	0.5	0.005		1.46E-08	NA	NA
612	5	30	0.5	0.005		1.46E-08	NA	NA
619	5	30	0.5	0.005		1.46E-08	NA	NA
625	5	30	0.5	0.005		1.46E-08	NA	NA
632	5	30	0.5	0.005		1.46E-08	NA	NA
639	5	30	1.0	0.009		2.92E-08	NA	NA
641	5	30	0.5	0.005		1.46E-08	NA	NA
642	5	30	0.5	0.005		1.46E-08	NA	NA
643	5	30	0.5	0.005		1.46E-08	NA	NA
644	5	30	0.0	0.000		0.00E+00	NA	NA
645	5	30	0.5	0.005		1.46E-08	NA	NA
646	5	30	0.5	0.005		1.46E-08	NA	NA
647	5	30	0.5	0.005		1.46E-08	NA	NA
654	5	30	1.0	0.009		2.92E-08	NA	NA
655	5	30	0.5	0.005		1.46E-08	NA	NA
656	5	30	1.0	0.009		2.92E-08	NA	NA
657	5	30	1.0	0.009		2.92E-08	NA	NA
658	5	30	1.0	0.009		2.92E-08	NA	NA
511	5	31	1.0	0.009		2.95E-08	NA	NA
514	5	31	1.0	0.009		2.95E-08	NA	NA
515	5	31	-2.5	-0.023		-7.38E-08	NA	NA
516	5	31	1.0	0.009		2.95E-08	NA	NA

Day	Site #	Piez #	Head	Gradient (I)	Mean K* ($m\ s^{-1}$)	Estimated Seepage ($m^3\ m^{-2}\ s^{-1}$)	Direct Seepage ($m^3\ m^{-2}\ s^{-1}$)	Total Time of Meas. (min)
517	5	31	1.5	0.014		4.43E-08	NA	NA
518	5	31	1.5	0.014		4.43E-08	NA	NA
577	5	31	-0.5	-0.005		-1.48E-08	NA	NA
586	5	31	0.5	0.005		1.48E-08	NA	NA
591	5	31	-0.5	-0.005		-1.48E-08	NA	NA
598	5	31	-3.5	-0.032		-1.03E-07	NA	NA
605	5	31	-3.0	-0.028		-8.85E-08	NA	NA
612	5	31	-2.0	-0.019		-5.90E-08	NA	NA
619	5	31	-2.5	-0.023		-7.38E-08	NA	NA
625	5	31	-2.5	-0.023		-7.38E-08	NA	NA
632	5	31	-1.0	-0.009		-2.95E-08	NA	NA
639	5	31	-1.0	-0.009		-2.95E-08	NA	NA
641	5	31	-1.0	-0.009		-2.95E-08	NA	NA
642	5	31	-1.0	-0.009		-2.95E-08	NA	NA
643	5	31	-1.2	-0.011		-3.54E-08	NA	NA
644	5	31	-1.5	-0.014		-4.43E-08	NA	NA
645	5	31	-0.5	-0.005		-1.48E-08	NA	NA
646	5	31	0.5	0.005		1.48E-08	NA	NA
647	5	31	0.5	0.005		1.48E-08	NA	NA
654	5	31	-0.5	-0.005		-1.48E-08	NA	NA
655	5	31	0.5	0.005		1.48E-08	NA	NA
656	5	31	0.5	0.005		1.48E-08	NA	NA
657	5	31	0.5	0.005		1.48E-08	NA	NA
658	5	31	0.8	0.007		2.36E-08	NA	NA
510	5	32	-4.0	-0.031		-9.88E-08	NA	NA
511	5	32	-1.5	-0.012		-3.71E-08	NA	NA
514	5	32	1.5	0.012		3.71E-08	NA	NA
515	5	32	-3.0	-0.023		-7.41E-08	NA	NA
516	5	32	1.0	0.008		2.47E-08	NA	NA
517	5	32	4.0	0.031		9.88E-08	NA	NA
518	5	32	5.5	0.043		1.36E-07	NA	NA
525	5	32	9.7	0.075		2.40E-07	NA	NA
577	5	32	0.0	0.000		0.00E+00	NA	NA
586	5	32	-1.6	-0.012		-3.95E-08	NA	NA
591	5	32	5.5	0.043		1.36E-07	NA	NA
598	5	32	2.2	0.017		5.44E-08	NA	NA
605	5	32	-0.5	-0.004		-1.24E-08	NA	NA
612	5	32	-3.0	-0.023		-7.41E-08	NA	NA
619	5	32	-3.0	-0.023		-7.41E-08	NA	NA
625	5	32	-6.0	-0.047		-1.48E-07	NA	NA
639	5	32	-5.5	-0.043		-1.36E-07	NA	NA
641	5	32	-5.5	-0.043		-1.36E-07	NA	NA
642	5	32	-6.0	-0.047		-1.48E-07	NA	NA
643	5	32	-5.5	-0.043		-1.36E-07	NA	NA
644	5	32	-13.0	-0.101		-3.21E-07	NA	NA
645	5	32	-15.0	-0.116		-3.71E-07	NA	NA
646	5	32	-22.0	-0.171		-5.44E-07	NA	NA
654	5	32	-2.0	-0.016		-4.94E-08	NA	NA
655	5	32	-2.0	-0.016		-4.94E-08	NA	NA
656	5	32	-1.5	-0.012		-3.71E-08	NA	NA
657	5	32	-0.2	-0.002		-4.94E-09	NA	NA
658	5	32	0.5	0.004		1.24E-08	NA	NA
511	5	33	-7.5	-0.068		-2.17E-07	NA	NA
514	5	33	-2.5	-0.023		-7.24E-08	NA	NA
515	5	33	-6.6	-0.060		-1.91E-07	NA	NA

Day	Site #	Piez #	Head	Gradient (I)	Mean K* ($m\ s^{-1}$)	Estimated Seepage ($m^3\ m^{-2}\ s^{-1}$)	Direct Seepage ($m^3\ m^{-2}\ s^{-1}$)	Total Time of Meas. (min)
516	5	33	-2.0	-0.018		-5.79E-08	NA	NA
517	5	33	1.7	0.015		4.93E-08	NA	NA
518	5	33	3.3	0.030		9.56E-08	NA	NA
598	5	33	7.5	0.068		2.17E-07	NA	NA
605	5	33	4.0	0.036		1.16E-07	NA	NA
612	5	33	0.5	0.005		1.45E-08	NA	NA
619	5	33	-2.0	-0.018		-5.79E-08	NA	NA
625	5	33	-2.0	-0.018		-5.79E-08	NA	NA
632	5	33	-3.2	-0.029		-9.27E-08	NA	NA
639	5	33	-1.8	-0.016		-5.22E-08	NA	NA
641	5	33	-2.0	-0.018		-5.79E-08	NA	NA
642	5	33	-1.7	-0.015		-4.93E-08	NA	NA
643	5	33	-2.0	-0.018		-5.79E-08	NA	NA
644	5	33	-8.0	-0.073		-2.32E-07	NA	NA
645	5	33	-13.5	-0.123		-3.91E-07	NA	NA
646	5	33	-16.5	-0.150		-4.78E-07	NA	NA
647	5	33	-10.0	-0.091		-2.90E-07	NA	NA
654	5	33	-0.5	-0.005		-1.45E-08	NA	NA
655	5	33	-0.5	-0.005		-1.45E-08	NA	NA
656	5	33	-0.5	-0.005		-1.45E-08	NA	NA
657	5	33	1.0	0.009		2.90E-08	NA	NA
658	5	33	1.2	0.011		3.48E-08	NA	NA
510	5	34	-5.0	-0.053		-1.70E-07	NA	NA
511	5	34	-5.5	-0.059		-1.86E-07	NA	NA
514	5	34	-3.0	-0.032		-1.02E-07	NA	NA
515	5	34	-7.5	-0.080		-2.54E-07	NA	NA
516	5	34	-4.0	-0.043		-1.36E-07	NA	NA
517	5	34	0.5	0.005		1.70E-08	NA	NA
518	5	34	1.8	0.019		6.10E-08	NA	NA
577	5	34	0.5	0.005		1.70E-08	NA	NA
586	5	34	1.0	0.011		3.39E-08	NA	NA
591	5	34	4.0	0.043		1.36E-07	NA	NA
598	5	34	2.2	0.023		7.46E-08	NA	NA
605	5	34	1.1	0.012		3.73E-08	NA	NA
612	5	34	0.5	0.005		1.70E-08	NA	NA
619	5	34	0.0	0.000		0.00E+00	NA	NA
625	5	34	0.0	0.000		0.00E+00	NA	NA
632	5	34	-1.0	-0.011		-3.39E-08	NA	NA
639	5	34	0.5	0.005		1.70E-08	NA	NA
641	5	34	0.5	0.005		1.70E-08	NA	NA
642	5	34	0.5	0.005		1.70E-08	NA	NA
643	5	34	0.5	0.005		1.70E-08	NA	NA
644	5	34	-7.0	-0.074		-2.37E-07	NA	NA
645	5	34	-12.0	-0.128		-4.07E-07	NA	NA
646	5	34	-14.5	-0.154		-4.92E-07	NA	NA
647	5	34	-8.0	-0.085		-2.71E-07	NA	NA
654	5	34	-0.5	-0.005		-1.70E-08	NA	NA
655	5	34	-0.5	-0.005		-1.70E-08	NA	NA
656	5	34	0.5	0.005		1.70E-08	NA	NA
657	5	34	1.0	0.011		3.39E-08	NA	NA
658	5	34	1.5	0.016		5.09E-08	NA	NA
510	5	35	0.5	0.005		1.63E-08	NA	NA
511	5	35	-13.5	-0.138		-4.39E-07	NA	NA
514	5	35	-0.5	-0.005		-1.63E-08	NA	NA
515	5	35	-4.5	-0.046		-1.46E-07	NA	NA

Day	Site #	Piez #	Head	Gradient (I)	Mean K* $(m\ s^{-1})$	Estimated Seepage $(m^3\ m^{-2}\ s^{-1})$	Direct Seepage $(m^3\ m^{-2}\ s^{-1})$	Total Time of Meas. (min)
516	5	35	-1.0	-0.010		-3.25E-08	NA	NA
517	5	35	3.0	0.031		9.76E-08	NA	NA
518	5	35	2.5	0.026		8.13E-08	NA	NA
577	5	35	1.4	0.013		4.02E-08	NA	NA
586	5	35	2.7	0.028		8.78E-08	NA	NA
591	5	35	2.0	0.020		6.50E-08	NA	NA
598	5	35	0.2	0.002		6.50E-09	NA	NA
605	5	35	-0.3	-0.003		-9.76E-09	NA	NA
612	5	35	0.5	0.005		1.63E-08	NA	NA
619	5	35	0.0	0.000		0.00E+00	NA	NA
625	5	35	0.0	0.000		0.00E+00	NA	NA
639	5	35	0.0	0.000		0.00E+00	NA	NA
641	5	35	0.2	0.002		6.50E-09	NA	NA
642	5	35	0.0	0.000		0.00E+00	NA	NA
643	5	35	0.0	0.000		0.00E+00	NA	NA
644	5	35	-5.5	-0.056		-1.79E-07	NA	NA
645	5	35	-4.5	-0.046		-1.46E-07	NA	NA
646	5	35	-3.5	-0.036		-1.14E-07	NA	NA
647	5	35	0.0	0.000		0.00E+00	NA	NA
654	5	35	1.0	0.010		3.25E-08	NA	NA
655	5	35	1.0	0.010		3.25E-08	NA	NA
656	5	35	1.0	0.010		3.25E-08	NA	NA
657	5	35	1.5	0.015		4.88E-08	NA	NA
658	5	35	1.0	0.010		3.25E-08	NA	NA
510	5	36	0.5	0.005		1.44E-08	NA	NA
511	5	36	1.0	0.009		2.87E-08	NA	NA
514	5	36	-7.0	-0.063		-2.01E-07	NA	NA
515	5	36	-11.0	-0.099		-3.16E-07	NA	NA
516	5	36	-7.5	-0.068		-2.15E-07	NA	NA
517	5	36	-3.0	-0.027		-8.61E-08	NA	NA
518	5	36	-0.5	-0.005		-1.44E-08	NA	NA
577	5	36	-0.5	-0.005		-1.45E-08	NA	NA
586	5	36	0.0	0.000		0.00E+00	NA	NA
591	5	36	5.0	0.045		1.44E-07	NA	NA
598	5	36	-1.2	-0.011		-3.45E-08	NA	NA
605	5	36	2.5	0.023		7.18E-08	NA	NA
612	5	36	1.5	0.014		4.31E-08	NA	NA
619	5	36	0.5	0.005		1.44E-08	NA	NA
625	5	36	1.0	0.009		2.87E-08	NA	NA
632	5	36	-1.0	-0.009		-2.87E-08	NA	NA
639	5	36	1.0	0.009		2.87E-08	NA	NA
641	5	36	1.0	0.009		2.87E-08	NA	NA
642	5	36	0.5	0.005		1.44E-08	NA	NA
643	5	36	1.0	0.009		2.87E-08	NA	NA
644	5	36	-7.7	-0.069		-2.21E-07	NA	NA
645	5	36	-12.0	-0.108		-3.45E-07	NA	NA
646	5	36	-16.0	-0.144		-4.59E-07	NA	NA
647	5	36	-10.0	-0.090		-2.87E-07	NA	NA
654	5	36	1.0	0.009		2.87E-08	NA	NA
655	5	36	0.5	0.005		1.44E-08	NA	NA
656	5	36	0.5	0.005		1.44E-08	NA	NA
657	5	36	1.4	0.013		4.02E-08	NA	NA
658	5	36	2.5	0.023		7.18E-08	NA	NA
511	5	37	-12.0	-0.109		-3.48E-07	NA	NA
514	5	37	-5.0	-0.045		-1.45E-07	NA	NA

Day	Site #	Piez #	Head	Gradient (I)	Mean K* (m s^{-1})	Estimated Seepage (m^3 m^{-2} s^{-1})	Direct Seepage (m^3 m^{-2} s^{-1})	Total Time of Meas. (min)
515	5	37	-9.5	-0.086		-2.75E-07	NA	NA
516	5	37	-6.5	-0.059		-1.88E-07	NA	NA
517	5	37	-0.5	-0.005		-1.45E-08	NA	NA
518	5	37	1.0	0.009		2.90E-08	NA	NA
577	5	37	-1.0	-0.011		-3.39E-08	NA	NA
586	5	37	1.0	0.009		2.90E-08	NA	NA
591	5	37	4.0	0.036		1.16E-07	NA	NA
598	5	37	-1.5	-0.014		-4.35E-08	NA	NA
605	5	37	-1.4	-0.013		-4.06E-08	NA	NA
612	5	37	-1.0	-0.009		-2.90E-08	NA	NA
619	5	37	-1.0	-0.009		-2.90E-08	NA	NA
625	5	37	-1.0	-0.009		-2.90E-08	NA	NA
632	5	37	-1.8	-0.016		-5.22E-08	NA	NA
639	5	37	-1.0	-0.009		-2.90E-08	NA	NA
641	5	37	-0.5	-0.005		-1.45E-08	NA	NA
642	5	37	-0.5	-0.005		-1.45E-08	NA	NA
643	5	37	-0.5	-0.005		-1.45E-08	NA	NA
644	5	37	-8.0	-0.073		-2.32E-07	NA	NA
645	5	37	-12.0	-0.109		-3.48E-07	NA	NA
646	5	37	-15.0	-0.136		-4.35E-07	NA	NA
647	5	37	-8.0	-0.073		-2.32E-07	NA	NA
654	5	37	1.0	0.009		2.90E-08	NA	NA
655	5	37	-0.5	-0.005		-1.45E-08	NA	NA
656	5	37	0.5	0.005		1.45E-08	NA	NA
657	5	37	1.5	0.014		4.35E-08	NA	NA
658	5	37	1.7	0.015		4.93E-08	NA	NA
510	5	38	-0.1	-0.001		-3.39E-09	NA	NA
511	5	38	0.7	0.007		2.37E-08	NA	NA
514	5	38	1.0	0.011		3.39E-08	NA	NA
515	5	38	-0.5	-0.005		-1.70E-08	NA	NA
516	5	38	1.5	0.016		5.09E-08	NA	NA
517	5	38	1.0	0.011		3.39E-08	NA	NA
518	5	38	1.0	0.011		3.39E-08	NA	NA
577	5	38	0.5	0.005		1.70E-08	NA	NA
586	5	38	1.2	0.013		4.07E-08	NA	NA
591	5	38	0.4	0.004		1.36E-08	NA	NA
598	5	38	-1.0	-0.011		-3.39E-08	NA	NA
605	5	38	-0.6	-0.006		-2.03E-08	NA	NA
612	5	38	0.0	0.000		0.00E+00	NA	NA
619	5	38	-0.3	-0.003		-1.02E-08	NA	NA
625	5	38	-0.5	-0.005		-1.70E-08	NA	NA
632	5	38	0.0	0.000		0.00E+00	NA	NA
632	5	38	-0.5	-0.005		-1.70E-08	NA	NA
639	5	38	0.1	0.001		3.39E-09	NA	NA
641	5	38	0.0	0.000		0.00E+00	NA	NA
642	5	38	0.0	0.000		0.00E+00	NA	NA
643	5	38	0.0	0.000		0.00E+00	NA	NA
644	5	38	-2.9	-0.031		-9.83E-08	NA	NA
645	5	38	-1.5	-0.016		-5.09E-08	NA	NA
646	5	38	-0.5	-0.005		-1.70E-08	NA	NA
647	5	38	1.0	0.011		3.39E-08	NA	NA
654	5	38	-0.5	-0.005		-1.70E-08	NA	NA
655	5	38	0.5	0.005		1.70E-08	NA	NA
656	5	38	0.5	0.005		1.70E-08	NA	NA
657	5	38	0.8	0.009		2.71E-08	NA	NA

Day	Site #	Piez #	Head	Gradient (I)	Mean K* (m s^{-1})	Estimated Seepage (m^3 m^{-2} s^{-1})	Direct Seepage (m^3 m^{-2} s^{-1})	Total Time of Meas. (min)
658	5	38	0.5	0.005		1.70E-08	NA	NA
510	5	39	0.5	0.005		1.70E-08	NA	NA
511	5	39	1.5	0.016		5.09E-08	NA	NA
514	5	39	-7.0	-0.074		-2.37E-07	NA	NA
515	5	39	-12.0	-0.128		-4.07E-07	NA	NA
516	5	39	-7.5	-0.080		-2.54E-07	NA	NA
517	5	39	-2.0	-0.021		-6.78E-08	NA	NA
518	5	39	-0.5	-0.005		-1.70E-08	NA	NA
586	5	39	-1.5	-0.016		-5.09E-08	NA	NA
591	5	39	4.0	0.043		1.36E-07	NA	NA
598	5	39	0.5	0.005		1.70E-08	NA	NA
605	5	39	-1.0	-0.011		-3.39E-08	NA	NA
612	5	39	2.5	0.027		8.48E-08	NA	NA
619	5	39	-2.5	-0.027		-8.48E-08	NA	NA
625	5	39	-3.0	-0.032		-1.02E-07	NA	NA
632	5	39	-3.9	-0.041		-1.32E-07	NA	NA
639	5	39	-1.0	-0.011		-3.39E-08	NA	NA
641	5	39	-1.0	-0.011		-3.39E-08	NA	NA
642	5	39	-0.5	-0.005		-1.70E-08	NA	NA
643	5	39	-0.5	-0.005		-1.70E-08	NA	NA
644	5	39	-7.0	-0.074		-2.37E-07	NA	NA
645	5	39	-13.0	-0.138		-4.41E-07	NA	NA
646	5	39	-18.5	-0.197		-6.27E-07	NA	NA
647	5	39	-11.0	-0.117		-3.73E-07	NA	NA
654	5	39	0.5	0.005		1.70E-08	NA	NA
655	5	39	-0.5	-0.005		-1.70E-08	NA	NA
656	5	39	0.5	0.005		1.70E-08	NA	NA
657	5	39	1.6	0.017		5.42E-08	NA	NA
658	5	39	2.0	0.021		6.78E-08	NA	NA
528	7	43	6.7	0.064	1.49E-06	9.60E-08	NA	NA
577	7	43	2.0	0.019		2.87E-08	NA	NA
586	7	43	4.5	0.043		6.45E-08	NA	NA
591	7	43	1.5	0.014		2.15E-08	NA	NA
598	7	43	1.0	0.010		1.43E-08	NA	NA
605	7	43	1.7	0.016		2.44E-08	NA	NA
612	7	43	-0.5	-0.005		-7.17E-09	NA	NA
625	7	43	-0.5	-0.005		-7.17E-09	NA	NA
632	7	43	0.0	0.000		0.00E+00	NA	NA
639	7	43	1.5	0.014		2.15E-08	NA	NA
641	7	43	0.5	0.005		7.17E-09	NA	NA
642	7	43	1.0	0.010		1.43E-08	NA	NA
643	7	43	-0.5	-0.005		-7.17E-09	NA	NA
644	7	43	0.2	0.002		2.87E-09	NA	NA
645	7	43	0.5	0.005		7.17E-09	NA	NA
646	7	43	0.0	0.000		0.00E+00	NA	NA
647	7	43	1.0	0.010		1.43E-08	NA	NA
654	7	43	1.7	0.016		2.44E-08	NA	NA
655	7	43	-0.2	-0.002		-2.87E-09	NA	NA
656	7	43	3.0	0.029		4.30E-08	NA	NA
657	7	43	1.7	0.016		2.44E-08	NA	NA
658	7	43	3.6	0.035		5.16E-08	NA	NA
508	7.5	47	3.0	0.027	1.98E-07	5.36E-09	NA	NA
516	7.5	47	-5.0	-0.045		-8.94E-09	NA	NA
517	7.5	47	3.0	0.027		5.36E-09	NA	NA
518	7.5	47	5.3	0.048		9.47E-09	NA	NA

Day	Site #	Piez #	Head	Gradient (I)	Mean K* (m s^{-1})	Estimated Seepage (m^3 m^{-2} s^{-1})	Direct Seepage (m^3 m^{-2} s^{-1})	Total Time of Meas. (min)
532	7.5	47	4.4	0.040		7.86E-09	NA	NA
577	7.5	47	0.5	0.005		8.94E-10	NA	NA
586	7.5	47	0.6	0.005		1.07E-09	NA	NA
591	7.5	47	0.6	0.005		1.07E-09	NA	NA
598	7.5	47	0.0	0.000		0.00E+00	NA	NA
632	7.5	47	0.0	0.000		0.00E+00	NA	NA
641	7.5	47	-0.5	-0.005		-8.94E-10	NA	NA
642	7.5	47	-1.5	-0.014		-2.68E-09	NA	NA
643	7.5	47	-2.5	-0.023		-4.47E-09	NA	NA
644	7.5	47	0.5	0.005		8.94E-10	NA	NA
645	7.5	47	-9.0	-0.081		-1.61E-08	NA	NA
646	7.5	47	-5.0	-0.045		-8.94E-09	NA	NA
647	7.5	47	1.9	0.017		3.40E-09	NA	NA
654	7.5	47	-0.5	-0.005		-8.94E-10	NA	NA
655	7.5	47	-0.5	-0.005		-8.94E-10	NA	NA
656	7.5	47	1.0	0.009		1.79E-09	NA	NA
657	7.5	47	1.5	0.014		2.68E-09	NA	NA
658	7.5	47	1.0	0.009		1.79E-09	NA	NA
508	7.5	48	-8.0	-0.054		-1.07E-08	NA	NA
509	7.5	48	-3.5	-0.023		-4.66E-09	NA	NA
510	7.5	48	-3.4	-0.023		-4.53E-09	NA	NA
511	7.5	48	1.0	0.007		1.33E-09	NA	NA
514	7.5	48	1.0	0.007		1.33E-09	NA	NA
515	7.5	48	-12.0	-0.081		-1.60E-08	NA	NA
516	7.5	48	-4.0	-0.027		-5.33E-09	NA	NA
517	7.5	48	4.0	0.027		5.33E-09	NA	NA
518	7.5	48	9.5	0.064		1.26E-08	NA	NA
577	7.5	48	-4.5	-0.030		-5.99E-09	NA	NA
586	7.5	48	7.0	0.047		9.32E-09	NA	NA
591	7.5	48	13.5	0.091		1.80E-08	NA	NA
598	7.5	48	5.5	0.037		7.32E-09	NA	NA
641	7.5	48	-8.5	-0.057		-1.13E-08	NA	NA
642	7.5	48	-10.0	-0.067		-1.33E-08	NA	NA
643	7.5	48	-7.0	-0.047		-9.32E-09	NA	NA
644	7.5	48	-12.0	-0.081		-1.60E-08	NA	NA
645	7.5	48	-30.0	-0.201		-3.99E-08	NA	NA
646	7.5	48	-34.0	-0.228		-4.53E-08	NA	NA
654	7.5	48	3.3	0.022		4.39E-09	NA	NA
655	7.5	48	-0.5	-0.003		-6.66E-10	NA	NA
656	7.5	48	1.0	0.007		1.33E-09	NA	NA
657	7.5	48	4.0	0.027		5.33E-09	NA	NA
658	7.5	48	5.2	0.035		6.92E-09	NA	NA
508	7.5	49	2.0	0.016		3.20E-09	NA	NA
509	7.5	49	4.0	0.032		6.40E-09	NA	NA
510	7.5	49	2.3	0.019		3.68E-09	NA	NA
511	7.5	49	5.5	0.044		8.80E-09	NA	NA
514	7.5	49	2.5	0.020		4.00E-09	NA	NA
515	7.5	49	-10.0	-0.081		-1.60E-08	NA	NA
516	7.5	49	-2.0	-0.016		-3.20E-09	NA	NA
517	7.5	49	8.4	0.068		1.34E-08	NA	NA
518	7.5	49	10.5	0.085		1.68E-08	NA	NA
577	7.5	49	-0.5	-0.004		-8.00E-10	NA	NA
586	7.5	49	8.3	0.067		1.33E-08	NA	NA
591	7.5	49	12.0	0.097		1.92E-08	NA	NA
598	7.5	49	5.0	0.040		8.00E-09	NA	NA

Day	Site #	Piez #	Head	Gradient (I)	Mean K* (m s^{-1})	Estimated Seepage (m^3 m^{-2} s^{-1})	Direct Seepage (m^3 m^{-2} s^{-1})	Total Time of Meas. (min)
605	7.5	49	1.5	0.012		2.40E-09	NA	NA
612	7.5	49	-1.0	-0.008		-1.60E-09	NA	NA
619	7.5	49	-1.0	-0.008		-1.60E-09	NA	NA
641	7.5	49	-2.3	-0.019		-3.68E-09	NA	NA
642	7.5	49	-7.0	-0.056		-1.12E-08	NA	NA
643	7.5	49	-5.0	-0.040		-8.00E-09	NA	NA
644	7.5	49	-8.5	-0.069		-1.36E-08	NA	NA
645	7.5	49	-28.0	-0.226		-4.48E-08	NA	NA
646	7.5	49	-27.0	-0.218		-4.32E-08	NA	NA
654	7.5	49	3.5	0.028		5.60E-09	NA	NA
655	7.5	49	-0.5	-0.004		-8.00E-10	NA	NA
656	7.5	49	1.0	0.008		1.60E-09	NA	NA
657	7.5	49	4.4	0.035		7.04E-09	NA	NA
658	7.5	49	5.0	0.040		8.00E-09	NA	NA
508	7.5	50	1.5	0.018		3.63E-09	NA	NA
509	7.5	50	0.5	0.006		1.21E-09	NA	NA
510	7.5	50	0.5	0.006		1.21E-09	NA	NA
511	7.5	50	1.5	0.018		3.63E-09	NA	NA
514	7.5	50	-1.5	-0.018		-3.63E-09	NA	NA
515	7.5	50	-2.0	-0.024		-4.84E-09	NA	NA
516	7.5	50	2.0	0.024		4.84E-09	NA	NA
517	7.5	50	2.5	0.030		6.05E-09	NA	NA
518	7.5	50	2.0	0.024		4.84E-09	NA	NA
577	7.5	50	1.5	0.018		3.63E-09	NA	NA
586	7.5	50	1.6	0.020		3.87E-09	NA	NA
591	7.5	50	1.0	0.012		2.42E-09	NA	NA
598	7.5	50	-0.5	-0.006		-1.21E-09	NA	NA
605	7.5	50	-1.5	-0.018		-3.63E-09	NA	NA
612	7.5	50	-1.5	-0.018		-3.63E-09	NA	NA
619	7.5	50	-1.0	-0.012		-2.42E-09	NA	NA
625	7.5	50	-1.5	-0.018		-3.63E-09	NA	NA
632	7.5	50	-1.0	-0.012		-2.42E-09	NA	NA
639	7.5	50	-1.0	-0.012		-2.42E-09	NA	NA
641	7.5	50	-1.5	-0.018		-3.63E-09	NA	NA
642	7.5	50	-1.5	-0.018		-3.63E-09	NA	NA
643	7.5	50	-1.5	-0.018		-3.63E-09	NA	NA
644	7.5	50	-2.0	-0.024		-4.84E-09	NA	NA
645	7.5	50	-4.0	-0.049		-9.68E-09	NA	NA
646	7.5	50	-1.5	-0.018		-3.63E-09	NA	NA
647	7.5	50	1.5	0.018		3.63E-09	NA	NA
654	7.5	50	-0.5	-0.006		-1.21E-09	NA	NA
655	7.5	50	-0.5	-0.006		-1.21E-09	NA	NA
656	7.5	50	0.8	0.010		1.94E-09	NA	NA
657	7.5	50	1.4	0.017		3.39E-09	NA	NA
658	7.5	50	1.0	0.012		2.42E-09	NA	NA
508	7.5	51	5.5	0.069		1.36E-08	NA	NA
509	7.5	51	3.0	0.038		7.44E-09	NA	NA
510	7.5	51	0.5	0.006		1.24E-09	NA	NA
511	7.5	51	2.5	0.031		6.20E-09	NA	NA
514	7.5	51	-2.5	-0.031		-6.20E-09	NA	NA
515	7.5	51	-9.5	-0.119		-2.36E-08	NA	NA
516	7.5	51	0.5	0.006		1.24E-09	NA	NA
517	7.5	51	5.0	0.063		1.24E-08	NA	NA
518	7.5	51	5.8	0.073		1.44E-08	NA	NA
577	7.5	51	2.0	0.025		4.96E-09	NA	NA

Day	Site #	Piez #	Head	Gradient (I)	Mean K* ($m\ s^{-1}$)	Estimated Seepage ($m^3\ m^{-2}\ s^{-1}$)	Direct Seepage ($m^3\ m^{-2}\ s^{-1}$)	Total Time of Meas. (min)
586	7.5	51	7.0	0.088		1.74E-08	NA	NA
591	7.5	51	3.2	0.040		7.94E-09	NA	NA
598	7.5	51	0.5	0.006		1.24E-09	NA	NA
605	7.5	51	-1.0	-0.013		-2.48E-09	NA	NA
612	7.5	51	-1.5	-0.019		-3.72E-09	NA	NA
619	7.5	51	-1.5	-0.019		-3.72E-09	NA	NA
625	7.5	51	-1.0	-0.013		-2.48E-09	NA	NA
632	7.5	51	-1.0	-0.013		-2.48E-09	NA	NA
639	7.5	51	-1.0	-0.013		-2.48E-09	NA	NA
641	7.5	51	-1.0	-0.013		-2.48E-09	NA	NA
642	7.5	51	-0.5	-0.006		-1.24E-09	NA	NA
643	7.5	51	-1.0	-0.013		-2.48E-09	NA	NA
644	7.5	51	-2.5	-0.031		-6.20E-09	NA	NA
645	7.5	51	-4.0	-0.050		-9.92E-09	NA	NA
646	7.5	51	-1.0	-0.013		-2.48E-09	NA	NA
647	7.5	51	1.8	0.023		4.46E-09	NA	NA
654	7.5	51	-1.0	-0.013		-2.48E-09	NA	NA
655	7.5	51	-0.5	-0.006		-1.24E-09	NA	NA
656	7.5	51	1.0	0.013		2.48E-09	NA	NA
657	7.5	51	1.7	0.021		4.22E-09	NA	NA
658	7.5	51	1.3	0.016		3.22E-09	NA	NA
500	7.5	52	-8.0	-0.063		-1.25E-08	NA	NA
507	7.5	52	7.0	0.055		1.09E-08	4.51E-09	1426
508	7.5	52	6.5	0.051		1.02E-08	6.22E-09	1447
509	7.5	52	4.0	0.031		6.25E-09	6.13E-09	1469
510	7.5	52	1.9	0.015		2.97E-09	5.34E-09	1532
511	7.5	52	4.8	0.038		7.50E-09	NA	NA
514	7.5	52	-1.0	-0.008		-1.56E-09	1.70E-09	1530
515	7.5	52	-8.0	-0.063		-1.25E-08	3.26E-09	1381
516	7.5	52	1.0	0.008		1.56E-09	5.08E-09	1392
517	7.5	52	6.0	0.047		9.37E-09	7.49E-09	1374
577	7.5	52	2.8	0.022		4.37E-09	NA	NA
586	7.5	52	8.5	0.067		1.33E-08	NA	NA
591	7.5	52	4.0	0.031		6.25E-09	NA	NA
598	7.5	52	2.0	0.016		3.12E-09	NA	NA
605	7.5	52	0.7	0.006		1.09E-09	NA	NA
612	7.5	52	0.0	0.000		0.00E+00	NA	NA
619	7.5	52	-0.5	-0.004		-7.81E-10	NA	NA
625	7.5	52	-1.0	-0.008		-1.56E-09	NA	NA
632	7.5	52	-1.0	-0.008		-1.56E-09	NA	NA
639	7.5	52	-2.0	-0.016		-3.12E-09	NA	NA
641	7.5	52	-2.0	-0.016		-3.12E-09	NA	NA
642	7.5	52	-2.0	-0.016		-3.12E-09	NA	NA
643	7.5	52	-2.0	-0.016		-3.12E-09	NA	NA
644	7.5	52	-7.0	-0.055		-1.09E-08	NA	NA
645	7.5	52	-14.0	-0.110		-2.19E-08	NA	NA
646	7.5	52	-9.0	-0.071		-1.41E-08	NA	NA
647	7.5	52	0.5	0.004		7.81E-10	NA	NA
654	7.5	52	0.5	0.004		7.81E-10	NA	NA
655	7.5	52	-1.2	-0.009		-1.87E-09	NA	NA
656	7.5	52	1.5	0.012		2.34E-09	NA	NA
657	7.5	52	3.9	0.031		6.09E-09	NA	NA
658	7.5	52	3.7	0.029		5.78E-09	NA	NA
500	7.5	53	-4.5	-0.034		-6.82E-09	NA	NA
507	7.5	53	5.0	0.038		7.57E-09	4.93E-09	1435

Day	Site #	Piez #	Head	Gradient (I)	Mean K* (m s^{-1})	Estimated Seepage (m^3 m^{-2} s^{-1})	Direct Seepage (m^3 m^{-2} s^{-1})	Total Time of Meas. (min)
508	7.5	53	5.0	0.038		7.57E-09	7.11E-09	1446
509	7.5	53	2.0	0.015		3.03E-09	5.23E-09	1476
510	7.5	53	1.7	0.013		2.57E-09	7.46E-09	1520
511	7.5	53	2.5	0.019		3.79E-09	NA	NA
514	7.5	53	-1.5	-0.011		-2.27E-09	5.93E-09	1536
515	7.5	53	-6.0	-0.046		-9.09E-09	3.72E-09	1382
516	7.5	53	2.0	0.015		3.03E-09	9.23E-09	1393
517	7.5	53	5.0	0.038		7.57E-09	1.55E-08	1369
577	7.5	53	1.0	0.008		1.51E-09	NA	NA
586	7.5	53	2.0	0.015		3.03E-09	NA	NA
591	7.5	53	1.2	0.009		1.82E-09	NA	NA
598	7.5	53	0.8	0.006		1.21E-09	NA	NA
605	7.5	53	0.2	0.002		3.03E-10	NA	NA
612	7.5	53	-0.5	-0.004		-7.57E-10	NA	NA
619	7.5	53	0.0	0.000		0.00E+00	NA	NA
625	7.5	53	0.0	0.000		0.00E+00	NA	NA
632	7.5	53	0.0	0.000		0.00E+00	NA	NA
639	7.5	53	-0.5	-0.004		-7.57E-10	NA	NA
641	7.5	53	-0.5	-0.004		-7.57E-10	NA	NA
642	7.5	53	-0.5	-0.004		-7.57E-10	NA	NA
643	7.5	53	-0.5	-0.004		-7.57E-10	NA	NA
644	7.5	53	-4.0	-0.031		-6.06E-09	NA	NA
645	7.5	53	-9.0	-0.069		-1.36E-08	NA	NA
646	7.5	53	-4.5	-0.034		-6.82E-09	NA	NA
647	7.5	53	2.0	0.015		3.03E-09	NA	NA
654	7.5	53	-0.5	-0.004		-7.57E-10	NA	NA
655	7.5	53	-1.0	-0.008		-1.51E-09	NA	NA
656	7.5	53	1.0	0.008		1.51E-09	NA	NA
657	7.5	53	1.5	0.011		2.27E-09	NA	NA
658	7.5	53	1.5	0.011		2.27E-09	NA	NA
500	7.5	54	-13.0	-0.125		-2.48E-08	NA	NA
507	7.5	54	8.0	0.077		1.53E-08	8.45E-09	1445
508	7.5	54	9.0	0.087		1.72E-08	1.02E-08	1444
509	7.5	54	7.0	0.067		1.34E-08	8.26E-09	1479
510	7.5	54	3.0	0.029		5.72E-09	6.67E-09	1510
511	7.5	54	4.2	0.040		8.01E-09	NA	NA
514	7.5	54	-1.0	-0.010		-1.91E-09	6.33E-09	1539
515	7.5	54	-11.5	-0.111		-2.19E-08	9.78E-09	1382
516	7.5	54	2.0	0.019		3.82E-09	6.01E-09	1391
517	7.5	54	4.0	0.038		7.63E-09	1.27E-08	1364
577	7.5	54	3.0	0.029		5.72E-09	NA	NA
586	7.5	54	7.5	0.072		1.43E-08	NA	NA
591	7.5	54	3.0	0.029		5.72E-09	NA	NA
598	7.5	54	1.2	0.012		2.29E-09	NA	NA
605	7.5	54	0.0	0.000		0.00E+00	NA	NA
612	7.5	54	0.0	0.000		0.00E+00	NA	NA
619	7.5	54	-0.5	-0.005		-9.54E-10	NA	NA
625	7.5	54	-0.5	-0.005		-9.54E-10	NA	NA
632	7.5	54	-0.5	-0.005		-9.54E-10	NA	NA
639	7.5	54	-0.5	-0.005		-9.54E-10	NA	NA
641	7.5	54	-0.5	-0.005		-9.54E-10	NA	NA
642	7.5	54	-0.5	-0.005		-9.54E-10	NA	NA
643	7.5	54	-0.5	-0.005		-9.54E-10	NA	NA
644	7.5	54	-5.5	-0.053		-1.05E-08	NA	NA
645	7.5	54	-16.0	-0.154		-3.05E-08	NA	NA

