

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

By Sandra Porter

**Thesis submitted to the School of Graduate Studies and Research for the
Degree of Master's of Science in Earth Sciences**

**Ottawa-Carleton Geoscience Centre
and University of Ottawa**

Ottawa, Ontario, Canada

Sandra Porter © (1996)



National Library
of Canada

Acquisitions and
Bibliographic Services Branch

395 Wellington Street
Ottawa, Ontario
K1A 0N4

Bibliothèque nationale
du Canada

Direction des acquisitions et
des services bibliographiques

395, rue Wellington
Ottawa (Ontario)
K1A 0N4

Your file - Votre référence

Our file - Notre référence

The author has granted an irrevocable non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of his/her thesis by any means and in any form or format, making this thesis available to interested persons.

L'auteur a accordé une licence irrévocable et non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de sa thèse de quelque manière et sous quelque forme que ce soit pour mettre des exemplaires de cette thèse à la disposition des personnes intéressées.

The author retains ownership of the copyright in his/her thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without his/her permission.

L'auteur conserve la propriété du droit d'auteur qui protège sa thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

ISBN 0-612-16457-8

Canada



UNIVERSITÉ D'OTTAWA
UNIVERSITY OF OTTAWA

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 which underlies 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 were 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 $-9.82 \times 10^{-9} \text{ m}^3 \text{ m}^{-2} \text{ s}^{-1}$, and hydraulic conductivity ranges from 10^{-6} to 10^{-9} ms^{-1} (a negative seepage flux indicates groundwater flow from the aquifer to the river). 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 cannot meaningfully represent 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. A cross-correlation of Raisin River discharge data and Cornwall area precipitation revealed a negative lag of 2 days, which 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.

ACKNOWLEDGEMENTS

The author would like to first thank the Institute for Research on the Environment and Economy (IREE) at the University of Ottawa for funding her research. The author is also truly grateful for the patience, help, and guidance of Dr. Michel Robin, Thesis Advisor. The author would like to express gratitude to the following people who were a tremendous help in the field: Greg Cane, Anne Watelet, Hassan Mirmejad, Miriam Kofri, Johannes Barth, John Torrance, and Jeff Carling. The author would especially like to thank Bahram Danesfar for computer/GIS assistance throughout. The author is also grateful for the assistance of Robert Hilliard and Mike Scaves at the Ontario Ministry of the Environment and Energy; Doug Rowe at Environment Canada; Richard Pilon at the Raisin Region Conservation Authority; Sid Van der Veen and Dale Miller at the Ontario Ministry of Agriculture; John Loop at the Ottawa-Carleton Geochemistry Laboratory; Natalie Morriset and Gilles St-Jean at the Ottawa-Carleton Stable Isotope Laboratory; Dr. Ian Clark at the University of Ottawa; and Gaetane Bellmare at IREE.

TABLE OF CONTENTS

ABSTRACT	i
ACKNOWLEDGEMENTS	iii
TABLE OF CONTENTS	iv
LIST OF FIGURES	vii
LIST OF TABLES	ix
LIST OF APPENDICES	x
CHAPTER 1.0 INTRODUCTION	1
1.1 BACKGROUND	1
1.2 SCOPE OF WORK	1
1.3 OBJECTIVES OF THIS STUDY	2
CHAPTER 2.0 STUDY AREA AND SITE DESCRIPTIONS	6
2.1 LOCATION	6
2.2 TOPOGRAPHY	7
2.3 LAND USE	7
2.4 CLIMATE	9
2.5 SITE DESCRIPTIONS AND SOIL CLASSIFICATIONS	9
2.5.1 STORMONT COUNTY SITES	11
2.5.2 GLENGARRY COUNTY SITES	14
2.6 REFERENCES	17
CHAPTER 3.0 GEOLOGY AND REGIONAL HYDROGEOLOGY	18
3.1 BEDROCK GEOLOGY (PALEOZOIC ERA)	18
3.2 SURFICIAL GEOLOGY (CENOZOIC ERA)	20

3.2.1 GLACIAL DEPOSITS	20
3.2.2 POST GLACIAL DEPOSITS	25
3.3 STRUCTURAL GEOLOGY	26
3.4 REGIONAL HYDROGEOLOGY	26
3.4.1 AQUIFERS	26
3.4.2 GROUNDWATER RECHARGE/DISCHARGE ZONES	30
3.4.3 GROUNDWATER FLOW	31
3.4.4 REGIONAL GROUNDWATER QUALITY	33
3.5 DISCUSSION	36
3.6 REFERENCES	38
CHAPTER 4.0 SURFACE WATER/GROUNDWATER INTERACTION	40
4.1 INTRODUCTION	40
4.2 PREVIOUS RESEARCH WITH SEEPAGE METERS AND MINI-PIEZOMETERS	43
4.3 PRESENT STUDY	46
4.3.1 METHODOLOGY OF FIELD MEASUREMENTS	46
4.3.2 PRESENT STUDY RESULTS	48
4.3.3 ERROR ESTIMATION	52
4.4 HYDRAULIC GRADIENT MEASUREMENTS	53
4.4.1 SPATIAL VARIABILITY OF HYDRAULIC GRADIENT MEASUREMENTS	54
4.4.2 COMPARISON BY PIEZOMETER - ANOVA RESULTS	56
4.5 ESTIMATES OF GROUNDWATER SEEPAGE FLUX, 1995	56
4.5.1 TEMPORAL VARIABILITY OF SEEPAGE FLUX ESTIMATES - ALL SITES	57
4.5.2 TEMPORAL VARIABILITY OF GROUNDWATER SEEPAGE FLUX ESTIMATES - SINGLE SITE	59
4.5.3 SPATIAL VARIABILITY OF GROUNDWATER SEEPAGE FLUX ESTIMATES - SINGLE SITE	60
4.5.4 COMPARISON OF DIRECT TO ESTIMATED SEEPAGE FLUX MEASUREMENTS	61
4.6 DISCUSSION	62
4.7 REFERENCES	63
CHAPTER 5.0 HYDRAULIC CONDUCTIVITY OF RAISIN RIVER SEDIMENTS	65
5.1 INTRODUCTION	65
5.2 FIELD MEASUREMENTS	65
5.3 VARIABILITY OF <i>K</i> MEASUREMENTS	67
5.4 REFERENCES	71
CHAPTER 6.0 RAISIN RIVER DISCHARGE AND PRECIPITATION DATA ANALYSES	72
6.1 BASEFLOW CONTRIBUTIONS FROM STREAM HYDROGRAPHS	72
6.2 PRECIPITATION AND STREAM DISCHARGE	76
6.3 PRECIPITATION AND GROUNDWATER RELATIONSHIPS	80
6.4 COMPARISON OF <i>EVENT DISCHARGE VOLUME</i> TO <i>STORM VOLUME</i>	83
6.5 REFERENCES	87

CHAPTER 7.0 STABLE ISOTOPE ANALYSIS OF WATERSHED	88
7.1 INTRODUCTION	88
7.2 ISOTOPIC COMPOSITION OF WATERS IN THE RAISIN RIVER WATERSHED	90
7.2.1 RAINFALL	90
7.2.2 SURFACE WATER	92
7.2.3 GROUNDWATER FROM PIEZOMETERS	95
7.2.4 TILE DRAINAGE	98
7.3 MEAN RESIDENCE TIME OF METEORIC WATER IN WATERSHED	100
7.4 ISOTOPIC SEPARATION OF A STORM HYDROGRAPH	102
7.5 REFERENCES	106
CHAPTER 8.0 GEOCHEMISTRY OF WATER SAMPLES	108
8.1 INTRODUCTION	108
8.2 METHOD OF ANALYSIS	109
8.3 RESULTS	109
8.3.1 CHLORIDE	113
8.3.2 NITRATE	114
8.3.3 SULPHATE	114
8.3.4 IRON	115
8.3.5 SODIUM	115
8.4 INFLUENCE OF BEDROCK	116
8.5 CONCLUSION	116
8.6 REFERENCES	117
CHAPTER 9.0 SUMMARY AND CONCLUSIONS	118

LIST OF FIGURES

Figure 1. Location Map of the Cornwall, Ontario _____	6
Figure 2. Map of Elevation in Stormont and Glengarry Counties _____	8
Figure 3. Map of Raisin River Watershed and Study Sites _____	10
Figure 4. Bedrock Geology (Paleozoic) of the Raisin River Watershed _____	19
Figure 5. Surficial Geology of the Raisin River Watershed _____	23
Figure 6. Water Wells in Stormont and Glengarry Counties _____	28
Figure 7. Map of Water Well Completions in Stormont and Glengarry Counties _____	29
Figure 8. Histogram of Overburden Thickness in Stormont and Glengarry Counties (from OMOEE water well data) _____	31
Figure 9. Depth of Overburden in Stormont and Glengarry Counties _____	32
Figure 10. Potentiometric Surface of Bedrock Wells in Stormont and Glengarry Counties _____	34
Figure 11. Seepage Meter and Mini-Piezometer Installation _____	45
Figure 12. Example of Seepage Flux vs. Time _____	58
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). _____	74
Figure 15. Raisin R. Discharge (at Williamstown) and Cornwall Area Precipitation _____	78
Figure 16. Raisin R. Discharge (at Williamstown) and Cornwall Area Precipitation _____	79
Figure 17. Histogram of Cross-Correlation Coefficients for Raisin R. Discharge and Rainfall (at Cornwall) _____	79
Figure 18. Autocorrelation of Raisin R. Discharge _____	80

Figure 19. Decline in Seepage Estimates after Storm Event on October 5-6, 1995 (Days 643-644)	82
Figure 20. Decline in Groundwater Seepage Estimates after Storm Event on May 28-20 (Days 513 and 514)	83
Figure 21. Stream Discharge and Rainfall for September 1994	84
Figure 22. Area Under Curve used to find Event Discharge Volume	85
Figure 23. Delta Oxygen-18 and Deuterium Graph for Rainfall	91
Figure 24. Delta Oxygen-18 and Deuterium Graph for Surface Water	91
Figure 25. Delta Oxygen-18 vs Time for Surface Water in the Raisin River Watershed (8 sampling sites)	94
Figure 26. Delta Deuterium vs Time for Surface Water in the Raisin River Watershed (8 sites)	94
Figure 27. Delta Oxygen-18 and Deuterium Graph for Groundwater (samples from piezometers)	96
Figure 28. Delta Oxygen-18 vs Time for Groundwater in the Raisin River Watershed	97
Figure 29. Delta Deuterium vs Time for Groundwater in the Raisin River Watershed	97
Figure 30. Delta Oxygen-18 vs Time in Tile Drainage Waters	99
Figure 31. Delta Oxygen-18 and Deuterium Graph for Tile Drainage Waters	99
Figure 32. and Figure 33. Amplitudes of Delta Oxygen-18 Curves for Precipitation (A) and Surface Water (B)	101
Figure 34. and Figure 35. Piper Plots of Geochemical Data from Surface Water (top) and Groundwater Samples (bottom)	111
Figure 36. and Figure 37. Piper Plots of Geochemical Data from Tile Drainage (top) and Rain Water Samples (bottom)	112

LIST OF TABLES

Table 1. Land Use Classification in the Raisin River Watershed, 1981 _____	7
Table 2. Soil Classifications within the Raisin River Watershed _____	11
Table 3. Geological Descriptions of Measurement Sites _____	21
Table 4. Summary of OMOEE Water Well Records in the United Counties of Stormont, Dundas and Glengarry (up to 1984) _____	30
Table 5. 1994 - 1995 Groundwater Seepage Flux Measurements and Estimates, Raisin River Watershed _____	49
Table 6. Range of Hydraulic Conductivity Values for Unconsolidated Deposits (with references) _____	66
Table 7. Mean K Results (Field Measurements with Seepage Meters/Mini-piezometers and Falling Head Permeameter/Mini-piezometers) _____	69
Table 8. Groundwater Recession Data, calculated from Stream Hydrographs of the Raisin River, at Williamstown (1993 to 1995) _____	75
Table 9. Groundwater Contributions to Streamflow, as calculated from Stream Hydrographs _____	75
Table 10. Estimates of Groundwater Seepage Flux for the Main Branch of the Raisin R. _____	76
Table 11. Results from Mass Spectrometric Analysis - Delta Oxygen-18 and Deuterium _____	92