Day	Site #	Piez #	Head	Gradient (I)	Mean K* ($m\ s^{-1}$)	Estimated Seepage ($m^3\ m^{-2}\ s^{-1}$)	Direct Seepage ($m^3\ m^{-2}\ s^{-1}$)	Total Time of Meas. (min)
646	7.5	54	-10.0	-0.096		-1.91E-08	NA	NA
647	7.5	54	0.2	0.002		3.82E-10	NA	NA
654	7.5	54	-1.0	-0.010		-1.91E-09	NA	NA
655	7.5	54	-3.0	-0.029		-5.72E-09	NA	NA
656	7.5	54	-0.5	-0.005		-9.54E-10	NA	NA
657	7.5	54	2.0	0.019		3.82E-09	NA	NA
658	7.5	54	2.4	0.023		4.58E-09	NA	NA
500	7.5	55	-10.5	-0.073		-1.46E-08	NA	NA
507	7.5	55	12.0	0.084		1.66E-08	3.54E-09	1455
508	7.5	55	14.5	0.101		2.01E-08	4.01E-09	1443
509	7.5	55	13.0	0.091		1.80E-08	2.60E-09	1482
510	7.5	55	10.0	0.070		1.39E-08	5.45E-09	1502
511	7.5	55	11.6	0.081		1.61E-08	NA	NA
514	7.5	55	7.0	0.049		9.71E-09	2.53E-09	1538
515	7.5	55	-6.0	-0.042		-8.32E-09	5.59E-09	1380
516	7.5	55	0.5	0.003		6.94E-10	6.93E-09	1392
517	7.5	55	8.0	0.056		1.11E-08	8.04E-09	1360
529	7.5	55	14.5	0.101		2.01E-08	NA	NA
577	7.5	55	1.0	0.007		1.39E-09	NA	NA
586	7.5	55	9.0	0.063		1.25E-08	NA	NA
591	7.5	55	13.0	0.091		1.80E-08	NA	NA
598	7.5	55	6.5	0.045		9.02E-09	NA	NA
605	7.5	55	3.2	0.022		4.44E-09	NA	NA
612	7.5	55	1.6	0.011		2.22E-09	NA	NA
619	7.5	55	0.5	0.003		6.94E-10	NA	NA
625	7.5	55	-1.0	-0.007		-1.39E-09	NA	NA
632	7.5	55	-1.9	-0.013		-2.64E-09	NA	NA
639	7.5	55	-1.5	-0.010		-2.08E-09	NA	NA
641	7.5	55	-2.0	-0.014		-2.77E-09	NA	NA
642	7.5	55	-2.5	-0.017		-3.47E-09	NA	NA
643	7.5	55	-2.0	-0.014		-2.77E-09	NA	NA
644	7.5	55	-8.0	-0.056		-1.11E-08	NA	NA
645	7.5	55	-23.0	-0.161		-3.19E-08	NA	NA
646	7.5	55	-28.0	-0.196		-3.88E-08	NA	NA
647	7.5	55	-15.0	-0.105		-2.08E-08	NA	NA
654	7.5	55	4.0	0.028		5.55E-09	NA	NA
655	7.5	55	-0.5	-0.003		-6.94E-10	NA	NA
656	7.5	55	1.5	0.010		2.08E-09	NA	NA
657	7.5	55	4.4	0.031		6.10E-09	NA	NA
658	7.5	55	5.5	0.038		7.63E-09	NA	NA
500	7.5	56	-8.5	-0.084		-1.67E-08	NA	NA
507	7.5	56	8.5	0.084		1.67E-08	4.83E-09	1464
508	7.5	56	8.5	0.084		1.67E-08	4.46E-09	1442
509	7.5	56	6.0	0.059		1.18E-08	3.46E-09	1485
510	7.5	56	2.5	0.025		4.91E-09	5.49E-09	1490
511	7.5	56	4.5	0.045		8.84E-09	NA	NA
514	7.5	56	-0.2	-0.002		-3.93E-10	3.78E-09	1539
515	7.5	56	-8.0	-0.079		-1.57E-08	2.79E-09	1383
516	7.5	56	0.5	0.005		9.82E-10	1.39E-09	1392
517	7.5	56	7.0	0.069		1.38E-08	7.10E-09	1358
577	7.5	56	4.0	0.040		7.86E-09	NA	NA
586	7.5	56	9.2	0.091		1.81E-08	NA	NA
591	7.5	56	1.7	0.017		3.34E-09	NA	NA
598	7.5	56	1.0	0.010		1.96E-09	NA	NA
605	7.5	56	0.6	0.006		1.18E-09	NA	NA

Day	Site #	Piez #	Head	Gradient (I)	Mean K* $(m\ s^{-1})$	Estimated Seepage $(m^3\ m^{-2}\ s^{-1})$	Direct Seepage $(m^3\ m^{-2}\ s^{-1})$	Total Time of Meas. (min)
612	7.5	56	0.5	0.005		9.82E-10	NA	NA
619	7.5	56	0.5	0.005		9.82E-10	NA	NA
625	7.5	56	-0.5	-0.005		-9.82E-10	NA	NA
632	7.5	56	0.0	0.000		0.00E+00	NA	NA
639	7.5	56	-0.5	-0.005		-9.82E-10	NA	NA
641	7.5	56	-0.5	-0.005		-9.82E-10	NA	NA
642	7.5	56	-0.2	-0.002		-3.93E-10	NA	NA
643	7.5	56	-0.2	-0.002		-3.93E-10	NA	NA
644	7.5	56	-2.0	-0.020		-3.93E-09	NA	NA
645	7.5	56	-6.0	-0.059		-1.18E-08	NA	NA
646	7.5	56	-3.5	-0.035		-6.88E-09	NA	NA
647	7.5	56	2.0	0.020		3.93E-09	NA	NA
654	7.5	56	1.0	0.010		1.96E-09	NA	NA
655	7.5	56	0.3	0.003		5.89E-10	NA	NA
656	7.5	56	0.5	0.005		9.82E-10	NA	NA
657	7.5	56	1.7	0.017		3.34E-09	NA	NA
658	7.5	56	1.0	0.010		1.96E-09	NA	NA
508	7.5	57	-4.0	-0.023		-4.64E-09	NA	NA
509	7.5	57	2.5	0.015		2.90E-09	NA	NA
510	7.5	57	5.5	0.032		6.38E-09	NA	NA
511	7.5	57	11.5	0.067		1.33E-08	NA	NA
514	7.5	57	15.0	0.088		1.74E-08	NA	NA
515	7.5	57	3.0	0.018		3.48E-09	NA	NA
516	7.5	57	11.0	0.064		1.28E-08	NA	NA
517	7.5	57	19.0	0.111		2.20E-08	NA	NA
518	7.5	57	24.5	0.143		2.84E-08	NA	NA
577	7.5	57	11.5	0.067		1.33E-08	NA	NA
586	7.5	57	20.5	0.120		2.38E-08	NA	NA
591	7.5	57	29.5	0.173		3.42E-08	NA	NA
598	7.5	57	22.0	0.129		2.55E-08	NA	NA
605	7.5	57	15.0	0.088		1.74E-08	NA	NA
612	7.5	57	9.5	0.056		1.10E-08	NA	NA
619	7.5	57	7.0	0.041		8.12E-09	NA	NA
625	7.5	57	4.0	0.023		4.64E-09	NA	NA
632	7.5	57	4.5	0.026		5.22E-09	NA	NA
639	7.5	57	3.8	0.022		4.41E-09	NA	NA
641	7.5	57	4.0	0.023		4.64E-09	NA	NA
642	7.5	57	4.0	0.023		4.64E-09	NA	NA
643	7.5	57	4.0	0.023		4.64E-09	NA	NA
644	7.5	57	1.5	0.009		1.74E-09	NA	NA
645	7.5	57	-15.0	-0.088		-1.74E-08	NA	NA
646	7.5	57	-20.0	-0.117		-2.32E-08	NA	NA
654	7.5	57	17.0	0.099		1.97E-08	NA	NA
655	7.5	57	13.5	0.079		1.57E-08	NA	NA
656	7.5	57	15.2	0.089		1.76E-08	NA	NA
657	7.5	57	18.4	0.108		2.13E-08	NA	NA
658	7.5	57	20.0	0.117		2.32E-08	NA	NA
508	7.5	58	5.0	0.040		7.94E-09	NA	NA
509	7.5	58	4.5	0.036		7.14E-09	NA	NA
510	7.5	58	1.8	0.014		2.86E-09	NA	NA
511	7.5	58	3.6	0.029		5.71E-09	NA	NA
514	7.5	58	-0.5	-0.004		-7.94E-10	NA	NA
516	7.5	58	-3.5	-0.028		-5.56E-09	NA	NA
517	7.5	58	4.0	0.032		6.35E-09	NA	NA
518	7.5	58	7.2	0.058		1.14E-08	NA	NA

Day	Site #	Piez #	Head	Gradient (I)	Mean K* (m s^{-1})	Estimated Seepage (m^3 m^{-2} s^{-1})	Direct Seepage (m^3 m^{-2} s^{-1})	Total Time of Meas. (min)
577	7.5	58	0.0	0.000		0.00E+00	NA	NA
586	7.5	58	8.2	0.066		1.30E-08	NA	NA
591	7.5	58	6.5	0.052		1.03E-08	NA	NA
598	7.5	58	2.0	0.016		3.17E-09	NA	NA
641	7.5	58	-1.0	-0.008		-1.59E-09	NA	NA
642	7.5	58	-2.0	-0.016		-3.17E-09	NA	NA
643	7.5	58	-3.0	-0.024		-4.76E-09	NA	NA
644	7.5	58	1.2	0.010		1.90E-09	NA	NA
645	7.5	58	-14.0	-0.112		-2.22E-08	NA	NA
646	7.5	58	-12.0	-0.096		-1.90E-08	NA	NA
647	7.5	58	-1.0	-0.008		-1.59E-09	NA	NA
654	7.5	58	0.5	0.004		7.94E-10	NA	NA
655	7.5	58	-3.0	-0.024		-4.76E-09	NA	NA
656	7.5	58	-0.5	-0.004		-7.94E-10	NA	NA
657	7.5	58	2.4	0.019		3.81E-09	NA	NA
658	7.5	58	3.3	0.026		5.24E-09	NA	NA
509	7.5	59	0.0	0.000		0.00E+00	NA	NA
510	7.5	59	-11.4	-0.088		-1.75E-08	NA	NA
511	7.5	59	-7.0	-0.054		-1.08E-08	NA	NA
514	7.5	59	-3.5	-0.027		-5.38E-09	NA	NA
516	7.5	59	-8.0	-0.062		-1.23E-08	NA	NA
517	7.5	59	1.0	0.008		1.54E-09	NA	NA
518	7.5	59	6.0	0.047		9.23E-09	NA	NA
577	7.5	59	3.0	0.023		4.61E-09	NA	NA
586	7.5	59	1.4	0.011		2.15E-09	NA	NA
591	7.5	59	13.5	0.105		2.08E-08	NA	NA
598	7.5	59	7.7	0.060		1.18E-08	NA	NA
605	7.5	59	2.0	0.016		3.08E-09	NA	NA
641	7.5	59	-8.0	-0.062		-1.23E-08	NA	NA
642	7.5	59	-7.5	-0.058		-1.15E-08	NA	NA
643	7.5	59	-8.0	-0.062		-1.23E-08	NA	NA
644	7.5	59	-9.0	-0.070		-1.38E-08	NA	NA
645	7.5	59	-26.0	-0.202		-4.00E-08	NA	NA
646	7.5	59	-32.0	-0.248		-4.92E-08	NA	NA
654	7.5	59	3.8	0.029		5.84E-09	NA	NA
655	7.5	59	-0.5	-0.004		-7.69E-10	NA	NA
656	7.5	59	1.0	0.008		1.54E-09	NA	NA
657	7.5	59	4.0	0.031		6.15E-09	NA	NA
658	7.5	59	5.0	0.039		7.69E-09	NA	NA
508	7.5	60	-7.5	-0.065		-1.29E-08	NA	NA
509	7.5	60	-5.0	-0.043		-8.63E-09	NA	NA
510	7.5	60	-5.0	-0.043		-8.63E-09	NA	NA
511	7.5	60	-1.5	-0.013		-2.59E-09	NA	NA
514	7.5	60	-1.0	-0.009		-1.73E-09	NA	NA
515	7.5	60	-15.0	-0.130		-2.59E-08	NA	NA
516	7.5	60	-7.0	-0.061		-1.21E-08	NA	NA
517	7.5	60	1.5	0.013		2.59E-09	NA	NA
518	7.5	60	6.5	0.057		1.12E-08	NA	NA
577	7.5	60	-3.9	-0.034		-6.73E-09	NA	NA
586	7.5	60	3.5	0.030		6.04E-09	NA	NA
591	7.5	60	10.7	0.093		1.85E-08	NA	NA
598	7.5	60	5.0	0.043		8.63E-09	NA	NA
605	7.5	60	1.5	0.013		2.59E-09	NA	NA
612	7.5	60	-0.5	-0.004		-8.63E-10	NA	NA
641	7.5	60	-3.0	-0.026		-5.18E-09	NA	NA

Day	Site #	Piez #	Head	Gradient (I)	Mean K* ($m\ s^{-1}$)	Estimated Seepage ($m^3\ m^{-2}\ s^{-1}$)	Direct Seepage ($m^3\ m^{-2}\ s^{-1}$)	Total Time of Meas. (min)
642	7.5	60	-3.6	-0.031		-6.21E-09	NA	NA
643	7.5	60	-3.5	-0.030		-6.04E-09	NA	NA
644	7.5	60	-7.0	-0.061		-1.21E-08	NA	NA
645	7.5	60	-25.0	-0.217		-4.31E-08	NA	NA
646	7.5	60	-30.0	-0.261		-5.18E-08	NA	NA
654	7.5	60	3.0	0.026		5.18E-09	NA	NA
655	7.5	60	-1.0	-0.009		-1.73E-09	NA	NA
656	7.5	60	0.5	0.004		8.63E-10	NA	NA
657	7.5	60	3.3	0.029		5.69E-09	NA	NA
658	7.5	60	4.0	0.035		6.90E-09	NA	NA
508	7.5	61	7.5	0.064		1.26E-08	NA	NA
509	7.5	61	1.5	0.013		2.52E-09	NA	NA
510	7.5	61	-1.0	-0.008		-1.68E-09	NA	NA
511	7.5	61	1.9	0.016		3.19E-09	NA	NA
514	7.5	61	-2.5	-0.021		-4.20E-09	NA	NA
515	7.5	61	-5.0	-0.042		-8.41E-09	NA	NA
516	7.5	61	2.0	0.017		3.36E-09	NA	NA
517	7.5	61	3.5	0.030		5.88E-09	NA	NA
518	7.5	61	3.0	0.025		5.04E-09	NA	NA
577	7.5	61	2.5	0.021		4.20E-09	NA	NA
586	7.5	61	7.0	0.059		1.18E-08	NA	NA
591	7.5	61	3.8	0.032		6.39E-09	NA	NA
598	7.5	61	0.5	0.004		8.41E-10	NA	NA
641	7.5	61	-4.0	-0.034		-6.73E-09	NA	NA
642	7.5	61	-3.6	-0.031		-6.05E-09	NA	NA
643	7.5	61	-5.5	-0.047		-9.25E-09	NA	NA
644	7.5	61	-7.0	-0.059		-1.18E-08	NA	NA
645	7.5	61	-19.0	-0.161		-3.19E-08	NA	NA
646	7.5	61	-15.0	-0.127		-2.52E-08	NA	NA
647	7.5	61	-2.0	-0.017		-3.36E-09	NA	NA
654	7.5	61	-1.0	-0.008		-1.68E-09	NA	NA
655	7.5	61	-3.0	-0.025		-5.04E-09	NA	NA
656	7.5	61	0.5	0.004		8.41E-10	NA	NA
657	7.5	61	2.5	0.021		4.20E-09	NA	NA
658	7.5	61	2.5	0.021		4.20E-09	NA	NA
530	8	64	2.0	0.017	5.22E-08	8.70E-10	NA	NA
532	8	64	1.7	0.014		7.39E-10	NA	NA
577	8	64	8.5	0.071		3.70E-09	NA	NA
586	8	64	11.5	0.096		5.00E-09	NA	NA
591	8	64	9.0	0.075		3.91E-09	NA	NA
598	8	64	8.0	0.067		3.48E-09	NA	NA
605	8	64	7.7	0.064		3.35E-09	NA	NA
612	8	64	6.2	0.052		2.70E-09	NA	NA
619	8	64	4.0	0.033		1.74E-09	NA	NA
625	8	64	4.0	0.033		1.74E-09	NA	NA
632	8	64	3.0	0.025		1.30E-09	NA	NA
639	8	64	3.0	0.025		1.30E-09	NA	NA
641	8	64	2.5	0.021		1.09E-09	NA	NA
642	8	64	2.4	0.020		1.04E-09	NA	NA
643	8	64	2.8	0.023		1.22E-09	NA	NA
644	8	64	-0.2	-0.002		-8.70E-11	NA	NA
645	8	64	4.5	0.038		1.96E-09	NA	NA
646	8	64	-5.5	-0.046		-2.39E-09	NA	NA
647	8	64	2.5	0.021		1.09E-09	NA	NA
654	8	64	5.0	0.042		2.17E-09	NA	NA

Day	Site #	Piez #	Head	Gradient (I)	Mean K* ($m\ s^{-1}$)	Estimated Seepage ($m^3\ m^{-2}\ s^{-1}$)	Direct Seepage ($m^3\ m^{-2}\ s^{-1}$)	Total Time of Meas. (min)
655	8	64	3.0	0.025		1.30E-09	NA	NA
656	8	64	4.5	0.038		1.96E-09	NA	NA
657	8	64	6.0	0.050		2.61E-09	NA	NA
658	8	64	6.0	0.050		2.61E-09	NA	NA
530	11	69	28.0	0.269	4.10E-07	1.10E-07	NA	NA
577	11	69	1.0	0.010		3.94E-09	NA	NA
591	11	69	7.0	0.067		2.76E-08	NA	NA
598	11	69	2.5	0.024		9.86E-09	NA	NA
632	11	69	-1.0	-0.010		-3.94E-09	NA	NA
639	11	69	-0.5	-0.005		-1.97E-09	NA	NA
641	11	69	-1.0	-0.010		-3.94E-09	NA	NA
642	11	69	-0.5	-0.005		-1.97E-09	NA	NA
643	11	69	0.0	0.000		0.00E+00	NA	NA
644	11	69	5.0	0.048		1.97E-08	NA	NA
646	11	69	1.5	0.014		5.91E-09	NA	NA
647	11	69	1.0	0.010		3.94E-09	NA	NA
654	11	69	1.5	0.014		5.91E-09	NA	NA
655	11	69	0.3	0.003		1.18E-09	NA	NA
656	11	69	0.5	0.005		1.97E-09	NA	NA
657	11	69	1.2	0.012		4.73E-09	NA	NA
658	11	69	0.5	0.005		1.97E-09	NA	NA
530	12	73	3.6	0.036	2.46E-07	8.87E-09	NA	NA
577	12	73	-8.0	-0.080		-1.97E-08	NA	NA
586	12	73	7.0	0.070		1.72E-08	NA	NA
591	12	73	3.5	0.035		8.62E-09	NA	NA
598	12	73	10.0	0.100		2.46E-08	NA	NA
605	12	73	2.9	0.029		7.14E-09	NA	NA
612	12	73	3.5	0.035		8.62E-09	NA	NA
619	12	73	3.0	0.030		7.39E-09	NA	NA
625	12	73	3.0	0.030		7.39E-09	NA	NA
632	12	73	4.0	0.040		9.85E-09	NA	NA
639	12	73	2.5	0.025		6.16E-09	NA	NA
641	12	73	2.0	0.020		4.93E-09	NA	NA
642	12	73	1.2	0.012		2.96E-09	NA	NA
643	12	73	1.2	0.012		2.96E-09	NA	NA
645	12	73	8.5	0.085		2.09E-08	NA	NA
646	12	73	7.5	0.075		1.85E-08	NA	NA
647	12	73	6.4	0.064		1.58E-08	NA	NA
654	12	73	4.0	0.040		9.85E-09	NA	NA
655	12	73	4.0	0.040		9.85E-09	NA	NA
656	12	73	3.5	0.035		8.62E-09	NA	NA
657	12	73	1.7	0.017		4.19E-09	NA	NA
658	12	73	3.8	0.038		9.36E-09	NA	NA
508	13	77	NA	NA	4.40E-06	NA	3.37E-08	1203
514	13	77	-4.8	-0.062		-2.74E-07	1.75E-08	1470
515	13	77	NA	NA		NA	2.49E-08	1394
516	13	77	-0.4	-0.005		-2.00E-08	3.88E-08	1408
517	13	77	3.4	0.044		1.94E-07	5.54E-08	1404
577	13	77	5.0	0.065		2.86E-07	NA	NA
586	13	77	5.7	0.074		3.26E-07	NA	NA
591	13	77	13.5	0.175		7.72E-07	NA	NA
598	13	77	7.0	0.091		4.00E-07	NA	NA
605	13	77	13.0	0.169		7.43E-07	NA	NA
612	13	77	0.5	0.006		2.86E-08	NA	NA
619	13	77	-2.4	-0.031		-1.37E-07	NA	NA

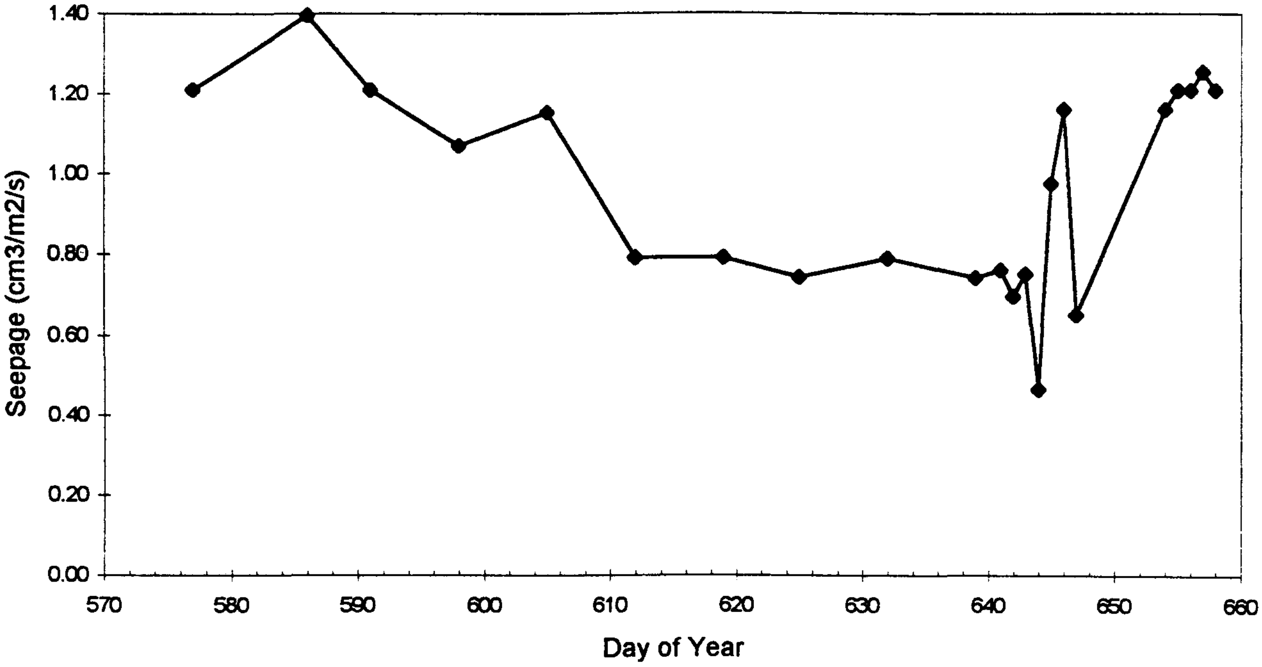
Day	Site #	Piez #	Head	Gradient (I)	Mean K* ($m\ s^{-1}$)	Estimated Seepage ($m^3\ m^{-2}\ s^{-1}$)	Direct Seepage ($m^3\ m^{-2}\ s^{-1}$)	Total Time of Meas. (min)
625	13	77	-1.5	-0.019		-8.57E-08	NA	NA
632	13	77	-2.0	-0.026		-1.14E-07	NA	NA
639	13	77	-0.5	-0.006		-2.86E-08	NA	NA
641	13	77	0.0	0.000		0.00E+00	NA	NA
642	13	77	-0.2	-0.003		-1.14E-08	NA	NA
643	13	77	-0.6	-0.008		-3.43E-08	NA	NA
647	13	77	-0.5	-0.006		-2.86E-08	NA	NA
654	13	77	-3.0	-0.039		-1.71E-07	NA	NA
655	13	77	-0.5	-0.006		-2.86E-08	NA	NA
656	13	77	2.4	0.031		1.37E-07	NA	NA
657	13	77	3.5	0.045		2.00E-07	NA	NA
658	13	77	3.0	0.039		1.71E-07	NA	NA
508	13	78	NA	NA		NA	4.33E-08	1217
514	13	78	-7.0	-0.057		-2.50E-07	4.29E-08	1484
515	13	78	NA	NA		NA	5.18E-08	1389
516	13	78	-1.8	-0.014		-6.26E-08	8.28E-08	1414
517	13	78	2.3	0.018		8.05E-08	1.04E-07	1395
577	13	78	4.0	0.033		1.43E-07	NA	NA
586	13	78	5.0	0.041		1.79E-07	NA	NA
591	13	78	19.0	0.154		6.80E-07	NA	NA
598	13	78	12.5	0.102		4.47E-07	NA	NA
605	13	78	6.5	0.053		2.33E-07	NA	NA
612	13	78	2.5	0.020		8.95E-08	NA	NA
619	13	78	-2.0	-0.016		-7.16E-08	NA	NA
625	13	78	-1.5	-0.012		-5.37E-08	NA	NA
632	13	78	-1.9	-0.015		-6.80E-08	NA	NA
639	13	78	0.5	0.004		1.79E-08	NA	NA
641	13	78	0.9	0.007		3.22E-08	NA	NA
642	13	78	0.5	0.004		1.79E-08	NA	NA
643	13	78	-0.3	-0.002		-1.07E-08	NA	NA
647	13	78	-3.0	-0.024		-1.07E-07	NA	NA
654	13	78	4.5	0.037		1.61E-07	NA	NA
655	13	78	5.5	0.045		1.97E-07	NA	NA
656	13	78	7.5	0.061		2.68E-07	NA	NA
657	13	78	8.0	0.065		2.86E-07	NA	NA
658	13	78	7.5	0.061		2.68E-07	NA	NA
507	13	79	1.0	0.013		5.87E-08	NA	NA
508	13	79	1.0	0.013		5.87E-08	1.62E-08	1234
514	13	79	-1.3	-0.017		-7.63E-08	1.47E-08	1491
515	13	79	-0.5	-0.007		-2.93E-08	2.15E-08	1390
516	13	79	2.0	0.027		1.17E-07	2.32E-08	1416
517	13	79	1.8	0.023		1.03E-07	2.53E-08	1390
532	13	79	1.5	0.020		8.80E-08	NA	NA
577	13	79	1.0	0.013		5.87E-08	NA	NA
586	13	79	5.2	0.069		3.05E-07	NA	NA
591	13	79	2.0	0.027		1.17E-07	NA	NA
598	13	79	2.0	0.027		1.17E-07	NA	NA
605	13	79	0.9	0.012		5.28E-08	NA	NA
612	13	79	0.5	0.007		2.93E-08	NA	NA
619	13	79	0.5	0.007		2.93E-08	NA	NA
625	13	79	0.5	0.007		2.93E-08	NA	NA
632	13	79	0.0	0.000		0.00E+00	NA	NA
507	13	80	2.0	0.016		7.10E-08	NA	NA
508	13	80	NA	NA		NA	1.39E-08	1246
514	13	80	-1.4	-0.011		-4.97E-08	8.60E-09	1495

Day	Site #	Piez #	Head	Gradient (I)	Mean K* ($m\ s^{-1}$)	Estimated Seepage ($m^3\ m^{-2}\ s^{-1}$)	Direct Seepage ($m^3\ m^{-2}\ s^{-1}$)	Total Time of Meas. (min)
515	13	80	-2.0	-0.016		-7.10E-08	1.30E-08	1389
516	13	80	3.8	0.030		1.33E-07	1.77E-08	1418
517	13	80	7.8	0.063		2.75E-07	3.20E-08	1386
577	13	80	5.0	0.040		1.77E-07	NA	NA
586	13	80	8.2	0.066		2.91E-07	NA	NA
591	13	80	21.0	0.169		7.45E-07	NA	NA
598	13	80	13.5	0.109		4.79E-07	NA	NA
605	13	80	7.2	0.058		2.56E-07	NA	NA
612	13	80	2.5	0.020		8.87E-08	NA	NA
619	13	80	-2.0	-0.016		-7.10E-08	NA	NA
625	13	80	-1.5	-0.012		-5.32E-08	NA	NA
632	13	80	-1.8	-0.015		-6.39E-08	NA	NA
639	13	80	1.2	0.010		4.26E-08	NA	NA
641	13	80	1.5	0.012		5.32E-08	NA	NA
642	13	80	1.0	0.008		3.55E-08	NA	NA
643	13	80	0.5	0.004		1.77E-08	NA	NA
647	13	80	6.5	0.052		2.31E-07	NA	NA
654	13	80	1.5	0.012		5.32E-08	NA	NA
655	13	80	3.6	0.029		1.28E-07	NA	NA
656	13	80	6.0	0.048		2.13E-07	NA	NA
657	13	80	7.4	0.060		2.63E-07	NA	NA
658	13	80	7.5	0.060		2.66E-07	NA	NA

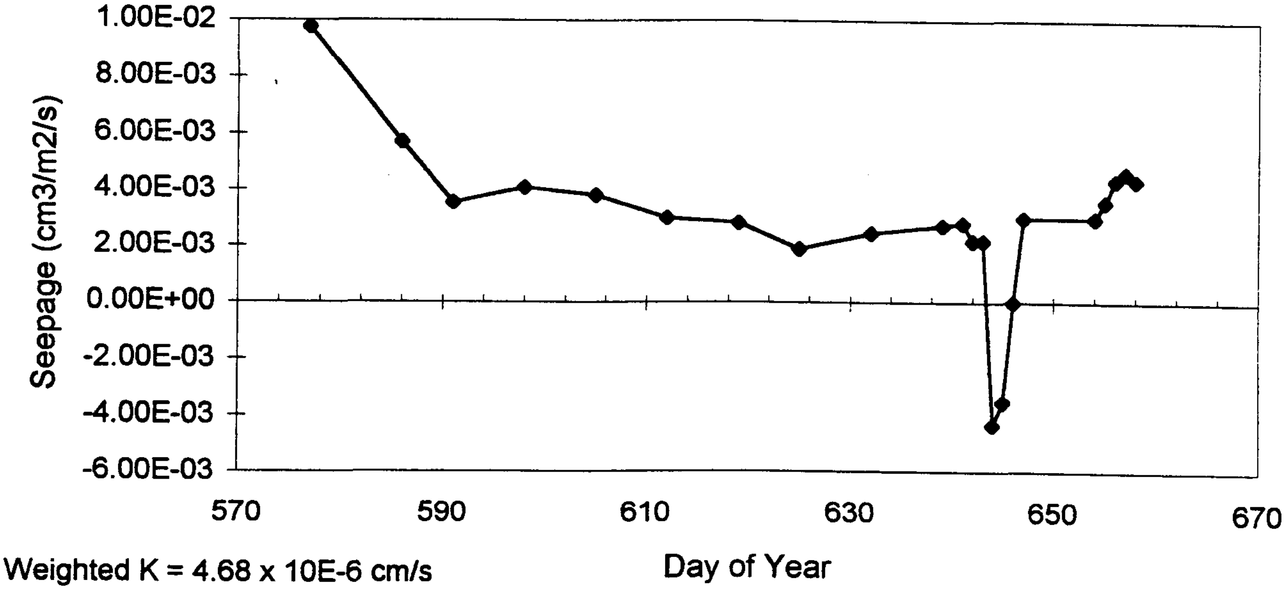
A2.5 Estimated Seepage Flux vs Time Figures for 1995

Figures 1 to 38 illustrate estimated seepage flux as a function of time at each piezometer throught the Raisin River watershed. The seepage was estimated from the local hydraulic head gradient and the measured local hydraulic conductivity.

Estimated GW Seepage vs Time (1995) Site #1 (Piez #1)



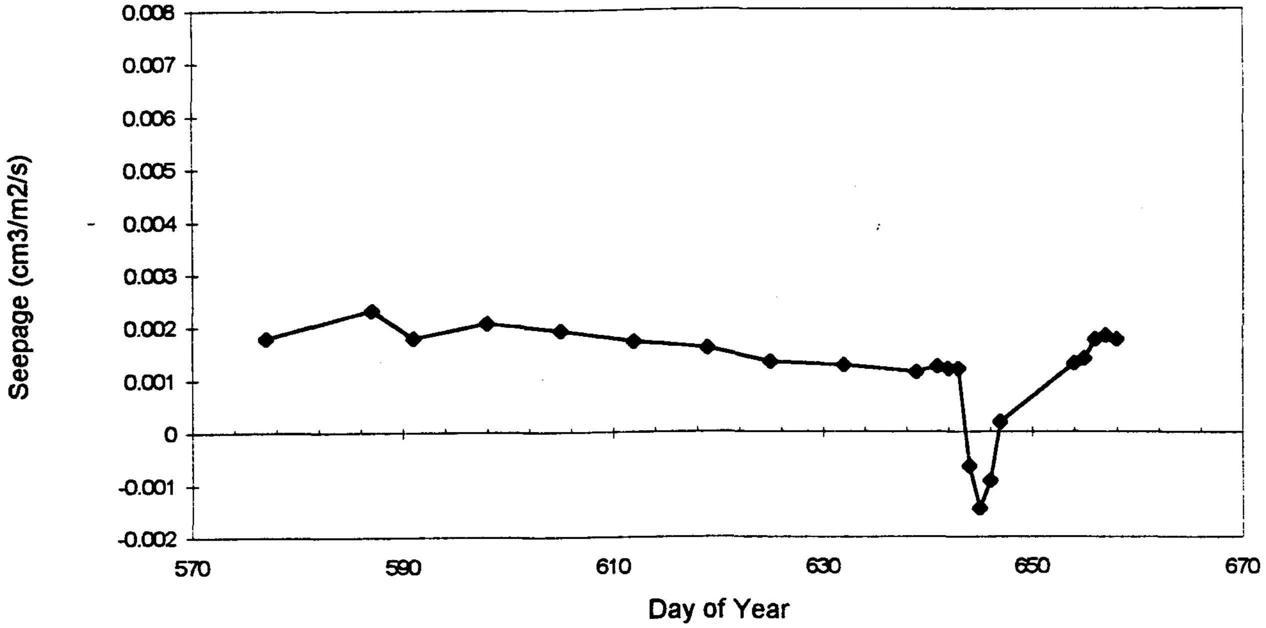
Estimated GW Seepage vs Time (1995) Site #2 (Piez #10)



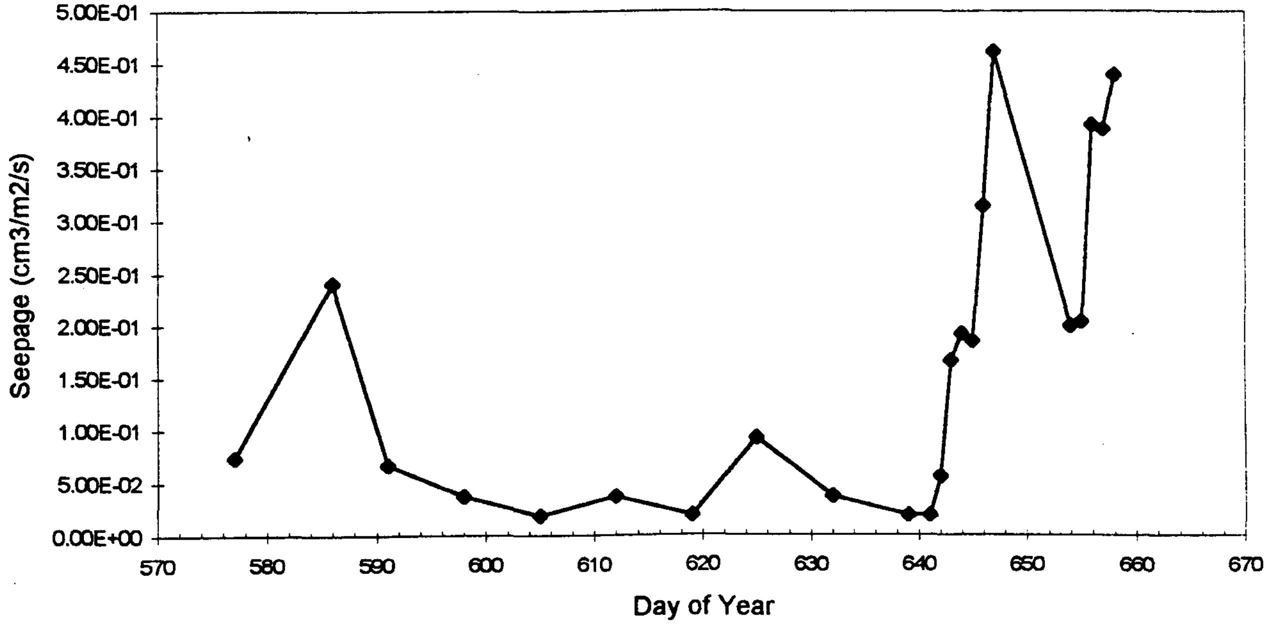
Weighted K = 4.68 x 10E-6 cm/s

Figures 3 and 4

Estimated GW Seepage vs Time (1995) Site #2 (Piez #10.5)

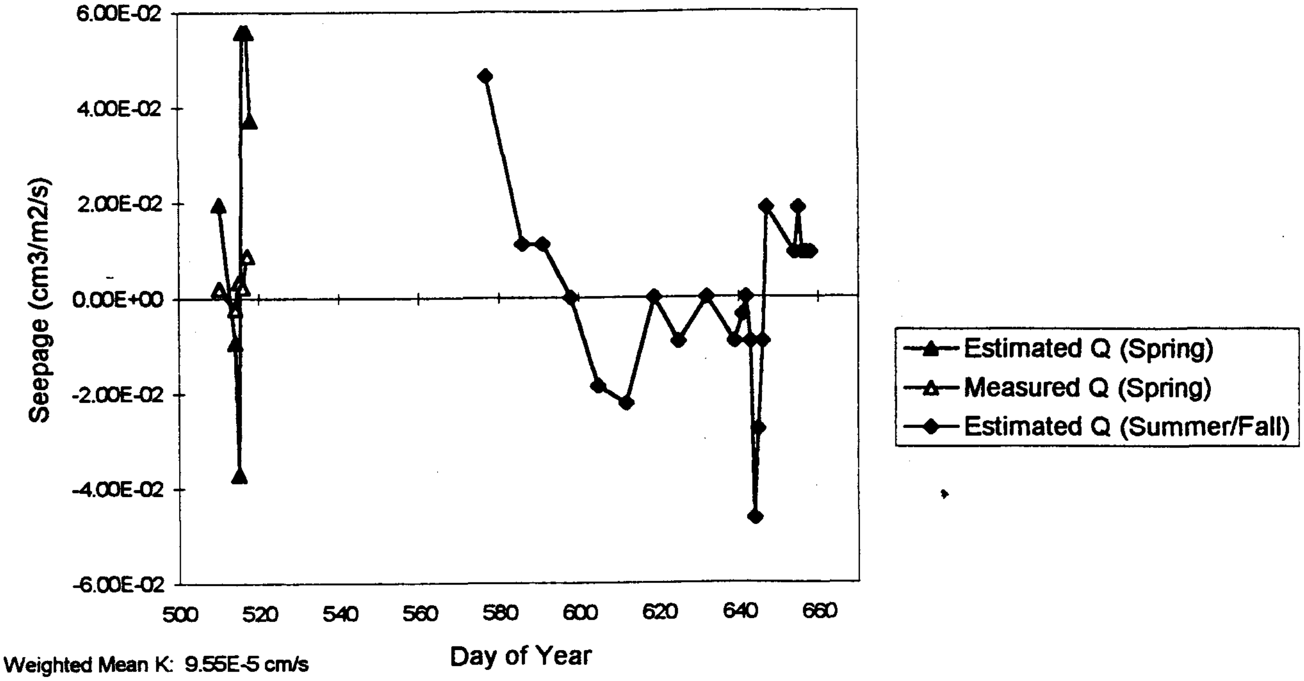


Estimated GW Seepage vs Time (1995) Site #3 (Piez #15)