LIST OF APPENDICES

APPENDIX 1	1.1
A1.1 BASEMAP	1.1
A1.2 ELEVATION MAP	1.1
A1.3 WATER WELL DATA	1.1
A1.3.1 WATER WELL COMPLETION	1.2
A1.3.2 POTENTIOMETRIC SURFACE	1.3
A1.3.3 DEPTH OF OVERBURDEN	1.4
A1.4 BEDROCK GEOLOGY AND SURFICIAL GEOLOGY MAPS	1.5
A1.5 REFERENCES	1.6
APPENDIX 2	2.1
A2.1 SEEPAGE METER	2.1
A2.2 SAMPLE CALCULATION OF GROUNDWATER SEEPAGE FLUX, Q	2.2
A2.3 MINI-PIEZOMETERS	2.2
A2.4 1994 AND 1994 GROUNDWATER SEEPAGE FLUX MEASUREMENTS, HYDRAULIC GRADIENT MEASUREMENTS, AND ESTIMATES OF GROUNDWATER SEEPAGE FLUX	2.4
A2.5 ESTIMATED SEEPAGE FLUX VS TIME FIGURES FOR 1995	2.5
A2.6 ANOVA RESULTS FOR COMPARISON OF SEEPAGE FLUX MEASUREMENTS AND ESTIMATES	2.6
A2.7 ESTIMATION OF ERROR ON SEEPAGE FLUX MEASUREMENTS FROM ANOVA	2.7
APPENDIX 3	3.1
A3.1 ANOVA RESULTS FOR HYDRAULIC GRADIENTS COMPARED BY PIEZOMETER SET (SITES NO. 5 AND 7A) AND BY PIEZOMETER (SITE 13)	3.1
A3.2 TEMPORAL VARIABILITY OF SEEPAGE FLUX ESTIMATES	3.4
A3.3 F TEST RESULTS	3.5
APPENDIX 4	4.1
A4.1 CALCULATION OF K - METHOD 1	4.1
A4.2 FALLING HEAD PERMEAMETER/SLUG TESTS FOR MEASUREMENT OF K	4.2
A4.2.1 SAMPLE CALCULATION OF K (TYPE 1)	4.6
A4.2.2 SAMPLE CALCULATION OF K (TYPE 2)	4.6
A4.2.3. PRECISION AND COMPARISON OF THE TWO K MEASUREMENT METHODS	4.7
A4.3 SAMPLE CALCULATION OF WEIGHTED MEAN K	4.8
A4.4 HYDRAULIC CONDUCTIVITY MEASUREMENTS, 1994/1995	4.10

	xi
APPENDIX 5	5.1

A5.1 DETERMINATION OF GROUNDWATER DISCHARGE FROM STREAM HYDROGRAPHS	5.1
A5.2 SAMPLE CALCULATIONS	5.3
A5.3 ESTIMATION OF GROUNDWATER DISCHARGE ALONG THE MAIN BRANCH	5.3
A5.4 RAISIN R. DISCHARGE AND CORNWALL AREA PRECIPITATION GRAPHS, 1994 - 1995	5.4
A5.5 RAISIN RIVER STAGE AND GROUNDWATER SEEPAGE GRAPHS OCTOBER 1995	5.8
A5.6 SAMPLE CALCULATION OF DISCHARGE VOLUME	5.9
A5.7 REFERENCES	5.11
APPENDIX 6	6.1
A6.1 OXYGEN-18 ISOTOPE ANALYSIS	6.1
A6.2 DEUTERIUM ANALYSIS	6.1
A6.3 REFERENCES	6.2

APPENDIX 7	7.3
-------------------	------------

A7.1 DELTA OXYGEN-18 AND DEUTERIUM DATA	7.3
A7.2 CALCULATION OF MEAN RESIDENCE TIME OF METEORIC WATER IN WATERSHED	7.7
A7.3 CALCULATION OF RESIDENCE TIME, T	7.7
A7.4 I.A.E.A. STABLE ISOTOPE DATA FOR PRECIPITATION IN OTTAWA, 1989 TO 1994	7.9
A7.5 ADDITIONAL OXYGEN-18 VS TIME GRAPHS FOR OTTAWA PRECIPITATION (1990 TO 1994)	7.11
A7.6 STATISTICAL RESULTS	7.14
A7.6.1 COMPARISON OF GROUNDWATER AND SURFACE WATER (COLLECTED ON SAME DAY)	7.14
A7.6.2. SPATIAL AND TEMPORAL VARIABILITY OF STABLE ISOTOPE CONTENT IN WATER SAMPLES - ANOVA RESULTS	7.15

APPENDIX 8	8.1
-------------------	------------

A8.1 ISOTOPIC SEPARATION OF STORM HYDROGRAPH	8.1
A8.2 UNCERTAINTY (EXPRESSED AS VARIANCE) OF Q_p	8.2
A8.3 CALCULATION OF UNCERTAINTY OF Q_p AND Q_p/Q_T	8.3

APPENDIX 9	9.1
-------------------	------------

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 was to describe the hydrogeology of the Raisin River watershed. This is to 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 was done. This includes 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™ were also used to meet this objective.

The second main objective was 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 impact of human activity on surface water and groundwater quality and 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 of the magnitude of 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 involves 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 the individual components of the hydrologic regime in the Raisin River watershed.

To examine variables a. through c., several field methods were used. A combination of seepage meters and mini-piezometers were 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 were performed with a falling head permeameter and mini-piezometers as a second method for measuring hydraulic conductivity in the field. Darcy's Law was 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 were used to understand the relationship between infiltration, streamflow, and baseflow (variable d). The magnitude and seasonality of baseflow contributions to the Raisin River were found through a stream hydrograph analysis. The temporal response of the watershed to storm events were examined with a cross-correlation analysis of stream discharge and precipitation.

Samples of groundwater (pumped from piezometers), surface water, tile drainage and rainfall were analysed for the stable isotopes of hydrogen and oxygen and subsequently used for the examination of variables e. to h. These

analyses were used to determine the origin of local groundwater (i.e., whether it is direct precipitation or from deeper bedrock systems) and show the seasonality of surface water. Stable isotopic data is also 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 is used in storm hydrograph separation, to determine the contribution to streamflow during a storm event.

Finally, the general geochemistry of water samples is examined and used to determine whether water has been recently recharged or has remained longer in deeper aquifers. Geochemical analyses were 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 km² 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 Lunenburg, Ontario. There are also two large tributaries, the North and South Branches, which start near Monkland and Long Sault, Ontario, respectively.

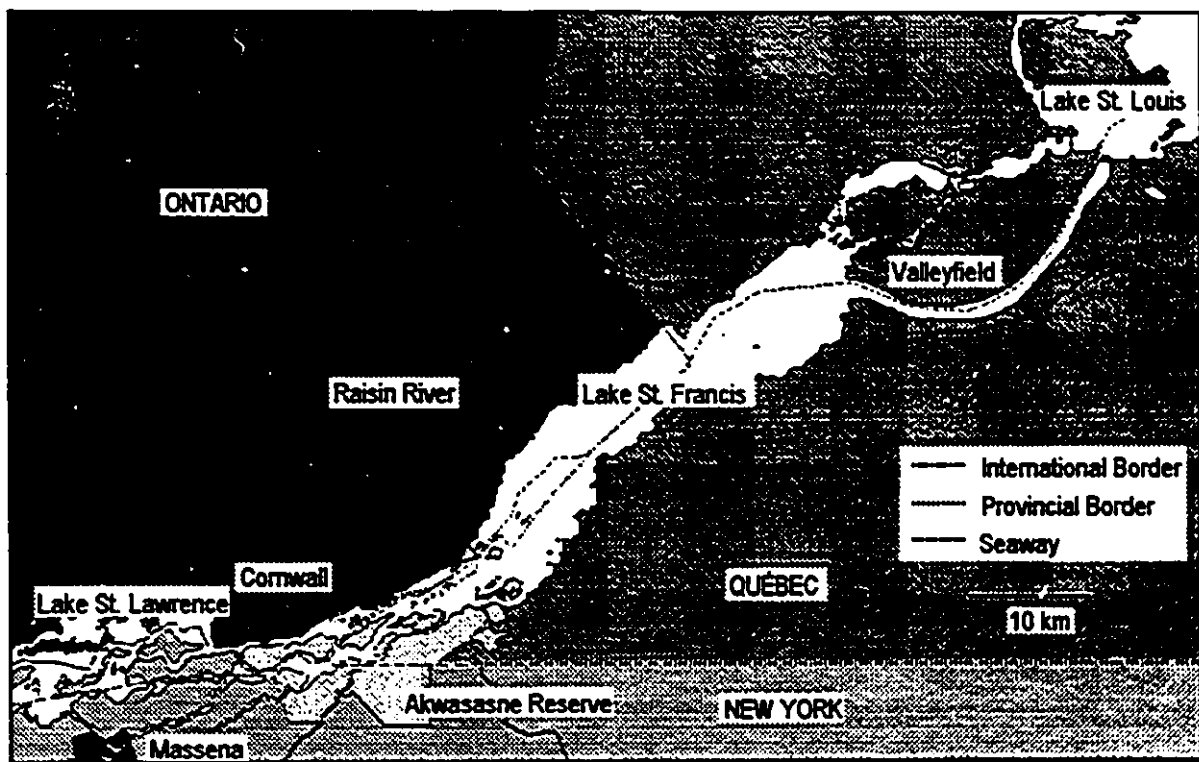


Figure 1. Location Map of the Cornwall, Ontario

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).

2.3 Land Use

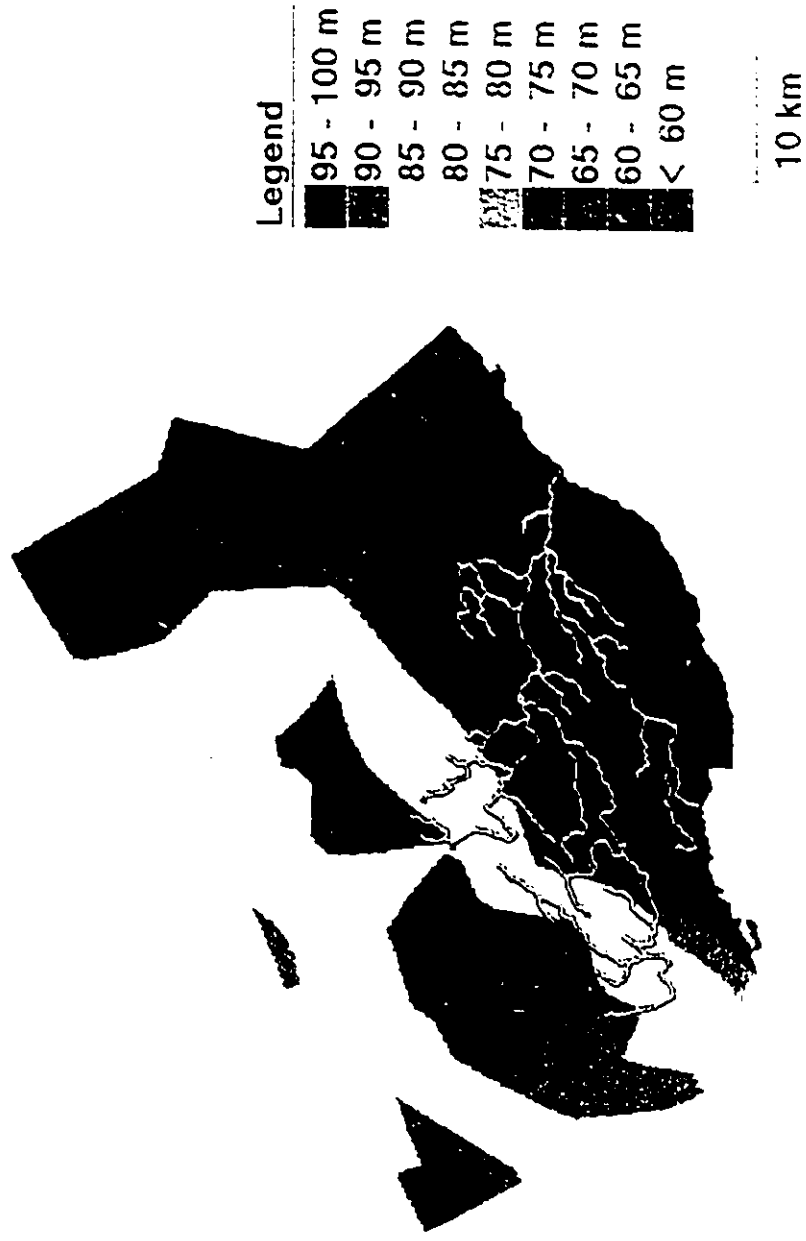
In 1986, the population within the United Counties of Stormont, Dundas, and Glengarry was approximately 55,837 persons (MacViro, 1992). The present land use in these three counties is principally agricultural (crops and numerous dairy cattle operations). In 1981, crop and pasture made up the greatest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

Figure 2: Map of Elevation in Stormont and Glengarry Counties



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.

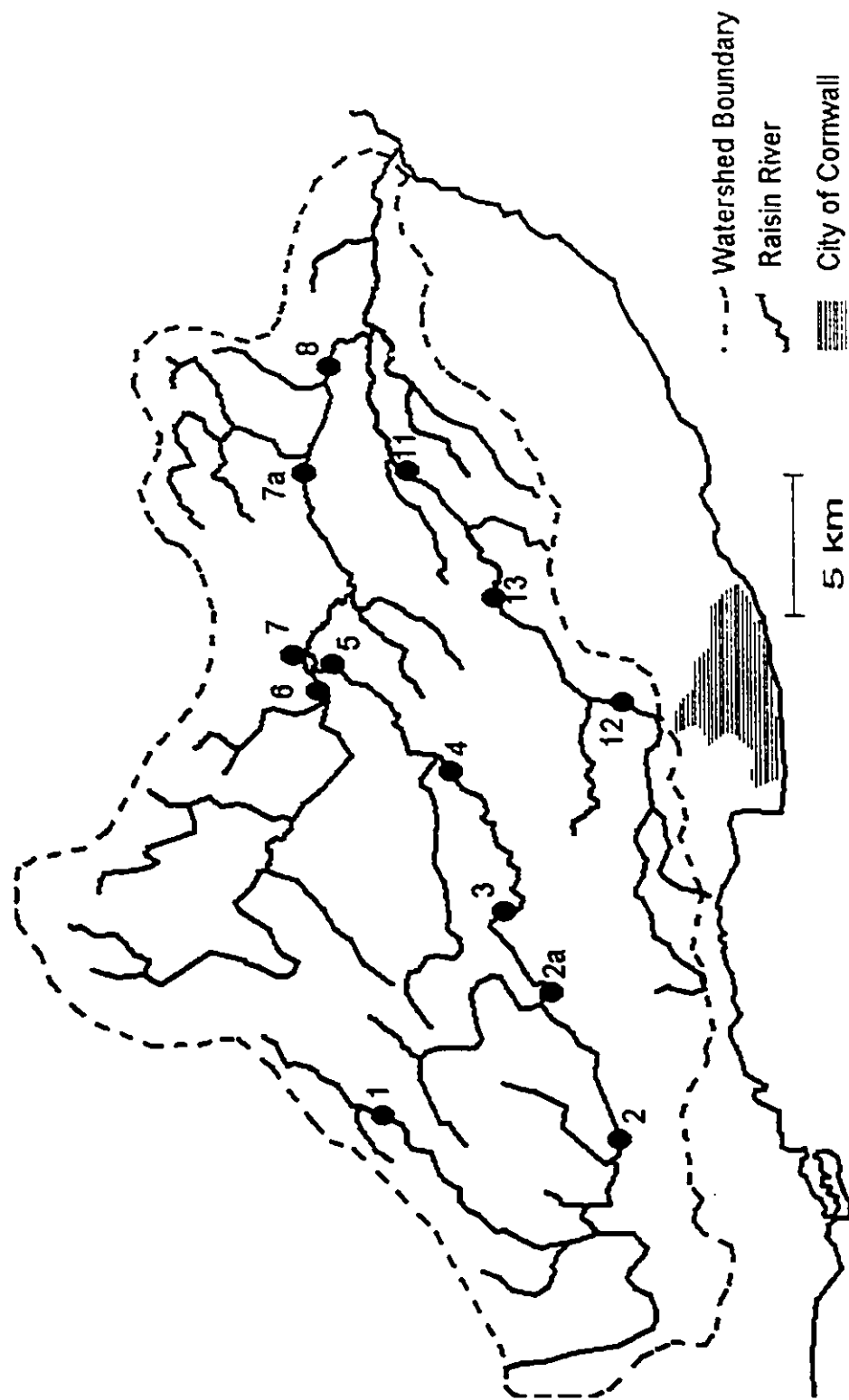
2.4 Climate

In the area, the average annual rainfall and snowfall is approximately 696 mm and 218 mm (water equivalent), 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

Figure 3: Map of Raisin River Watershed and Study Sites



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.

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).

2.5.1 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 acids¹ 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 Lunenburg), Main Branch Raisin River

The soil on the shoreline was dark brown and the sediment was a mixture of gravel and blue-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

¹ Humic acids are formed by the partial decay of organic matter.

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. Land use 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 is 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 a very soft clay with a considerable layer of loose, organic deposition. 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). The 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 consists of clay, overlain by soft, loose organic matter. Land use along the shoreline is residential and parkland. Cattle were observed in the river upstream from the 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 predominantly clay. There are cultivated fields (corn) on both sides of the river. The site topography is 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. Land use around the site is residential and agricultural. There are fairly steep slopes along the 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. Cultivated fields (corn and soybean) are drained artificially directly into the 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 a firm clay. There are cultivated fields on both sides of the river (corn). The south side is artificially drained into the river by tile drains.

2.6 References

Clayton, J.S., et al., (1977), Soils of Canada. Vol. 1. Soil Report, Research Branch, Canada Department of Agriculture, Ottawa, Ontario.

Habicht, M.H., Cornfield, H.W., (Lavalin/MacLaren Plansearch), (1981), "Water Management Study of the Raisin River (Main Branch), Report to Raisin Region Conservation Authority, Phase II, Final Report.

Matthews, B.C., Richards, N.R., and Wicklund, R.E., (May 1957), Soils of Glengarry County, Ontario, Soil Survey Report No. 24 (including map), Ontario Agricultural College and Agriculture Canada, Scale: 1:63,360, Guelph, Ontario.

Matthews, B.C., Richards, N.R., (1954), Soil Map of Stormont County, Soil Survey Report No. 20, including map, Soil Survey by the Dept. of Soils, Ontario Agricultural College, Guelph and the Experimental Farms Service, Agriculture Canada, Scale: 1:63,360, Ottawa, Ontario.

MacViro Consultants Inc., (July 1992), United Counties of Stormont, Dundas, and Glengarry, Solid Waste Management Master Plan, Draft Stage 1 Report, no.3183, prepared for United Counties of Stormont, Dundas, and Glengarry.

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

Maps:

OMAF, (June 1983, revised Aug. 1992), Artificial Drainage System, County: Glengarry, Township: Charlottenburgh, Drawing No. 01-060, Drawn by Lang, J., Scale: 1:25,000.

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

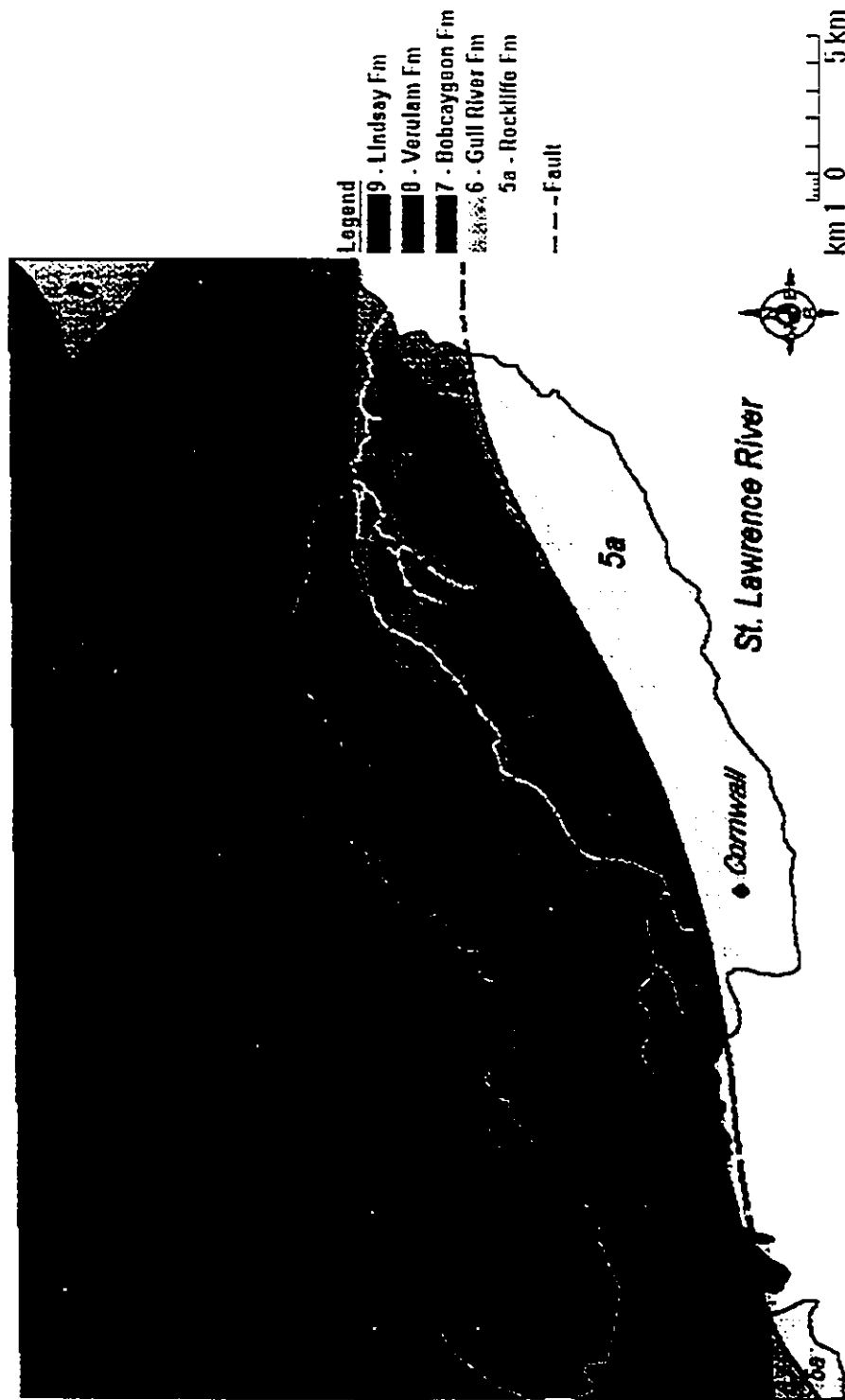
3.1 Bedrock Geology (Paleozoic Era)

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 (between 430 to 500 million years before present (B.P.)), as described by Williams (1991). Four of these formations are part of the Ottawa Group², and are named (from most to least recent): the Lindsay, Verulam, Bobcaygeon, and Gull River Formations. The Rockcliffe Formation³, 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.

² 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.

³ 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

Lawrence 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. For individual site descriptions, see Table 3.

3.2.1 Glacial Deposits

The province of Ontario was subjected to repeated glaciation over the Quaternary period. However, in the Ottawa-St. Lawrence Lowlands, evidence exists mainly for glacial deposition during the Wisconsinan Age. Pre-Wisconsinan glacial deposits were mostly removed by erosion which is indicated

Table 3. Geological Descriptions of Measurement Sites

Site	Bedrock Geology ^a	Surficial Geology ^b	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)	Lunenburg - 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	Upstream Williamstown - east of McGillvrays Bridge, Main Branch Raisin

Site	Bedrock Geology ^a	Surficial Geology ^b	Notes
		m, commonly underlain by soft marine clay	R.; Bedrock visible downstream from site where fault crosses 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.