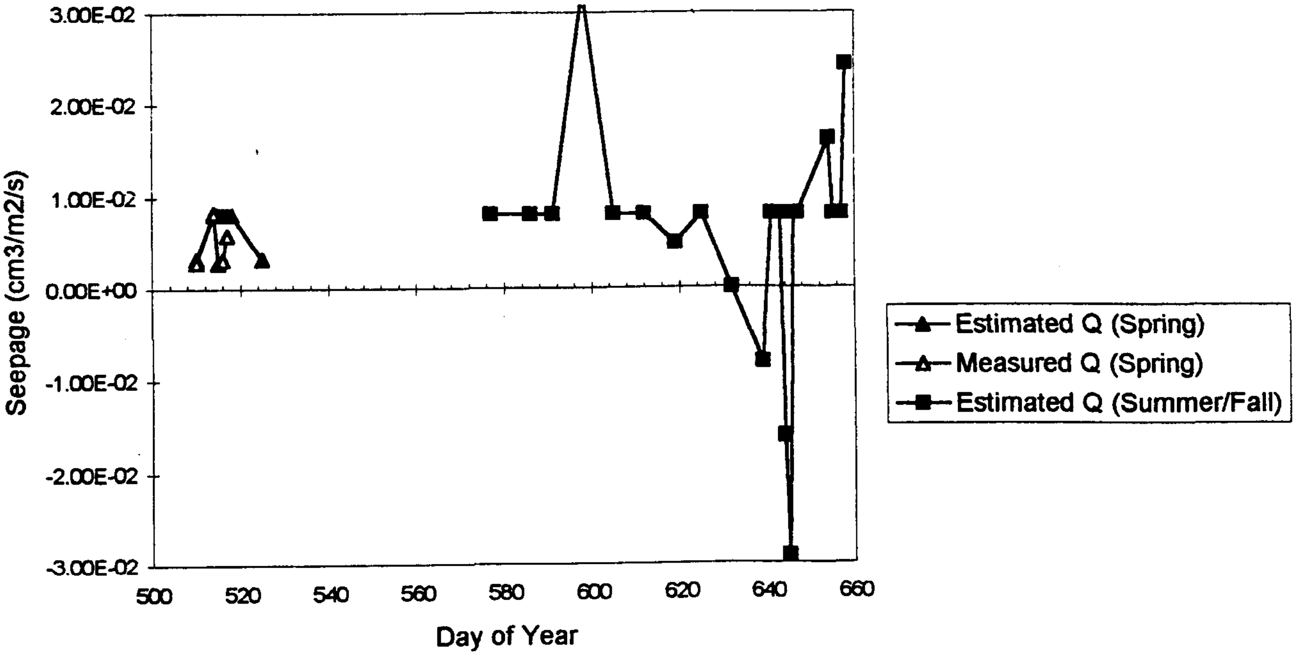


Weighted Mean K = 2.77 x 10E-4 cm/s

Figures 5 and 6

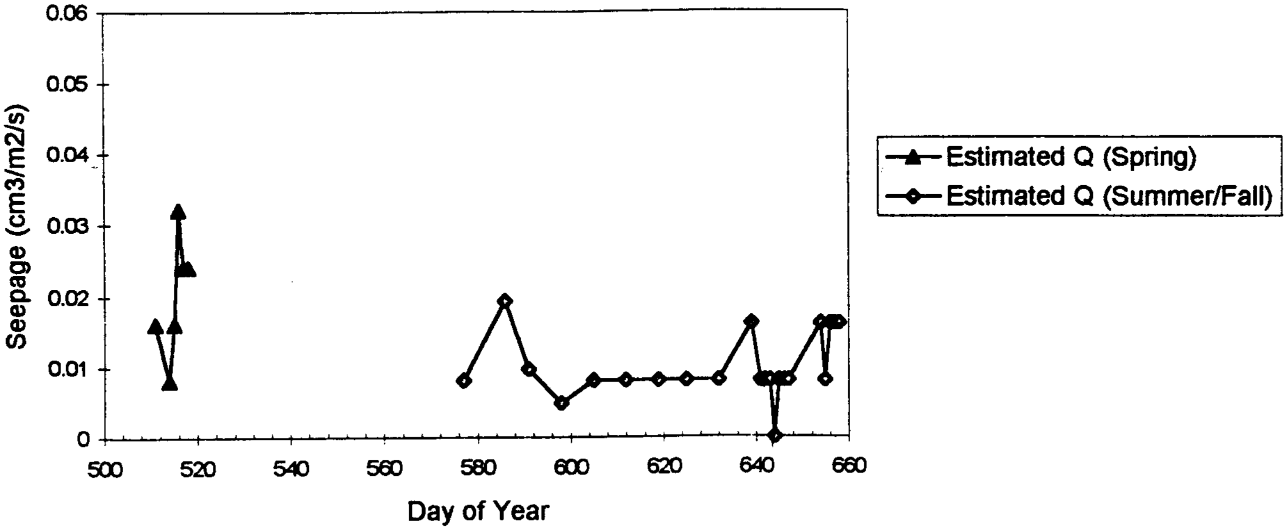

Estimated GW Seepage vs Time (1995)
Site #5 (Piez #28) 1st Set

Weighted Mean K: 9.55E-5 cm/s

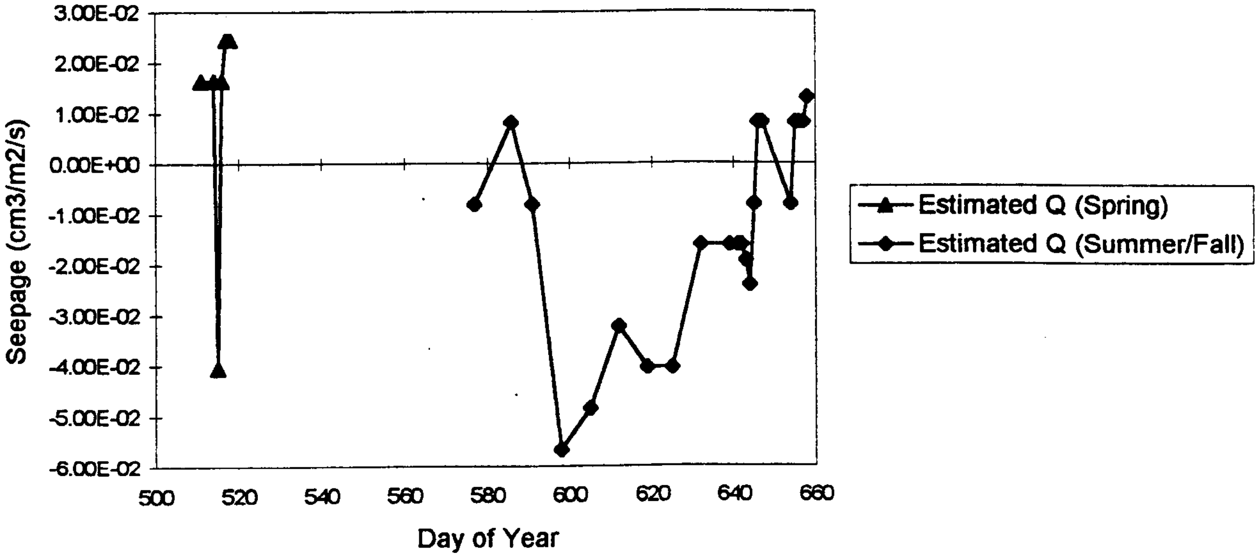

Estimated GW Seepage vs Time (1995)
Site #5 (Piez #29) 1st Set

Figures 7 and 8

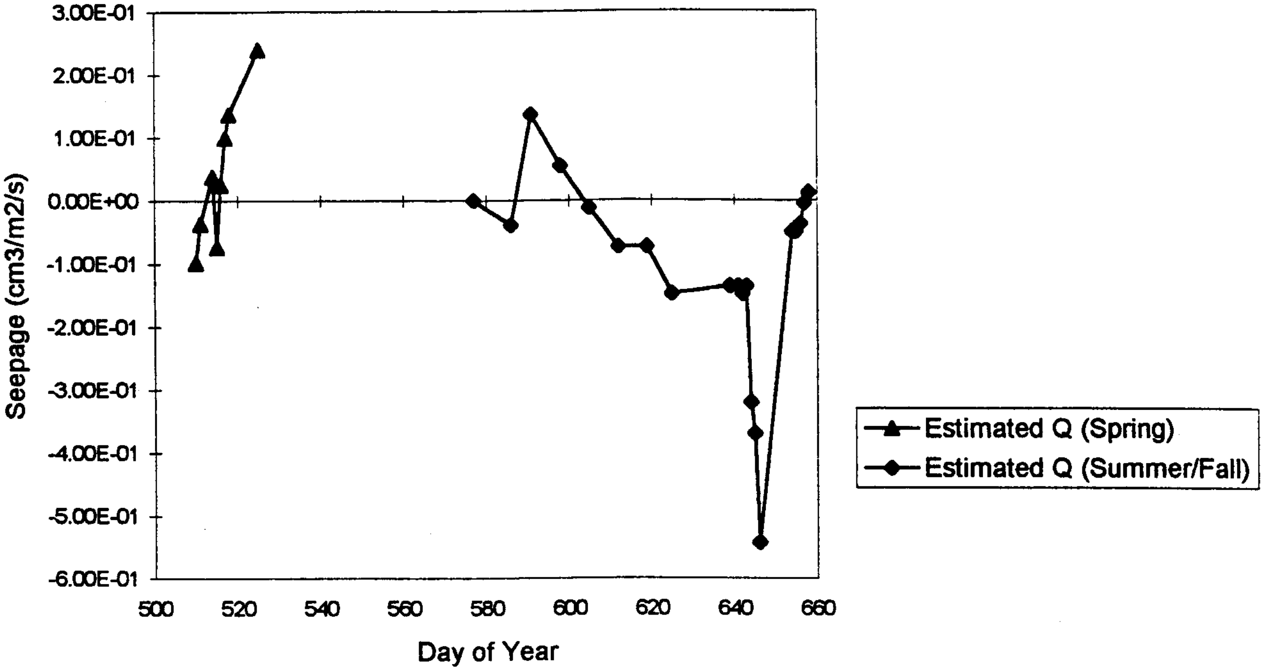
Estimated GW Seepage vs Time (1995)
Site #5 (Piez #30) 2nd Set



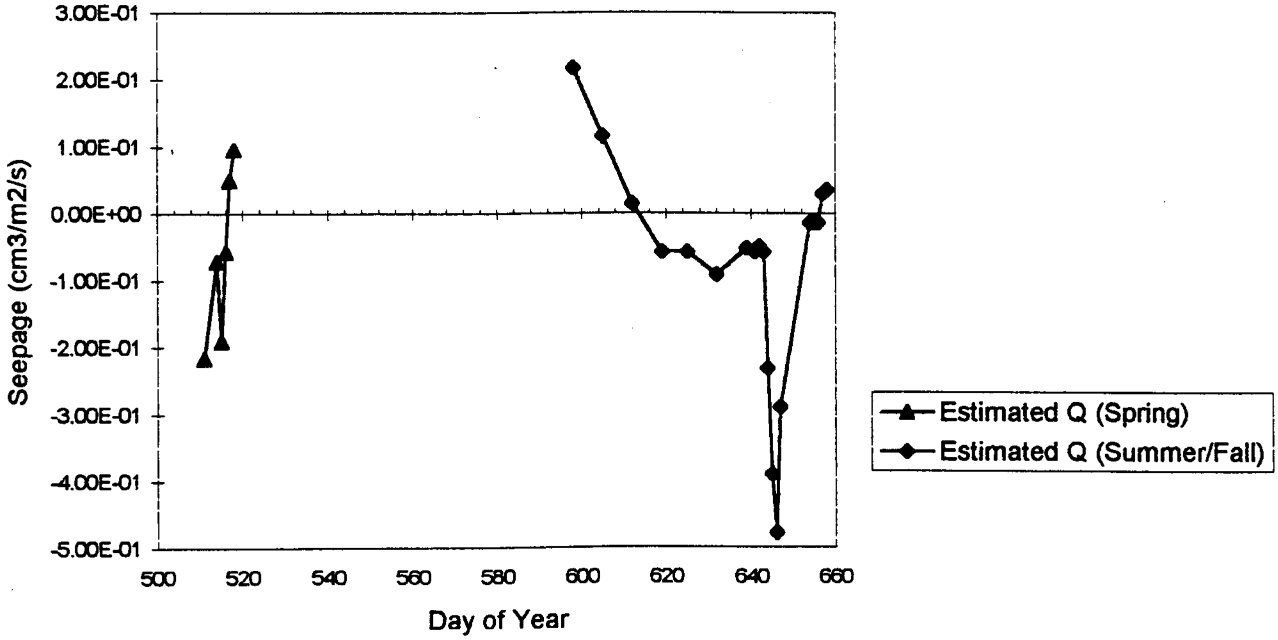
Estimated GW Seepage 1995
Site #5 (Piez #31) 2nd Set

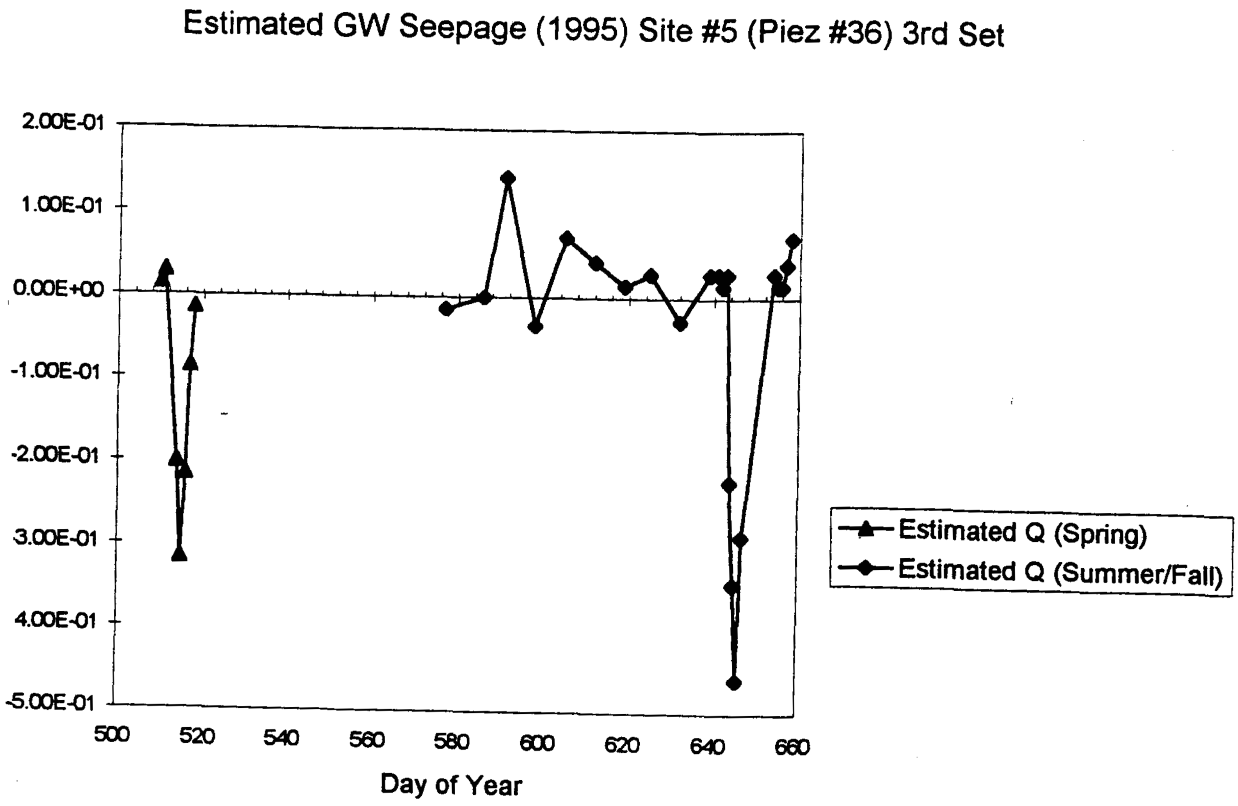


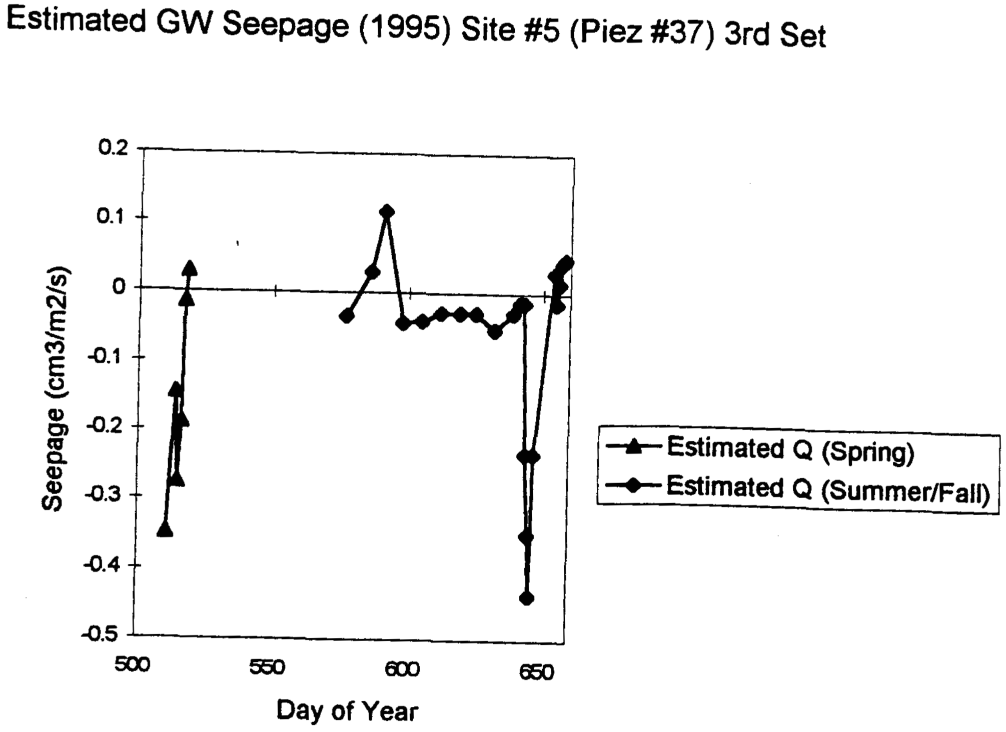
Estimated GW Seepage (1995) Site #5 (Piez #32) 2nd Set



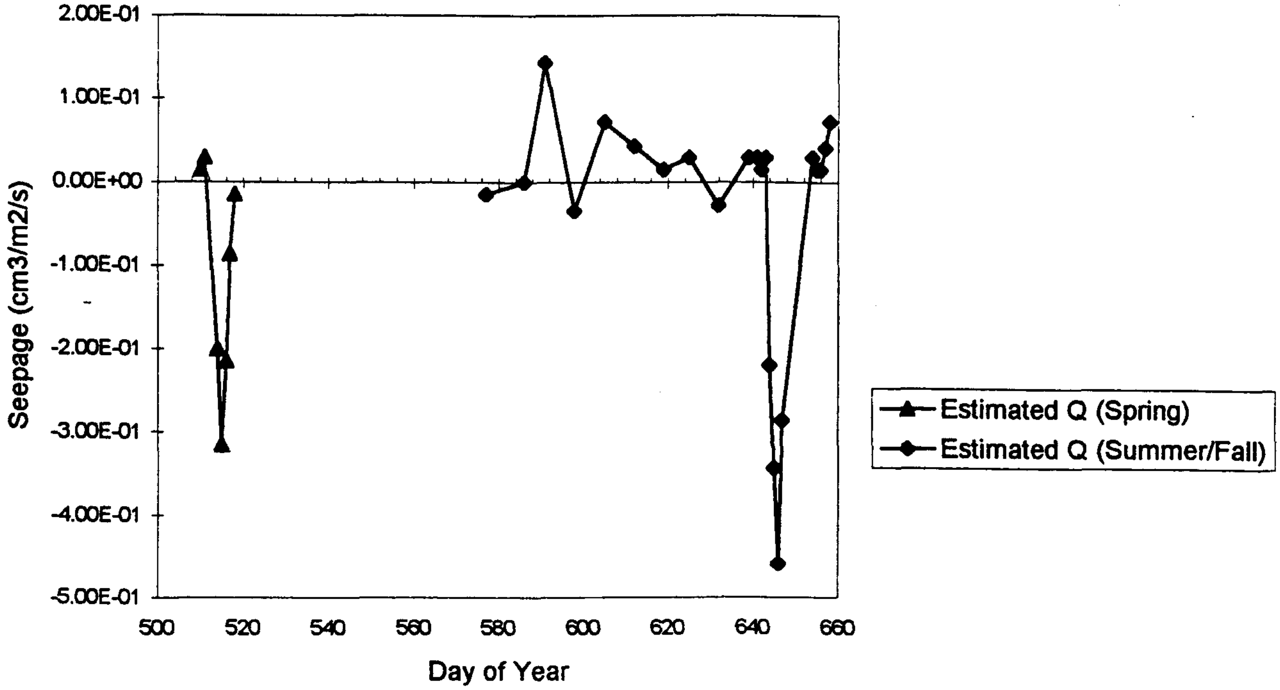
Estimated GW Seepage (1995) Site #5 (Piez #33) 2nd Set



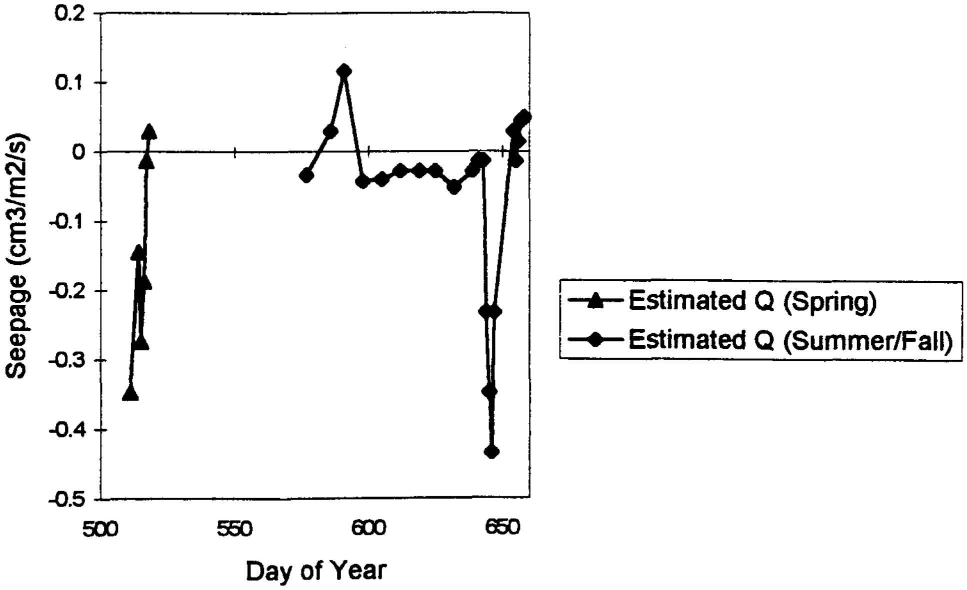

Estimated GW Seepage (1995) Site #5 (Piez #36) 3rd Set
2.00E-01
1.00E-01
0.00E+00
-1.00E-01
-2.00E-01
3.00E-01
4.00E-01
-5.00E-01
500
520
540
560
580
600
620
640
660
Day of Year
Estimated Q (Spring)
Estimated Q (Summer/Fall)


Estimated GW Seepage (1995) Site #5 (Piez #37) 3rd Set
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
Seepage (cm3/m2/s)
500
550
600
650
Day of Year
Estimated Q (Spring)
Estimated Q (Summer/Fall)

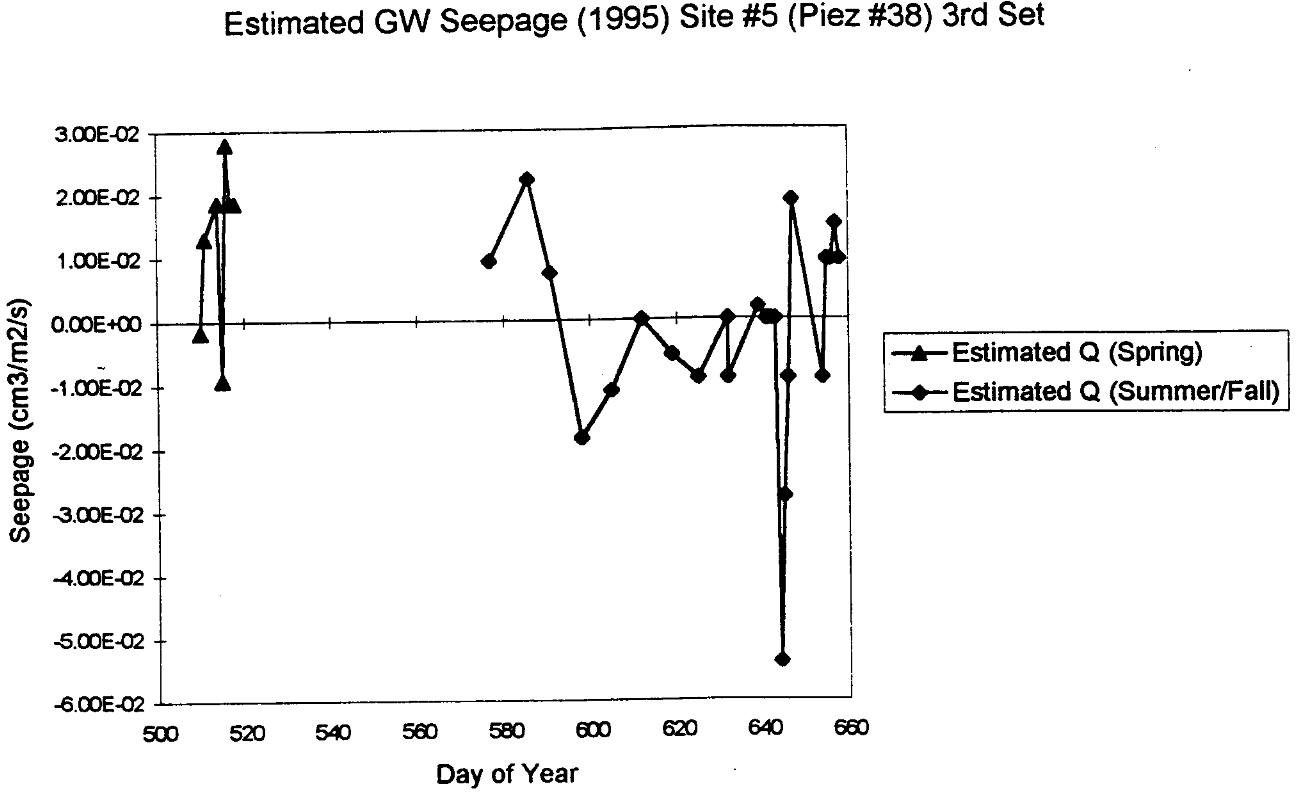
Estimated GW Seepage (1995) Site #5 (Piez #36) 3rd Set

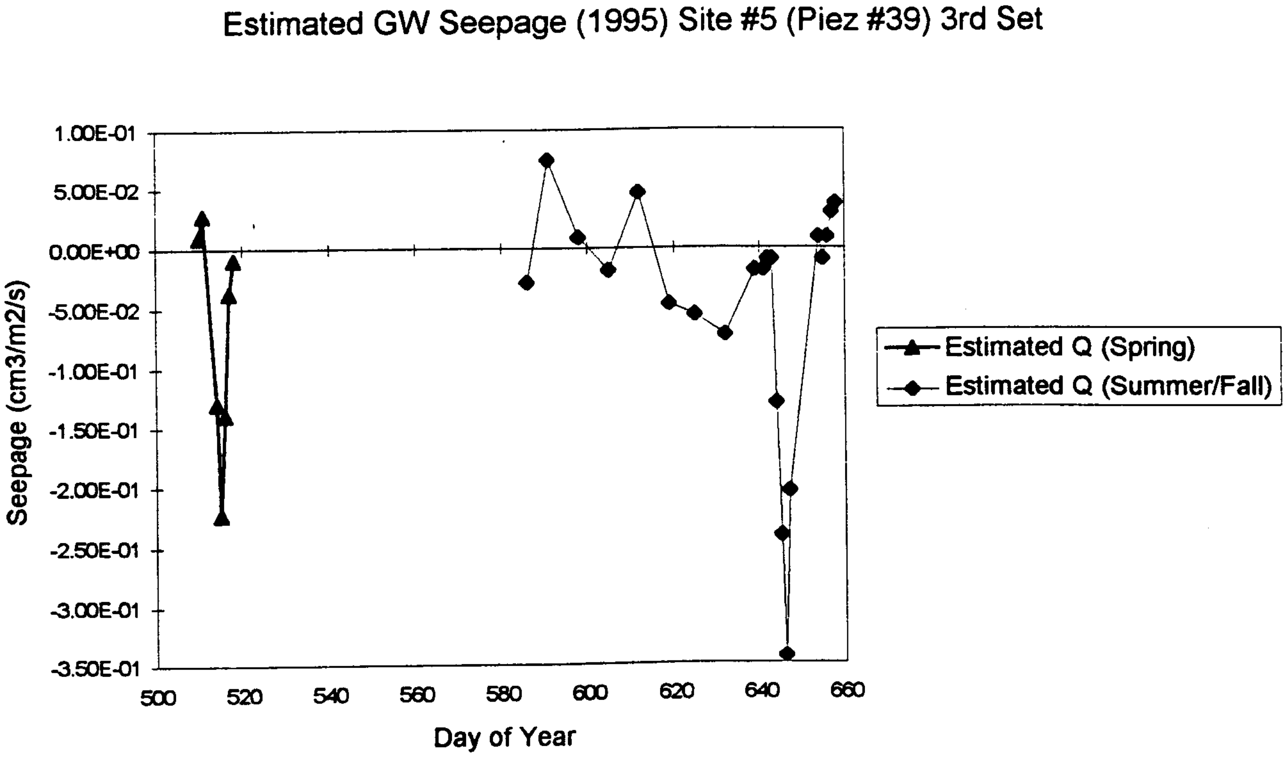


Estimated GW Seepage (1995) Site #5 (Piez #37) 3rd Set

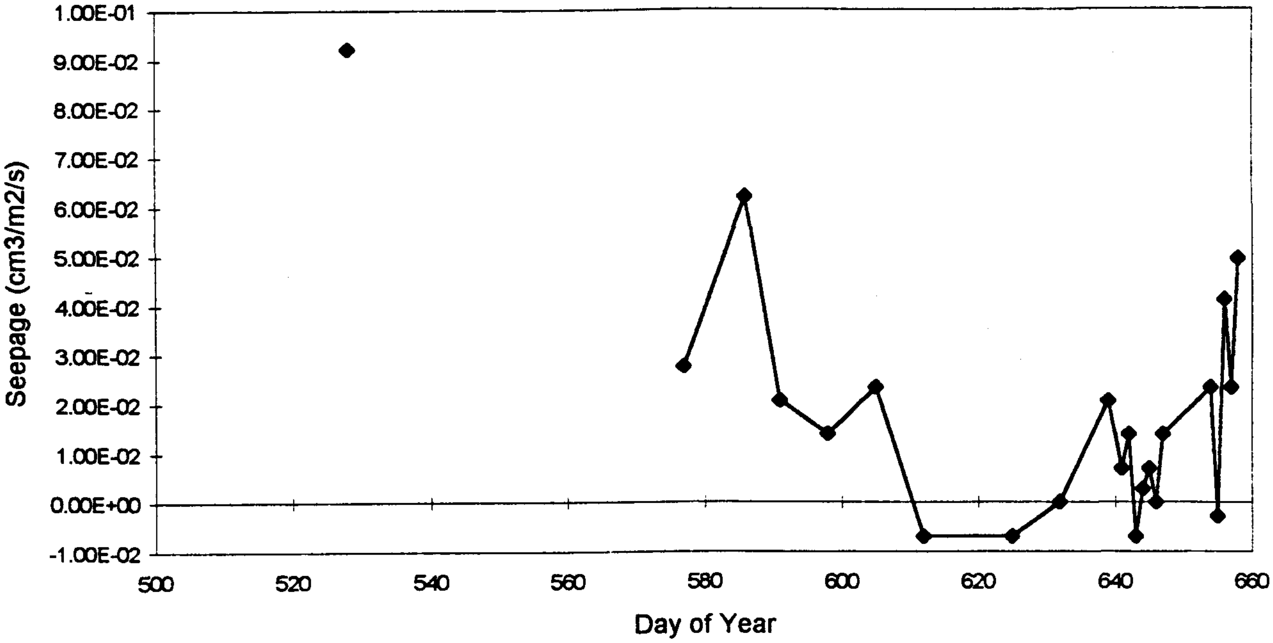


Figures 15 and 16



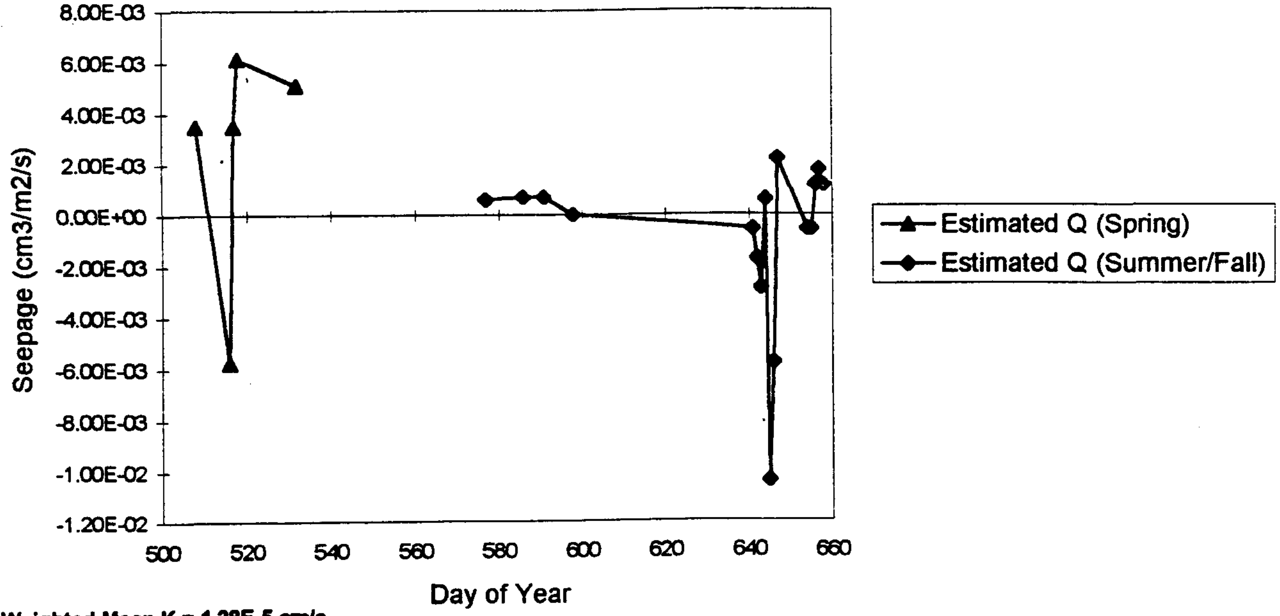


Figures 17 and 18 Estimated GW Seepage (1995) Site #7 (Piez #43)



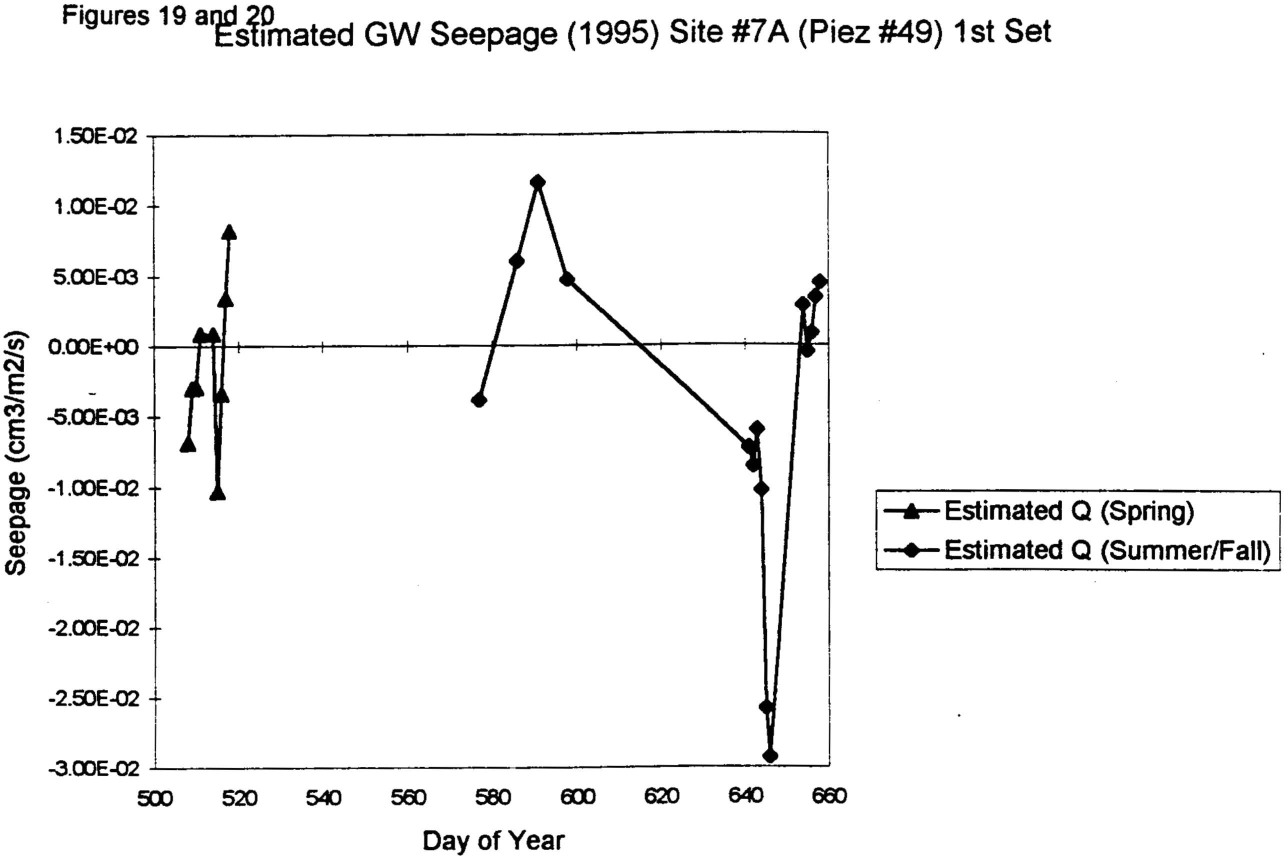
Weighted Mean K = 1.43E-4 cm/s

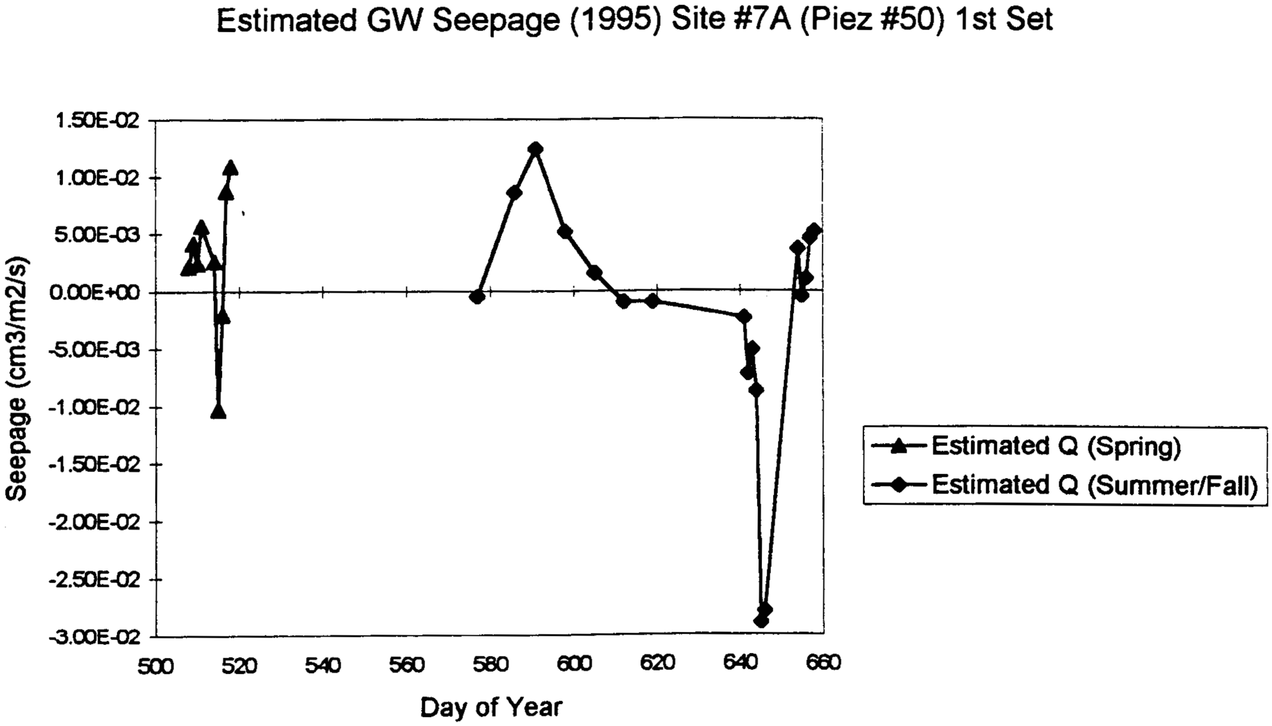
Estimated GW Seepage (1995) Site #7A (Piez #48) 1st Set