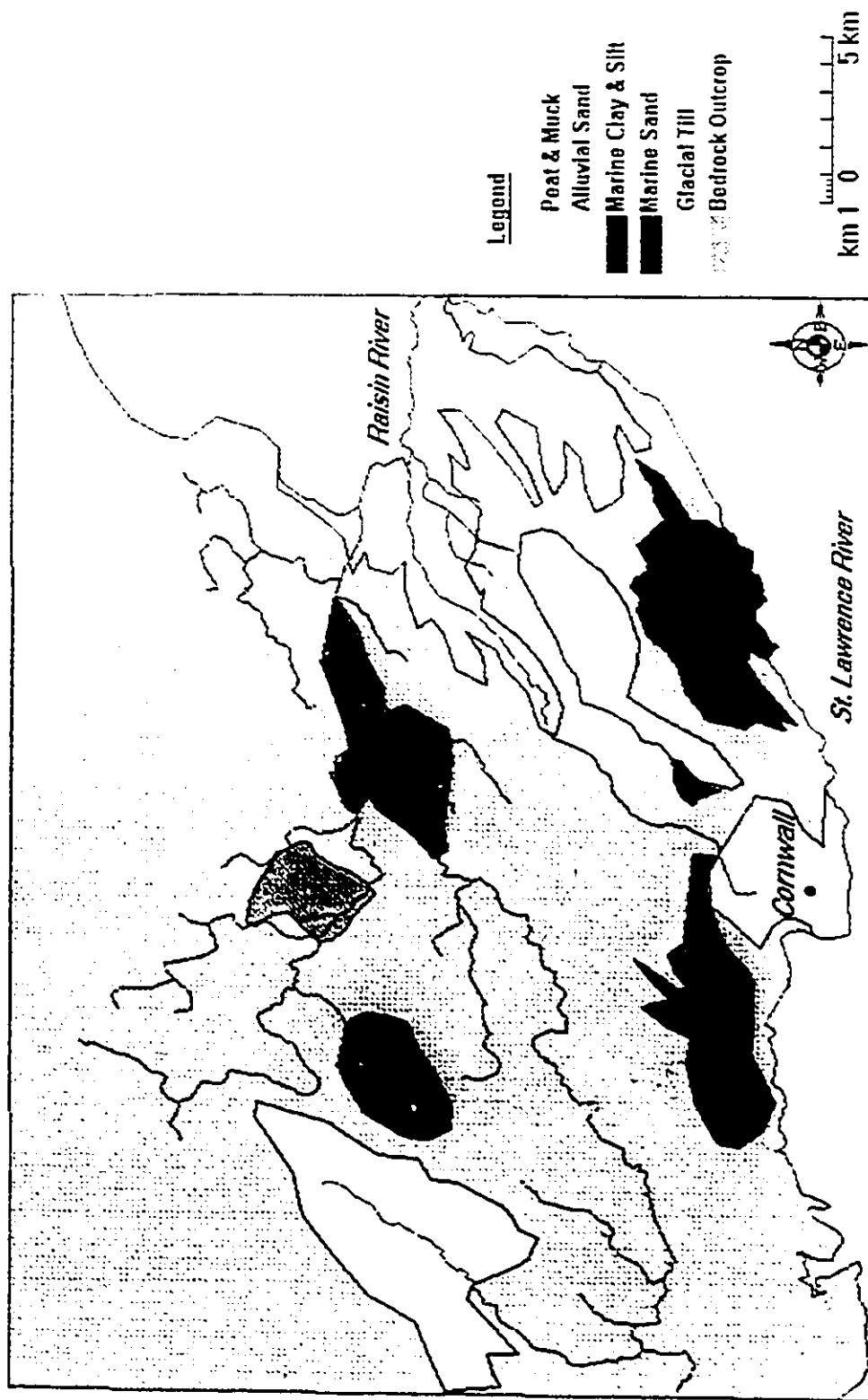
References:

^a- From Williams, D.A. (1991)^b- Terasmae, J. (1965)

by the unconformity which lies between the Ordovician bedrock and material deposited by Wisconsinan 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 & 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

Figure 5. Surficial Geology of the Raisin River Watershed



Edited from Terasmae, J., 1965

ranges up to several tens of metres (m). Charron (1978) describes a long, flat till ridge between the Ottawa River and the St. Lawrence River, which has an elevation ranging from 76 m a.s.l. at the base to 114 m a.s.l. at the highest point. This study classifies the till ridge as semipermeable (Charron, 1978).

The Malone Advance is considered part of the large Laurentide Ice Sheet which flowed from the northeast. The Malone Till has been described as clayey silt, 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 $4.5 \times 10^{-9} \text{ m s}^{-1}$ (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 $1.9 \times 10^{-8} \text{ m s}^{-1}$ (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 B.P.) are also found within the counties of Stormont and Glengarry (Ontario Ministry of Natural Resources (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 around 12,000 years B.P. until close to 11,200 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 sizeable peat bog. Layers of peat can act as a sponge which will delay surface runoff (Ineson and Downing, 1964).

3.3 Structural Geology

Four normal faults which generally run west to east through the study area act as borders between the various formations (Figure 4). The faults strike from southeast to northeast 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 (intergranular) spaces

throughout, also provides a smaller portion of water storage. Furthermore, in fault zones there are typically large numbers 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 3.05×10^{-8} and $2.25 \times 10^{-6} \text{ m s}^{-1}$. The hydraulic conductivity of the deeper zone ranged from 9.05×10^{-8} to $5.40 \times 10^{-7} \text{ m s}^{-1}$. 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 Voronoi⁴ map of water well completions which illustrates the extent of bedrock wells in the two counties of Stormont and

⁴ 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

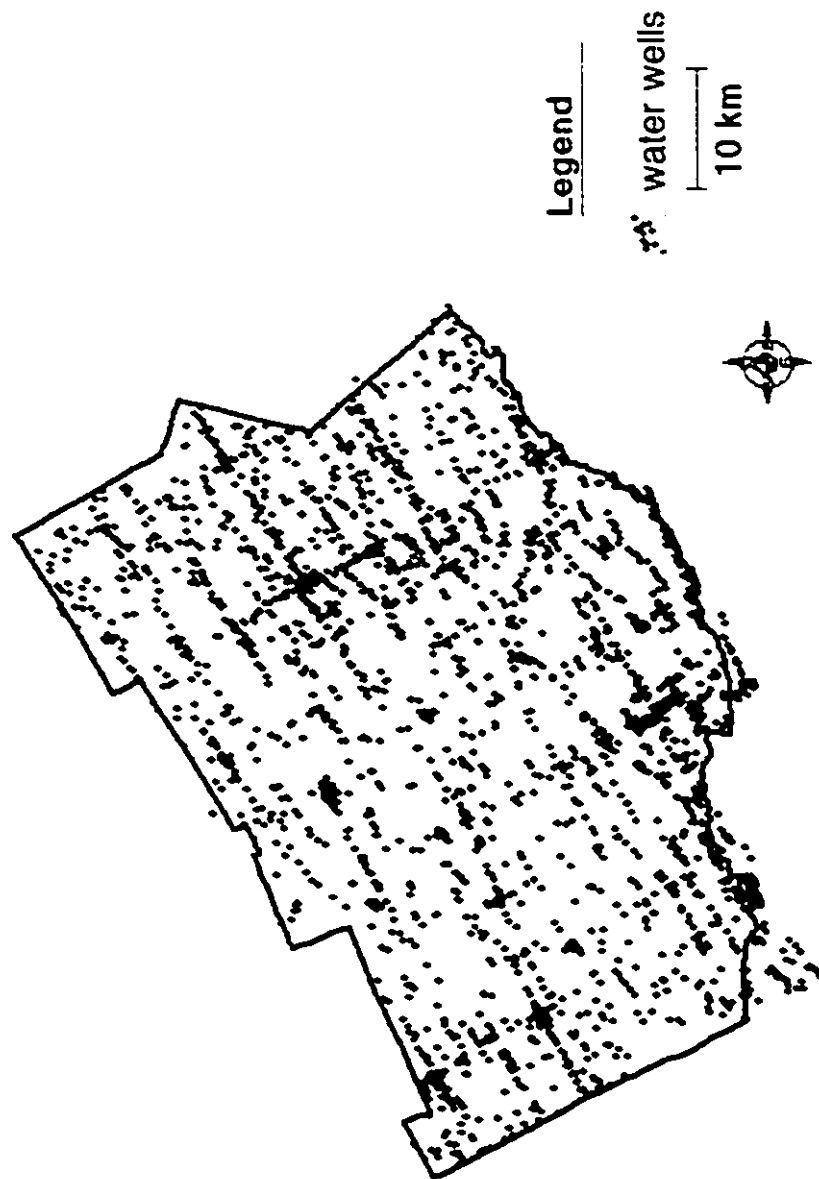


Figure 7: Map of Water Well Completions in Stormont and Glengarry Counties



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

Glengarry. A drift thickness map, generated by Gwyn, Q.H.J., et al., (1974), indicates that most water wells in the region reach bedrock.

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. Based on bedrock studies of the area, Charron (1978) reports that recharge areas generally have depths to bedrock of 46 m or less and discharge areas tend to have depths greater than 46 m. In Stormont and Glengarry counties, the depth to bedrock ranges from -0.6 to 73.8 m (negative values indicate outcrops of bedrock). A histogram, whose classes were generated from a normal probability plot (Figure 32, Appendix 1), illustrates the distribution of data (Figure 8) and a contour map of overburden depths is shown in Figure 9. The large area where depth to bedrock is between 0 and 12 meters is the most

likely recharge area. This corresponds to the region of glacial till (Figure 5).

Thus, groundwater discharge would likely be in the coastal area of the map (i.e., along side the St. Lawrence River).

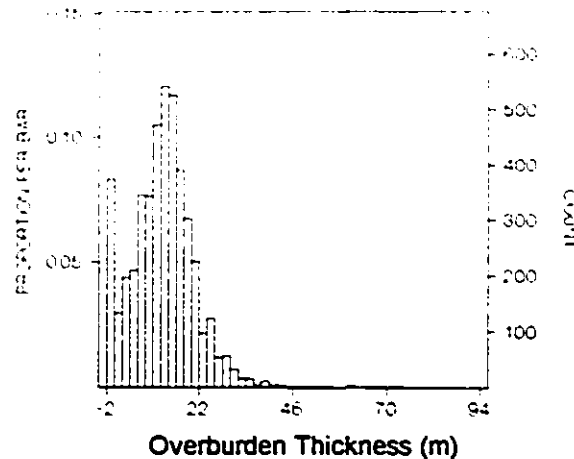
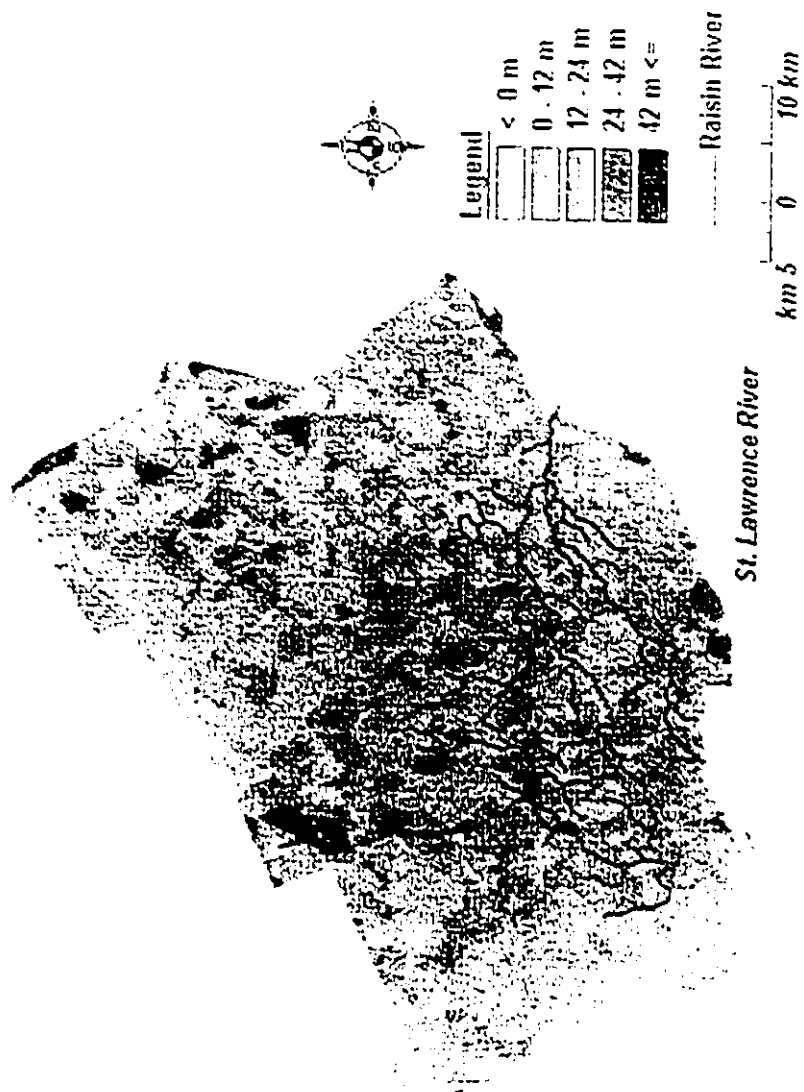


Figure 8. Histogram of Overburden Thickness in Stormont and Glengarry Counties (from OMOEE water well data)

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).

Figure 9: Depth of Overburden in Stormont and Glengarry Counties



Estimates made by Gartner Lee Assoc. Ltd. (1982) indicate that the lateral groundwater flow rate is considerably larger through bedrock than through overburden with flow rates of 30 m per year and less than 1 m per year, respectively. In 1984, the 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

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



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 from 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 the Ontario Ministry of Agriculture and Food (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 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 were only available up to 1984 (more recent data were unavailable due to economic constraints) and older records are perhaps not as accurate, eg., 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 between the bedrock and the overburden (Figure 7). The overburden is highly variable in texture, has fairly low hydraulic conductivities, and it assumed that regional groundwater recharge takes place where this layer is thinnest (between 0 and 12 m). Maps of depth of overburden and hydraulic head contours indicate that 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 site nos. 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.