Weighted Mean K = 1.28E-5 cm/s

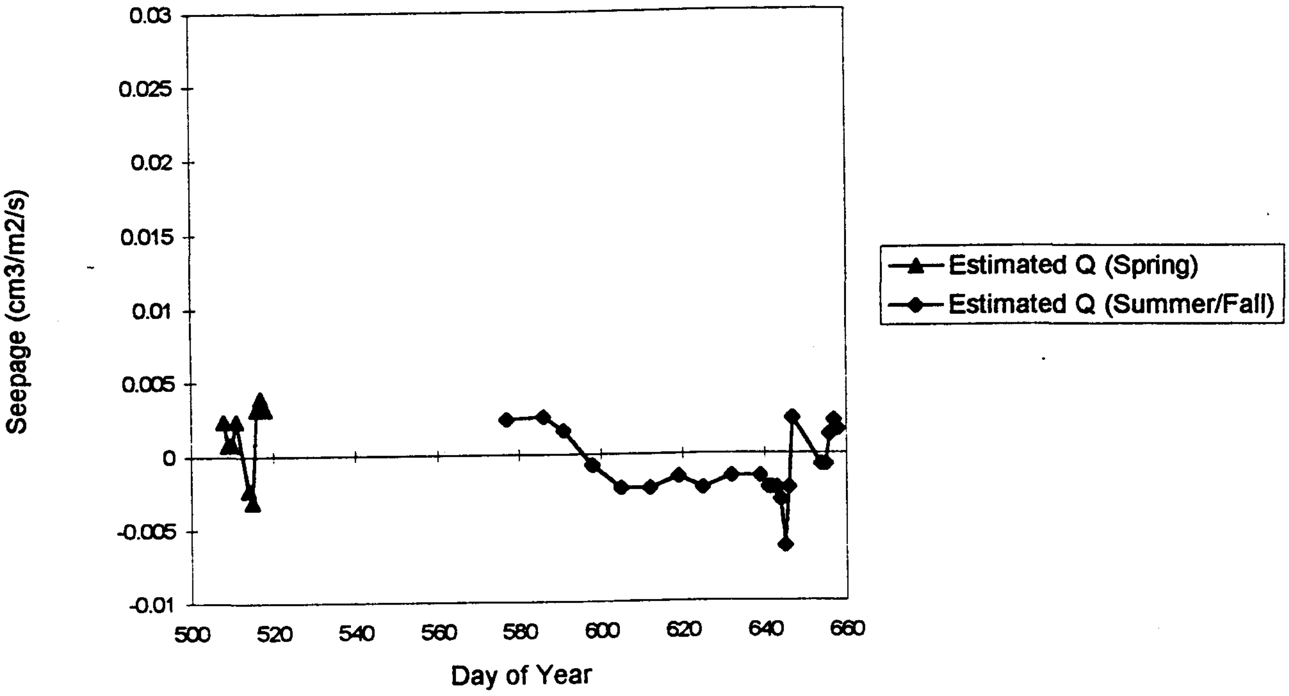
Figures 19 and 20



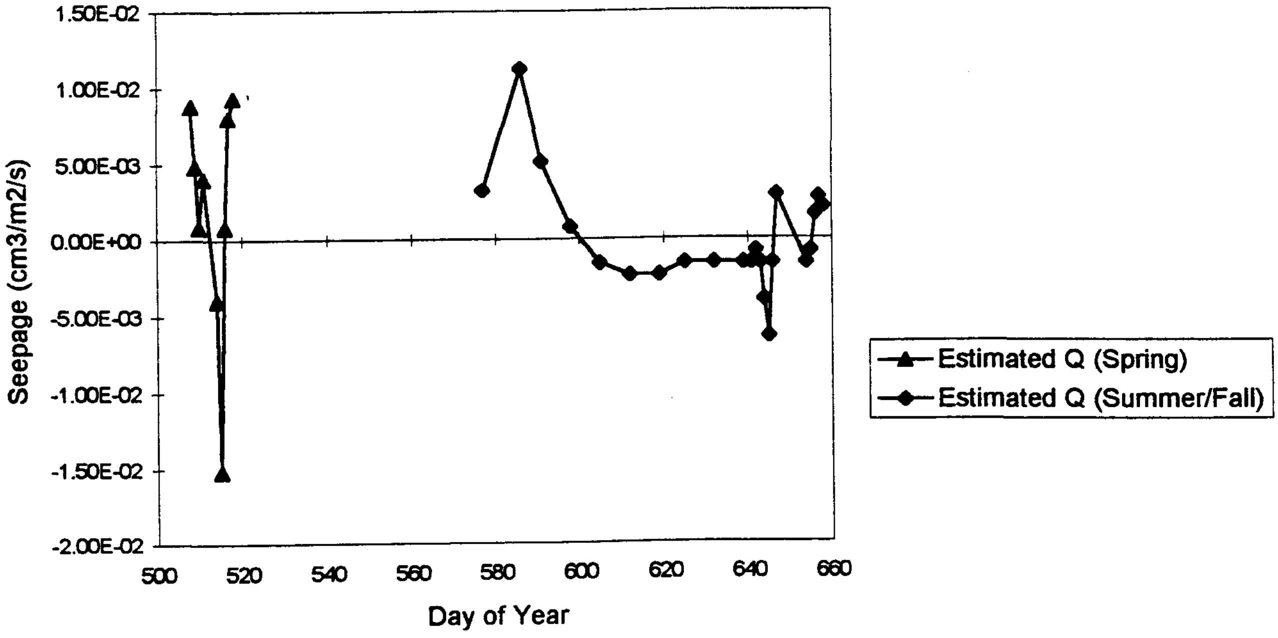


Figures 21 and 22

Estimated GW Seepage (1995) Site #7A (Piez #51) 1st Set

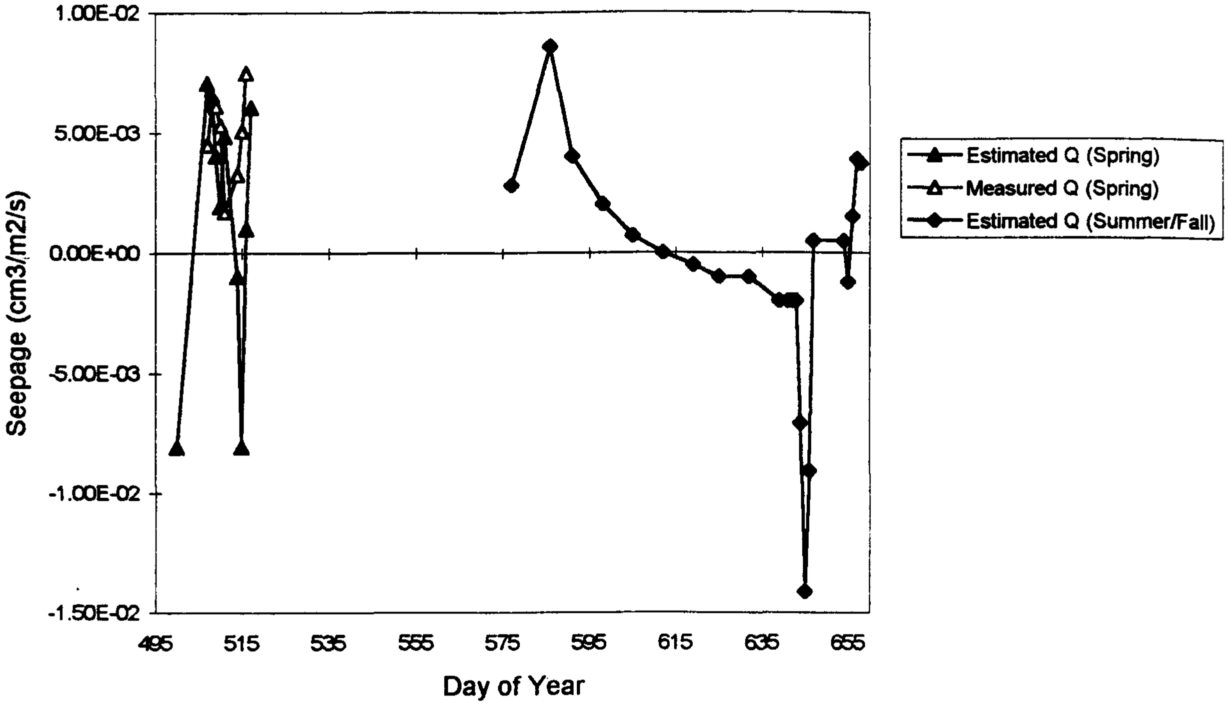


Estimated GW Seepage (1995) Site #7A (Piez #52) 1st Set

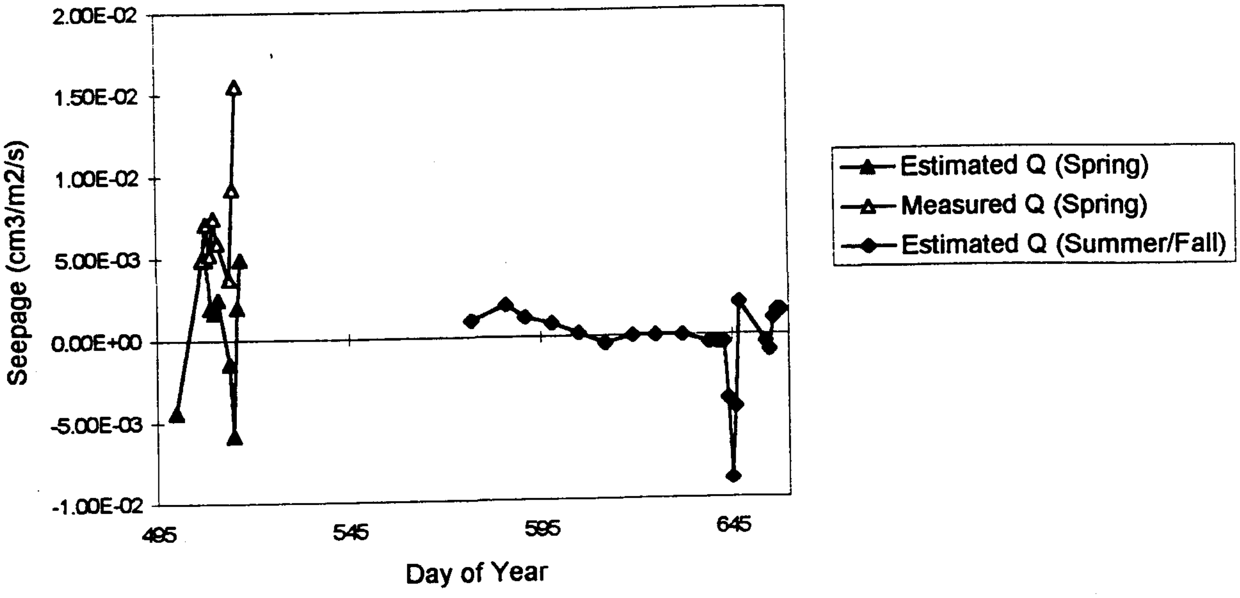


Figures 23 and 24

Estimated GW Seepage (1995) Site #7A (Piez #53) 2nd Set

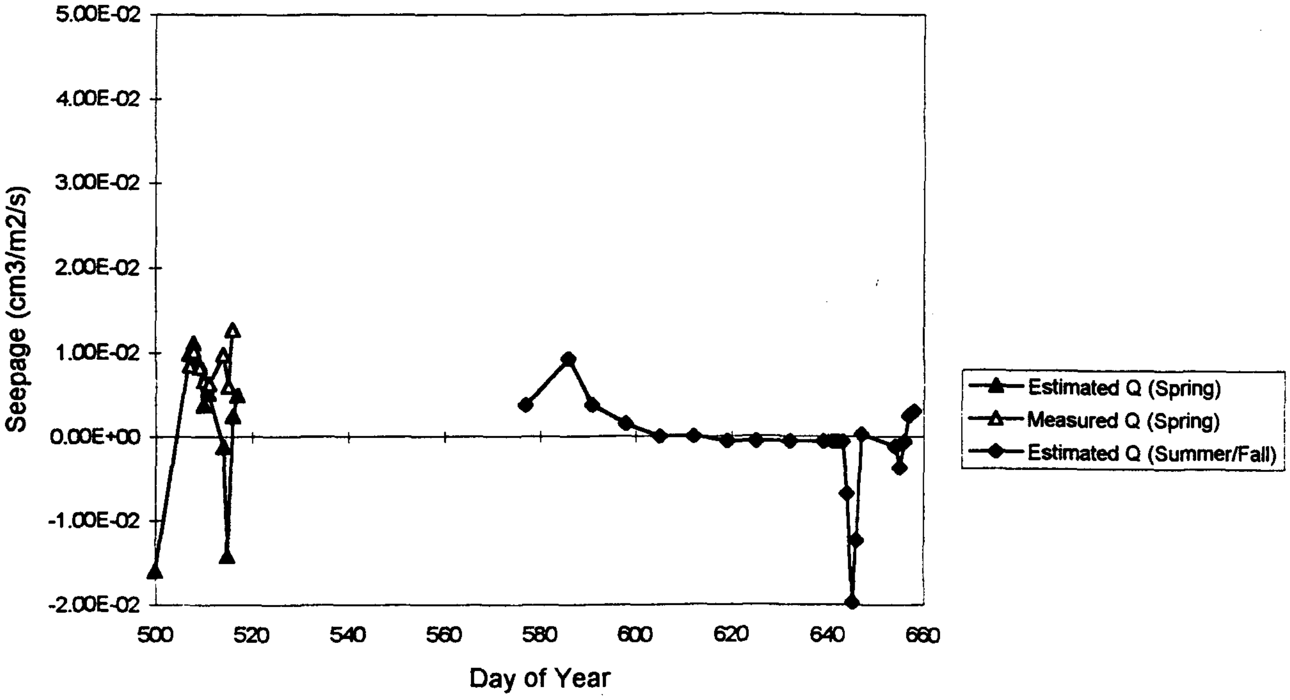


Estimated GW Seepage (1995) Site #7A (Piez #54) 2nd Set

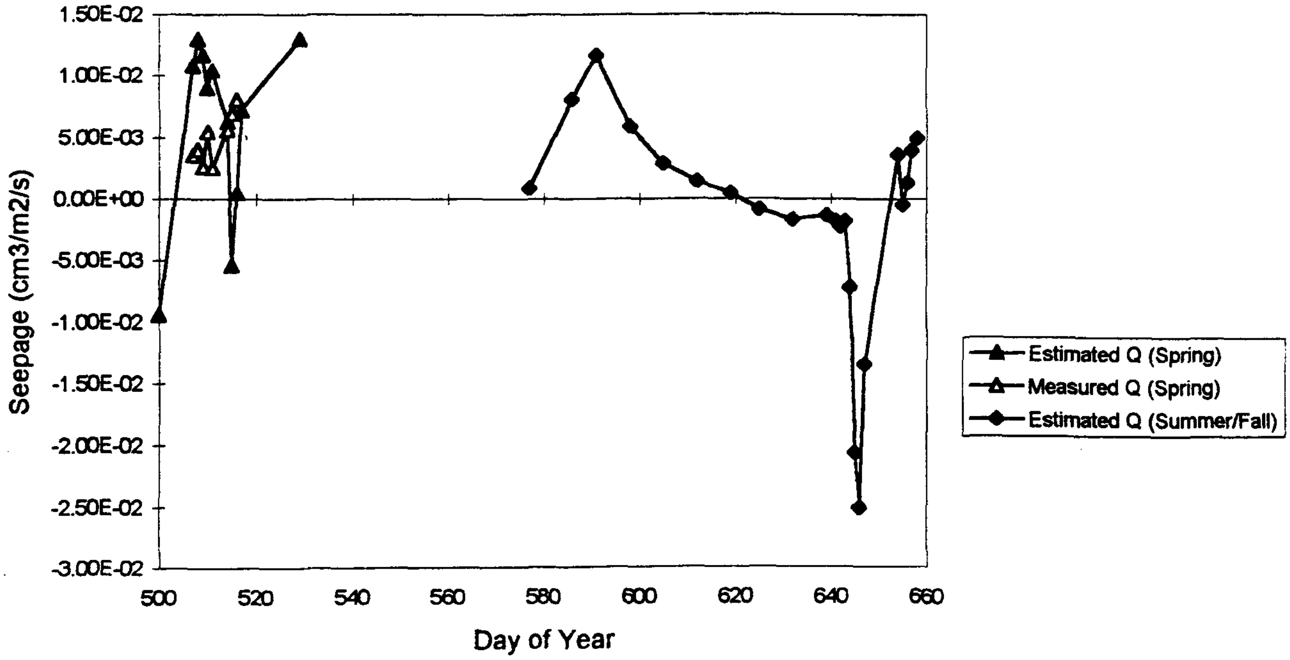


Figures 25 and 26

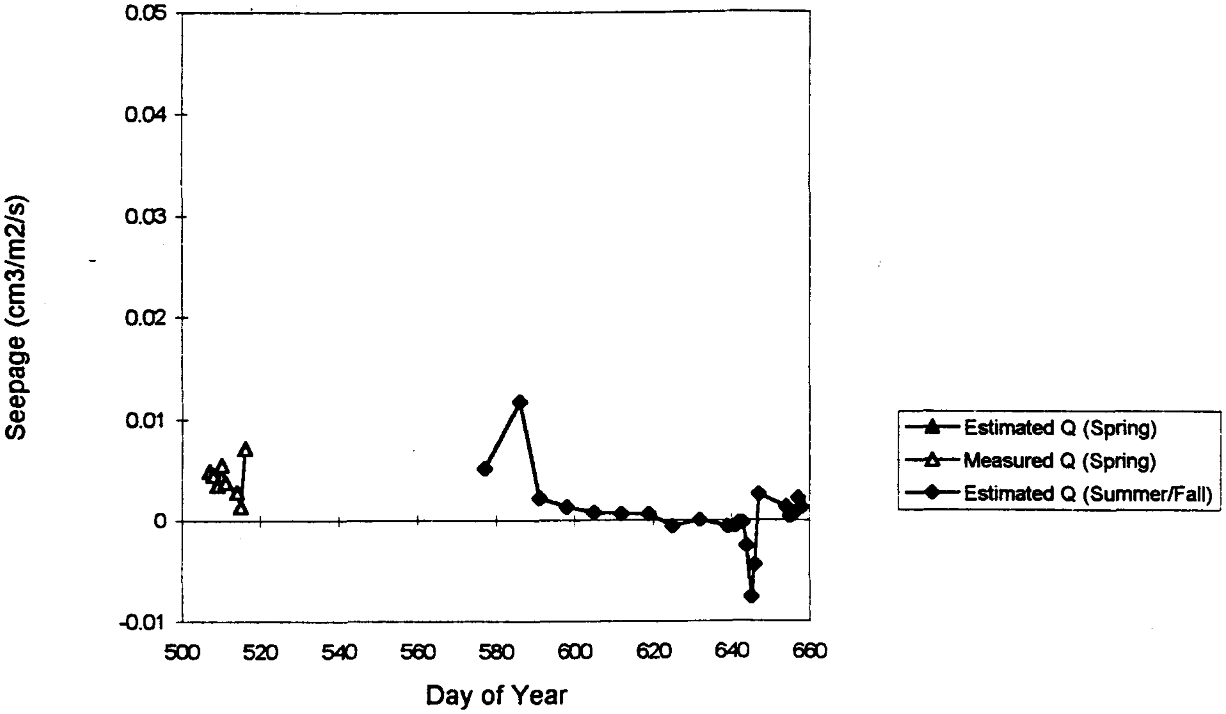
Estimated GW Seepage (1995) Site #7A (Piez #55) 2nd Set



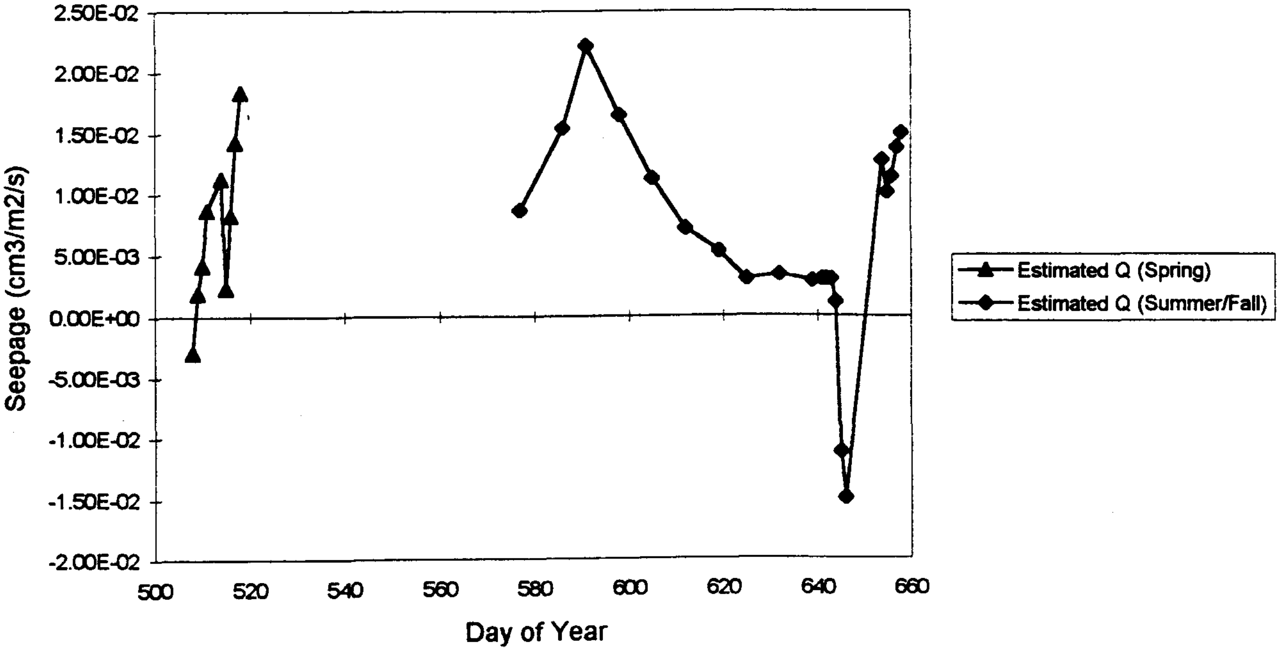
GW Seepage (1995) Site #7A (Piez #56) 2nd Set



Figures 27 and 28



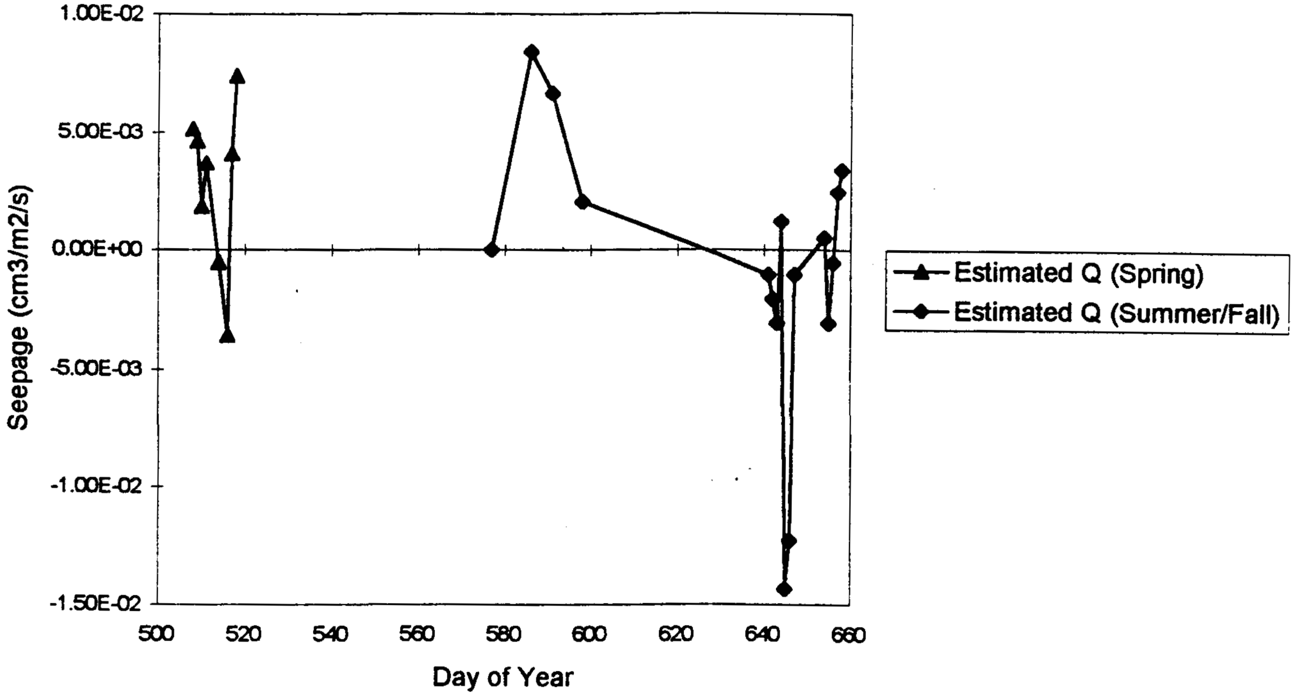
Estimated GW Seepage (1995)
Site #7A (Piez #57) 2nd Set



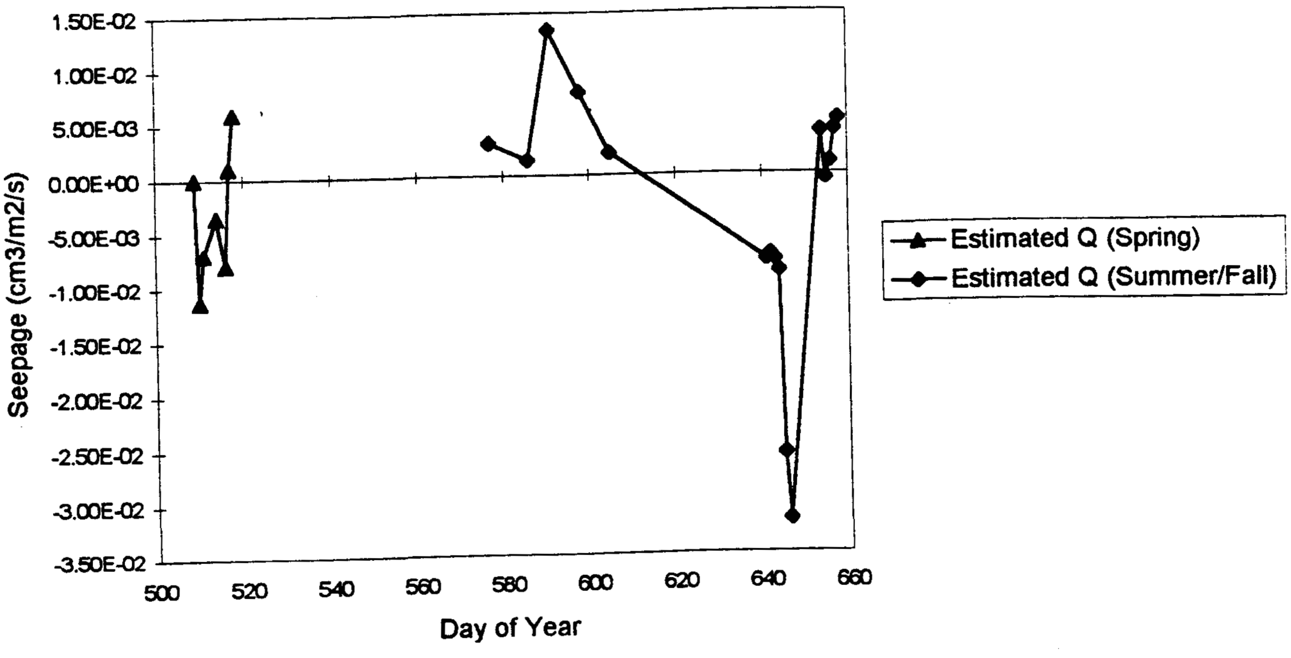
Estimated GW Seepage (1995) Site #7A (Piez #58) 3rd Set

Figures 29 and 30

Estimated GW Seepage (1995) Site #7A (Piez #59) 3rd Set

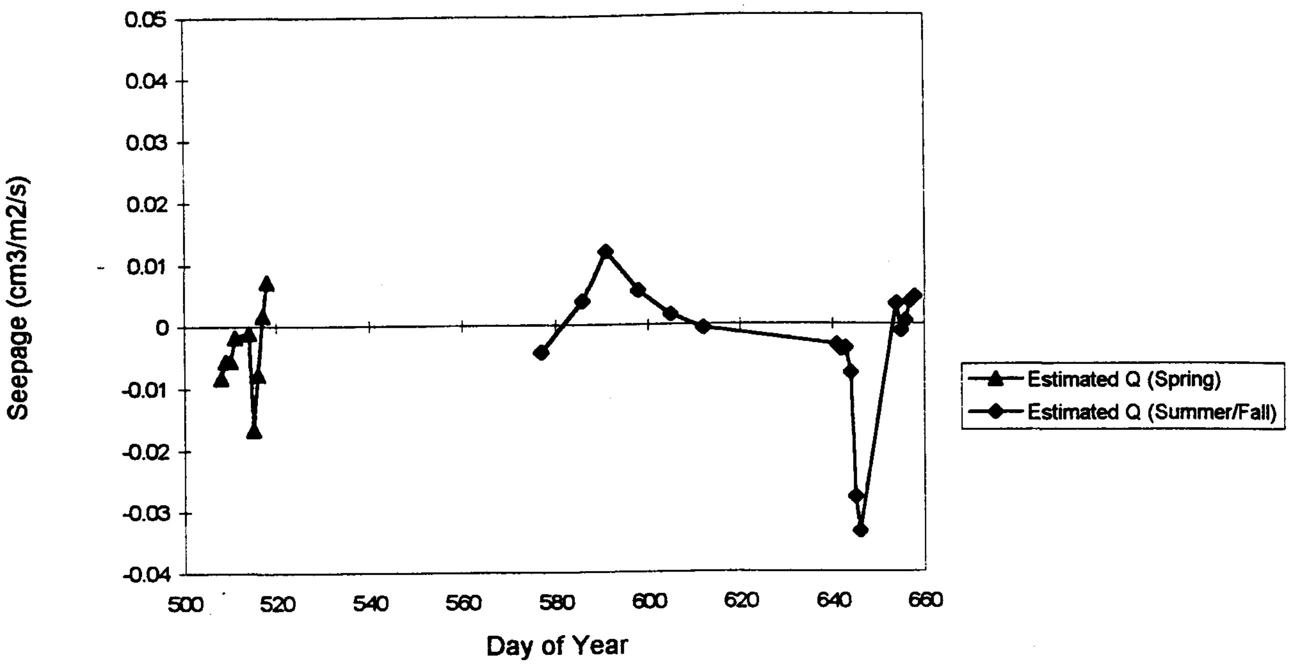


Estimate GW Seepage (1995) Site #7A (Piez #60) 3rd Set

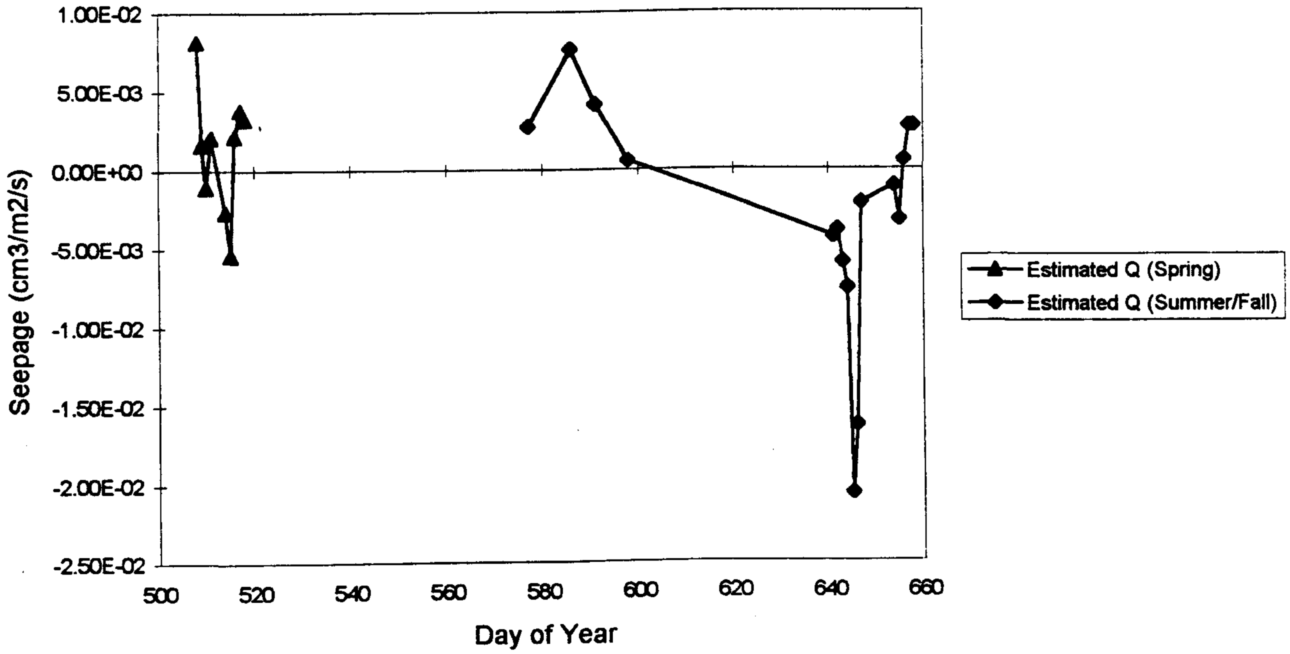


Figures 31 and 32

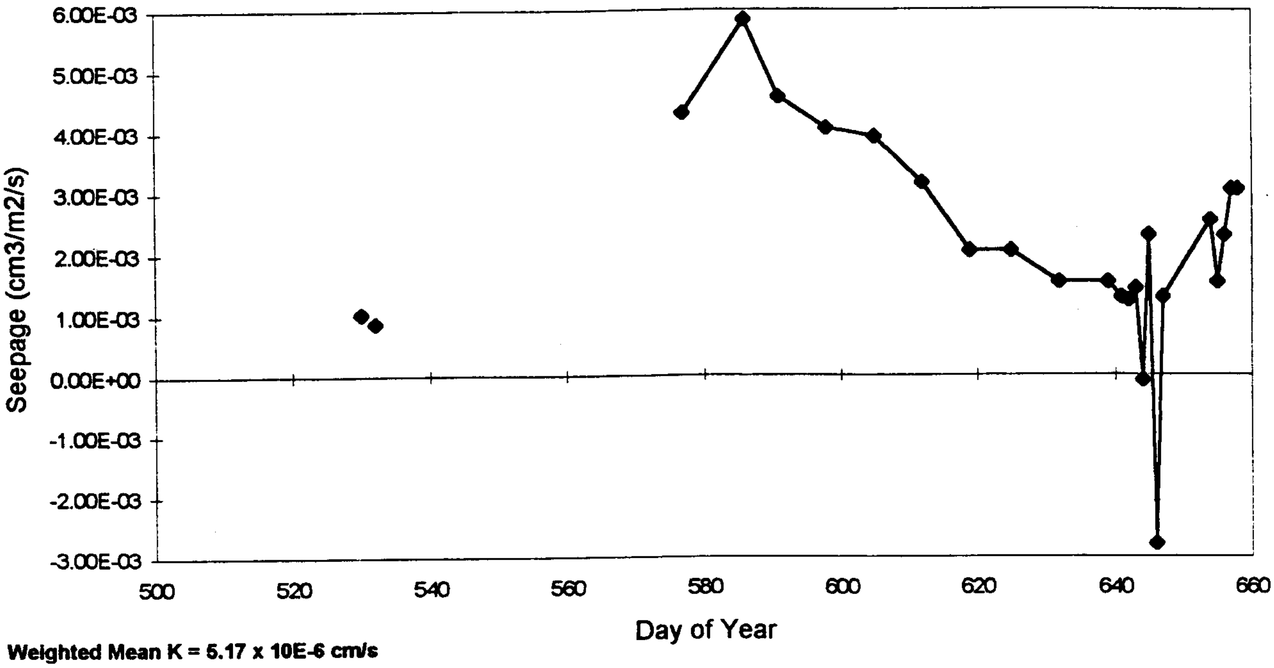
Estimated GW Seepage (1995) Site #7A (Piez #61) 3rd Set



Estimated GW Seepage (1995) Site #7A (Piez #62) 3rd Set

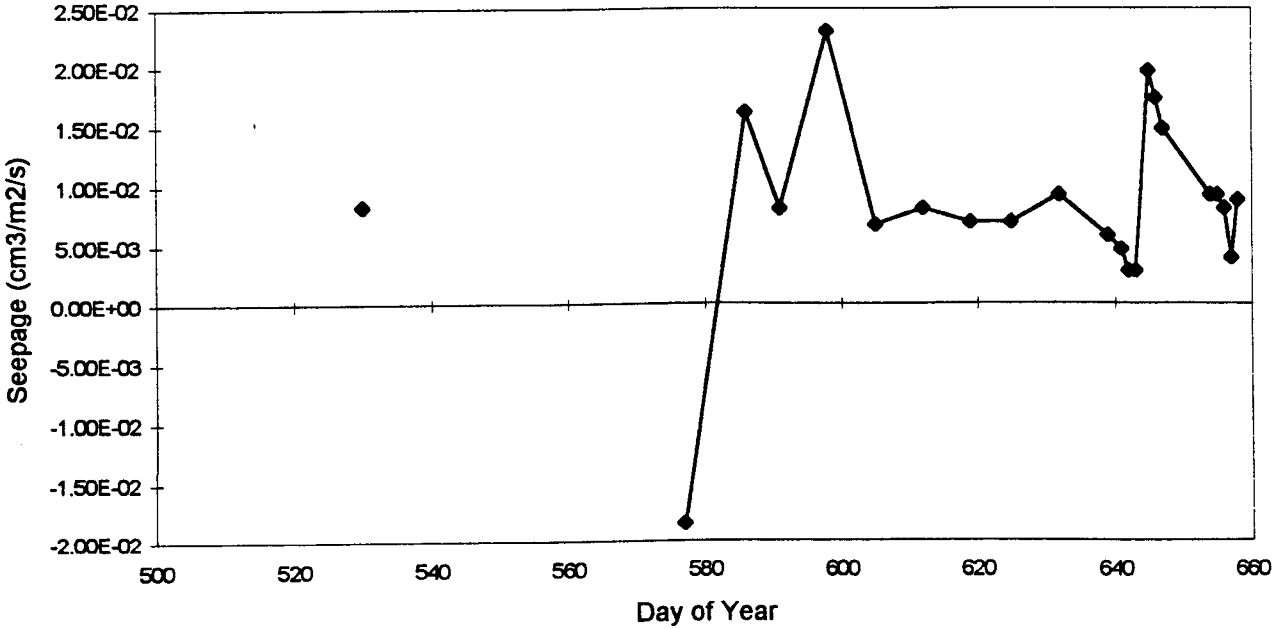


Figures 33 and 34



Estimated GW Seepage (1995) Site #8 (Piez #64)

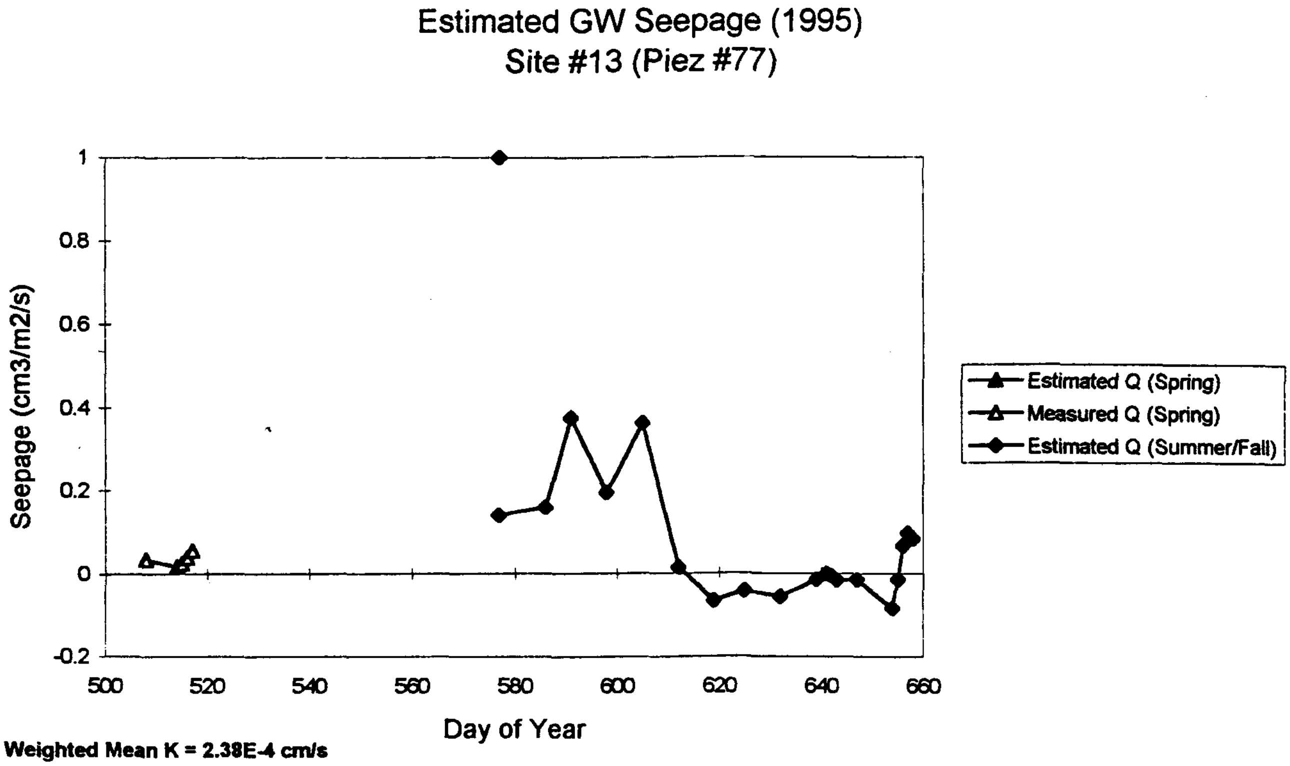
Weighted Mean K = 5.17 x 10E-6 cm/s



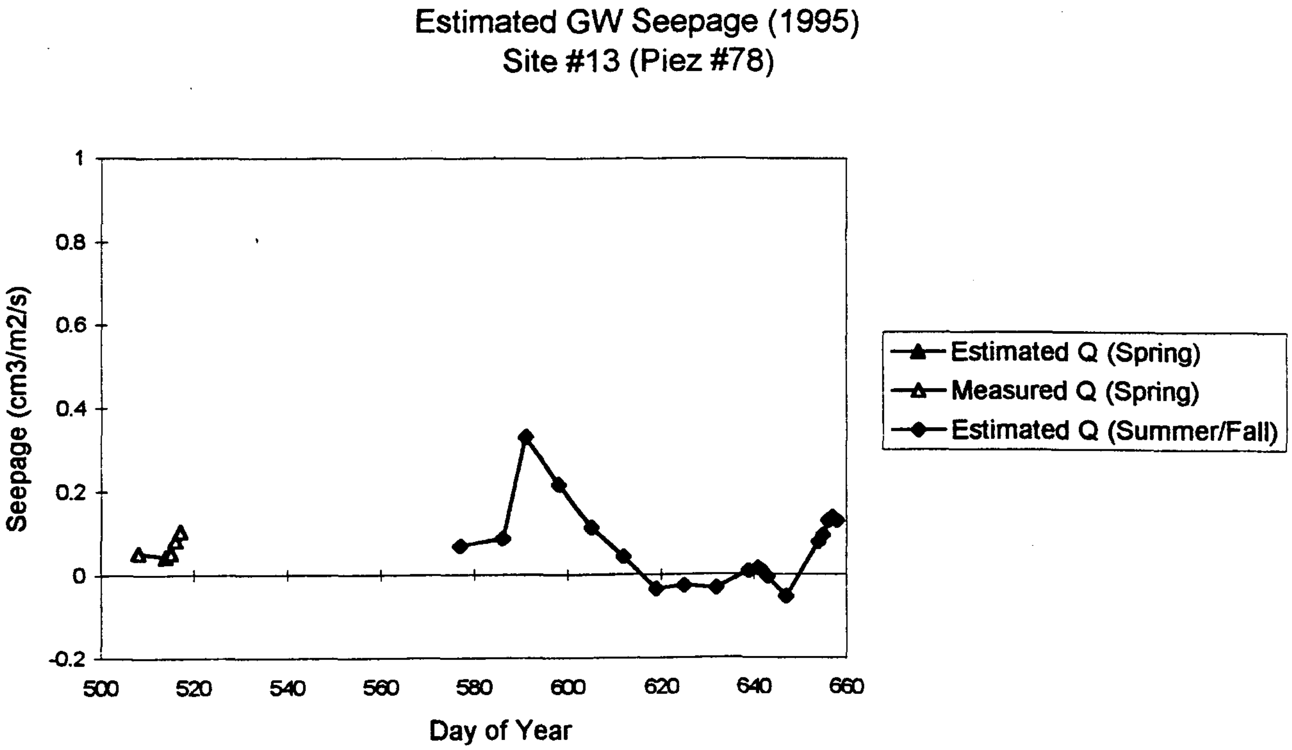
Estimated GW Seepage (1995) Site #12 (Piez #73)

Weighted Mean K = 3.44 x 10E-5 cm/s

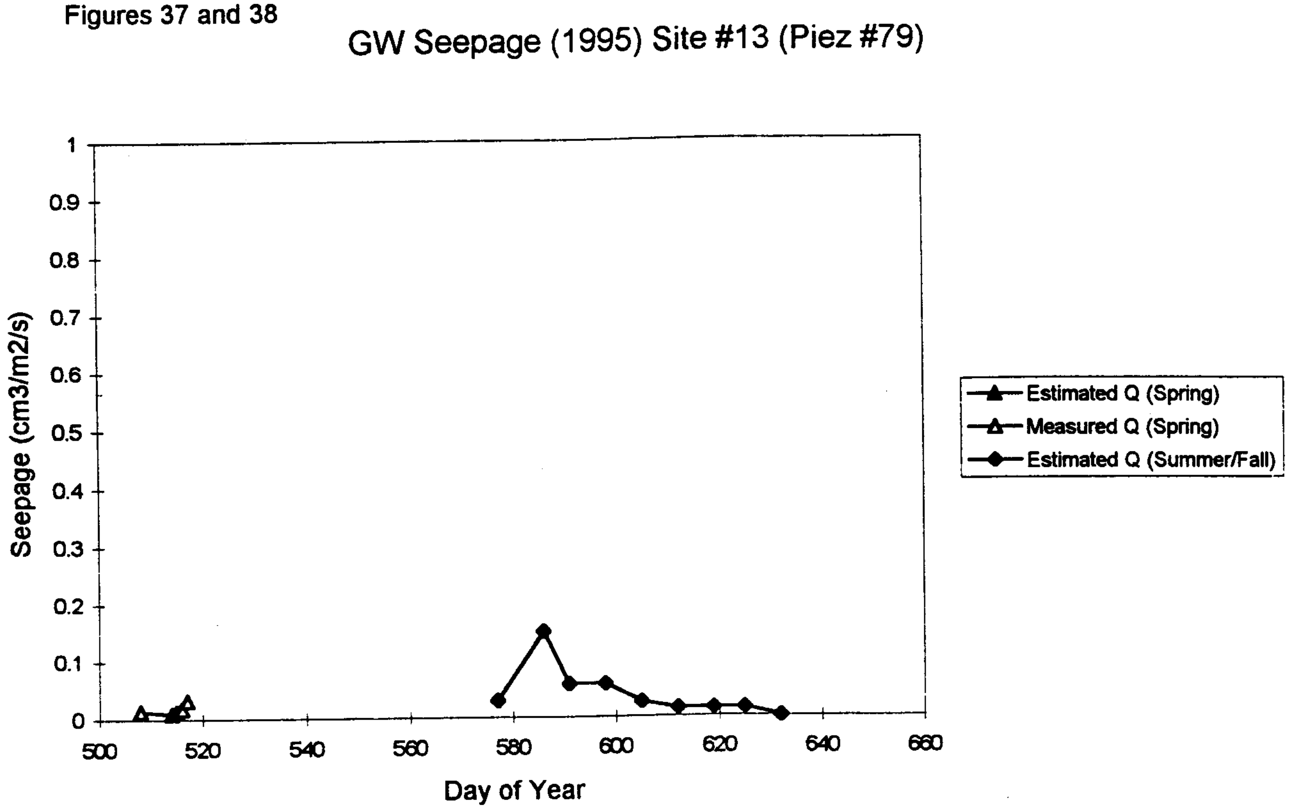
Figures 35 and 36

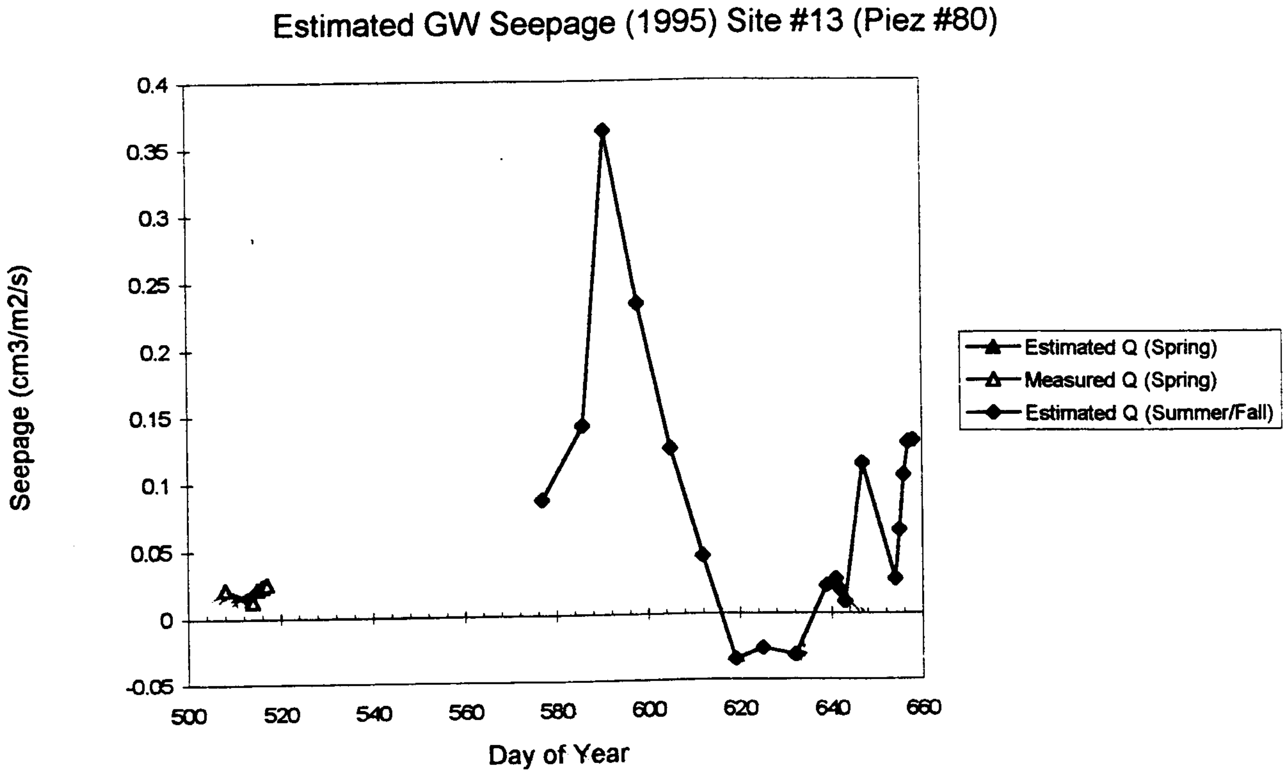


Weighted Mean K = 2.38E-4 cm/s



Figures 37 and 38





A2.6 ANOVA Results for comparison of seepage flux measurements and estimates

Direct seepage flux measurements were compared to seepage fluxes estimated from hydraulic gradients and hydraulic conductivity values at site nos. 5, 7A, and 13 using ANOVA's. The results are discussed in Chapter 4, (Section 4.5.4)

In the statistical model, seepage flux is the dependent variable and the independent variables are "Day" (time) and "type", either "Dir" (direct measurement) or "Est" (estimated value). The model is factorial (2-way) and without interaction. "Day" is treated as a random block variable to remove its effect on the type of measurement.

Site No. 5:

```
TYPES$
  Dir           Est

 DEP VAR: SEEPAGE      N:       48  MULTIPLE R: 0.135  SQUARED MULTIPLE R: 0.018

                         ANALYSIS OF VARIANCE

 SOURCE        SUM-OF-SQUARES   DF  MEAN-SQUARE      F-RATIO        P

 TYPES$              0.00000     1       0.00000    0.00012      0.99131
 DAY                 0.00155     1       0.00155    0.83088      0.36688

 ERROR               0.08419    45       0.00187
```

Site No. 7A:

```
 TYPES$
  Dir           Est

 DEP VAR: SEEPAGE      N:       80  MULTIPLE R: 0.325  SQUARED MULTIPLE R: 0.105

                         ANALYSIS OF VARIANCE

 SOURCE        SUM-OF-SQUARES   DF  MEAN-SQUARE      F-RATIO        P

 TYPES$             0.000006     1      0.000006   0.138236     0.711062
 DAY                0.000404     1      0.000404   8.925038     0.003772
```

```
ERROR                0.003485   77      0.000045
```

Site No. 13:

```
TYPE$
  Dir           Est

DEP VAR: SEEPAGE       N:        28  MULTIPLE R: 0.656  SQUARED MULTIPLE R: 0.430

                             ANALYSIS OF VARIANCE

SOURCE        SUM-OF-SQUARES   DF  MEAN-SQUARE      F-RATIO        P

TYPE$              0.006545     1    0.006545     0.857997     0.363156
DAY                0.137597     1    0.137597    18.038488     0.000262

ERROR              0.190699    25    0.007628
```

For all three sites, there was no significant difference between methods (as indicated by the large p values).

A2.7 Estimation of Error on Seepage Flux Measurements from ANOVA

This section contains seepage flux measurements made in the Spring of 1995 and the ANOVA's used to describe the error or variability of the measurements. The results are discussed in Chapter 4, section 4.3.3.

Table 3 - Spring 1995 Groundwater Seepage Flux Results (SM = seepage meter)

Day[5]	Seepage Measurements (m^3/m^2s) - Spring 1995 Seepage Meters (SM): 1 to 5				
Site no. 5	**SM1**	**SM2**	**SM3**	**SM4**	**SM5**
510	1.23×10^{-8}	6.72×10^{-9}	1.36×10^{-8}	1.19×10^{-8}	na
514	4.52×10^{-9}	3.35×10^{-9}	6.11×10^{-9}	6.86×10^{-9}	7.72×10^{-9}
515	6.38×10^{-9}	3.76×10^{-9}	7.52×10^{-9}	8.23×10^{-9}	1.07×10^{-8}
516	2.06×10^{-9}	-2.30×10^{-9}	3.29×10^{-9}	2.29×10^{-9}	8.76×10^{-9}
517	2.89×10^{-9}	8.36×10^{-10}	2.81×10^{-9}	3.19×10^{-9}	5.86×10^{-9}
Site no. 7A					
507	4.51×10^{-9}	4.93×10^{-9}	8.45×10^{-9}	3.54×10^{-9}	4.83×10^{-9}
508	6.22×10^{-9}	7.11×10^{9}	1.02×10^{-8}	4.01×10^{-9}	4.46×10^{-9}
509	6.13×10^{-9}	5.23×10^{9}	8.26×10^{-9}	2.60×10^{-9}	3.46×10^{-9}
510	5.43×10^{-9}	7.46×10^{9}	6.67×10^{-9}	5.45×10^{-9}	5.49×10^{-9}
514	1.70×10^{-9}	5.93×10^{9}	6.33×10^{-9}	2.53×10^{-9}	3.78×10^{-9}
515	3.26×10^{-9}	3.72×10^{9}	9.78×10^{-9}	5.59×10^{-9}	2.79×10^{-9}
516	5.08×10^{-9}	9.23×10^{9}	6.01×10^{-9}	6.93×10^{-9}	1.39×10^{-9}
517	7.49×10^{-9}	1.55×10^{-8}	1.27×10^{-8}	8.04×10^{-9}	7.10×10^{-9}
Site no. 13					
508	3.37×10^{-8}	4.33×10^{-8}	1.62×10^{-8}	1.39×10^{-8}	na
514	1.75×10^{-8}	4.29×10^{-8}	1.47×10^{-8}	8.60×10^{-9}	na
515	2.49×10^{-8}	5.18×10^{-8}	2.15×10^{-8}	1.30×10^{-8}	na
516	3.88×10^{-8}	8.28×10^{-8}	2.32×10^{-8}	1.77×10^{-8}	na
517	5.54×10^{-8}	1.04×10^{-7}	2.53×10^{-8}	3.20×10^{-8}	na

The ANOVA design used to analyse the above data set is a nested design with repeated measures. The effect of site location is at the highest hierarchal level, and the seepage meter locations are nested within the site locations - both are

---

[5] Days of the year (or Julian Days) were used for ease in graphing temporal data.

January 1 = Day 1, December 31 = Day 365, for 1994

January 1 = Day 366, December 31 = Day 730, for 1995 random variables. The error is estimated from the repeated measures over five days. The ANOVA model is:

$$\mathrm{Rep}_{l(ij)} = \mu + \mathrm{site}_i + \mathrm{MN}_{i(j)} + \epsilon_{l(ij)}$$

where:

μ = the overall mean of seepage flux

site = site location effect

MN = seepage meter location at a given site

ϵ = random error

The ANOVA table produced by Systat is:

```
SITES$
  5         7a        13

 2 CASES DELETED DUE TO MISSING DATA.
 NUMBER OF CASES PROCESSED:  13

 DEPENDENT VARIABLE MEANS (Seepage Flux (cm^3m^-2s^-1))

 R1           R2           R3           R4           R5

 0.014        0.010        0.012        0.015        0.022

 UNIVARIATE AND MULTIVARIATE REPEATED MEASURES ANALYSIS

 BETWEEN SUBJECTS
 ----------------

 SOURCE                  SS         DF        MS               F            P

 SITE$                    0.011      2         0.005         7.489        0.010
 ERROR                    0.007     10      .728987E-03

 WITHIN SUBJECTS
 ---------------

 SOURCE                   SS         DF           MS           F        P          G-G      H-F

 temporal                 0.001       4   .291027E-03     7.830   .9E-04     0.010    0.005
 temporal*SITES$          0.002       8   .259956E-03     6.994   .1E-04     0.006    0.002
 ERROR                    0.001      40   .371666E-04
```

In the ANOVA table the mean squared deviations (MS) are the basis from which variance components caused by the factors examined are obtained. In this case, the error on seepage flux measurements (excluding temporal and spatial variation), is given by the Error MS. Thus the error on seepage measurements, expressed as variance, is 3.72×10^{-5} with 40 degrees of freedom (df).

Appendix 3

A3.1 ANOVA Results for Hydraulic Gradients Compared by Piezometer Set (Sites no. 5 and 7A) and by Piezometer (Site 13)

Hydraulic gradients were measured on several piezometers at three sites. Site no. 5 had 3 sets of 5 piezometers; site no. 7A had 3 sets of 5 piezometers; and site no. 13 had 1 set of 4 piezometers. At each site, the sets of piezometers were separated by 10 m along the course of the river, and within each set the distance between each piezometer was approximately 3 m. The set location and piezometer location within each set were selected based on sampling locations chosen by another colleague and landuse characteristics (eg. proximity to cultivated fields). Measurements were made daily over several days.

The data sets for the three sites can be analysed as a nested design with a statistical model, where "Day" is treated as a random block variable:

$$\text{Gradient} = \mu + \text{Set} + \text{Piez (Set)} + \text{Day} + \varepsilon$$

In this model, the error, ε, is evaluated from all the possible interactions between the main variables. The ANOVAs evaluate the variability in gradient measurements caused by the set location, by the piezometer location (within each set) and by the "Day". The effect due to "Day" is included explicitly so that the variability it produces can be removed from the overall variability. The first ANOVA for site no. 5 indicates a significant variability of the hydraulic gradient measurements between sets of piezometers. However, after deleting data from several piezometers believed to be defective, the variability becomes insignificant (p = 0.53). The first test for site no. 7A indicates that there is a significant difference of the hydraulic gradients between sets but not after defective piezometer data was removed (p = 0.46). Site no. 13 was examined for the variability of the hydraulic gradient measurements between the four piezometers and the ANOVA test revealed insignificant variability for piezometer location and time. The ANOVA results, generated in Systat™ are given below. These results are also discussed in Chapter 4 (Section 4.4.1 and 4.4.2)

Site No. 5:

Test 1.

```
LEVELS ENCOUNTERED DURING PROCESSING ARE:
 PIEZ
      24.00000      25.00000      26.00000      27.00000      28.00000      29.00000
      30.00000      31.00000      32.00000      33.00000      34.00000      35.00000
      36.00000      37.00000      38.00000
 SET
       1.00000       2.00000       3.00000


 DEP VAR:GRADIENT      N:      379   MULTIPLE R: 0.336   SQUARED MULTIPLE R: 0.113

                           ANALYSIS OF VARIANCE

 SOURCE         SUM-OF-SQUARES   DF  MEAN-SQUARE     F-RATIO       P

 DAY                  0.00037    1       0.00037     0.22737     0.63377
 SET                  0.03045    2       0.01523     9.41181     0.00010
 PIEZ{SET}            0.04229   12       0.00352     2.17834     0.01228

 ERROR                0.58729  363       0.00162
```

Test 2.

```
LEVELS ENCOUNTERED DURING PROCESSING ARE:
 SET
       2.00000       3.00000
 PIEZ
      31.00000      32.00000      33.00000      34.00000      35.00000      36.00000
      38.00000
```

```
DEP VAR:GRADIENT      N:     199  MULTIPLE R: 0.173  SQUARED MULTIPLE R: 0.030

                              ANALYSIS OF VARIANCE

SOURCE        SUM-OF-SQUARES   DF  MEAN-SQUARE     F-RATIO        P

SET                0.00105    1      0.00105     0.40394     0.52582
PIEZ{SET}          0.01424    5      0.00285     1.09716     0.36338
DAY                0.00006    1      0.00006     0.02423     0.87646

ERROR              0.49586  191      0.00260
```

Site 7A:

Test 1.

```
LEVELS ENCOUNTERED DURING PROCESSING ARE:
 SET
        1.000        2.000        3.000
 PIEZ
       47.000       48.000       49.000       50.000       51.000       52.000
       53.000       54.000       55.000       56.000       57.000       58.000
       59.000       60.000       61.000


DEP VAR:GRADIENT      N:     471  MULTIPLE R: 0.458  SQUARED MULTIPLE R: 0.210

                              ANALYSIS OF VARIANCE

SOURCE        SUM-OF-SQUARES   DF  MEAN-SQUARE     F-RATIO        P

DAY                  0.108    1        0.108      24.814 .898482E-06
SET                  0.085    2        0.043       9.854 .646505E-04
PIEZ{SET}            0.326   12        0.027       6.254 .291473E-09

ERROR                1.974  455        0.004
```

Test 2.

```
LEVELS ENCOUNTERED DURING PROCESSING ARE:
 SET
        1.000        2.000        3.000
 PIEZ
       47.000       48.000       49.000       52.000       53.000       54.000
       55.000       57.000       58.000       59.000       60.000       61.000


DEP VAR:GRADIENT      N:     330  MULTIPLE R: 0.412  SQUARED MULTIPLE R: 0.170

                              ANALYSIS OF VARIANCE

SOURCE        SUM-OF-SQUARES   DF  MEAN-SQUARE     F-RATIO        P

DAY                  0.075    1        0.075      22.641 .297212E-05
SET                  0.005    2        0.003       0.781       0.459
PIEZ{SET}            0.136    9        0.015       4.598 .100980E-04
```

```
ERROR                   1.045  317        0.003
```

Site 13:

```
LEVELS ENCOUNTERED DURING PROCESSING ARE:
 PIEZ
       77.0000       78.0000       79.0000       80.0000


 DEP VAR:GRADIENT       N:      97  MULTIPLE R: 0.204  SQUARED MULTIPLE R: 0.042

                                 ANALYSIS OF VARIANCE

 SOURCE          SUM-OF-SQUARES   DF  MEAN-SQUARE      F-RATIO        P

 DAY                    0.0022    1        0.0022      0.2752      0.6012
 PIEZ                   0.0320    3        0.0107      1.3173      0.2736

 ERROR                  0.7441   92        0.0081
```

A3.2 Temporal Variability of Seepage Flux Estimates

In this section seepage flux estimates made on several days before a storm event (October 1 to 5, 1995) are compared to estimates made several days after the storm event (October 16 to 20). The first group of measurements is treated as Group A and the second as Group B. The two groups are compared to estimate the temporal variability of seepage flux estimates from hydraulic gradient and hydraulic conductivity measurements over a short period of time. ANOVA results, given in the following table, indicate a significant difference between the two groups of days ($p = 1.74 \times 10^{-8}$).

ANOVA Results:

The following data set was analysed with MGLH/General Linear Model, in Systat™, to compare two sets of daily seepage measurements, Group A (Oct. 1 to 4) and Group B (Oct. 16 to 20) to determine if they were significantly different.

```
LEVELS ENCOUNTERED DURING PROCESSING ARE:
 TIMES$
  A            B
```

```
PIEZ
   1.0000000   10.0000000   10.5000000   15.0000000   27.0000000   28.0000000
  29.0000000   30.0000000   31.0000000   32.0000000   33.0000000   34.0000000
  35.0000000   36.0000000   37.0000000   38.0000000   43.0000000   47.0000000
  48.0000000   49.0000000   50.0000000   51.0000000   52.0000000   53.0000000
  54.0000000   55.0000000   56.0000000   57.0000000   58.0000000   59.0000000
  60.0000000   61.0000000   64.0000000   69.0000000   73.0000000   77.0000000
  78.0000000   80.0000000

DEP VAR: SEEPAGE      N:      343  MULTIPLE R: 0.962  SQUARED MULTIPLE R: 0.925

                         ANALYSIS OF VARIANCE

SOURCE         SUM-OF-SQUARES   DF  MEAN-SQUARE     F-RATIO        P

TIME$              0.0761495     1    0.0761495   33.5454146 .173681E-07
PIEZ               8.4710353    37    0.2289469  100.8557464 .999201E-15

ERROR              0.6900931   304    0.0022700
```

A3.3 F Test Results

F Tests indicate that for a large number of sites the variance for the two groups of days are insignificantly different. F Tests, from Excel 5.0, returns the one-tailed probability, p, that the variances in the two groups are not significantly different (or more correctly stated: p is the probability of committing an error in declaring the variances different from each other). Test results are given below.

Table 1. Comparison of Daily Seepage Measurements (before and after storm on Day 644), 1995

Site #	Piez #	F Test (P)	Days	No. of Meas.
1	1		639 to 643	4
1	1	0.8671	654 to 658	5
2	10		639 to 643	4
2	10	0.3063	654 to 658	5
2	10.5		639 to 643	4
2	10.5	0.0188	654to 658	5
3	15		639 to 643	4
3	15	0.4469	654 to 658	5
5	27		639 to 643	4
5	27	0.8332	654 to 658	5
5	28		639 to 643	4
5	28	0.8057	654 to 658	5
5	29		639 to 643	4

Site #	Piez #	F Test (P)	Days	No. of Meas.
5	30		639 to 643	4
5	30	0.0247	654 to 658	5
5	31		639 to 643	4
5	31	0.0324	654 to 658	5
5	32		639 to 643	4
5	32	0.0154	654 to 658	5
5	33		639 to 643	4
5	33	7.44E-47	654 to 658	5
5	34		639 to 643	4
5	34	0.2171	654 to 658	5
5	35		639 to 643	4
5	35	0.0776	654 to 658	5
5	36		639 to 643	4
5	36	0.0654	654 to 658	5
5	37		639 to 643	4
5	37	0.0032	654 to 658	5
5	38		639 to 643	4
5	38	0.0701	654 to 658	5
7	43		639 to 643	4
7	43	0.4024	654 to 658	5
7.5	47		508 to 511	4
7.5	47	0.9641	514 to 518	5
7.5	47		639 to 643	4
7.5	47	0.0023	654 to 658	5
7.5	48		508 to 511	4
7.5	48	0.2204	514 to 518	5
7.5	48		639 to 643	4
7.5	48	0.1031	654 to 658	5
7.5	49		508 to 511	4
7.5	49	0.0233	514 to 518	5
7.5	49		639 to 643	4
7.5	49	0.0406	654 to 658	5
7.5	50		508 to 511	4
7.5	50	0.0554	514 to 518	5
7.5	50		639 to 643	4
7.5	50	0.0648	654 to 658	5
7.5	51		508 to 511	4
7.5	51	0.0991	514 to 518	5
7.5	51		639 to 643	4
7.5	51	0.0287	654 to 658	5
7.5	52		507 to 511	5
7.5	52	0.0723	514 to 517	4
7.5	52		639 to 643	4
7.5	52	1.38E-47	654 to 658	5

Site #	Piez #	F Test (P)	Days	No. of Meas.
7.5	53		507 to 511	5
7.5	53	0.0669	514 to 517	4
7.5	53		639 to 643	4
7.5	53	2.19E-47	654 to 658	5
7.5	54		507 to 511	5
7.5	54	0.0841	514 to 517	4
7.5	54		639 to 643	4
7.5	54	3.79E-50	654 to 658	5
7.5	55		507 to 511	5
7.5	55	0.0239	514 to 517	4
7.5	55		639 to 643	4
7.5	55	0.0147	654 to 658	5
7.5	56		507 to 511	5
7.5	56	0.1299	514 to 517	4
7.5	56		639 to 643	4
7.5	56	0.0903	654 to 658	5
7.5	57		508 to 511	4
7.5	57	0.7312	514 to 518	5
7.5	57		639 to 643	4
7.5	57	1.92E-04	654 to 658	5
7.5	58		508 to 511	4
7.5	58	0.0074	514 to 518	5
7.5	58		639 to 643	4
7.5	58	0.0305	654 to 658	5
7.5	59		508 to 511	4
7.5	59	0.8135	514 to 518	5
7.5	59		639 to 643	4
7.5	59	0.0916	654 to 658	5
7.5	60		508 to 511	4
7.5	60	0.0749	514 to 518	5
7.5	60		639 to 643	4
7.5	60	0.0230	654 to 658	5
7.5	61		508 to 511	4
7.5	61	0.9806	514 to 518	5
7.5	61		639 to 643	4
7.5	61	0.0417	654 to 658	5
8	64		639 to 643	4
8	64	0.0326	654 to 658	5
11	69		639 to 643	4
11	69	0.7211	654 to 658	5
12	73		639 to 643	4
12	73	0.5176	654 to 658	5
13	77		639 to 643	4
13	77	0.0032	654 to 658	5

Site #	Piez #	F Test (P)	Days	No. of Meas.
13	78		639 to 643	4
13	78	0.1006	654 to 658	5
13	80		639 to 643	4
13	80	0.0132	654 to 658	5

A second ANOVA test was on a single site (site no. 7A) with two groups of measurements made over a short period of time. Group 1 = May 23 to May 26, 1995 and Group 2 = May 29 to June 2, 1995. ANOVA results, given below, indicate that the seepage flux estimates from one group to the next is insignificantly different (p = 0.16).

```
LEVELS ENCOUNTERED DURING PROCESSING ARE:
 TIME
        1.000         2.000
 PIEZ
       47.000        48.000        49.000        50.000        51.000        52.000
       53.000        54.000        55.000        56.000        57.000        58.000
       59.000        60.000        61.000


 DEP VAR: SEEPAGE      N:      135  MULTIPLE R: 0.602   SQUARED MULTIPLE R: 0.362

                        ANALYSIS OF VARIANCE

 SOURCE        SUM-OF-SQUARES   DF  MEAN-SQUARE     F-RATIO        P

 TIME           .982863E-04     1   .982863E-04      1.976       0.162
 PIEZ                 0.003    14   .229035E-03      4.604 .129349E-05

 ERROR                0.006   119   .497501E-04
```

Appendix 4

This appendix includes sample calculations of hydraulic conductivity, *K*, for two different methods: Method 1 - using seepage flux and hydraulic gradient measurements; and Method 2 - using infiltration measurements from a falling head permeameter. A description of the permeameter assemblage in the field is also given. Sample calculations for a weighted mean *K*; and groundwater seepage flux estimated from *K* and hydraulic gradient are also included. Finally, the calculated *K* values, for both measurement methods, are also given.

A4.1 Calculation of *K* - Method 1

From the hydraulic gradient and seepage flux, one can calculate the hydraulic conductivity of the sediments between the piezometer screen and the river bed with the following formula:

$$K = -\frac{q}{h/l}$$

where:

K = hydraulic conductivity (10^{-2} m s^{-1})
q = seepage flux (10^{-6} m^{3} m^{-2} s^{-1}) or (µm s^{-1})
h/l = hydraulic gradient (hydraulic head (m)/length (m))

Sample Calculation of *K*

$$K = -\frac{q}{h/l} = \frac{\left(7.26 \times 10^{-10} m s^{-1}\right)}{\frac{0.0795 m}{1.475 m}} = 1.35 \times 10^{-8} m s^{-1}$$

A4.2 Falling Head Permeameter/Slug Tests for Measurement of K

The horizontal hydraulic conductivities (K_h) of the Raisin River sediments were estimated using the method described by Lee and Cherry (1978) and originally by Hvorslev (1951). A falling head permeameter was designed with four lines having the following inner diameters: 0.3, 0.5, 0.9, 1.2 cm. The four lines, which hold different volumes of water, enable the infiltrometer to be used with sediments of differing infiltration rates. For a particular test, a line is connected to a mini-piezometer (installed in the sediments) after having noted the original hydraulic head in the piezometer. The air in the lines and piezometer is then removed by means of a 3-way purge valve. Water is then allowed to flow by gravity from the infiltrometer into the piezometer and the water levels in the infiltrometer are noted as a function of time. Water level (or hydraulic head) measurements were generally taken at intervals of 30 to 60 seconds for durations ranging from less than one minute to 15 minutes as the added water infiltrates into the sediments. Tests were repeated at least three times after allowing several minutes for the piezometer to recover.

The method used by Hvorslev (1951) to determine K (hydraulic conductivity) with a slug test, requires the estimation of a time lag. The time lag, T, is basically the time required for equalization of pressure differences in a piezometer and is found by plotting the hydraulic head ratio (h_2/h_1, head (t) during the falling head test / initial head) versus time on a semi-log scale. T is the time that corresponds to h_2/h_1= 0.37 along this line. Curvature at the beginning of an h_2/h_1 vs time plot is attributed to changing volumes of gas in the sediment as the first amount of water is added. If results indicate such a curvature, Hvorslev recommended plotting a straight line through the origin but drawing it parallel to the lower part of the curve in order to find T. This was done in several cases in this study.

Hvorslev's hydraulic conductivity calculations are based on the following assumptions: Darcy's Law is valid; water and soil are incompressible; artesian conditions exist or pressure equalization does not cause any draw down of the groundwater level; soil at intake has infinite depth and directional isotropy (K_v and K_h are equal); no disturbance, segregation, swelling or consolidation of soil; no sedimentation or leakage; no air or gas in soil, well point, or pipe; hydraulic losses in pipes, well point or filter negligible; and assuming uniform soil.

Because water infiltrated much faster during some of the permeameter tests, K was calculated in two ways. Type 1 calculations were used for slower tests, i.e. when a time lag was determined from a h_2/h_1 plot (see Figure 2). A Type 2 calculation was used for faster tests, e.g. when only two hydraulic head measurements were obtained from the falling head permeameter test.

Type 1:

$$K_h = \frac{d^2 \ln\left(\frac{2mL}{D}\right)}{8LT}$$

where K_h = hydraulic conductivity (cm s^{-1})
d = diameter of falling head permeameter line (cm)
L = length of filtered piezometer tip (10 cm)
D = diameter of piezometer tip (0.6 cm)
T = Time Lag (sec)
m = anisotropy ratio, which are assumed to be equal to 1
$m = \sqrt{\frac{k_h}{k_v}} \approx 1$ (Lee and Cherry (1978)
where k_h = horizontal hydraulic conductivity, k_v = vertical hydraulic conductivity

Type 2:

$$K_h = \frac{d^2 \ln\left(\frac{2mL}{D}\right)}{8L(t_2 - t_1)} \ln\frac{h_1}{h_2}$$

where t = time (sec) and h_n = hydraulic head of groundwater (cm) for time $t = t_n$.