3.6 References

Agriculture Canada (June 1993), Ontario Farm Groundwater Quality Survey, Summer 1992, prepared under the Federal-Provincial Land Management Assistance Program, 1992, edited by Rudolph, D. and Goss, M., Ottawa, Ont.

Bonham-Carter, G.F., (1994), Geographic Information Systems for Geoscientists, Modelling with GIS, Computer Methods in the Geosciences, Vol. 13, Pergamon, Ont.

Chapman, L.J., Putnam, D.F., (1966), The Physiography of Southern Ontario, 2nd Edition, Ontario Research Foundation, University of Toronto Press, Toronto, Ont.

Charron, J.E, (1978), Hydrochemical Study of Groundwater Flow in the Interstream Area between the Ottawa and St. Lawrence Rivers, Scientific Series No. 76, Inland Waters Directorate, Water Resources Branch, Environment Canada, Ottawa, Ont.

Freeze, R.A., Cherry, J.A., (1979) Groundwater, Prentice-Hall Inc., New Jersey, U.S.

Gartner Lee Associates Limited, (September 1982), Primary Environmental Information, Part 1, Geological/Hydrogeological Inventory for Ontario Waste Management Corporation, Project No. 82-1002, Toronto, Ontario.

Ineson, J., and Downing, R.A., (1964), "The Groundwater Component of River Discharge and its Relationship to Hydrogeology", Journal for the Institution of Water Engineers and Scientists, Vol. 18.

MacViro Consultants Inc., (July 1992), United Counties of Stormont, Dundas, and Glengarry, Solid Waste Management Master Plan, Draft Stage 1 Report, # 3183, prepared for United Counties of Stormont, Dundas, and Glengarry.

OMNR, (June 1984), Water Quantity Resources of Ontario, Publication No. 5932.

OMOEE, (1992), Water Pollution Survey, Community of Martintown.

Proctor & Redfern Limited, (May 12, 1992), Hydrogeological Investigation and Sampling Program, BASF Canada Inc., Cornwall, Project EO 91469/91P12/92422.

St. Lawrence Remedial Action Plan (RAP), (August 1992), Remedial Action Plan for the Cornwall-Lake St. Francis Area, Stage 1 Report: Environmental Conditions and Problem Definitions for the St. Lawrence River Area of Concern, Catalogue #: EN40-218/1-1E, ISBN: 0-662-19958-8.

St. Lawrence RAP and St. Lawrence (Cornwall) Public Advisory Committee, (August 1994), Choices for Cleanup: Deciding the Future of a Great River, St. Lawrence River Remedial Action Plan, Options Discussion Paper

Terasmae, J., (1965) Surficial Geology of the Cornwall and St. Lawrence Seaway Project Areas, Ontario, Geological Survey of Canada, Bulletin No. 121.

Williams, D.A., (1991), Paleozoic Geology of the Ottawa-St. Lawrence Lowland, Southern Ontario, Ontario Geological Survey, Open File Report 5770, Ministry of Northern Development and Mines.

Wilson, A.E., (1946), Geology of the Ottawa-St. Lawrence Lowland, Ontario and Quebec, Memoir 241, Geological Survey of Canada, Department of Mines and Technical Surveys.

Maps

Gwyn, Q.H.J., et al., Drift Thickness of the Cornwall-Huntingdon Area, Southern Ontario, Ontario Division of Mines, Preliminary Map P.1013, Drift Thickness Series, Scale: 1:50,000, (Geology and Compilation, 1974).

Terasmae, J., Mott, R.J. (1965), Surficial Geology, Cornwall, Ontario-Quebec, Map 1175A, Scale: 1:63,360 (Geology 1958-1959).

Williams, D.A., et al., (1985), Paleozoic Geology, Cornwall-Huntingdon Area, Southern Ontario, Ontario Geological Survey, Map P. 2720, Geologic Series - Preliminary Map, Scale: 1:50,000, (Geology 1981-1982).

Wilson, A.E., Ottawa-Cornwall, Ontario and Quebec, Map 852A, Mines and Geology Branch, Bureau of Geology and Topography, Department of Mines and Resources. Scale: 1:253,440 (Geology 1929, 1935-1946).

Chapter 4.0 Surface Water/Groundwater Interaction

4.1 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 recommendation for research 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 storage zone that discharges 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) give a rough estimate of the annual groundwater contribution to streamflow as being between 0 and 20% for this region (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 ($\text{m}^3 \text{m}^{-2} \text{s}^{-1}$)

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

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 $9 \times 10^{-6} \text{ m}^3 \text{m}^{-2} \text{s}^{-1}$ 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 currents⁵ 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 $4.07 \times 10^{-7} \text{ m}^3 \text{m}^{-2} \text{s}^{-1}$ and only groundwater discharge conditions were found at the

⁵ Lee and Cherry (1978) recommended that seepage meters not be used where currents were greater than 0.2 m s^{-1} .

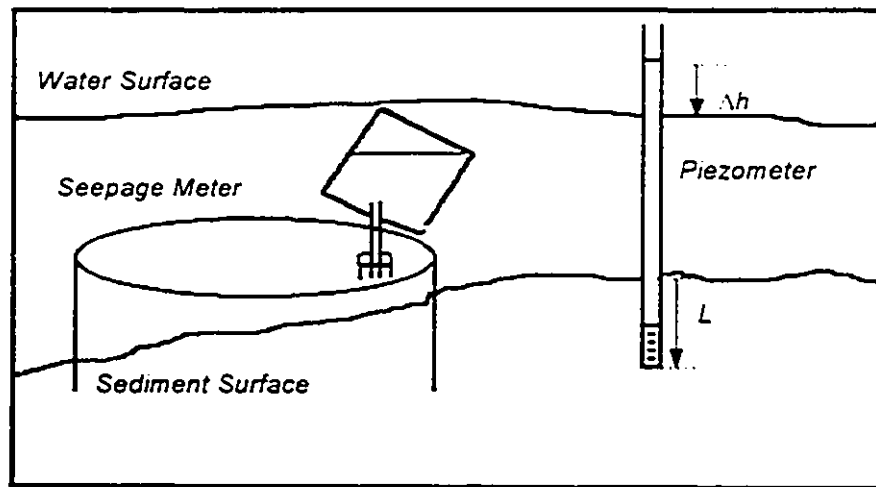


Figure 11. Seepage Meter and Mini-Piezometer Installation

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 zero to $8.9 \times 10^{-10} \text{ m}^3 \text{ m}^{-2} \text{ s}^{-1}$ 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, only positive groundwater seepage flux was measured, between 1.56×10^{-6} and $2.50 \times 10^{-6} \text{ m}^3 \text{ m}^{-2} \text{ s}^{-1}$. 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.⁶ Seepage meters could not be installed in rocky river bed areas; and there is a need for a reliable method in such areas. 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.

⁶ There was some bias in the placement of seepage meters, since they were placed where there was sediment, i.e. no seepage flux measurements were made in bedrock outcrop zones.

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:

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

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, $\text{m}^3 \text{m}^{-2} \text{s}^{-1}$)

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 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 generally measured at all sites, ranging from 4.31×10^{-10} to $2.23 \times 10^{-6} \text{ m}^3 \text{ m}^{-2} \text{ s}^{-1}$. 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 $-1.93 \times 10^{-8} \text{ m}^3 \text{ m}^{-2} \text{ s}^{-1}$. 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, while positive seepage fluxes were 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 beside positive seepage measurements at sites no. 5, 7A, and 13. This might be due to defective equipment. Some piezometer tips were constructed with faulty silicone, became plugged with sediment when pumped, and thus did not give proper readings. These piezometers were easily detected and their measurements discarded. The total range of seepage measurements for all three sites was -2.3×10^{-9} to $1.04 \times 10^{-7} \text{ m}^3 \text{ m}^{-2} \text{ s}^{-1}$. 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

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

Year	Site no.	Seepage Flux Range ($\text{m}^3 \text{m}^{-2} \text{s}^{-1}$)		Mean Seepage ($\text{m}^3 \text{m}^{-2} \text{s}^{-1}$)	C.V. (%) ^b	No. of Meas.
1994	1	Max:	2.23×10^{-6}	1.25×10^{-6}	50.1	32
		Min:	4.31×10^{-10}			
1995	1 ^a	Max:	1.40×10^{-6}	9.73×10^{-7}	3.1	22
		Min:	4.65×10^{-7}			
1994	2	Max:	8.63×10^{-7}	9.31×10^{-8}	247.7	5
		Min:	4.47×10^{-10}			
1995	2 ^a	Max:	9.76×10^{-9}	3.24×10^{-9}	918.3	45
		Min:	-4.73×10^{-9}			
1994	2A	Max:	1.08×10^{-6}	1.88×10^{-7}	194.0	4
		Min:	4.70×10^{-9}			
1994	3	Max:	7.62×10^{-7}	1.84×10^{-7}	155.7	4
		Min:	2.45×10^{-9}			
1995	3 ^a	Max:	1.37×10^{-6}	4.86×10^{-7}	20.6	23
		Min:	5.48×10^{-8}			
1994	4	Max:	9.19×10^{-7}	1.47×10^{-7}	191.9	5
		Min:	2.37×10^{-9}			
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}			

Year	Site no.	Seepage Flux Range ($\text{m}^3 \text{m}^{-2} \text{s}^{-1}$)		Mean Seepage ($\text{m}^3 \text{m}^{-2} \text{s}^{-1}$)	C.V. (%) ^b	No. of Meas.
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.

of variability (C.V. = $\frac{s}{\bar{x}}$, where s is the standard deviation and $\bar{x}$ is the seepage flux mean) are given in Table 5. The variability between seepage flux measurements at individual seepage meters at a particular site gives an estimate of the error of seepage measurements, assuming that groundwater flux is fairly uniform along that portion of the river. For estimates of seepage flux, the

variance (s^2_{Qest}) was calculated from an equation developed by Leaver and Thomas (1974):

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

where s^2_K = variance on hydraulic conductivity (K) and s^2_I = variance on hydraulic gradient (I) measurements. 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 ranged from 3 to 918% seepage flux estimates and from 25 to 464% for seepage flux measurements (Table 5). Negative C.V. values in Table 5 are generated from the mean of negative seepage flux measurements. 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, is 3.72×10^{-5} with 40 degrees of freedom. This is an estimate of the error on seepage measurements which excludes the effects of spatial and temporal 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 measure 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.⁷ Daily measurements, taken over the Spring, Summer and Fall, were used to investigate the spatial or temporal variability of the hydraulic gradients.

⁷ These are different piezometers from those described on page 48. They were installed in the second year of study.

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 therefore were performed separately for each site. A total of 379 data points for site no. 5 and 471 for site no. 7A⁸ 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 set⁹. Measurements

⁸ Measurements were made in Summer 1994 and Spring 1995.

⁹ 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 $1.40 \times 10^{-6} \text{ m}^3 \text{ m}^{-2} \text{ s}^{-1}$.

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 4¹⁰ and Group 2: October 16 to 20¹¹). These groups consist of measurements made before and after a notable storm event which occurred on October 5th and 6th, 1995¹². 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

¹⁰ Dates correspond to Julian Days 639 to 643 on Figure 12.

¹¹ Dates correspond to Julian Days 654 to 658 on Figure 12.

¹² Julian Days 644 to 645. This storm was Hurricane Opal, during which, 61.4 mm of rain fell over the course of two days.

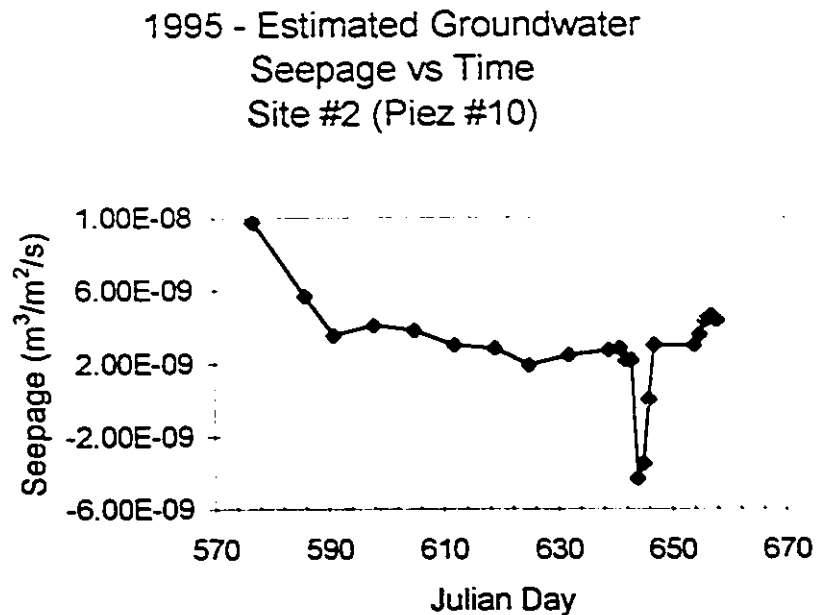


Figure 12. Example of Seepage Flux vs. Time¹³

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

¹³ January 1, 1994 = Julian Day 1 and December 31, 1994 = Julian Day 365.