The following diagram is an illustration of the apparatus used indicating which measurements were taken:

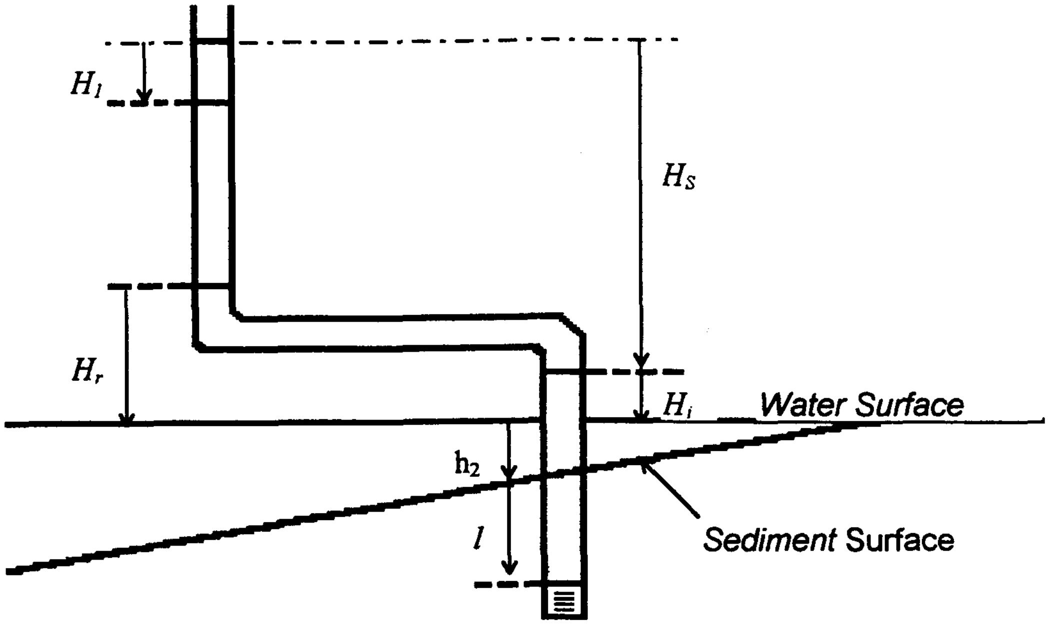


Figure 1. Falling Head Permeameter/Piezometer Apparatus

Diagram Notes:

H_i = Initial hydraulic head in piezometer
H_s = Level of water added to falling head permeameter line at start of test
H_1 = First level of water in permeameter after test has begun
H_r = Reference point on permeameter with respect to river
h_2 = $H_s - H_1 + H_r - H_i$
h_1 = $H_s + H_r - H_i$

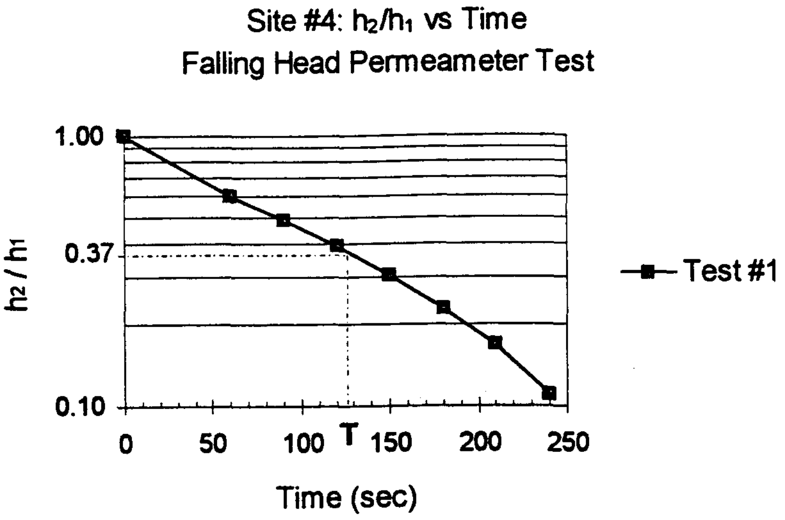


Figure 2 - Sample Plot of Slug Test Data, used to determine Time Lag, T

A4.2.1 Sample Calculation of *K (Type 1)*

From Figure 2, time, *T*, at $h_2/h_1 = 0.37$ is 128 seconds for Test #1.

$d = 0.9$ cm, $m = 1$, $L = 10$ cm, $D = 0.6$ cm,

$$K_h = \frac{(0.9)^2 \ln\left(2 * \frac{1*10}{0.6}\right)}{8*10*128} = \frac{2.84}{10240} = 2.77 \times 10^{-6} ms^{-1}$$

A4.2.2 Sample Calculation of *K (Type 2)*

For Site #6, where start of test, $t_1 = 0$ seconds, and second measurement, $t_2 = 26.41$ seconds; $d = 0.5$ cm; $H_s = 152.5$ cm, $H_r = 47$ cm, $H_i = 0.5$ cm, $H_1 = 142$ cm;

$$h_1 = 152.5 + 47 - 0.5 = 199\, cm$$
$$h_2 = 152.5 - 142 + 47 - 0.5 = 57\, cm$$

$$K_h = \frac{(0.5)^2 \ln\left(2 * \frac{1*10}{0.6}\right)}{8*10*(26.41)} * \ln\left(\frac{199}{57}\right) = 5.19 \times 10^{-6}\, m\, s^{-1}$$

A4.2.3. Precision and Comparison of the two *K* Measurement Methods

H_o: $\mu_1 = \mu_2$

The following ANOVA test, generated with the statistical software package, Systat©, is to determine whether there was any significant difference between Hydraulic Conductivity measurements (ln *K*) made with two different methods. (Method 1 = Seepage Meter/Mini-Piezometer, Method 2 = Falling Head Permeameter). A second test was performed to see if there was any significant difference between ln *K* measurments with regards to piezometer location ("Piez"). Both "Method" and "Piez" were treated as categorical variables and 27 outliers have been deleted from the original data set of 225, because of defective piezometers. The statistical model used was :

$\ln K = \mu + \text{Method} + \text{Piez} + \in$

The error term therefore includes variability caused by the precision of each method and the interaction between method and piezometer location.

```
VARIABLES IN SYSTAT RECT FILE ARE:
          DAY             DATE$           SITE          METHOD            SET$
         PIEZ           BRANCH$          SGEOL$              K            LNK


C:\SYSTATW5\SFILES\KRSLTSC.SYS
LEVELS ENCOUNTERED DURING PROCESSING ARE:

METHOD
          1.000         2.000
PIEZ
          6.000         7.000         8.000         9.000        10.000        15.000
         16.000        17.000        18.000        19.000        20.000        21.000
```

```
      22.000        23.000        24.000        25.000        26.000        27.000
      28.000        39.000        40.000        41.000        42.000        43.000
      44.000        45.000        46.000        47.000        48.000        49.000
      50.000        51.000        52.000        53.000        54.000        55.000
      56.000        62.000        63.000        64.000        65.000        66.000
      67.000        69.000        70.000        71.000        72.000        74.000
      75.000        76.000        77.000        78.000        79.000        80.000

DEP VAR:     LNK      N:      198  MULTIPLE R: 0.866  SQUARED MULTIPLE R: 0.750

                         ANALYSIS OF VARIANCE

SOURCE        SUM-OF-SQUARES   DF  MEAN-SQUARE     F-RATIO       P

METHOD             0.147        1       0.147       0.142       0.707
PIEZ             443.154       53       8.361       8.045       0.1 x 10^-14

ERROR            148.618      143       1.039
```

The ANOVA indicates that there was no significant difference between methods (p = 0.707) but that there were significant differences between piezometers (p = 10^{-15}). The precision of the methods, expressed as variance is 1.039 (ln K)^2 m s^{-1} with 143 degrees of freedom. The corresponding coefficient of variability on the ln K measurements is 20%.

A4.3 Sample Calculation of Weighted Mean K

In order to get a single K value to be used in estimating seepage, a weighted mean K was calculated using the results from the two different measurement methods (method 1: mini-piezometers and seepage meters; and method 2: falling head permeameter) for each site with the following formula:

$$\mathit{Weighted\,Mean\,K} = \frac{\sum w_i\,\bar{x}_i}{\sum w_i}$$

where i is the method number. The weight, w, of each K value if the number of measurements performed with each method, and $\bar{x}$ is the arithmetic mean of the K measurements for each method. For example, at site no. 2, there were five K measurements using method 1 and three from method 2. The weighted mean K was calculated as follows:

$$\text{Weighted Mean K} = \frac{\sum\left[\left(2.3 \text{ x } 10^{-8}\right)(5)\right]+\left[\left(1.38 \text{ x } 10^{-8}\right)(3)\right]}{\sum(5+3)} = 1.96 \text{ x } 10^{-8} \text{ m s}^{-1}$$

A4.4 Hydraulic Conductivity Measurements, 1994/1995

The following table holds the results of field measurements of hydraulic conductivity, K. The methods are given as 1 (seepage meter/mini-piezometer) or 2 (slug tests with a falling head permeameter). The results are discussed in Chapter 5.

	Hydraulic Conductivity Measurements - Raisin R. Sediments								
							Surficial	K	LnK
Day	Date	Site	Method	Set	Piez	Branch	Geology	(m/s)	(m/s)
251	94.09.08	1	1	"1 of 1st"	1	main	peat	1.91E-07	-15.47
251	94.09.08	1	1	"2 of 1st"	2	main	peat	1.80E-06	-13.23
251	94.09.08	1	1	"3 of 1st"	3	main	peat	6.64E-07	-14.22
251	94.09.08	1	1	"5 of 1st"	5	main	peat	1.90E-07	-15.48
264	94.09.21	1	1	"1 of 1st"	1	main	peat	4.77E-07	-14.56
264	94.09.21	1	1	"2 of 1st"	2	main	peat	6.69E-07	-14.22
264	94.09.21	1	1	"3 of 1st"	3	main	peat	4.63E-07	-14.59
264	94.09.21	1	1	"4 of 1st"	4	main	peat	3.52E-07	-14.86
264	94.09.21	1	1	"5 of 1st"	5	main	peat	7.73E-08	-16.38
271	94.09.28	1	1	"1 of 1st"	1	main	peat	2.91E-07	-15.05
271	94.09.28	1	1	"2 of 1st"	2	main	peat	3.00E-08	-17.32
271	94.09.28	1	1	"3 of 1st"	3	main	peat	1.28E-08	-18.17
271	94.09.28	1	1	"4 of 1st"	4	main	peat	3.43E-09	-19.49
271	94.09.28	1	1	"5 of 1st"	5	main	peat	2.73E-09	-19.72
586	95.08.09	1	2	"2 of 1st"	1	main	peat	4.40E-05	-10.03
586	95.08.09	1	2	"2 of 1st"	1	main	peat	3.79E-05	-10.18
586	95.08.09	1	2	"2 of 1st"	1	main	peat	4.67E-05	-9.97
586	95.08.09	1	2	"2 of 1st"	1	main	peat	5.28E-05	-9.85
586	95.08.09	1	2	"2 of 1st"	1	main	peat	5.89E-05	-9.74
236	94.08.24	2	1	"1 of 1st"	6	main	till/sand	4.24E-09	-19.28
236	94.08.24	2	1	"2 of 1st"	7	main	till/sand	3.10E-08	-17.29
236	94.08.24	2	1	"3 of 1st"	8	main	till/sand	3.33E-07	-14.91
236	94.08.24	2	1	"4 of 1st"	9	main	till/sand	1.01E-07	-16.11
236	94.08.24	2	1	"5 of 1st"	10	main	till/sand	1.47E-09	-20.34
531	95.06.15	2	2	"5 of 1st"	10	main	till/sand	1.38E-08	-18.10
531	95.06.15	2	2	"5 of 1st"	10	main	till/sand	1.38E-08	-18.10
531	95.06.15	2	2	"5 of 1st"	10	main	till/sand	1.38E-08	-18.10
181	94.06.30	3	1	"1 of 1st"	15	main	till/clay	1.36E-06	-13.51
181	94.06.30	3	1	"2 of 1st"	16	main	till/clay	2.11E-07	-15.37
181	94.06.30	3	1	"3 of 1st"	17	main	till/clay	5.94E-07	-14.34
181	94.06.30	3	1	"4 of 1st"	18	main	till/clay	2.90E-07	-15.05
528	95.06.12	3	2	"1 of 1st"	15	main	till/clay	2.50E-06	-12.90
528	95.06.12	3	2	"1 of 1st"	15	main	till/clay	1.07E-05	-11.45
528	95.06.12	3	2	"1 of 1st"	15	main	till/clay	2.74E-05	-10.50
528	95.06.12	3	2	"1 of 1st"	15	main	till/clay	5.34E-05	-9.84
528	95.06.12	3	2	"1 of 1st"	15	main	till/clay	3.42E-06	-12.59
531	95.06.15	3	2	"1 of 1st"	15	main	till/clay	7.45E-07	-14.11
531	95.06.15	3	2	"1 of 1st"	15	main	till/clay	3.96E-07	-14.74
531	95.06.15	3	2	"1 of 1st"	15	main	till/clay	7.45E-07	-14.11
531	95.06.15	3	2	"1 of 1st"	15	main	till/clay	7.45E-07	-14.11
586	95.08.09	3	2	"1 of 1st"	15	main	till/clay	3.76E-06	-12.49
586	95.08.09	3	2	"1 of 1st"	15	main	till/clay	4.81E-06	-12.24
586	95.08.09	3	2	"1 of 1st"	15	main	till/clay	4.64E-06	-12.28
586	95.08.09	3	2	"1 of 1st"	15	main	till/clay	4.30E-06	-12.36
586	95.08.09	3	2	"1 of 1st"	15	main	till/clay	4.32E-06	-12.35
223	94.08.11	4	1	"1 of 1st"	19	main	till	2.56E-08	-17.48
223	94.08.11	4	1	"2 of 1st"	20	main	till	5.55E-09	-19.01
223	94.08.11	4	1	"3 of 1st"	21	main	till	6.78E-08	-16.51
223	94.08.11	4	1	"4 of 1st"	22	main	till	2.90E-08	-17.36
223	94.08.11	4	1	"5 of 1st"	23	main	till	5.72E-07	-14.37
529	95.06.13	4	2	"4 of 1st"	22	main	till	7.41E-07	-14.12
529	95.06.13	4	2	"4 of 1st"	22	main	till	7.41E-07	-14.12
529	95.06.13	4	2	"4 of 1st"	22	main	till	6.52E-07	-14.24
216	94.08.04	5	1	"3 of 1st"	26	main	clay	1.59E-07	-15.65
216	94.08.04	5	1	"4 of 1st"	27	main	clay	6.63E-08	-16.53
216	94.08.04	5	1	"5 of 1st"	28	main	clay	3.25E-06	-12.64
510	95.05.25	5	1	"1 of 1st"	24	main	clay	1.48E-06	-13.42
510	95.05.25	5	1	"2 of 1st"	25	main	clay	8.55E-07	-13.97
510	95.05.25	5	1	"3 of 1st"	26	main	clay	1.17E-05	-11.35

Day	Date	Site	Method	Set	Piez	Branch	Surficial Geology	K (m/s)	LnK (m/s)
510	95.05.25	5	1	"4 of 1st"	27	main	clay	1.84E-07	-15.51
510	95.05.25	5	1	"5 of 1st"	28	main	clay	1.56E-06	-13.37
514	95.05.29	5	1	"1 of 1st"	24	main	clay	6.46E-07	-14.25
514	95.05.29	5	1	"2 of 1st"	25	main	clay	1.27E-07	-15.88
514	95.05.29	5	1	"3 of 1st"	26	main	clay	6.92E-07	-14.18
514	95.05.29	5	1	"4 of 1st"	27	main	clay	4.32E-07	-14.65
514	95.05.29	5	1	"5 of 1st"	28	main	clay	1.80E-07	-15.53
515	95.05.30	5	1	"2 of 1st"	25	main	clay	2.31E-07	-15.28
515	95.05.30	5	1	"3 of 1st"	26	main	clay	2.77E-06	-12.80
515	95.05.30	5	1	"4 of 1st"	27	main	clay	6.18E-07	-14.30
515	95.05.30	5	1	"5 of 1st"	28	main	clay	6.08E-07	-14.31
516	95.05.31	5	1	"1 of 1st"	24	main	clay	8.46E-07	-13.98
516	95.05.31	5	1	"2 of 1st"	25	main	clay	7.13E-07	-14.15
516	95.05.31	5	1	"3 of 1st"	26	main	clay	3.37E-07	-14.90
516	95.05.31	5	1	"4 of 1st"	27	main	clay	7.16E-08	-16.45
516	95.05.31	5	1	"5 of 1st"	28	main	clay	6.90E-07	-14.19
517	95.06.01	5	1	"2 of 1st"	25	main	clay	2.68E-07	-15.13
517	95.06.01	5	1	"3 of 1st"	26	main	clay	3.92E-07	-14.75
517	95.06.01	5	1	"4 of 1st"	27	main	clay	3.29E-07	-14.93
517	95.06.01	5	1	"5 of 1st"	28	main	clay	1.27E-06	-13.58
525	95.06.09	5	2	"2 of 1st"	25	main	clay	8.02E-07	-14.04
525	95.06.09	5	2	"2 of 1st"	25	main	clay	1.40E-07	-15.78
525	95.06.09	5	2	"3 of 1st"	26	main	clay	1.11E-07	-16.01
525	95.06.09	5	2	"3 of 1st"	26	main	clay	1.11E-07	-16.01
525	95.06.09	5	2	"3 of 1st"	26	main	clay	1.11E-07	-16.01
528	95.06.12	5	2	"1 of 1st"	24	main	clay	9.73E-06	-11.54
528	95.06.12	5	2	"1 of 1st"	24	main	clay	2.32E-05	-10.67
528	95.06.12	5	2	"1 of 1st"	24	main	clay	3.13E-05	-10.37
528	95.06.12	5	2	"1 of 1st"	24	main	clay	3.46E-05	-10.27
528	95.06.12	5	2	"1 of 1st"	24	main	clay	9.73E-05	-9.24
215	94.08.03	6	1	"1 of 1st"	39	north	till	1.29E-07	-15.86
215	94.08.03	6	1	"2 of 1st"	40	north	till	2.39E-06	-12.94
216	94.08.04	6	1	"3 of 1st"	41	north	till	2.22E-06	-13.02
221	94.08.09	6	1	"1 of 1st"	39	north	till	2.02E-07	-15.41
530	95.06.14	6	2	"3 of 1st"	39	north	till	5.19E-06	-12.17
530	95.06.14	6	2	"3 of 1st"	39	north	till	1.03E-05	-11.48
530	95.06.14	6	2	"3 of 1st"	39	north	till	9.25E-06	-11.59
223	94.08.11	7	1	"1 of 1st"	42	main	till	4.57E-07	-14.60
223	94.08.11	7	1	"2 of 1st"	43	main	till	2.49E-07	-15.21
223	94.08.11	7	1	"3 of 1st"	44	main	till	8.42E-07	-13.99
223	94.08.11	7	1	"4 of 1st"	45	main	till	2.92E-07	-15.05
223	94.08.11	7	1	"5 of 1st"	46	main	till	2.65E-07	-15.14
528	95.06.12	7	2	"1 of 1st"	42	main	till	3.50E-06	-12.56
528	95.06.12	7	2	"1 of 1st"	42	main	till	3.21E-06	-12.65
528	95.06.12	7	2	"1 of 1st"	42	main	till	2.09E-06	-13.08
528	95.06.12	7	2	"1 of 1st"	42	main	till	2.06E-06	-13.09
528	95.06.12	7	2	"1 of 1st"	42	main	till	1.96E-06	-13.14
266	94.09.23	7.5	1	"1 of 1st"	47	main	sand/siclay	1.35E-07	-15.82
266	94.09.23	7.5	1	"2 of 1st"	48	main	sand/siclay	6.91E-07	-14.19
266	94.09.23	7.5	1	"3 of 1st"	49	main	sand/siclay	6.54E-08	-16.54
266	94.09.23	7.5	1	"4 of 1st"	50	main	sand/siclay	2.01E-07	-15.42
266	94.09.23	7.5	1	"5 of 1st"	51	main	sand/siclay	3.71E-07	-14.81
271	94.09.28	7.5	1	"1 of 1st"	47	main	sand/siclay	4.65E-07	-14.58
271	94.09.28	7.5	1	"2 of 1st"	48	main	sand/siclay	2.23E-07	-15.32
271	94.09.28	7.5	1	"3 of 1st"	49	main	sand/siclay	3.70E-08	-17.11
271	94.09.28	7.5	1	"4 of 1st"	50	main	sand/siclay	1.51E-07	-15.70
271	94.09.28	7.5	1	"5 of 1st"	51	main	sand/siclay	1.80E-06	-13.23
507	95.05.22	7.5	1	"1 of 2nd"	52	main	sand/siclay	1.04E-07	-16.08
507	95.05.22	7.5	1	"2 of 2nd"	53	main	sand/siclay	1.84E-07	-15.51
507	95.05.22	7.5	1	"3 of 2nd"	54	main	sand/siclay	1.17E-07	-15.96

							Surficial	K	LnK
Day	Date	Site	Method	Set	Piez	Branch	Geology	(m/s)	(m/s)
507	95.05.22	7.5	1	"4 of 2nd"	55	main	sand/slclay	4.04E-08	-17.02
507	95.05.22	7.5	1	"5 of 2nd"	56	main	sand/slclay	6.73E-08	-16.51
508	95.05.23	7.5	1	"1 of 2nd"	52	main	sand/slclay	1.50E-07	-15.71
508	95.05.23	7.5	1	"2 of 2nd"	53	main	sand/slclay	2.66E-07	-15.14
508	95.05.23	7.5	1	"3 of 2nd"	54	main	sand/slclay	1.33E-07	-15.83
508	95.05.23	7.5	1	"4 of 2nd"	55	main	sand/slclay	4.17E-08	-16.99
508	95.05.23	7.5	1	"5 of 2nd"	56	main	sand/slclay	6.21E-08	-16.59
509	95.05.24	7.5	1	"1 of 2nd"	52	main	sand/slclay	2.64E-07	-15.15
509	95.05.24	7.5	1	"2 of 2nd"	53	main	sand/slclay	3.70E-07	-14.81
509	95.05.24	7.5	1	"3 of 2nd"	54	main	sand/slclay	1.72E-07	-15.58
509	95.05.24	7.5	1	"4 of 2nd"	55	main	sand/slclay	3.24E-08	-17.25
509	95.05.24	7.5	1	"5 of 2nd"	56	main	sand/slclay	8.23E-08	-16.31
510	95.05.25	7.5	1	"1 of 2nd"	52	main	sand/slclay	2.03E-07	-15.41
510	95.05.25	7.5	1	"2 of 2nd"	53	main	sand/slclay	4.65E-07	-14.58
510	95.05.25	7.5	1	"3 of 2nd"	54	main	sand/slclay	1.93E-07	-15.46
510	95.05.25	7.5	1	"4 of 2nd"	55	main	sand/slclay	7.22E-08	-16.44
510	95.05.25	7.5	1	"5 of 2nd"	56	main	sand/slclay	1.58E-07	-15.66
514	95.05.29	7.5	1	"1 of 2nd"	52	main	sand/slclay	4.79E-08	-16.85
514	95.05.29	7.5	1	"2 of 2nd"	53	main	sand/slclay	2.07E-07	-15.39
514	95.05.29	7.5	1	"3 of 2nd"	54	main	sand/slclay	1.05E-07	-16.07
514	95.05.29	7.5	1	"4 of 2nd"	55	main	sand/slclay	7.23E-07	-14.14
514	95.05.29	7.5	1	"5 of 2nd"	56	main	sand/slclay	9.31E-08	-16.19
515	95.05.30	7.5	1	"1 of 2nd"	52	main	sand/slclay	1.18E-07	-15.95
515	95.05.30	7.5	1	"2 of 2nd"	53	main	sand/slclay	2.44E-07	-15.23
515	95.05.30	7.5	1	"3 of 2nd"	54	main	sand/slclay	2.14E-07	-15.36
515	95.05.30	7.5	1	"4 of 2nd"	55	main	sand/slclay	2.91E-07	-15.05
515	95.05.30	7.5	1	"5 of 2nd"	56	main	sand/slclay	7.51E-08	-16.40
516	95.05.31	7.5	1	"1 of 2nd"	52	main	sand/slclay	1.84E-07	-15.51
516	95.05.31	7.5	1	"2 of 2nd"	53	main	sand/slclay	3.02E-07	-15.01
516	95.05.31	7.5	1	"3 of 2nd"	54	main	sand/slclay	2.08E-07	-15.38
516	95.05.31	7.5	1	"4 of 2nd"	55	main	sand/slclay	2.33E-07	-15.27
516	95.05.31	7.5	1	"5 of 2nd"	56	main	sand/slclay	3.73E-08	-17.10
517	95.06.01	7.5	1	"1 of 2nd"	52	main	sand/slclay	1.46E-07	-15.74
517	95.06.01	7.5	1	"2 of 2nd"	53	main	sand/slclay	4.06E-07	-14.72
517	95.06.01	7.5	1	"3 of 2nd"	54	main	sand/slclay	2.41E-07	-15.24
517	95.06.01	7.5	1	"4 of 2nd"	55	main	sand/slclay	1.15E-07	-15.98
517	95.06.01	7.5	1	"5 of 2nd"	56	main	sand/slclay	9.56E-08	-16.16
529	95.06.13	7.5	2	"2 of 2nd"	53	main	sand/slclay	1.16E-07	-15.97
529	95.06.13	7.5	2	"2 of 2nd"	53	main	sand/slclay	2.47E-07	-15.21
529	95.06.13	7.5	2	"2 of 2nd"	53	main	sand/slclay	2.47E-07	-15.21
529	95.06.13	7.5	2	"4 of 2nd"	55	main	sand/slclay	6.04E-09	-18.92
529	95.06.13	7.5	2	"4 of 2nd"	55	main	sand/slclay	6.04E-09	-18.92
532	95.06.16	7.5	2	"1 of 1st"	47	main	sand/slclay	8.43E-08	-16.29
532	95.06.16	7.5	2	"1 of 1st"	47	main	sand/slclay	2.21E-08	-17.63
532	95.06.16	7.5	2	"1 of 1st"	47	main	sand/slclay	2.21E-08	-17.63
243	94.08.31	8	1	"1 of 1st"	62	main	sand/slclay	1.95E-08	-17.75
243	94.08.31	8	1	"2 of 1st"	63	main	sand/slclay	3.43E-07	-14.89
243	94.08.31	8	1	"4 of 1st"	65	main	sand/slclay	5.69E-08	-16.68
251	94.09.08	8	1	"1 of 1st"	62	main	sand/slclay	1.35E-08	-18.12
251	94.09.08	8	1	"2 of 1st"	63	main	sand/slclay	1.52E-07	-15.70
251	94.09.08	8	1	"3 of 1st"	64	main	sand/slclay	3.25E-08	-17.24
251	94.09.08	8	1	"4 of 1st"	65	main	sand/slclay	1.22E-07	-15.92
251	94.09.08	8	1	"5 of 1st"	66	main	sand/slclay	2.90E-08	-17.35
586	95.08.09	8	2	"2 of 1st"	63	main	sand/slclay	2.28E-08	-17.60
586	95.08.09	8	2	"2 of 1st"	63	main	sand/slclay	2.28E-08	-17.60
586	95.08.09	8	2	"2 of 1st"	63	main	sand/slclay	2.28E-08	-17.60
293	94.10.20	11	1	"3 of 1st"	69	south	strsnd/slclay	6.24E-07	-14.29
293	94.10.20	11	1	"4 of 1st"	70	south	strsnd/slclay	6.24E-07	-14.29
293	94.10.20	11	1	"5 of 1st"	71	south	strsnd/slclay	8.65E-07	-13.96
530	95.06.14	11	2	"3 of 1st"	67	south	strsnd/slclay	2.19E-07	-15.33

Day	Date	Site	Method	Set	Piez	Branch	Surficial Geology	K (m/s)	LnK (m/s)
530	95.06.14	11	2	"3 of 1st"	67	south	strsnd/slclay	6.45E-08	-16.56
530	95.06.14	11	2	"3 of 1st"	67	south	strsnd/slclay	6.45E-08	-16.56
293	94.10.20	12	1	"1 of 1st"	72	south	mclay/silt	7.91E-07	-14.05
293	94.10.20	12	1	"3 of 1st"	74	south	mclay/silt	6.58E-07	-14.23
293	94.10.20	12	1	"4 of 1st"	75	south	mclay/silt	2.64E-07	-15.15
293	94.10.20	12	1	"5 of 1st"	76	south	mclay/silt	4.77E-07	-14.56
530	95.06.14	12	2	"1 of 1st"	72	south	mclay/silt	2.65E-08	-17.45
530	95.06.14	12	2	"1 of 1st"	72	south	mclay/silt	2.65E-08	-17.45
530	95.06.14	12	2	"1 of 1st"	72	south	mclay/silt	2.65E-08	-17.45
508	95.05.23	13	1	"3 of 4"	79	south	strsnd/slclay	1.21E-06	-13.62
508	95.05.29	13	1	"1 of 4"	77	south	strsnd/slclay	2.81E-07	-15.09
508	95.05.29	13	1	"2 of 4"	78	south	strsnd/slclay	7.54E-07	-14.10
508	95.05.29	13	1	"3 of 4"	79	south	strsnd/slclay	1.22E-06	-13.62
508	95.05.29	13	1	"4 of 4"	80	south	strsnd/slclay	6.27E-07	-14.28
508	95.05.29	13	1	"1 of 4"	77	south	strsnd/slclay	1.94E-06	-13.15
508	95.05.29	13	1	"2 of 4"	78	south	strsnd/slclay	3.99E-06	-12.43
508	95.05.29	13	1	"3 of 4"	79	south	strsnd/slclay	8.60E-07	-13.97
508	95.05.29	13	1	"4 of 4"	80	south	strsnd/slclay	1.86E-07	-15.50
515	95.05.30	13	1	"1 of 4"	77	south	strsnd/slclay	9.59E-07	-13.86
515	95.05.30	13	1	"2 of 4"	78	south	strsnd/slclay	2.13E-06	-13.06
515	95.05.30	13	1	"3 of 4"	79	south	strsnd/slclay	2.15E-06	-13.05
515	95.05.30	13	1	"4 of 4"	80	south	strsnd/slclay	8.27E-07	-14.01
515	95.05.30	13	1	"1 of 4"	77	south	strsnd/slclay	6.43E-06	-11.95
515	95.05.30	13	1	"2 of 4"	78	south	strsnd/slclay	1.72E-06	-13.27
515	95.05.30	13	1	"3 of 4"	79	south	strsnd/slclay	3.51E-07	-14.86
516	95.05.31	13	1	"1 of 4"	77	south	strsnd/slclay	8.54E-06	-11.67
516	95.05.31	13	1	"2 of 4"	78	south	strsnd/slclay	5.82E-06	-12.05
516	95.05.31	13	1	"3 of 4"	79	south	strsnd/slclay	8.68E-07	-13.96
516	95.05.31	13	1	"4 of 4"	80	south	strsnd/slclay	5.85E-07	-14.35
516	95.05.31	13	1	"1 of 4"	77	south	strsnd/slclay	5.86E-07	-14.35
516	95.05.31	13	1	"2 of 4"	78	south	strsnd/slclay	3.67E-06	-12.52
516	95.05.31	13	1	"3 of 4"	79	south	strsnd/slclay	4.69E-07	-14.57
516	95.05.31	13	1	"4 of 4"	80	south	strsnd/slclay	2.78E-07	-15.10
517	95.06.01	13	1	"1 of 4"	77	south	strsnd/slclay	1.25E-06	-13.59
517	95.06.01	13	1	"2 of 4"	78	south	strsnd/slclay	5.69E-06	-12.08
517	95.06.01	13	1	"3 of 4"	79	south	strsnd/slclay	1.09E-06	-13.73
517	95.06.01	13	1	"4 of 4"	80	south	strsnd/slclay	5.12E-07	-14.48
517	95.06.01	13	1	"1 of 4"	77	south	strsnd/slclay	1.15E-06	-13.68
517	95.06.01	13	1	"2 of 4"	78	south	strsnd/slclay	7.18E-06	-11.84
517	95.06.01	13	1	"3 of 4"	79	south	strsnd/slclay	7.43E-07	-14.11
517	95.06.01	13	1	"4 of 4"	80	south	strsnd/slclay	5.50E-07	-14.41
532	95.06.16	13	2	"3 of 4"	79	south	strsnd/slclay	4.39E-06	-12.34
532	95.06.16	13	2	"3 of 4"	79	south	strsnd/slclay	5.16E-06	-12.17
532	95.06.16	13	2	"3 of 4"	79	south	strsnd/slclay	1.42E-05	-11.16
532	95.06.16	13	2	"3 of 4"	79	south	strsnd/slclay	2.65E-06	-12.84
532	95.06.16	13	2	"3 of 4"	79	south	strsnd/slclay	2.32E-06	-12.98

Appendix 5

A5.1 Determination of Groundwater Discharge from Stream Hydrographs

The groundwater discharge component of a river, which is otherwise known a baseflow, can be estimated with stream hydrographs, using a method described by Domenico and Schwartz (1990). Stream hydrographs were plotted from daily discharge data of the Raisin River and are discussed in Chapter 6, Section 1. The data was collected from site no. 7A, near Williamstown, by Environment Canada, Water Survey Division.

Barnes (1939) expressed total potential groundwater discharge (Q_{tp}) during a baseflow recession as a general regression equation:

$$Q_{tp} = Q_o \mathrm{K}^t$$

When the integral is taken between the limits of infinity and $t = 0$, Q_{tp} becomes

$$Q_{tp} = \int_{t_o}^{\infty} Q_o \, dt = \frac{\mathrm{K}_1 \mathrm{K}_2}{2.3}$$

where Q = river discharge, K = recession constant

($\mathrm{K}_1 = Q$ at $t = 0$ (or Q_o); and $\mathrm{K}_2 = t$, when $Q = 0.1\mathrm{K}_1$)

Thus, the *total potential groundwater discharge,* Q_{tp} :

$$Q_{tp} = \frac{Q_o t_1}{2.3}$$

where Q_o is river discharge at the beginning of the recession ($m^3\ s^{-1}$), time, t, is the total time for a recession (days, weeks, etc.) and t_1 is the time for one log cycle from the beginning of the recession, which is read from the plot.

Q_{tp} is the volume of groundwater water that could potentially discharge into a stream if complete removal of groundwater from storage were to take place during a recession.

Actual groundwater discharge (AGD) for a recession is found by evaluating the integral over the limits of $t = 0$ to $t = n$ days (Domenico and Schwartz, 1990):

$$AGD = \int_{t_o}^{t} Q_o\, dt = \left[\left(\frac{Q_o\, t_1}{2.3} \right) - \left(\frac{-\frac{Q_o\, t_1}{2.3}}{10^{t/t_1}} \right) \right]$$

Baseflow storage (BS) at the end of a recession is found by subtracting *actual groundwater discharge* from *total potential groundwater discharge*:

$$BS = \left(Q_{tp} - AGD \right)_{\textbf{At end of recession}}$$

Groundwater recharge (GR) between recessions is calculated by subtracting *baseflow storage* from the previous recession from Q_{tp}.

$$GR = Q_{tp} - BS$$

A5.2 Sample Calculations

$Q_o = 7.0\ m^3/s$, t_o = day 480, t_1 = 52 days (1 log cycle), t = 115 days

The *total potential groundwater discharge*, Q_{tp} is:

$$Q_{tp} = \frac{\frac{7\,m^3}{sec} * 56\,days * \frac{1440\,min}{1\,day} * \frac{60\,sec}{1\,min}}{2.3} = 5.259 \times 10^6\ m^3$$

Actual Groundwater Discharge (AGD) is:

$$AGD = \left(5.259 \times 10^6\right) - \frac{5.259 \times 10^6}{10^{96/56}} = 5.157 \times 10^6 m^3$$

Thus, *Baseflow Storage (BS)* at end of recession:

$$BS = 5.259 \times 10^6 - 5.157 \times 10^6 = 1.02 \times 10^5\ m^3$$

Groundwater Recharge (GR) between recession is calculated, using *baseflow storage* from previous recession ($1.02 \times 10^5\ m^3$) to be:

$$GR = 1.367 \times 10^7 - 1.02 \times 10^5 = 1.357 \times 10^7\ m^3$$

A5.3 Estimation of Groundwater Discharge along the Main Branch

From the stream hydrograph/groundwater discharge calculations, an estimate of groundwater seepage flux along the length of the Raisin River from Dixon Creek to

Williamstown was found using an approximation of the riverbed surface area. The average width of the river was estimated to be 18 m and the total length of the river, measured from the 1:50,000 NTS map, was 5.82×10^4 m. Thus, the estimate of *total area* (A) was 1.05×10^6 m^2. The *actual groundwater discharge* (AGD, calculated in section A5.2, above) was divided by the *total area* to obtain an estimate of seepage flux, $\bar{q}$ (the groundwater discharge per unit area, A, of the river bed, per unit time, t):

$$q = \frac{AGD}{(A)(t)} = \frac{5.157 \text{ x } 10^6\, m^3}{\left(1.05 \text{ x } 10^6\, m^2\right)\left(96\, days\right)\left(\dfrac{86400 s}{1 day}\right)} = 5.92 \text{ x } 10^{-7}\, m^3\, m^{-2}\, s^{-1}$$

This is around the same order of magnitude of actual seepage flux measurements.

A5.4 Raisin R. Discharge and Cornwall Area Precipitation Graphs, 1994 - 1995

Both snow and rainfall are presented on the following graphs (Figures 1 to 6). These are discussed in Chapter 6, Section 2. Ward (1967) uses an equivalent water depth of snow as a ratio of 12:1, assuming the density of snow is uniform at all times. Thus, 1 cm snow is approximately equal to 0.83 mm rain.

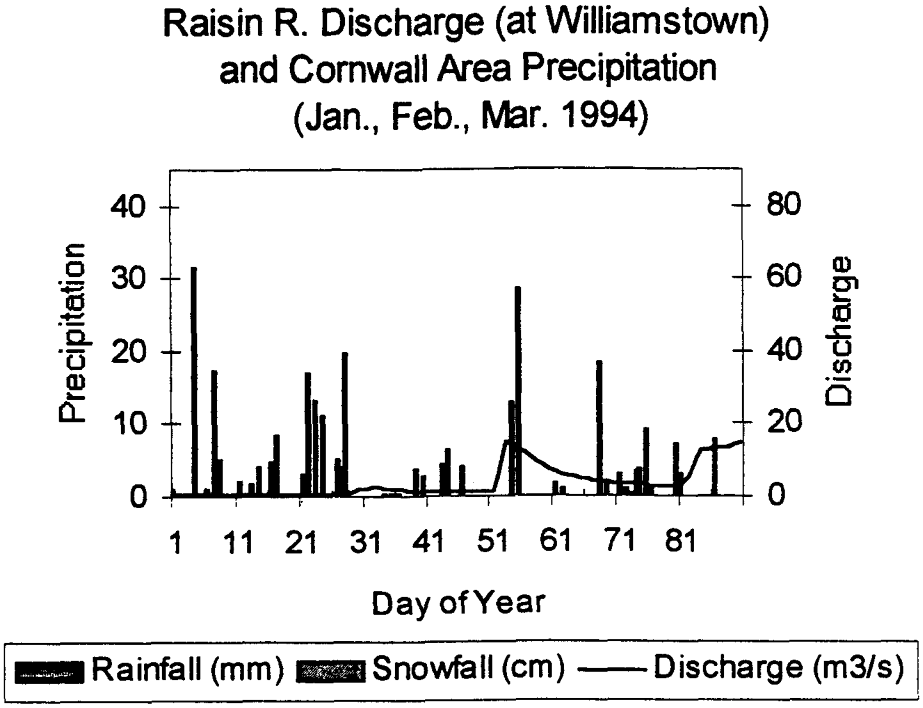

Raisin R. Discharge (at Williamstown)
and Cornwall Area Precipitation
(Jan., Feb., Mar. 1994)

Figure 1.

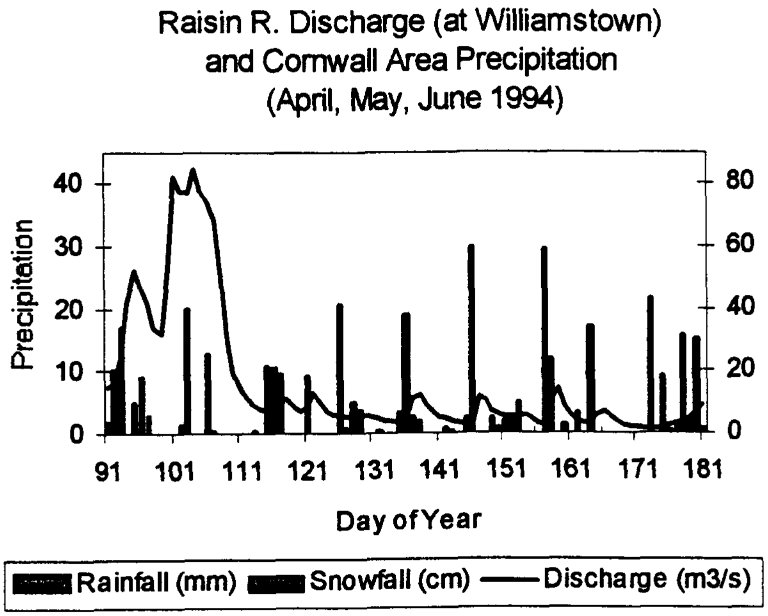
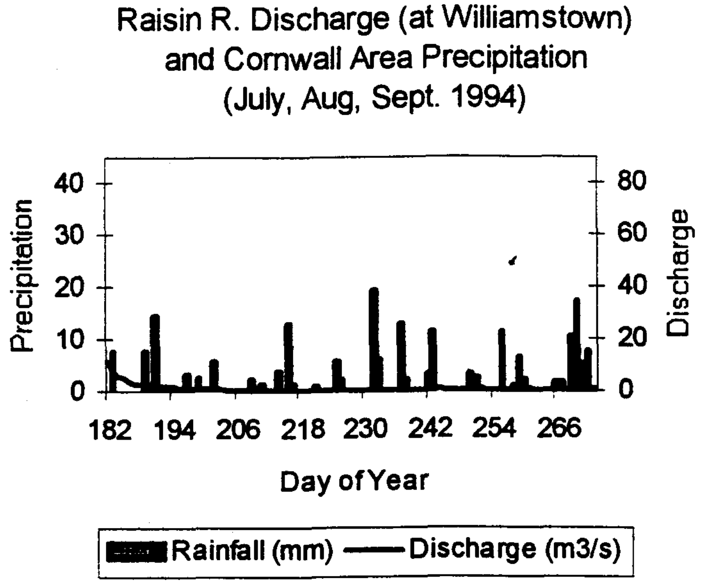
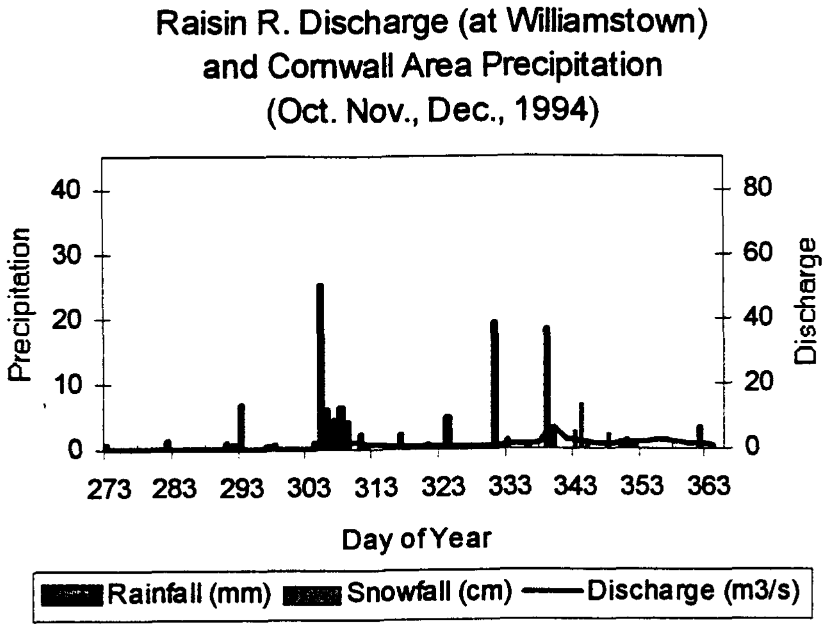

Raisin R. Discharge (at Williamstown)
and Cornwall Area Precipitation
(April, May, June 1994)

Figure 2.



Raisin R. Discharge (at Williamstown)
and Cornwall Area Precipitation
(July, Aug, Sept. 1994)

Figure 3.



Raisin R. Discharge (at Williamstown)
and Cornwall Area Precipitation
(Oct. Nov., Dec., 1994)

Figure 4.

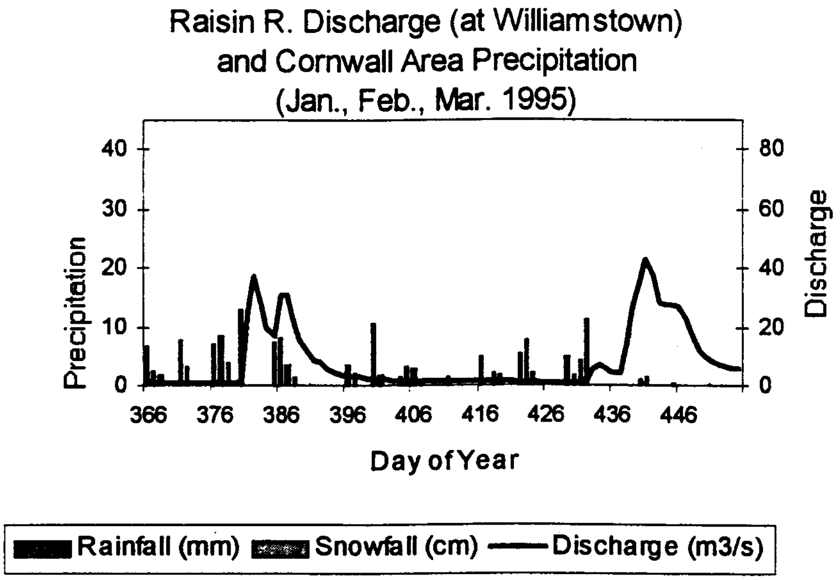


Figure 5.

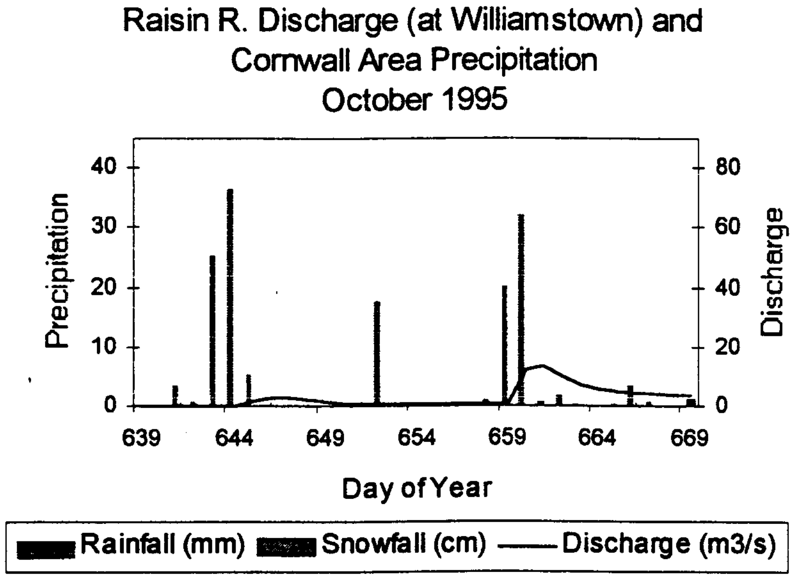


Figure 6.

A5.5 Raisin River Stage and Groundwater Seepage Graphs, Site nos. 7A and 8, October 1995

Figures 7 to 9 illustrate estimated groundwater seepage plotted with the stage in the River. These are discussed in Chapter 6, Section 3.

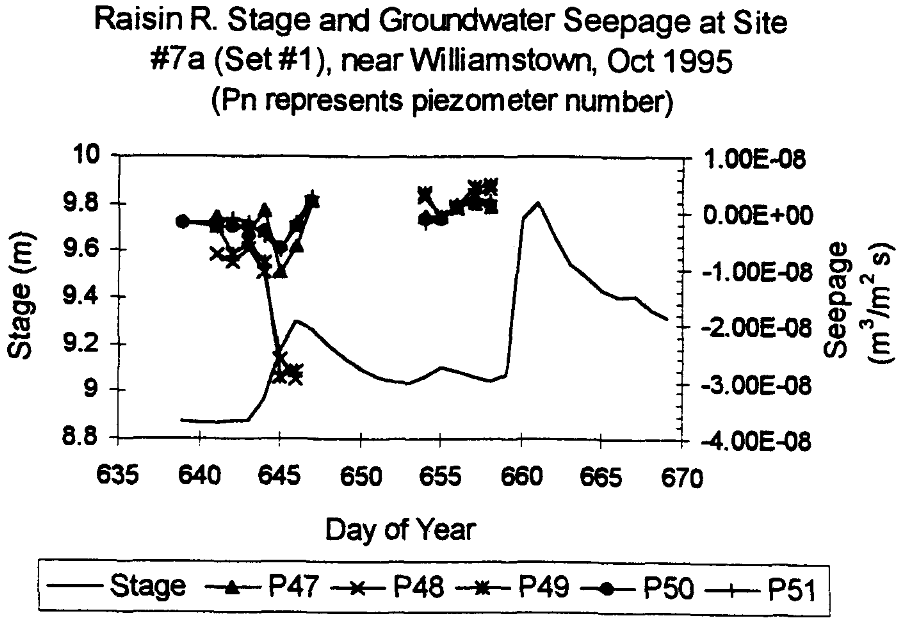

Raisin R. Stage and Groundwater Seepage at Site #7a (Set #1), near Williamstown, Oct 1995
(Pn represents piezometer number)

Figure 7.

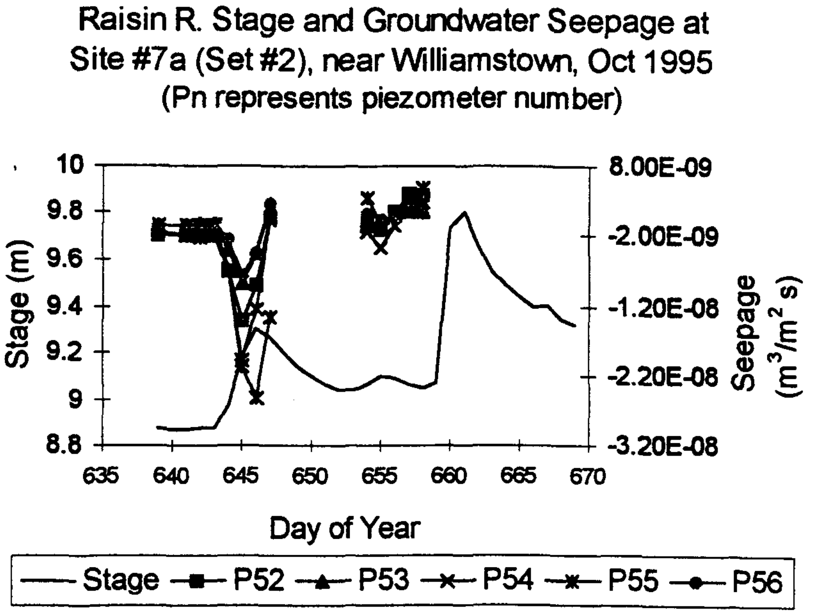

Raisin R. Stage and Groundwater Seepage at Site #7a (Set #2), near Williamstown, Oct 1995
(Pn represents piezometer number)

Figure 8.

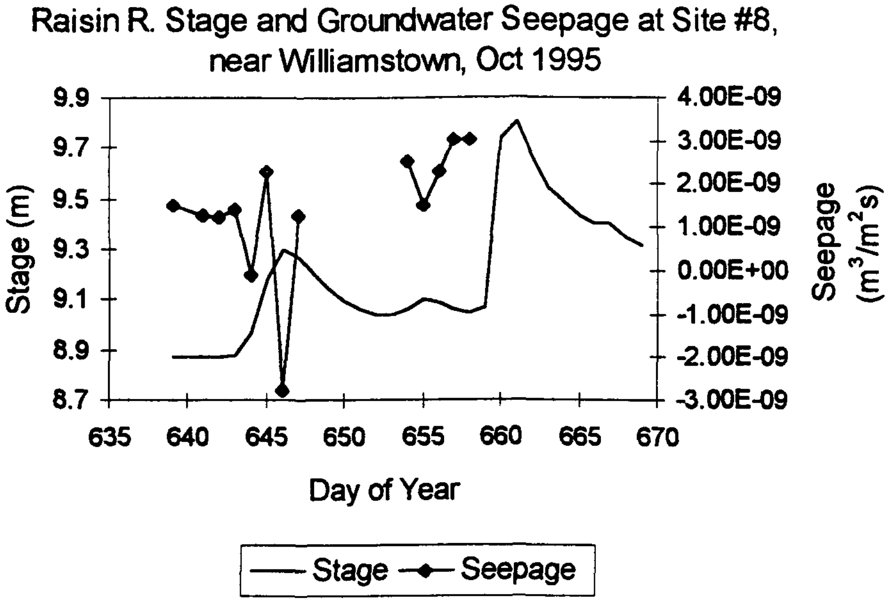


Figure 9.

A5.6 Sample Calculation of Discharge Volume

In order to estimate the volume of stream discharge attributed to a storm, which occurred in the Raisin River watershed on September 13 and 14, 1994, the stream discharge relationship used by Sklash and Farvolden (1979) was used:

$$Q_t = Q_e + Q_p$$

where Q_t is total stream discharge, Q_e is event discharge, and Q_p is pre-event discharge. For this estimation, Q_p was assumed to remain constant over the course of the storm event. Q_p was determined to be 0.045 $m^3 s^{-1}$ from an isotope analysis of this storm event (see Chapter 7). Therefore, $Q_e = Q_t - 0.045$. A plot of Q_e (t) vs. t, over the period of the storm discharge (September 14 to 19), is shown below (Figure 11). The curve was integrated to find the discharge volume attributed to the storm. Thus, the area under the curve was estimated to be equivalent to a volume of 6383 m^3. This is discussed in more detail in Chapter 6, Section 4.

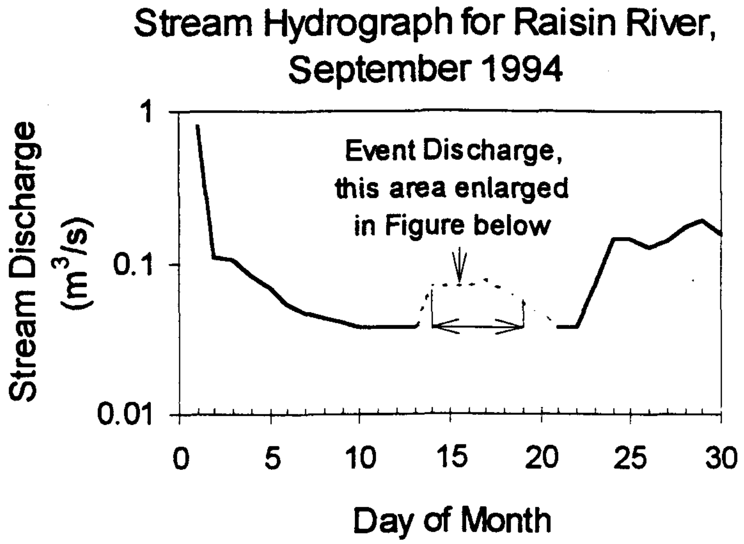


Figure 10. Stream Hydrograph of Raisin River Discharge, September 1994

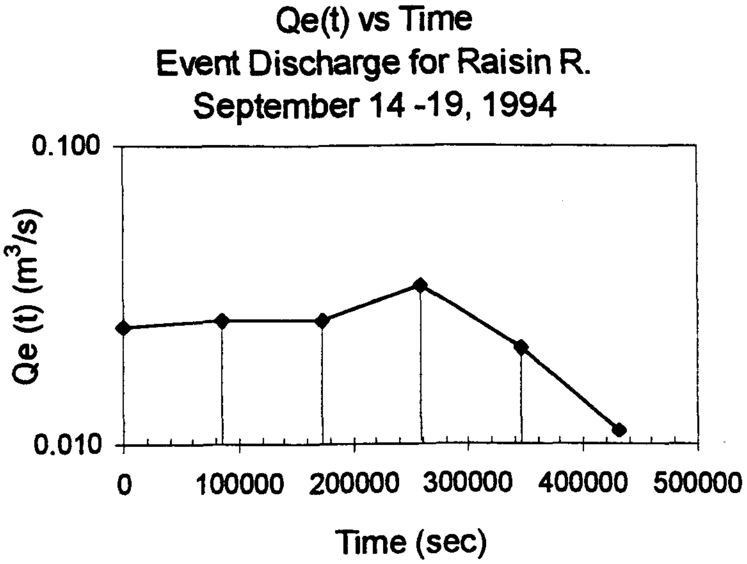


Figure 11. Event Discharge (t) vs. t for September 14, 1995 Storm Event

A5.7 References

Sklash M.G., and Farvolden, R.N., (1979) "The Role of Groundwater in Storm Runoff", Journal of Hydrology, Vol. 43, 45-65.

Ward, R.C., (1967), Principles of Hydrology, McGraw-Hill Publishing Co. Limited, London.

Appendix 6

This Appendix contains the methodologies used for stable isotopes analyses. Analysis of water samples was done at the Ottawa-Carleton Geoscience Centre Stable Isotope Laboratory located at the University of Ottawa. Analytical results are given in Appendix 7 and discussed throughout Chapter 7.

A6.1 Oxygen-18 Isotope Analysis

1 mL aliquot of water sample is equilibrated with carbon dioxide gas for approximately 6 hours at 25°C and then the carbon dioxide is directly analysed on a triple collector VG SIRA 12 mass spectrometer. Sixteen samples, with four standards (distilled water) can be analysed per run. Precision on analysis is 0.10‰ (two standard deviations).

A6.2 Deuterium Analysis

3 µL aliquots of water samples are used in a extraction method that employs the reduction of zinc at 500°C. The extracted deuterium is analysed on an automated double collector VG 602D mass spectrometer, one at a time. Standards of heavy water and light water were analysed in order to calculate a linear regression. The slope and intercept generated from the regression are used as a correction for the final deuterium results. Routine precision is 1.5‰ (equal to 2s).

For example:

$\delta D_{SMOW} = M \ \delta D_{MEAS} - B$

where M = slope and B = intercept

A6.3 References

Clark, I., Fritz, P., (1995), Environmental Isotopes in Hydrogeology, unpublished course notes.

Morriset, N., and St. Jean, G., (1995) “Stable Isotope Techniques”, Ottawa-Carleton Geoscience Centre Stable Isotope Facility, unpublished.

Appendix 7

This appendix includes delta oxygen-18 and deuterium data measured from water samples (groundwater, surface water, tile drainage, and rainfall) collected within the Raisin River watershed. It also contains calculations of mean residence time of meteoric water in the Raisin River watershed. It also includes stable isotope data for precipitation in Ottawa for the years 1989 to 1994 which was collected by the International Atomic Energy Agency. This data is also displayed in oxygen-18 vs time graphs for each year. Analytical results are discussed throughout Chapter 7 in the text.

A7.1 Delta Oxygen-18 and Deuterium Data

In the following data tables, p represent groundwater collected from piezometers, r represents rainfall, s represents surface waters, and t represents tile drainage waters. Dates are given in Julian days, 1994 (0 to 365) and 1995 (366 to 730).

Table of Delta Oxygen-18 and Deuterium Results:

Day of Year	Date	Type	Site	Sample No.	Delta O-18	Delta D
158	94.06.07	p	1	19	-11.12	-73.2
158	94.06.07	p	1	20	-11.14	-75.2
158	94.06.07	p	1	21	-11.18	-72.4
159	94.06.08	p	1	22	-11.16	-74.9
159	94.06.08	p	1	23	-11.17	-73.9
174	94.06.23	p	1	43	-11.25	-73.7
174	94.06.23	p	1	44	-11.19	-71.4
182	94.07.01	p	1	G24	-11.22	-75.0
196	94.07.15	p	1	G25	-11.23	-74.1
210	94.07.29	p	1	G26	-11.26	-73.5
224	94.08.12	p	1	G27	-11.18	-75.1
238	94.08.26	p	1	G28	-11.19	-75.3
253	94.09.10	p	1	G29	-11.27	-76.3
255	94.09.12	p	1	81	-11.30	-60.2
266	94.09.23	p	1	G30	-11.21	-75.8
288	94.10.15	p	1	G31	-11.21	-74.0
313	94.11.09	p	1	138	-11.27	-73.3
319	94.11.15	p	1	G32	-11.01	-74.5
510	95.05.25	p	1	42A	-11.36	-73.9
172	94.06.21	p	2	33	-10.61	-71.6
174	94.06.23	p	2	45	-10.74	-71.3
196	94.07.15	p (s)	2	G33	-10.15	-70.6
210	94.07.29	p (s)	2	G34	-10.70	-74.6
224	94.08.12	p (s)	2	G35	-9.62	-69.7
228	94.08.16	p	2	64	-11.11	-72.9
238	94.08.26	p (s)	2	G36	-9.10	-68.7
252	94.09.09	p	2	75	-10.90	-77.6
253	94.09.10	p (s)	2	G37	-9.17	-67.5
266	94.09.23	p	2	G38	-10.72	-74.7
286	94.10.13	p	2	106	-11.30	-77.5
288	94.10.15	p	2	G39	-10.93	-76.4
313	94.11.09	p	2	140	-11.24	-73.0
319	94.11.15	p	2	G40	-11.00	-77.0
320	94.11.16	p	2	G41	-11.16	-77.6
510	95.05.25	p	2	44A	-11.22	-75.3
174	94.06.23	p	3	46	-11.12	-72.2
252	94.09.09	p	3	79	-10.53	-71.1
286	94.10.13	p	3	112	-10.76	-74.5
307	94.11.03	p	3	134	-10.75	-69.8
188	94.07.07	p	4	58	-10.67	-69.0
255	94.09.12	p	4	83	-10.56	-71.0
286	94.10.13	p	4	114	-10.71	-72.2
313	94.11.09	p	4	145	-10.55	-68.6
510	95.05.25	p	4	46A	-10.64	-74.9
258	94.09.15	p	5	86	-9.74	-68.6
286	94.10.13	p	5	116	-10.41	-72.4
313	94.11.09	p	5	148	-10.32	-71.1
507	95.05.22	p	5	31A	-9.66	-69.5
196	94.07.15	p(s)	6	G52	-10.16	-72.0
210	94.07.29	p(s)	6	G53	-9.79	-70.6
224	94.08.12	p	6	G54	-11.46	-78.9
238	94.08.26	p	6	G55	-11.39	-79.9
253	94.09.10	p	6	G56	-11.45	-79.1
258	94.09.15	p	6	88	-11.58	-76.1
266	94.09.23	p	6	G57	-10.32	-73.0
286	94.10.13	p	6	118	-10.99	-74.5
288	94.10.15	p	6	G59	-10.94	-73.2

Year	Date	Type	Site	Sample No.	Delta O-18	Delta D
313	94.11.09	p	6	151	-10.93	-70.9
319	94.11.15	p	6	G60	-10.80	-73.7
510	95.05.25	p	6	51A	-11.18	-75.8
258	94.09.15	p	7	90	-11.20	-77.0
286	94.10.13	p	7	120	-11.16	-73.0
313	94.11.09	p	7	153	-11.17	-75.1
259	94.09.16	p	8	94	-10.81	-76.7
261	94.09.18	p	8	96	-9.98	-66.1
286	94.10.13	p	8	124	-10.74	-74.3
313	94.11.09	p	8	157	-10.80	-70.8
510	95.05.25	p	8	55A	-10.98	-79.3
293	94.10.20	p	11	128	-11.37	-75.0
313	94.11.09	p	11	159	-11.44	-78.6
508	95.05.23	p	11	35A	-11.39	-80.8
300	94.10.27	p	12	133	-10.97	-73.7
313	94.11.09	p	12	161	-11.10	-76.2
510	95.05.25	p	12	37A	-11.17	-75.6
313	94.11.09	p	13	163	-10.44	-72.0
508	95.05.23	p	13	39A	-10.62	-71.1
172	94.06.21	p	2a	34	-11.05	-75.1
172	94.06.21	p	2a	35	-11.76	-79.3
182	94.07.01	p	2a	G42	-11.56	-80.6
196	94.07.15	p	2a	G44	-11.35	-78.1
210	94.07.29	p	2a	G45	-11.15	-78.1
224	94.08.12	p	2a	G46	-11.37	-79.7
238	94.08.26	p	2a	G47	-11.05	-79.1
252	94.09.09	p	2a	77	-11.08	-76.9
253	94.09.10	p	2a	G48	-10.77	-76.1
266	94.09.23	p	2a	G49	-10.55	-75.9
286	94.10.13	p	2a	108	-11.23	-76.9
286	94.10.13	p	2a	110	-10.78	-74.5
288	94.10.15	p	2a	G50	-10.31	-73.7
313	94.11.09	p	2a	142	-10.50	-70.2
319	94.11.15	p	2a	G51	-10.07	-71.3
289	94.09.16	p	7a	95	-10.47	-71.6
286	94.10.13	p	7a	122	-10.06	-71.4
313	94.11.09	p	7a	155	-10.37	-72.0
490	95.05.03	p	7a	30A	-10.48	-70.9
507	95.05.22	p	7a	33A	-10.62	-63.2
510	95.05.25	p	7a	53A	-10.56	-76.4
201	94.07.20	r	1	59	-8.11	-50.7
216	94.08.03	r	1	61	-8.88	-60.4
237	94.08.25	r	1	69	-6.69	-39.2
257	94.09.14	r	1	84	-5.68	-26.4
259	94.09.16	r	1	93	-5.20	-26.6
264	94.09.21	r	1	97	-3.20	-12.5
266	94.09.23	r	1	98	-7.46	-57.2
272	94.09.29	r	1	103	-13.97	-95.5
293	94.10.20	r	1	129	-8.90	-55.1
201	94.07.20	r	3	60	-6.67	-43.4
217	94.08.05	r	3	190	-6.42	-40.3
229	94.08.17	r	3	191	-6.23	-36.2
241	94.08.29	r	3	70	-5.39	-32.8
243	94.08.31	r	3	71	-11.52	-86.8
251	94.09.08	r	3	72	-13.13	-95.8
271	94.09.28	r	3	101	-8.66	-60.6
293	94.10.20	r	3	130	-8.49	-57.0
300	94.10.27	r	3	131	-11.89	-79.1
313	94.11.09	r	3	144	-7.58	-42.0
102	94.04.12	s	1	1	-15.02	-108.0
116	94.04.26	s	1	9	-13.03	-89.7

Year	Date	Type	Site	Sample No.	Delta O-18	Delta D
131	94.05.11	s	1	173	-12.41	-83.2
154	94.06.03	s	1	G61	-11.88	-82.2
159	94.06.08	s	1	25	-11.33	-76.3
173	94.06.22	s	1	36	-10.83	-71.8
182	94.07.01	s	1	G62	-10.67	-72.9
187	94.07.06	s	1	49	-10.37	-70.5
224	94.09.12	s	1	80	-9.74	-69.2
286	94.10.13	s	1	105	-10.45	-73.3
288	94.10.15	s	1	G63	-10.44	-70.8
313	94.11.09	s	1	137	-10.54	-70.5
319	94.11.15	s	1	G64	-10.70	-70.4
349	94.12.15	s	1	G65	-11.02	-74.7
380	95.01.15	s	1	G66	-11.35	-73.1
411	95.02.15	s	1	4A	-10.84	-73.9
439	95.03.15	s	1	10A	-12.99	-88.0
467	95.04.12	s	1	17A	-11.79	-78.1
510	95.05.25	s	1	43A	-10.71	-72.8
102	94.04.12	s	2	2	-14.99	-103.7
116	94.04.26	s	2	10	-12.42	-84.3
131	94.05.11	s	2	174	-12.25	-83.8
154	94.06.03	s	2	G67	-11.37	-81.5
159	94.06.08	s	2	26	-10.51	-69.4
168	94.06.17	s	2	G68	-10.55	-72.4
173	94.06.22	s	2	37	-10.45	-70.4
182	94.07.01	s	2	G69	-10.13	-68.2
187	94.07.06	s	2	50	-10.62	-71.8
252	94.09.09	s	2	74	-10.90	-64.1
288	94.10.15	s	2	G70	-8.84	-64.0
131	94.11.09	s	2	139	-10.50	-69.8
319	94.11.15	s	2	G71	-10.32	-69.1
349	94.12.15	s	2	G72	-11.13	-74.1
380	95.01.15	s	2	G73	-11.58	-75.5
411	95.02.15	s	2	9A	-11.40	-76.3
439	95.03.15	s	2	16A	-14.28	-101.7
467	95.04.12	s	2	23A	-11.71	-79.4
510	95.05.25	s	2	45A	-10.47	-69.0
102	94.04.12	s	3	3	-15.19	-106.0
116	94.04.26	s	3	12	-12.73	-86.7
131	94.05.11	s	3	175	-12.19	-84.5
154	94.06.03	s	3	G74	-10.60	-77.6
159	94.06.08	s	3	27	-10.46	-67.4
168	94.06.17	s	3	G75	-10.74	-74.5
173	94.06.22	s	3	38	-10.39	-71.0
182	94.07.01	s	3	G76	-10.05	-68.6
187	94.07.06	s	3	51	-10.55	-69.5
215	94.08.03	s	3	183	-9.13	-66.9
252	94.09.09	s	3	78	-8.76	-64.5
286	94.10.13	s	3	111	-8.63	-61.8
288	94.10.15	s	3	G77	-8.37	-63.5
313	94.11.09	s	3	143	-10.38	-68.6
315	94.11.15	s	3	G78	-10.25	-67.9
349	94.12.15	s	3	G79	-11.27	-75.0
380	95.01.15	s	3	G80	-11.52	-72.2
411	95.02.15	s	3	5A	-11.53	-78.3
439	95.03.15	s	3	11A	-14.42	-101.5
467	95.04.12	s	3	18A	-11.71	-80.0
102	94.04.12	s	4	4	-15.16	-106.3
116	94.04.26	s	4	13	-12.68	-87.7
131	94.05.11	s	4	176	-12.06	-84.7
159	94.06.08	s	4	28	-10.32	-70.2
173	94.06.22	s	4	39	-10.36	-70.1

Year	Date	Type	Site	Sample No.	Delta O-18	Delta D
187	94.07.06	s	4	52	-10.26	-68.0
215	94.08.03	s	4	184	-9.68	-70.7
255	94.09.12	s	4	82	-8.22	-61.1
286	94.10.13	s	4	113	-7.17	-60.1
313	94.11.09	s	4	146	-10.36	-68.6
411	95.02.15	s	4	6A	-11.55	-76.9
439	95.03.15	s	4	12A	-14.33	-103.1
467	95.04.12	s	4	19A	-11.75	-77.9
510	95.05.25	s	4	47A	-10.50	-73.1
102	94.04.12	s	5	5	-15.18	-106.7
116	94.04.26	s	5	14	-12.21	-87.6
131	94.05.11	s	5	177	-12.18	-84.9
159	94.06.08	s	5	29	-10.46	-67.8
173	94.06.22	s	5	40	-10.21	-67.4
187	94.07.06	s	5	53	-10.35	-69.2
215	94.08.03	s	5	185	-9.76	-67.3
258	94.09.15	s	5	85	-7.40	-54.2
286	94.10.13	s	5	115	-7.20	-57.7
313	94.11.09	s	5	149	-10.32	-68.2
465	95.04.10	s	5	27A	-11.57	-82.2
467	95.04.12	s	5	25A	-11.70	-80.9
507	95.05.22	s	5	32A	-10.20	-71.1
510	95.05.25	s	5	49A	-10.45	-74.9
102	94.04.12	s	6	6	-15.17	-107.0
116	94.04.26	s	6	15	-13.00	-88.8
131	94.05.11	s	6	178	-12.42	-86.9
159	94.06.08	s	6	30	-10.80	-72.9
173	94.06.22	s	6	41	-11.01	-75.1
187	94.07.06	s	6	54	-10.40	-71.8
215	94.08.03	s	6	186	-8.94	-64.9
258	94.09.15	s	6	87	-8.25	-59.3
286	94.10.13	s	6	117	-8.51	-62.5
288	94.10.15	s	6	G58	-8.59	-61.6
313	94.11.09	s	6	152	-10.16	-69.9
467	95.04.12	s	6	24A	-11.66	-81.1
510	95.05.25	s	6	52A	-10.36	-67.5
102	94.04.12	s	7	7	-14.87	-105.7
116	94.04.26	s	7	16	-12.82	-90.1
131	94.05.11	s	7	179	-12.22	-83.1
159	94.06.08	s	7	31	-10.29	-68.2
187	94.07.06	s	7	55	-10.49	-72.2
215	94.08.03	s	7	187	-9.02	-63.4
258	94.09.15	s	7	89	-7.49	-57.0
286	94.10.13	s	7	119	-7.52	-57.2
313	94.11.09	s	7	154	-10.18	-67.1
102	94.04.12	s	8	8	-15.11	-106.6
131	94.05.11	s	8	180	-12.23	-84.8
159	94.06.08	s	8	32	-10.66	-69.5
173	94.06.22	s	8	42	-10.44	-70.5
187	94.07.06	s	8	56	-10.36	-66.9
215	94.08.03	s	8	188	-9.17	-64.3
234	94.08.22	s	8	67	-8.66	-62.4
251	94.09.08	s	8	73	-8.97	-63.1
258	94.09.15	s	8	92	-8.07	-59.9
286	94.10.13	s	8	123	-7.61	-57.5
313	94.11.09	s	8	158	-9.72	-66.4
510	95.05.25	s	8	56A	-10.45	-74.4
168	94.06.17	s	11	G96	-10.08	-66.3
182	94.07.01	s	11	G97	-9.92	-66.0
266	94.09.23	s	11	99	-7.02	-53.6
286	94.10.13	s	11	125	-7.76	-55.7

Year	Date	Type	Site	Sample No.	Delta O-18	Delta D
293	94.10.20	s	11	127	-8.08	-58.0
313	94.11.09	s	11	160	-10.23	-68.2
349	94.12.15	s	11	G100	-11.36	-78.9
380	95.01.15	s	11	G101	-10.96	-68.6
411	95.02.15	s	11	8A	-11.30	-77.8
439	95.03.15	s	11	15A	-14.42	-103.7
467	95.04.12	s	11	22A	-11.25	-77.4
508	95.05.23	s	11	36A	-10.26	-73.1
279	94.10.06	s	12	104	-7.63	-57.5
286	94.10.13	s	12	126	-7.46	-53.4
300	94.10.27	s	12	132	-8.17	-57.5
313	94.11.09	s	12	162	-9.75	-69.2
508	95.05.23	s	12	38A	-10.04	-72.8
313	94.11.09	s	13	164	-10.09	-69.1
467	95.04.12	s	13	26A	-10.95	-75.6
508	95.05.23	s	13	40A	-10.06	-74.4
313	94.11.09	s	14	167	-6.73	-46.4
335	94.12.01	s	14	172	-6.68	-45.5
116	94.04.26	s	2a	11	-12.59	-82.1
188	94.07.07	s	2a	57	-10.50	-68.6
223	94.08.11	s	2a	62	-9.50	-65.4
229	94.08.17	s	2a	65	-9.60	-73.5
235	94.08.23	s	2a	68	-9.18	-61.3
252	94.09.09	s	2a	76	-9.71	-65.9
286	94.10.13	s	2a	107	-8.92	-63.8
286	94.10.13	s	2a	109	-8.05	-61.0
313	94.11.09	s	2a	141	-10.48	-67.3
116	94.04.26	s	7a	17	-12.60	-88.7
227	94.08.15	s	7a	63	-8.60	-65.5
234	94.08.22	s	7a	66	-8.34	-68.8
258	94.09.15	s	7a	91	-7.66	-60.8
286	94.10.13	s	7a	121	-7.15	-55.2
313	94.11.09	s	7a	156	-9.93	-65.2
439	95.03.15	s	7a	14A	-14.86	-106.2
467	95.04.12	s	7a	21A	-11.71	-80.8
507	95.05.22	s	7a	34A	-10.42	-74.4
510	95.05.25	s	7a	54A	-10.24	-72.7
181	94.06.30	t	4	47	-9.89	-62.3
313	94.11.09	t	4	147	-10.77	-75.4
510	95.05.25	t	4	48A	-10.44	-70.1
116	94.04.26	t	5	18	-11.91	-80.1
144	94.05.24	t	5	189	-12.31	-84.4
185	94.07.04	t	5	48	-11.65	-77.0
271	94.09.28	t	5	100	-11.69	-80.8
307	94.11.03	t	5	135	-11.44	-76.4
313	94.11.09	t	5	150	-11.50	-72.5
335	94.12.01	t	5	169	-11.49	-77.4
465	95.04.10	t	5	28A	-11.35	-75.8
510	95.05.25	t	5	50A	-11.50	-78.9
271	94.09.28	t	11	102	-9.05	-61.7
307	94.11.03	t	13	136	-10.83	-66.8
313	94.11.09	t	13	165	-10.80	-71.7
327	94.11.23	t	13	168	-10.76	-70.2
335	94.12.01	t	13	170	-10.94	-71.1
465	95.04.10	t	13	29A	-11.16	-75.3
508	95.05.23	t	13	41A	-10.96	-58.3

A7.2 Calculation of Mean Residence Time of Meteoric Water in Watershed

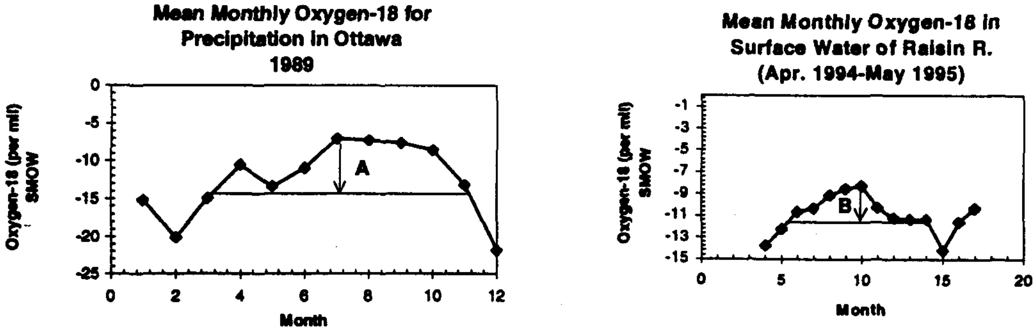


Figure 1. and 2. Amplitudes of Oxygen-18 Curves for Precipitation and Surface Water

Mean Residence Time , T, in years can be calculated with the following equation from

Pearce et al. (1986):

$$T = w^{-1} \left[\left(A/B \right)^{2} - 1 \right]^{1/2}$$

where A/B = amplitude damping, A is the amplitude of oxygen-18 precipitation values and B is the amplitude of oxygen-18 in river values (see Figures 1 and 2). Also, w = period of 2π per year.