Since data was collected over two years, sequential numbers were used for the second year, i.e. January 1, 1995 = Day 366, etc.

piezometer were analysed on an individual basis using F tests¹⁴ 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 from 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.

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

¹⁴ 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, $H_0: s_1^2 = s_2^2$, 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.)

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 were 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 rigorously 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 an estimate 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 Discussion

Both positive and negative seepage flux were measured during this study. Mean seepage flux measurements, made during the summer and fall of 1994 and 1995, along the main and south branches of the Raisin River, range from 10^{-7} to $10^{-10} \text{ m}^3\text{m}^{-2}\text{s}^{-1}$ (excluding the site located in the peat bog). This indicates considerable spatial variability throughout the watershed. Statistical tests indicate insignificant variability of seepage flux over short distances and short periods of time. However, there is considerable variability from one year to the next and storm events have an observable effect on seepage flux.

4.7 References

- Cruickshanks, F.B., Francis, R.M., and Jardine, D.E., (1988), "A Study of Groundwater - Surface Water Interaction in the Winter River, Prince Edward Island Using Seepage Meters and Mini-Piezometers", paper presented at the International Groundwater Symposium of the International Association of Hydrogeologists, Canadian National Chapter, Atlantic Region, Halifax, Nova Scotia, May 1-5, 1988.
- Eddie, J.D., (1982), "Temporal Variation of Southwestern Ontario Streamflow and the Possible Influence of Agricultural Land Drainage", Paper No. 15, Ontario Ministry of the Environment and Energy, Water Resources, Toronto, Ontario.
- Habicht, M.H., and Cornfield, H.W., (MacLaren Plansearch), (1982), Water Management Study of the Raisin River (Main Branch), Report to Raisin Region Conservation Authority, Phase II, Final Report.
- Ineson, J., and Downing, R.A., (1964) "The Groundwater Component of River Discharge and its Relationship to Hydrogeology", Journal Institution of Water Engineers and Scientists, Vol. 18.
- Irwin, R.W., and Whiteley, H.R., (1983), "Effects of Land Drainage on Streamflow", Canadian Water Resources Journal, Vol. 8, No. 2, pp. 88-103.
- Lee, D.R. and Hynes, H.B.N., (1977/1978), "Identification of Groundwater Discharge Zones in a Reach of Hillman Creek in Southern Ontario", Water Poll. Res. Canada, Vol. 13.
- Lee, D.R. and Cherry, J.A., (1978), "A Field Exercise on Groundwater Flow using Seepage Meters and Mini-piezometers", Journal of Geological Education, V. 27.
- Long Point Conservation Authority, (1978), Background Studies to Watershed Plan - Big Creek, Otter Creek, Black Creek, Lynn River, Unpublished Report.
- Morrow, W.H., May 1989, "The Hydrogeology of Lower Otego Creek Valley, Upper Susquehanna Drainage Basin, New York", M.A. Thesis in Geology, State University College at Oneonta, New York.
- Norman, W.R., Ostrye, and D.P., Hobin, J.S., (1986), "Use of Seepage Meters to Quantify Groundwater Discharge and Contaminant Flux into Surface Water at the Baird & McGuire Site (NPL No. 14)", Proceedings of the Third Annual

Eastern Regional Groundwater Conference, National Water Well Association, Dublin, OH, U.S., July 28-30, 1986, p. 472-493.

Ontario Ministry of Natural Resources, (June 1984), Water Quantity Resources of Ontario, Publication No. 5932.

Wolf, S.H., Lachance, J.C., and Wolf, L.J., (1991), "Techniques for Monitoring Flux and Transport between Groundwater and Surface Water Systems", Proceedings of the Fifth National Outdoor Action Conference on Aquifer Restoration, Groundwater Monitoring, and Geophysical Methods, Groundwater Management, Las Vegas, Nevada, May 13-16, 1991, p. 179-192

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 (eg., 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 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: $\ln K = \mu + \text{"Method"} + \text{"Piez"} + \epsilon$. 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 2. Weighted

mean K values ranged from $1.30 \times 10^{-5} \text{ ms}^{-1}$ (for organic-rich bog) to $6.40 \times 10^{-8} \text{ ms}^{-1}$ (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	4.96×10^{-7}	14	125	4.81×10^{-5}	5	17	1.30×10^{-5}
2	9.41×10^{-8}	5	148	1.38×10^{-9}	3	0	6.40×10^{-8}
2A	7.05×10^{-7}	4	133	na	na	na	na
3	6.14×10^{-7}	4	85	3.23×10^{-6}	14	148	7.78×10^{-6}
4	1.40×10^{-7}	5	173	7.10×10^{-7}	3	7	3.54×10^{-7}
5	1.19×10^{-6}	25	196	4.83×10^{-6}	10	124	3.19×10^{-6}
6	1.24×10^{-6}	4	100	7.91×10^{-6}	3	33	4.24×10^{-6}
7	4.21×10^{-7}	5	59	2.49×10^{-6}	5	29	1.49×10^{-6}
7A	2.17×10^{-7}	45	129	4.25×10^{-8}	8	109	1.98×10^{-7}
8	6.98×10^{-8}	5	78	2.28×10^{-8}	3	0	5.22×10^{-8}

Site	Method 1 Mean $\bar{K}$ (ms^{-1})	No. of Meas.	C.V. (%)	Method 2 Mean $\bar{K}$ (ms^{-1})	No. of Meas.	C.V. (%)	Weighted Mean $\bar{K}$ (ms^{-1})
11	7.04×10^{-7}	3	20	9.69×10^{-7}	3	77	4.10×10^{-7}
12	4.66×10^{-7}	3	42	2.65×10^{-8}	3	0	2.46×10^{-7}
13	2.17×10^{-6}	3	114	4.56×10^{-6}	5	85	4.40×10^{-6}

5.4 References

Brassington, R., (1988), Field Hydrogeology, Geological Society of London Professional Handbook, Ed. M.H. de Freitas, Open University Press, Milton Keynes and Halsted Press, John Wiley and Sons, New York.

Domenico, P.A., Schwartz, F.W., (1990), Physical and Chemical Hydrogeology, John Wiley and Sons, New York.

Freeze, R.A., Cherry, J.A., (1979), Groundwater, Prentice-Hall, Inc., N.J.

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 ($\text{m}^3 \text{ s}^{-1}$)

Q_o = river discharge at any given time ($\text{m}^3 \text{ s}^{-1}$). ($Q_t = Q_o$ 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 m³ (Table 8). The rate of baseflow contributions ranged from 0.62 to 1.37 m³ 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).

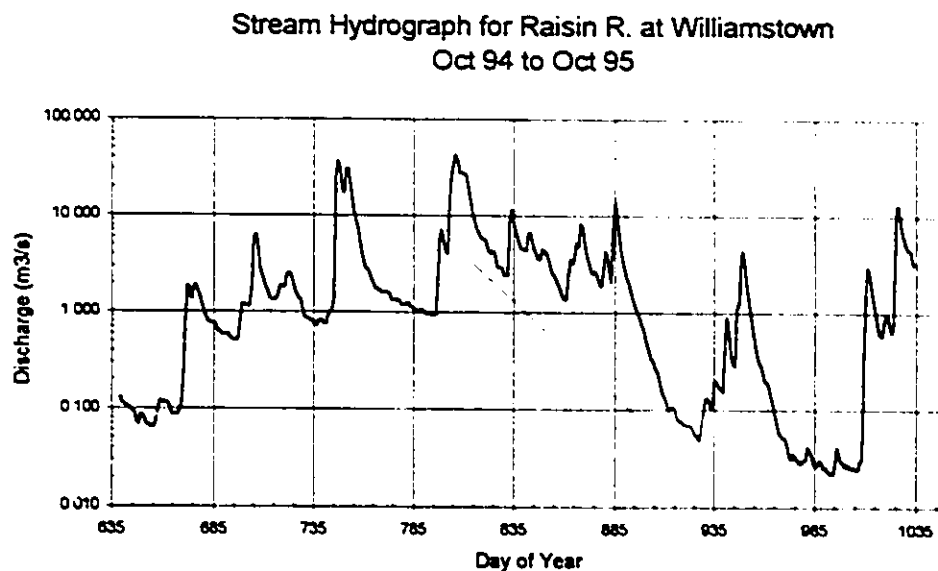
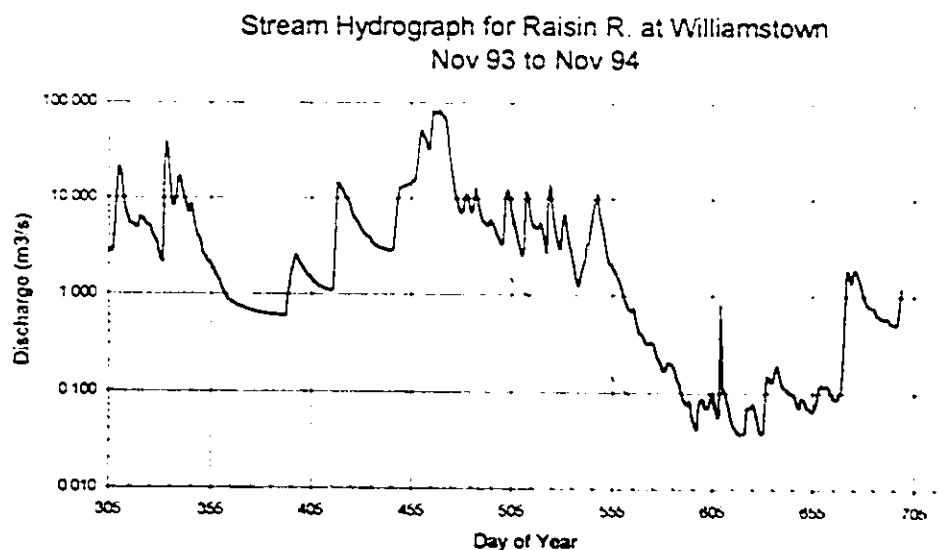


Figure 13 and Figure 14. Stream Hydrographs for the Raisin River, from Stream Discharge Data provided by Environment Canada, 1993 to 1995 (provisional and unpublished).¹⁵

¹⁵ "Day of Year" on the horizontal axes are sequential Julian Days as described in footnote of page 58.

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, excluding tributaries, (from Dixon Creek to Williamstown)

with the above baseflow calculations, the total area of the riverbed was roughly estimated to be $1.05 \times 10^6 \text{ m}^2$. 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 $\text{m}^3 \text{ m}^{-2} \text{ s}^{-1}$. A sample calculation is given in Appendix 6. Results are given in Table 10. These values of seepage flux are notably higher than most of the values found with seepage meters. This difference might be an indication that groundwater discharge from tributaries and also from bedrock is substantial.

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

Duration of Recession (Days)	Estimated Groundwater Discharge to river ($\text{m}^3 \text{ m}^{-2} \text{ s}^{-1}$)
115 (1994)	1.30×10^{-6}
96 (1995)	5.92×10^{-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 events¹⁶ (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 with the aid of 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).