A7.3 Calculation of Residence Time, T

Plots of mean monthly oxygen-18 in precipitation vs time were generated for each of the six years (see following pages). A mean amplitude for precipitation was calculated from 6 plots of monthly oxygen-18 in precipitation (from 1989 to

1994) to derive $A = 7.05$. The amplitude, B, of the oxygen-18 in surface water plot was estimated as $B = 3$, based on data collection in this study over the period of April 1994 to May 1995.

$$T = w^{-1}\left[\left(A/B\right)^2 - 1\right]^{1/2} = \frac{1}{2\pi}\left[\left(\frac{7.05}{3}\right)^2 - 1\right]^{1/2} = 0.338 \text{ years (or 4.061 months)}$$

Theoretically, the error on T could be estimated from the covariance matrix of A with B. However, only the variance on A is available and therefore, the error on T could not be estimated.

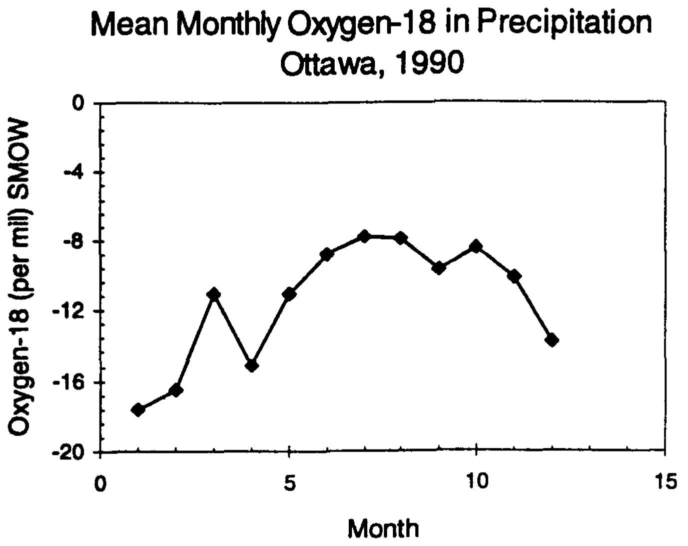
A7.4 I.A.E.A. Stable Isotope Data for Precipitation in Ottawa, 1989 to 1994

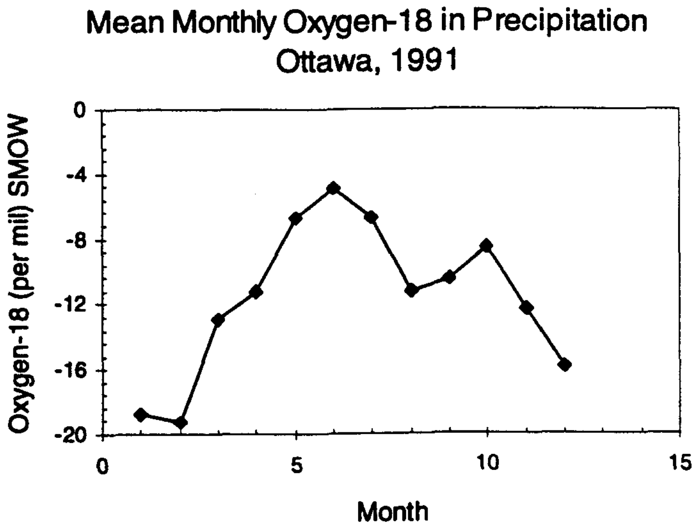
Table 1. Monthly Isotope Values for Precipitation in Ottawa, 1989 to 1994

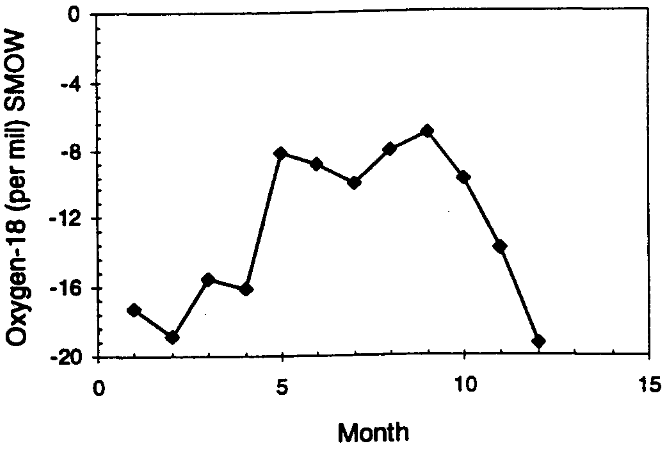
Year	Month	Precip (mm)	Oxygen-18 (per mil)	Deuterium (per mil)
1989	1	63.8	-15.22	-106.4
1989	2	30.6	-20.23	-147.4
1989	3	80.8	-14.98	-107.3
1989	4	24.2	-10.54	-68.9
1989	5	101.2	-13.38	-97.6
1989	6	70.6	-10.99	-80.6
1989	7	67.2	-7.06	-46.5
1989	8	53.2	-7.30	-50.8
1989	9	31.2	-7.61	-45.9
1989	10	96.2	-8.61	-50.2
1989	11	140.3	-13.20	-88.8
1989	12	45.8	-21.91	-155.7
1990	1	73.7	-17.62	-125.6
1990	2	84.2	-16.49	-118.2
1990	3	35.3	-11.06	-86.7
1990	4	83.3	-15.10	-122.0
1990	5	54.0	-11.10	-70.8
1990	6	38.0	-8.85	-57.0
1990	7	114.3	-7.82	-59.9
1990	8	135.0	-7.95	-49.9
1990	9	103.0	-9.70	-62.9
1990	10	95.9	-8.47	-53.9
1990	11	70.2	-10.19	-65.9
1990	12	121.5	-13.81	-97.1
1991	1	51.4	-18.81	-134.7
1991	2	45.7	-19.29	-138.0
1991	3	87.1	-12.88	-119.3
1991	4	130.8	-11.23	-75.5
1991	5		-6.67	-39.0
1991	6	14.0	-4.87	-27.3
1991	7	49.1	-6.67	-42.6
1991	8	83.6	-11.21	-74.9
1991	9	61.4	-10.44	-72.2
1991	10	62.6	-8.59	-54.3
1991	11	40.7	-12.30	-82.9
1991	12	70.0	-15.88	-109.2

Year	Month	Precip (mm)	Oxygen-18 (per mil)	Deuterium (per mil)
1992	1	61.0	-17.21	-122.2
1992	2	78.2	-18.80	-134.6
1992	3	97.6	-15.50	-107.2
1992	4	51.4	-16.04	-122.3
1992	5	63.8	-8.21	-53.8
1992	6	57.8	-8.88	-61.3
1992	7	186.3	-10.05	-71.2
1992	8	105.0	-8.04	-62.3
1992	9	76.6	-7.01	-41.1
1992	10	48.8	-9.77	-61.0
1992	11	94.0	-13.77	-94.4
1992	12	51.7	-19.31	-134.7
1993	1	109.2	-16.62	-125.9
1993	2	80.5	-21.30	-156.1
1993	3	86.5	-21.41	-158.0
1993	4	144.1	-12.24	-83.1
1993	5	80.2	-7.53	-45.0
1993	6	101.4	-7.54	-47.7
1993	7	65.6	-8.07	-56.7
1993	8	50.4	-8.01	-38.7
1993	9	91.6	-10.73	-74.9
1993	10	101.2	-9.98	-64.3
1993	11	96.4	-11.76	-78.6
1993	12	53.8	-19.29	-136.8
1994	1	67.6	-22.06	-160.4
1994	2	55.8	-19.54	-145.0
1994	3	62.8	-20.38	-153.4
1994	4	84.9	-11.04	-78.2
1994	5	77.4	-9.39	-67.1
1994	6	165.4	-8.58	-57.4
1994	7	114.6	-8.18	-49.7
1994	8	120.4	-7.01	-41.0
1994	9	58.0	-7.81	-48.6
1994	10	15.4	-9.18	-62.5
1994	11	88.1	-12.17	-82.2
1994	12	37.0	-17.13	-119.8

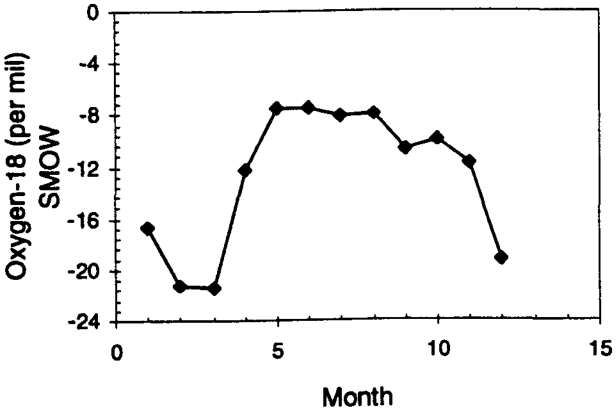
A7.5 Additional Oxygen-18 vs Time Graphs for Ottawa Precipitation (1990 to 1994)


Mean Monthly Oxygen-18 in Precipitation
Ottawa, 1990

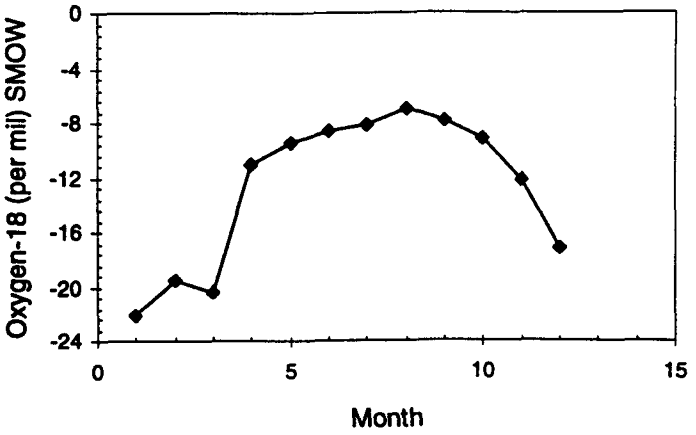

Mean Monthly Oxygen-18 in Precipitation
Ottawa, 1991



Mean Monthly Oxygen-18 in Precipitation
Ottawa, 1992



Mean Monthly Oxygen-18 in Precipitation
Ottawa, 1993



Mean Monthly Oxygen-18 in Precipitation
Ottawa, 1994

A7.6 Statistical Results

A7.6.1 Comparison of Groundwater and Surface Water (collected on same day)

This section contains the results of an ANOVA between groundwater (water collected from piezometers) and surface water samples collected on the same day. The model with which they were analysed is:

$$\delta\,^{18}\mathrm{O} \text{ or } \mathrm{D} = \mu + \mathrm{Day} + \mathrm{Type} + \mathrm{Site} + \varepsilon$$

Day (time) and Site (sample location) were included to remove temporal and spatial variability when comparing the two water types (p = groundwater and s = surface water). The ANOVA results indicate that there is a significant difference between the concentration of oxygen-18 or deuterium for groundwater and surface water samples ($p = 8.4 \times 10^{-12}$ for ^{18}O and $p = 1.7 \times 10^{-12}$ for D). There is a much smaller effect from the day of sampling and the site location. The ANOVA tables (generated in Systat™) are given below.

```
SYSTAT FILE VARIABLES AVAILABLE TO YOU ARE:
        DAY              D             oxygen-18          SITE           TYPE$

Oxygen-18:
LEVELS ENCOUNTERED DURING PROCESSING ARE:
 SITE
       1.0000       2.0000       2.5000       3.0000       4.0000       5.0000
       6.0000       7.0000       7.5000       8.0000      11.0000      12.0000
      13.0000

TYPE$
 p          s

 DEP VAR:    oxygen-18      N:      92  MULTIPLE R: 0.750  SQUARED MULTIPLE R: 0.562

                           ANALYSIS OF VARIANCE

 SOURCE        SUM-OF-SQUARES   DF  MEAN-SQUARE      F-RATIO        P

 SITE                21.3197   12       1.7766       2.6095       0.0057
 DAY                  5.5854    1       5.5854       8.2036       0.0054
 TYPE$               44.0360    1      44.0360      64.6784 .843214E-11
```

```
 ERROR               52.4251   77        0.6808

Deuterium:
LEVELS ENCOUNTERED DURING PROCESSING ARE:
 SITE
        1.0000       2.0000       2.5000       3.0000       4.0000       5.0000
        6.0000       7.0000       7.5000       8.0000      11.0000      12.0000
       13.0000
 TYPE$
  p            s


 DEP VAR:       D       N:       92  MULTIPLE R: 0.749  SQUARED MULTIPLE R: 0.561

                             ANALYSIS OF VARIANCE

 SOURCE        SUM-OF-SQUARES   DF  MEAN-SQUARE      F-RATIO        P

 SITE              432.6507   12      36.0542       1.9139       0.0454
 DAY               181.4400    1     181.4400       9.6317       0.0027
 TYPE$            1328.6890    1    1328.6890      70.5334 .173517E-11

 ERROR            1450.5053   77      18.8377
```

A7.6.2. Spatial and Temporal Variability of Stable Isotope Content in Water Samples - ANOVA Results

The following ANOVA's are an examination of the variability of the different water types. This is discussed in Chapter 7.

Rain: The two ANOVA's for deuterium and oxygen-18 indicate that there is no significant difference in the isotopic concentration of rain water samples over time (p = 0.49 and p = 0.34). In other words, there is an insignificant relationship of the stable isotope content of rain with time. See results below.

Tile Drainage: The ANOVA reveals that there is no significant difference with time for either isotope (p = 0.42 for oxygen-18 and p = 0.53 for deuterium). However, there is some significant difference of the isotope composition between sites ($p = 9.79 \times 10^{-7}$ for oxygen-18 and $p = 6.00 \times 10^{-3}$ for deuterium). See ANOVA results below.

Surface Water: The ANOVA indicates that there is no significant difference in oxygen-18 composition from day to day ($p = 0.21$) or from site to site ($p = 0.21$). There is also no significant difference in deuterium composition over time ($p = 0.16$) or with site ($p = 0.48$). See ANOVA results below.

Groundwater: ANOVA's indicate that there is a significant difference in the deuterium and oxygen-18 content in groundwater from site to site ($p = 4.5 \times 10^{-5}$ for deuterium and $p = 3.87 \times 10^{-3}$ for oxygen-18). The analysis indicates an insignificant difference from day to day for both isotopes ($p = 0.30$ for oxygen-18 and $p = 0.35$ for deuterium). See ANOVA results below.

Rain:

Deuterium:

```
 DEP VAR:  DELTAD       N:       19  MULTIPLE R: 0.171  SQUARED MULTIPLE R: 0.029
 ADJUSTED SQUARED MULTIPLE R:   .000    STANDARD ERROR OF ESTIMATE:       23.793

 VARIABLE      COEFFICIENT    STD ERROR      STD COEF TOLERANCE     T   P(2 TAIL)

 CONSTANT          -21.360       43.966         0.000       .      -0.486     0.633
 DAY                -0.123        0.172        -0.171     1.000   -0.714     0.485

                           ANALYSIS OF VARIANCE

 SOURCE         SUM-OF-SQUARES   DF  MEAN-SQUARE      F-RATIO        P

 REGRESSION          288.564      1       288.564       0.510       0.485
 RESIDUAL           9623.528     17       566.090
```

Oxygen-18

```
 DEP VAR:DELTA18O       N:       19  MULTIPLE R: 0.233  SQUARED MULTIPLE R: 0.054
 ADJUSTED SQUARED MULTIPLE R:   .000    STANDARD ERROR OF ESTIMATE:        2.832

 VARIABLE      COEFFICIENT    STD ERROR      STD COEF TOLERANCE     T   P(2 TAIL)
```

```
CONSTANT              -2.973        5.233        0.000        .      -0.568    0.577
DAY                   -0.020        0.020       -0.233     1.000     -0.989    0.337


                             ANALYSIS OF VARIANCE

SOURCE         SUM-OF-SQUARES    DF  MEAN-SQUARE      F-RATIO        P

REGRESSION             7.845      1        7.845        0.978       0.337
RESIDUAL             136.338     17        8.020
```

Tile Drainage Waters:

```
Deuterium

LEVELS ENCOUNTERED DURING PROCESSING ARE:
 SITE
       4.0000        5.0000        11.0000       13.0000


 DEP VAR:  DELTAD       N:        19  MULTIPLE R: 0.776  SQUARED MULTIPLE R: 0.603
                             ANALYSIS OF VARIANCE

 SOURCE        SUM-OF-SQUARES   DF  MEAN-SQUARE      F-RATIO        P

 SITE               465.8935    3     155.2978      6.3631      0.0060
 DAY                 10.1375    1      10.1375      0.4154      0.5297

 ERROR              341.6863   14      24.4062

Oxygen-18:

LEVELS ENCOUNTERED DURING PROCESSING ARE:
 SITE
       4.0000        5.0000        11.0000       13.0000

 DEP VAR:DELTA180       N:        19  MULTIPLE R: 0.940  SQUARED MULTIPLE R: 0.884

                             ANALYSIS OF VARIANCE

 SOURCE        SUM-OF-SQUARES   DF  MEAN-SQUARE      F-RATIO        P

 SITE                 8.5782    3       2.8594     34.6957 .979267E-06
 DAY                  0.0578    1       0.0578      0.7019      0.4162

 ERROR                1.1538   14       0.0824
```

Groundwater:

```
Oxygen-18:

LEVELS ENCOUNTERED DURING PROCESSING ARE:
 SITE
       1.000         2.000         2.500         3.000        4.000         5.000
       6.000         7.000         7.500         8.000       11.000        12.000
      13.000

 DEP VAR:DELTA180       N:        97  MULTIPLE R: 0.616  SQUARED MULTIPLE R: 0.380

                             ANALYSIS OF VARIANCE
```

```
SOURCE         SUM-OF-SQUARES   DF  MEAN-SQUARE     F-RATIO       P

SITE                    9.454   12        0.788       4.148 .449604E-04
DAY                     0.207    1        0.207       1.092       0.299

ERROR                  15.763   83        0.190
```

```
Deuterium:

LEVELS ENCOUNTERED DURING PROCESSING ARE:
SITE
       1.0000       2.0000       2.5000       3.0000       4.0000       5.0000
       6.0000       7.0000       7.5000       8.0000      11.0000      12.0000
      13.0000

DEP VAR:   DELTAD       N:      97  MULTIPLE R: 0.531  SQUARED MULTIPLE R: 0.282

                        ANALYSIS OF VARIANCE

SOURCE         SUM-OF-SQUARES   DF  MEAN-SQUARE     F-RATIO       P

SITE                 346.0692   12      28.8391      2.7133      0.0039
DAY                    8.9455    1       8.9455      0.8416      0.3616

ERROR                882.2006   83      10.6289
```

Surface Water:

```
Oxygen-18:

LEVELS ENCOUNTERED DURING PROCESSING ARE:
SITE
       1.0000       2.0000       2.5000       3.0000       4.0000       5.0000
       6.0000       7.0000       7.5000       8.0000      11.0000      12.0000
      13.0000

DEP VAR:DELTA18O        N:     159  MULTIPLE R: 0.337  SQUARED MULTIPLE R: 0.113

                        ANALYSIS OF VARIANCE

SOURCE         SUM-OF-SQUARES   DF  MEAN-SQUARE     F-RATIO       P

SITE                  53.3394   12       4.4449      1.3319      0.2065
DAY                    5.3932    1       5.3932      1.6160      0.2057

ERROR                483.9094  145       3.3373
```

```
Deuterium:

LEVELS ENCOUNTERED DURING PROCESSING ARE:
SITE
       1.0000       2.0000       2.5000       3.0000       4.0000       5.0000
       6.0000       7.0000       7.5000       8.0000      11.0000      12.0000
      13.0000

DEP VAR:   DELTAD       N:     159  MULTIPLE R: 0.298  SQUARED MULTIPLE R: 0.089


                        ANALYSIS OF VARIANCE

SOURCE         SUM-OF-SQUARES   DF  MEAN-SQUARE     F-RATIO       P

SITE                1759.8203   12     146.6517      0.9665      0.4836
DAY                  307.7923    1     307.7923      2.0284      0.1565

ERROR              22002.5535  145     151.7417
```

Appendix 8

A8.1 Isotopic Separation of Storm Hydrograph

A storm hydrograph (stream discharge vs time) can be separated into pre-event water, which consists of groundwater, vadose water, and surface storage; and event water (precipitation or direct runoff) using the steady state mass balance equations describing tracer isotope fluxes (Sklash, et al. 1979):

$$C_t Q_t = C_p Q_p + C_e Q_e$$

where:

Q = stream discharge (m^3s^{-1})
C = isotopic tracer concentration (^{18}O, ^2H - per mil SMOW)
t = total stream component
p = pre-event component
e = event component

which is used to obtain:

$$Q_p = Q_t\left(\frac{C_t - C_e}{C_p - C_e}\right)$$

The pre-event component, Q_p, of total stream discharge resulting from the September 13 -14 storm is calculated to be:

$$Q_p = \left(0.071 m^3 s^{-1}\right)\left(\frac{-7.77-(-5.68)}{-8.98-(-5.68)}\right) = 0.04497$$

Therefore,

A8.2 Uncertainty (expressed as variance) of Q_p

Using Equation 5 from Leaver and Thomas (1974), $s_{Q_p}{}^2$ can be calculated:

$$s^2{}_{Q_p} = \left(\frac{\partial Q_p}{\partial Q_t}\right)^2 s_{Q_t}{}^2 + \left(\frac{\partial Q_p}{\partial C_t}\right)^2 s_{C_t}{}^2 + \left(\frac{\partial Q_p}{\partial C_e}\right)^2 s_{C_e}{}^2 + \left(\frac{\partial Q_p}{\partial C_p}\right)^2 s_{C_p}{}^2$$

where:

$$\left(\frac{\partial Q_p}{\partial Q_t}\right) = \left(\frac{C_t - C_e}{C_p - C_e}\right); \quad \left(\frac{\partial Q_p}{\partial C_t}\right) = \left(\frac{Q_t}{C_p - C_e}\right);$$

and using the Quotient Rule: $\frac{d}{dx}\left(\frac{g}{h}\right) = \frac{h\frac{dg}{dx} - g\frac{dh}{dx}}{h^2}$ to determine:

$$\frac{\partial Q_p}{\partial C_e} = \frac{\partial}{\partial C_e}\left(\frac{Q_t C_t}{C_p - C_e}\right) - \frac{\partial}{\partial C_e}\left(\frac{Q_t C_e}{C_p - C_e}\right)$$

$$= \left(\frac{(C_p - C_e)\left(\frac{\partial(Q_t C_t)}{\partial C_e}\right) - Q_t C_t\left(\frac{\partial(C_p - C_e)}{\partial C_e}\right)}{(C_p - C_e)^2}\right) - \left(\frac{(C_p - C_e)\left(\frac{\partial(Q_t C_e)}{\partial C_e}\right) - Q_t C_e\left(\frac{\partial(C_p - C_e)}{\partial C_e}\right)}{(C_p - C_e)^2}\right)$$

$$= \left(\frac{Q_t C_t}{(C_p - C_e)^2}\right) - \left(\frac{Q_t(C_p - C_e) + Q_t C_e}{(C_p - C_e)^2}\right)$$

$$= \left(\frac{Q_t C_t - Q_t(C_p - C_e) + Q_t C_e}{(C_p - C_e)^2}\right)$$

$$= \left(\frac{Q_t}{(C_p - C_e)^2}\right)(C_t - C_p + C_e - C_e) = Q_t\left(\frac{(C_t - C_p)}{(C_p - C_e)^2}\right)$$

and,

$$\frac{\partial Q_p}{\partial C_p} = \left(\frac{\partial}{\partial C_p}\left(\frac{Q_t C_t}{C_p - C_e}\right)\right) - \frac{\partial}{\partial C_p}\left(\frac{Q_t C_e}{C_p - C_e}\right)$$

$$= \left(\frac{\left((C_p - C_e)\frac{\partial(Q_t C_t)}{\partial C_p}\right) - \left(Q_t C_t \frac{\partial(C_p - C_e)}{\partial C_p}\right)}{(C_p - C_e)^2}\right) - \left(\frac{\left((C_p - C_e)\frac{\partial(Q_t C_e)}{\partial C_p}\right) - \left(Q_t C_e \frac{\partial(C_p - C_e)}{\partial C_p}\right)}{(C_p - C_e)^2}\right)$$

$$= \left(-\frac{Q_t C_t}{(C_p - C_e)^2}\right) - \left(-\frac{Q_t C_e}{(C_p - C_e)^2}\right)$$

$$= \frac{-Q_t C_t + Q_t C_e}{(C_p - C_e)^2} = Q_t\left(\frac{C_e - C_t}{(C_p - C_e)^2}\right)$$

Thus:

$$s_{Q_p}{}^2 = \left(\frac{C_t - C_e}{C_p - C_e}\right)^2 s_{Q_t}{}^2 + \left(\frac{Q_t}{C_p - C_e}\right)^2 s_{C_t}{}^2 + Q_t\left(\frac{C_t - C_p}{(C_p - C_e)^2}\right)^2 s_{C_e}{}^2 + \left(\frac{-Q_t C_t + Q_t C_e}{(C_p - C_e)^2}\right)^2 s_{C_p}{}^2$$

A8.3 Calculation of Uncertainty of Q_p, and Q_p/Q_t

The error on the measurement of C was assumed to be same for C_t, C_e and C_p and therefore:

$$s_{C_t}{}^2 = s_{C_e}{}^2 = s_{C_p}{}^2 = s_C{}^2$$

$s_C{}^2$ for $\delta^{18}O$ is derived from $2s = 0.1$ per mil SMOW (as calculated by the University of Ottawa Isotope Laboratory) which gives:

$s_C{}^2 = \left(\frac{0.1}{2}\right)^2 = 0.0025$ per mil SMOW

$s_{Q_t}{}^2 = 2.5 \times 10^{-7}\left(m^3 s^{-1}\right)^2$ (estimated from a flat portion (four days) of the stream hydrograph for the month of September,1994)

$$s_{Q_p}{}^2 = \left[\left(\frac{-7.77-(-5.68)}{-8.98-(-5.68)}\right)^2\left(2.5 \times 10^{-7}\right)\right]+\left[\left(\frac{0.071}{-8.98-(-5.68)}\right)^2(0.0025)\right]$$

$$+\left[\left((0.071)\left(\frac{-7.77-(-8.98)}{(-8.98-(-5.68))^2}\right)\right)^2(0.0025)\right]+\left[\left((0.071)\left(\frac{-5.68-(-7.77)}{(-8.98-(-5.68))^2}\right)\right)^2(0.0025)\right]$$

$$= 1.88 \times 10^{-6}\left(m^3 s^{-1}\right)^2$$

$$s_{\left(\frac{Q_p}{Q_t}\right)}{}^2 = \left(\frac{Q_p}{Q_t}\right)^2\left(\frac{s_{Q_p}{}^2}{Q_p{}^2}+\frac{s_{Q_t}{}^2}{Q_t{}^2}\right) \quad \text{(From Kretz, 1985)}$$

$$= \left(\frac{0.045}{0.071}\right)^2\left(\left(\frac{1.88 \times 10^{-6}}{(0.045)^2}\right)+\left(\frac{2.5 \times 10^{-7}}{(0.071)^2}\right)\right) = 3.93 \times 10^{-4} = 0.04\%$$

Appendix 9

This Appendix holds the results for major ion analyses of surface water, groundwater (from piezometers), tile drainage waters and rainfall samples, which are discussed in Chapter 8. The number of samples analysed is given in Table 1. Table 2 contains measurements of HCO_3^- standard solutions used in examining the accuracy of the digital titrator. The charge balances in Table 3 were calculated with a geochemical software called Hydrowin™. Hydrowin™ was also used to generate Piper diagrams, given in Chapter 8. This Appendix also includes some general statistics on the data (Table 4).

Table 3. Number and Type of Samples Analysed for Geochemistry

Type of Sample	No. of Sample
Groundwater	35
Surface Water	32
Tile Drainage	7
Rainfall	6

Table 4. Measurements of Bicarbonate Standard Solutions, with Digital Titrator

Standard Solution No.	pH	HCO_3^- (mg/L)
1 (103.77 mg/L)	4.03	96.20
1	3.77	87.32
1	3.84	93.24
1	3.60	94.72
1	3.77	88.80
2 (116.11 mg/L)	3.77	115.44
2	3.59	103.60

Standard Solution No.	pH	HCO_3^- (mg/L)
2	3.81	94.70
2	3.73	115.44
2	3.67	100.64
3 (117.64 mg/L)	3.44	103.60
3	3.57	112.48
3	3.70	100.64
3	3.79	112.48
3	3.60	119.88

Table 5. Ion Concentrations from Water Samples collected in Raisin River Watershed, 1994

Site No.	Date	Water Type	Cl (mg/L)	HCO_3 (mg/L)	NO_3 (mg/L)	SO_4 (mg/L)	Ca (mg/L)	Fe (mg/L)	Na (mg/L)	Mg (mg/L)	Charge Balance (%)
1	94.06.23	groundwater	28.7	NA	8.8	40.9	82.5	1.80	20.3	28.0	NA
1	94.09.12	groundwater	23.7	NA	3.7	42.3	77.5	8.05	9.1	18.0	NA
1	94.10.20	groundwater	27.7	274.7	0.0	55.9	120.5	0.41	10.0	16.2	10.5
1	94.11.09	groundwater	24.2	274.7	0.1	56.0	108.8	0.45	8.7	18.6	7.6
1	94.06.22	surface water	2.1	NA	0.0	5.0	42.0	0.12	1.5	5.5	NA
1	94.09.14	surface water	4.9	NA	0.0	14.7	69.2	0.03	3.9	9.3	NA
1	94.10.12	surface water	4.4	199.9	1.9	12.7	78.5	0.05	3.3	10.8	15.2
1	94.11.16	surface water	3.4	118.4	1.0	15.3	NA	NA	NA	5.3	NA
1	94.06.22	rain	1.4	NA	11.0	6.6	11.3	0.01	0.2	0.6	NA
1	94.10.13	rain	34.0	NA	1.5	34.9	NA	NA	NA	NA	NA
2	94.09.09	groundwater	6.8	NA	0.0	48.1	90.0	3.57	4.7	22.1	NA
2	94.10.20	groundwater	5.6	183.1	0.0	13.9	97.7	0.03	6.1	12.6	13.2
2	94.11.09	groundwater	5.3	201.4	0.0	12.9	102.7	0.02	6.3	13.9	9.1
2	94.06.22	surface water	4.0	NA	1.1	8.2	68.3	0.11	2.6	8.7	NA
2	94.09.14	surface water	7.1	231.8	0.4	11.4	64.9	0.02	4.3	9.8	2.9
2	94.10.12	surface water	5.5	231.8	0.0	14.3	72.2	0.05	3.3	11.5	5.6
2	94.11.16	surface water	7.9	201.3	2.4	54.9	NA	NA	NA	9.3	NA
2	94.06.22	rain	1.1	NA	0.0	7.5	6.6	0.01	0.2	0.7	NA
2	94.11.16	rain	7.6	NA	2.4	14.4	NA	NA	NA	NA	NA
3	94.09.09	groundwater	29.2	NA	1.1	9.3	90.0	5.97	10.2	15.4	NA
3	94.10.20	groundwater	45.8	238.0	0.0	32.5	97.7	0.03	6.1	14.61	5.3
3	94.11.03	groundwater	40.1	238.0	0.0	31.9	86.1	0.05	12.8	16.7	5.0
3	94.09.14	surface water	13.3	NA	0.0	21.4	89.5	0.01	8.2	13.2	NA
3	94.10.12	surface water	10.6	275.3	0.0	18.6	92.0	0.02	5.8	13.6	7.4
3	94.11.16	surface water	0.0	219.0	0.0	61.0	NA	NA	NA	10.6	NA
3	94.11.03	rain	7.1	36.6	0.0	0.0	2.9	0.01	0.2	0.7	15.4

Site No.	Date	Water Type	Cl (mg/L)	HCO_3 (mg/L)	NO_3 (mg/L)	SO_4 (mg/L)	Ca (mg/L)	Fe (mg/L)	Na (mg/L)	Mg (mg/L)	Charge Balance (%)
3	94.11.16	rain	2.0	23.7	2.2	5.3	NA	NA	NA	NA	NA
4	94.09.12	groundwater	21.8	NA	8.7	51.7	64.0	2.12	9.9	23.2	NA
4	94.10.20	groundwater	16.1	238.0	0.0	47.1	61.8	0.01	11.4	23.6	2.8
4	94.11.09	groundwater	15.3	238.0	0.0	48.1	67.0	0.08	10.7	28.6	7.8
4	94.06.22	surface water	12.44	NA	0.6	15.0	82.4	0.03	6.3	10.8	NA
4	94.09.14	surface water	23.88	295.6	0.12	21.2	88.5	0.00	14.0	13.3	2.2
4	94.10.12	surface water	20.4	295.6	0.0	15.3	94.8	0.01	9.6	14.3	4.8
4	94.11.16	surface water	16.2	239.8	2.6	61.4	NA	NA	NA	10.7	NA
4	94.06.30	tile drainage	8.0	NA	27.8	17.3	73.5	0.09	11.7	15.4	NA
4	94.11.03	tile drainage	13.3	256.3	67.2	15.3	88.0	0.02	5.3	10.6	1.9
5	94.09.15	groundwater	9.4	NA	1.3	3.2	71.4	20.63	10.0	33.0	NA
5	94.10.20	groundwater	8.5	311.3	0.0	0.0	58.9	0.01	13.3	40.1	13.0
5	94.11.09	groundwater	8.3	329.6	0.0	0.0	57.4	0.01	12.7	40.5	9.7
5	94.09.14	surface water	20.4	250.6	0.0	18.8	77.1	0.01	11.4	11.8	3.2
5	94.10.12	surface water	18.7	250.5	0.0	16.6	107.2	0.01	7.6	16.6	17.6
5	94.11.16	surface water	16.9	241.2	2.6	61.7	NA	NA	NA	NA	NA
5	94.11.03	tile drainage	218.9	219.7	2.9	57.8	136.5	0.02	68.1	18.1	0.9
5	94.12.01	tile drainage	144.0	370.0	4.7	26.1	NA	NA	NA	NA	NA
6	94.09.15	groundwater	20.0	NA	5.0	9.1	73.7	11.05	11.3	26.1	NA
6	94.10.20	groundwater	59.8	274.7	0.0	14.9	104.2	0.01	14.1	30.1	12.7
6	94.11.09	groundwater	81.6	274.4	0.0	19.1	85.3	0.01	14.5	32.5	3.1
6	94.09.14	surface water	10.5	266.6	0.0	20.0	78.9	0.00	5.7	13.0	2.8
6	94.10.12	surface water	10.4	266.6	0.0	23.0	102.7	0.01	5.4	15.5	13.3
6	94.11.16	surface water	17.9	297.5	0.6	59.7	NA	NA	NA	11.3	NA
7	94.09.15	groundwater	40.0	NA	0.8	0.8	90.0	11.68	15.8	16.4	NA
7	94.10.20	groundwater	33.5	457.8	0.0	0.0	139.4	1.60	18.2	21.9	NA
7	94.11.09	groundwater	33.1	457.8	0.0	0.0	119.8	0.02	17.4	20.5	0.3
7	94.09.14	surface water	16.3	269.5	0.0	16.2	80.2	0.00	9.5	11.6	2.3
7	94.10.12	surface water	20.1	269.5	0.0	19.0	86.6	0.01	9.3	0.0	5.7
7	94.11.16	surface water	17.6	276.8	1.8	59.7	NA	NA	NA	11.1	NA
7A	94.09.16	groundwater	50.6	NA	2.0	2.1	52.3	0.69	65.6	36.9	NA
7A	94.10.20	groundwater	29.8	347.9	0.0	0.0	67.6	0.03	48.1	38.4	15.4
7A	94.11.09	groundwater	29.5	366.2	0.0	0.0	63.2	0.03	44.3	20.5	10.9
7A	94.11.09	surface water	17.9	201.4	2.7	44.3	79.7	0.13	10.2	34.5	7.0
8	94.09.16	groundwater	11.4	NA	0.0	0.8	NA	NA	NA	38.2	NA
8	94.10.20	groundwater	8.4	311.3	0.2	1.6	62.5	0.11	15.4	41.1	16.5
8	94.11.09	groundwater	11.9	329.6	0.0	0.0	59.9	0.06	14.0	37.3	8.6
8	94.09.14	surface water	14.8	263.7	0.0	14.9	85.2	0.00	9.0	11.8	4.3
8	94.10.12	surface water	14.7	263.7	0.0	16.9	109.4	0.01	6.4	15.0	15.9
8	94.11.16	surface water	19.05	279.7	2.6	57.7	NA	NA	NA	12.2	NA
11	94.11.09	groundwater	56.0	256.3	0.0	30.7	68.1	0.01	38.1	29.1	8.3
11	94.10.20	surface water	72.7	164.8	0.0	69.9	67.1	0.05	53.6	19.6	9.6

Site No.	Date	Water Type	Cl (mg/L)	HCO_3 (mg/L)	NO_3 (mg/L)	SO_4 (mg/L)	Ca (mg/L)	Fe (mg/L)	Na (mg/L)	Mg (mg/L)	Charge Balance (%)
11	94.11.09	surface water	60.0	263.4	4.3	88.6	72.6	0.03	40.9	17.7	6.6
12	94.10.27	groundwater	231.1	183.1	0.0	49.0	74.9	0.01	92.8	32.3	0.0
12	94.11.09	groundwater	252.9	183.1	0.0	47.4	86.8	0.01	102.2	36.5	3.4
12	94.10.27	surface water	65.1	219.7	0.0	90.9	78.6	0.03	43.2	21.2	2.3
12	94.11.09	surface water	62.0	236.8	1.8	114.9	72.4	0.05	45.5	17.6	5.8
13	94.11.09	groundwater	15.5	366.2	0.0	2.5	76.5	0.04	18.7	31.9	6.7
13	94.11.09	surface water	79.5	260.5	1.7	104.7	81.9	0.03	57.2	18.7	3.0
13	94.11.03	tile drainage	173.8	256.3	1.7	57.5	122.2	0.00	18.9	46.3	6.3
13	94.11.09	tile drainage	72.9	256.3	6.1	41.0	86.0	0.01	21.9	12.4	6.6
13	94.12.01	tile drainage	104.2	390.0	4.4	47.0	NA	NA	NA	NA	NA

Table 6. General Statistics on Geochemical Data

Water Type	Ion	Min (mg/L)	Max (mg/L)	Mean (mg/L)	C.V. (%)
Surface Water	K^+	0.50	7.10	2.73	93
	Mg^{2+}	0.01	21.23	12.94	100
	Ca^{2+}	40.15	109.4	83.57	63
	Na^+	2.34	57.20	15.05	96
	Cl^-	3.40	79.50	23.92	96
	SO_4^{2-}	11.40	114.90	41.55	90
	HCO_3^-	164.80	299.55	249.06	45
Groundwater	K^+	0.90	12.00	3.96	93
	Mg^{2+}	10.85	41.05	26.05	74
	Ca^{2+}	32.95	139.37	82.72	76
	Na^+	6.05	102.20	24.66	94
	Cl^-	5.30	252.90	44.09	98
	SO_4^{2-}	0	57.50	23.20	100
	HCO_3^-	183.10	457.8	286.87	60
Tile Drainage	K^+	0.60	1.30	0.94	54
	Mg^{2+}	10.63	46.64	31.63	77
	Ca^{2+}	86.01	135.74	110.65	37
	Na^+	5.27	68.19	26.1	92
	Cl^-	13.30	218.90	124.34	94
	SO_4^{2-}	15.30	58.00	45.92	74
	HCO_3^-	201.4	256.3	237.86	21
Rain	K^+	1.9	14.9	7.897	87
	Mg^{2+}	0.71	2.09	1.233	66
	Ca^{2+}	2.85	11.8	6.64	76

Water Type	Ion	Min (mg/L)	Max (mg/L)	Mean (mg/L)	C.V. (%)
	Na^+	0.18	0.41	0.257	56
	Cl^-	6.12	7.1	6.747	14
	SO_4^{2-}	0.0	8.8	5.533	100
	HCO_3^-	20.28	36.6	27.653	45