¹⁶ 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 fluctuations in the Raisin River discharge that are separated by more than 20 days are uncorrelated. A periodicity of about one year could be identified in the data,

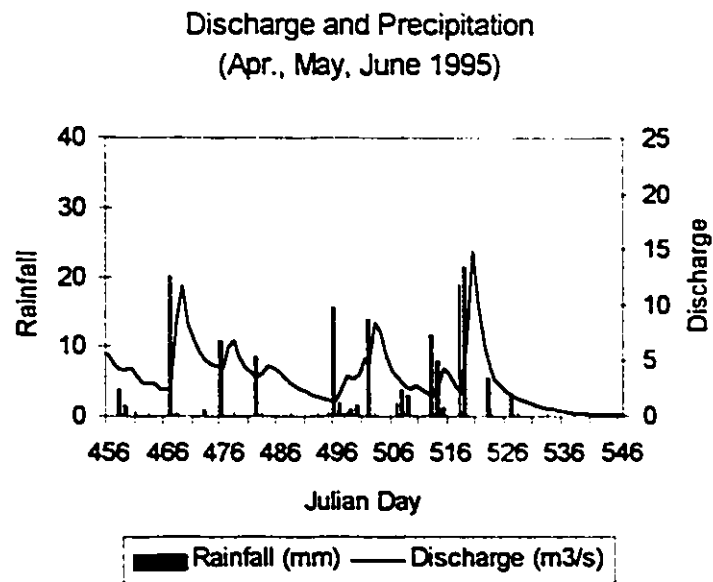


Figure 15. Raisin R. Discharge (at Williamstown) and Cornwall Area Precipitation

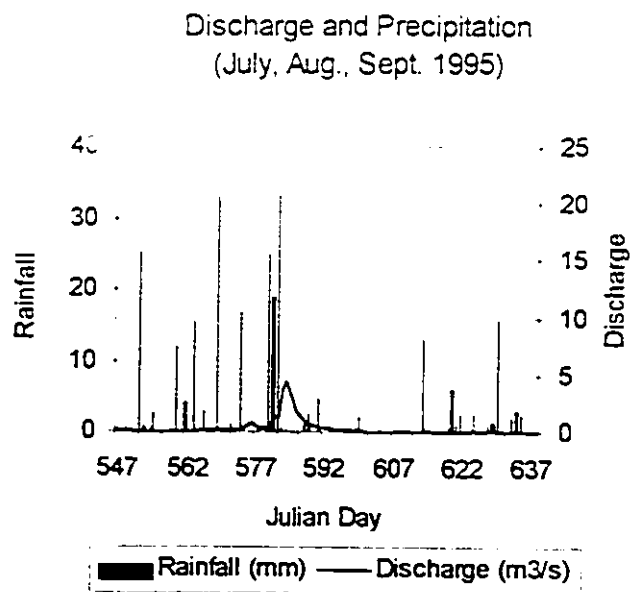


Figure 16. Raisin R. Discharge (at Williamstown) and Cornwall Area Precipitation

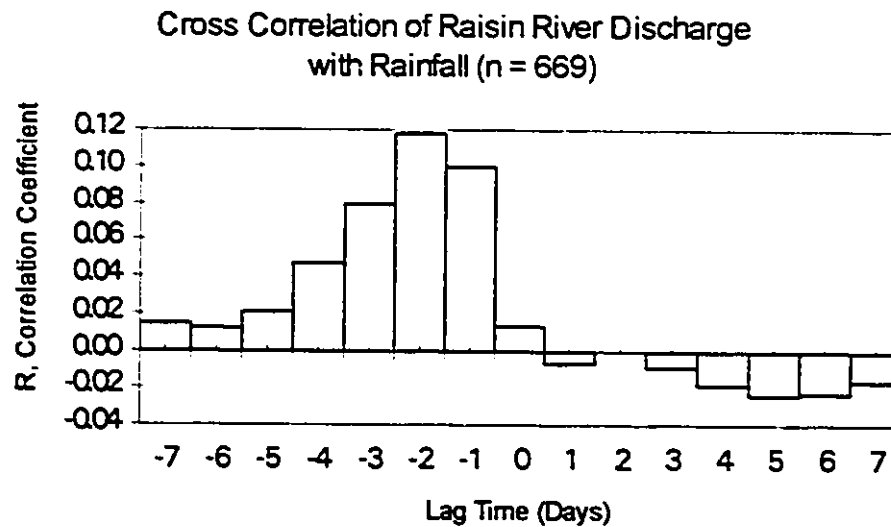


Figure 17. Histogram of Cross-Correlation Coefficients for Raisin R. Discharge and Rainfall (at Cornwall)

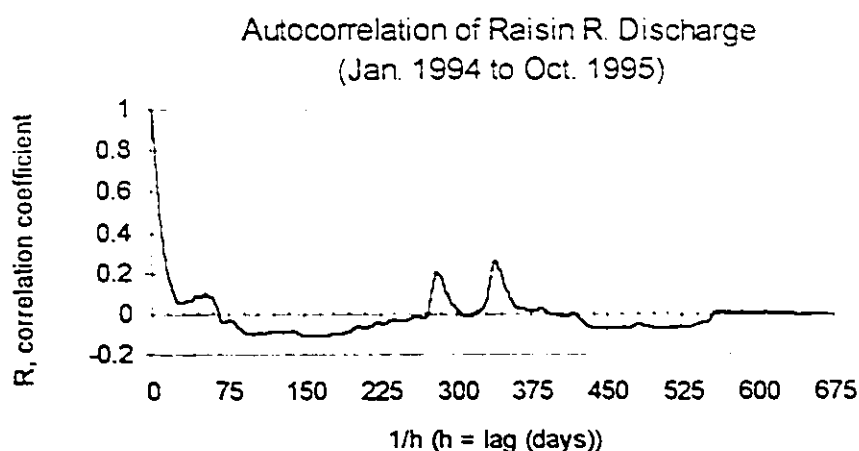


Figure 18. Autocorrelation of Raisin R. Discharge

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 rainfall exceeds evapotranspiration. 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 due to bank infiltration and storage (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,

was 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, when storm events occur in the watershed.

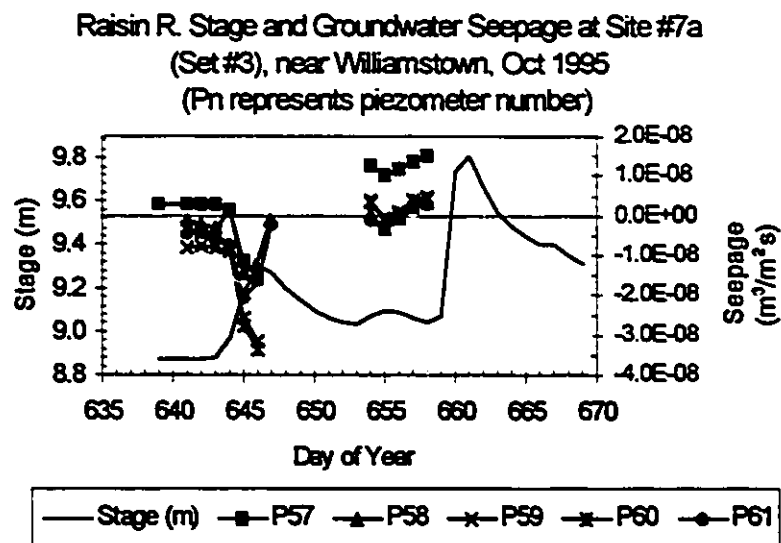


Figure 19. Decline in Seepage Estimates after Storm Event on October 5-6, 1995 (Days 643-644)

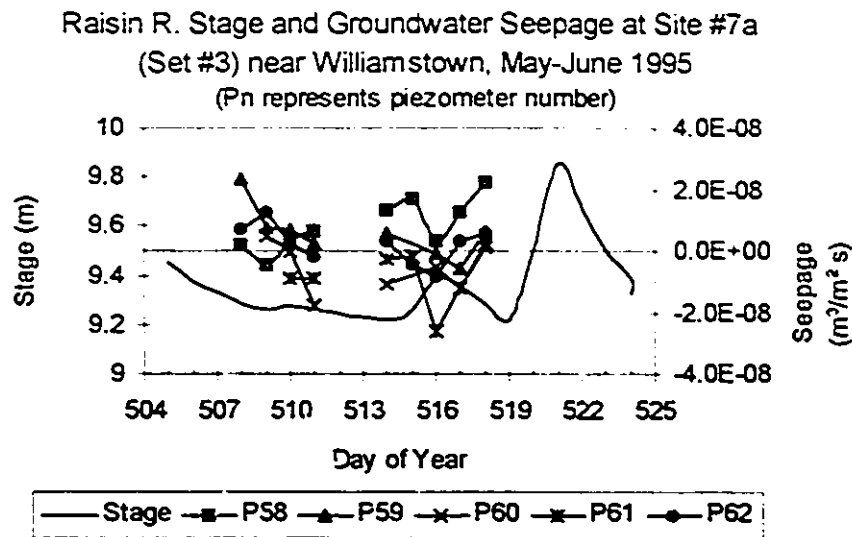


Figure 20. Decline in Groundwater Seepage Estimates after Storm Event on May 28-20 (Days 513 and 514)

6.4 Comparison of *Event Discharge Volume* to *Storm Volume*

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

$$Q_t = Q_e + Q_p$$

Q_t and Q_p are obtained directly from a stream 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 (Figure 21).

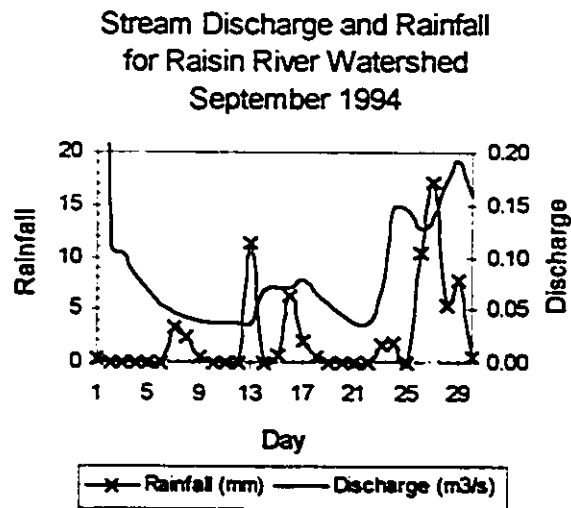


Figure 21. Stream Discharge and Rainfall for September 1994

i. **Event Discharge Volume:** The volume of Raisin River water attributed to the September 13,14 storm event (*Event Discharge Volume*) was found by first, plotting $Q_e(t)$ vs time, t (seconds), for the period of the peak discharge. (Note: Q_p is assumed to be constant over this period.) Secondly, the area underneath the curve in Figure 22 was calculated with the following equation:

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

Thus, the volume of water in the river from the September storm event, the *Event Discharged Volume*, was found to be $6.38 \times 10^3 \text{ m}^3$. The detailed calculation is shown in Appendix 5.

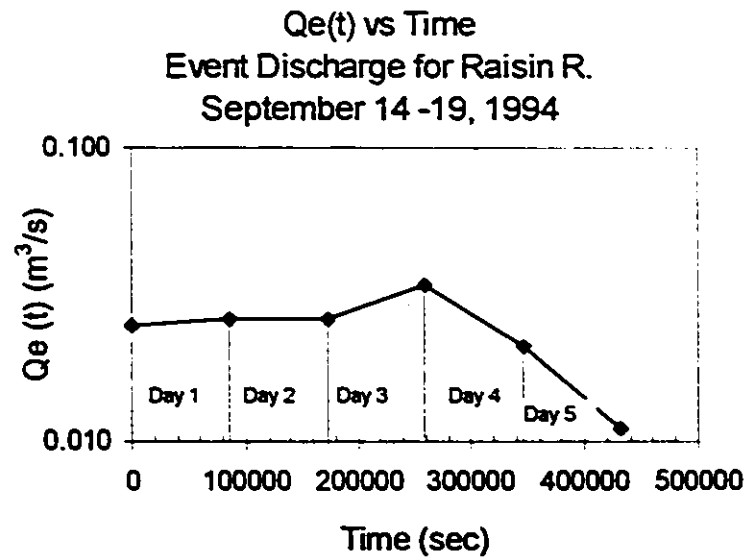


Figure 22. Area Under Curve used to find Event Discharge Volume

ii. *Storm 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):

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

The difference between *Storm Volume* and *Event Discharge Volume* is $6.20 \times 10^6 \text{ m}^3$. This indicates that most of the precipitation from a storm event recharges the phreatic aquifers or contributes to evapotranspiration rather than contributing to streamflow. Neglecting evapotranspiration as a first approximation, and assuming 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. Thus, groundwater seepage may comprise a significant portion of streamflow as a result of storm events.

6.5 References

Domenico, P.A., Schwartz, F.W., (1990), Physical and Chemical Hydrogeology, John Wiley and Sons, Inc., New York.

Farvolden, R.N., (1963), "Geologic Controls on Groundwater Storage and Base Flow", *Journal of Hydrology*, Vol. 1, 219-249.

Ineson, J., Downing, R.A., (1964), "The Groundwater Component of River Discharge and its Relationship to Hydrogeology", *Journal Institution of Water Engineers and Scientists*, Vol. 18.

Jury, W.A., Gardner, W.R., and Gardner, W.H., (1991), Soil Physics, Fifth Edition, John Wiley and Sons, Inc., New York.

Meyboom, P., (April 1961), "Estimating Groundwater Recharge from Stream Hydrographs", *Journal of Geophysical Research*, Vol. 66, No. 4.

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

Serrano, S.E., Whiteley, H.R., and Irwin, R.W., (1985), "Effects of Agricultural Drainage on Streamflow in the Middle Thames River, Ontario, 1949-1980", *Canadian Journal of Civil Engineering*, Vol. 12.

Chapter 7.0 Stable Isotope Analysis of Watershed

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. For a review of oxygen and hydrogen isotopes in water, the author refers the reader to Clark and Fritz (1997, in press). 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. 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 mille) and is calculated as:

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

where R = the ratio of heavy to light isotopes. 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 modified by Gat (1980) to:

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

Stable isotope values can also be compared to a Local Meteoric Water Line (LMWL) if precipitation data have been collected for a certain area. The University of Waterloo has collected such data for Ottawa, Ontario. Fritz et al., (1987) report that the mean annual LMWL for Ottawa is:

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

This LMWL will be used in this study because of the close proximity of Ottawa to the study site. Its validity for precipitation in the Cornwall area has been documented by Barth (1996). 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 23).

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.

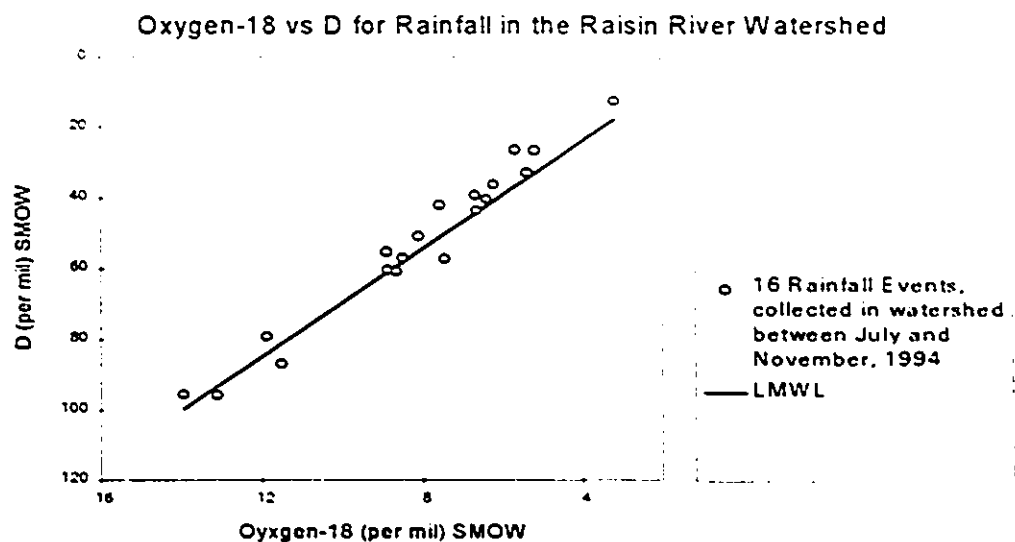


Figure 23. Delta Oxygen-18 and Deuterium Graph for Rainfall

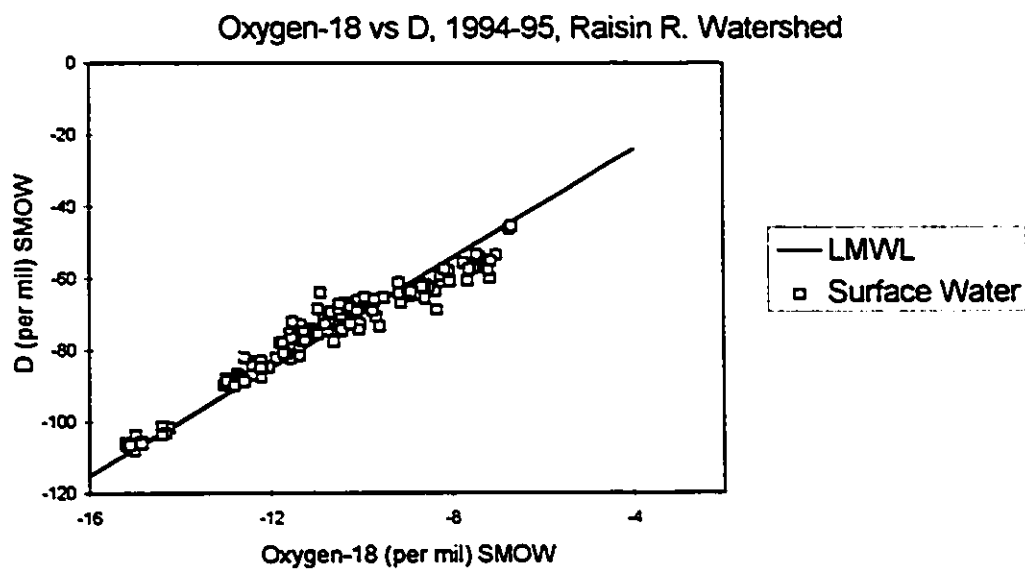


Figure 24. Delta Oxygen-18 and Deuterium Graph for Surface Water

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 waters are largely unmodified prior to discharge (Figure 24).

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

Water Type	$\delta^{18}\text{O}$			δD			
	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 to 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 attenuation of seasonal variations in precipitation during flow in the subsurface. 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 25 and 26. Analyses of variance on the isotope data revealed that there was no significant differences between sampling sites for both oxygen-18 ($p = 0.21$) and D ($p = 0.48$) and no detectable effect due to the time (i.e. day to day variability is insignificant) for both oxygen-18 ($p = 0.21$) and D ($p = 0.16$). Data and statistical results are shown in Appendix 7.

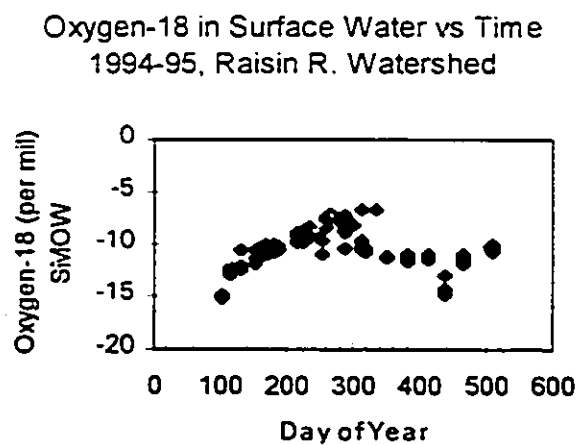


Figure 25. Delta Oxygen-18 vs Time for Surface Water in the Raisin River Watershed (8 sampling sites)

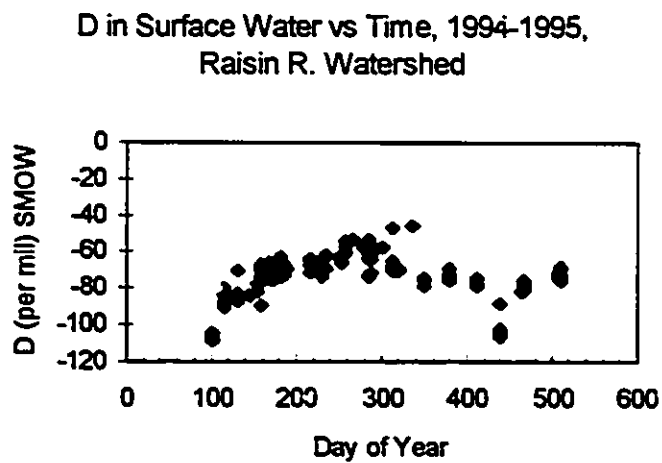


Figure 26. Delta Deuterium vs Time for Surface Water in the Raisin River Watershed (8 sites)

7.2.3 Groundwater from Piezometers

Groundwater isotope values of waters, collected from piezometers installed in the Raisin River bed, also plot close to the LMWL. This indicates that little subsurface modification has occurred (Figure 27). 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 illustrate this (Figures 28 and 29). The author refers readers to Cane (1996) for an in-depth study of stable isotopes in groundwaters for this area. 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 of groundwater 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).

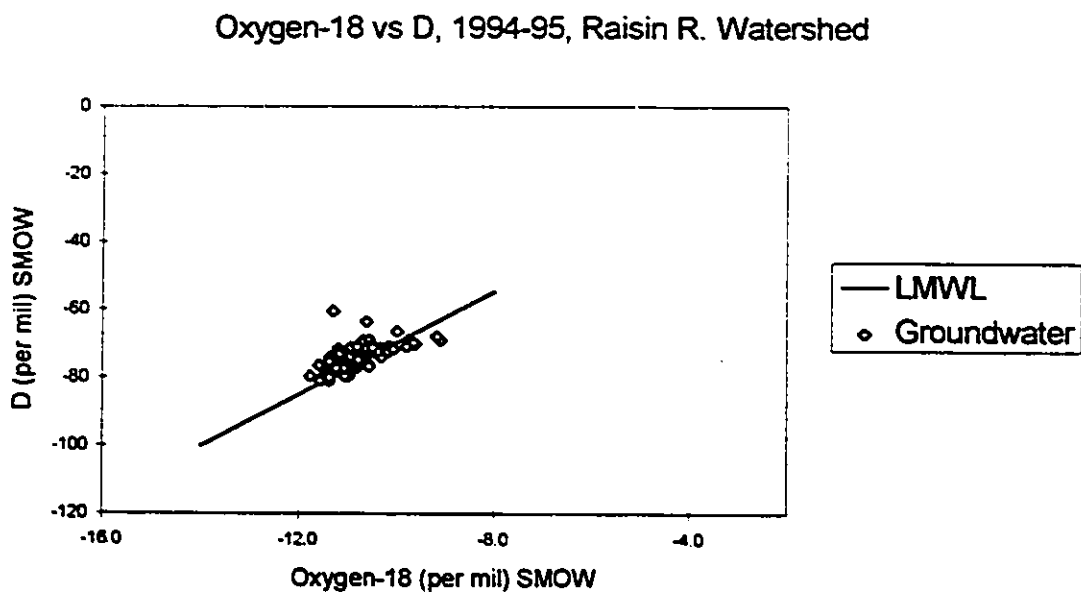


Figure 27. Delta Oxygen-18 and Deuterium Graph for Groundwater (samples from piezometers)

Oxygen-18 in Groundwater vs Time, 1994-95,
Raisin R. Watershed

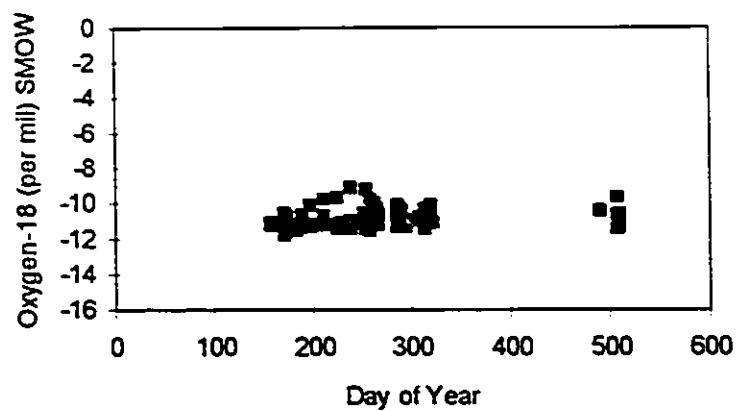


Figure 28. Delta Oxygen-18 vs Time for Groundwater in the Raisin River Watershed

D in Groundwater vs Time, 1994-1995,
Raisin R. Watershed

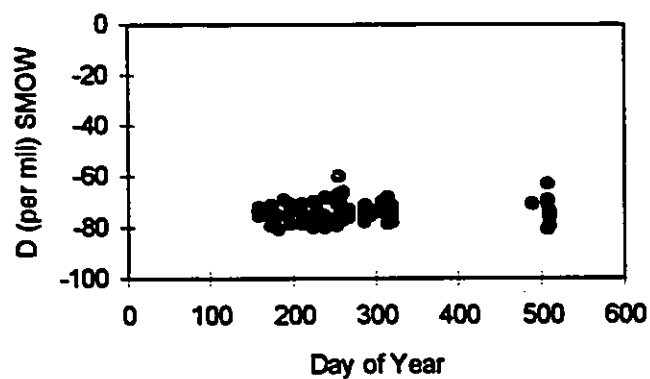


Figure 29. Delta Deuterium vs Time for Groundwater in the Raisin River Watershed

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 (Fritz et al., 1987). 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 30). However, a significant difference in oxygen-18 values between sites was found ($p = 10^{-6}$). Again, this might indicate a mixture of waters (as mentioned above). 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 31). Data and statistical results are shown in Appendix 7.

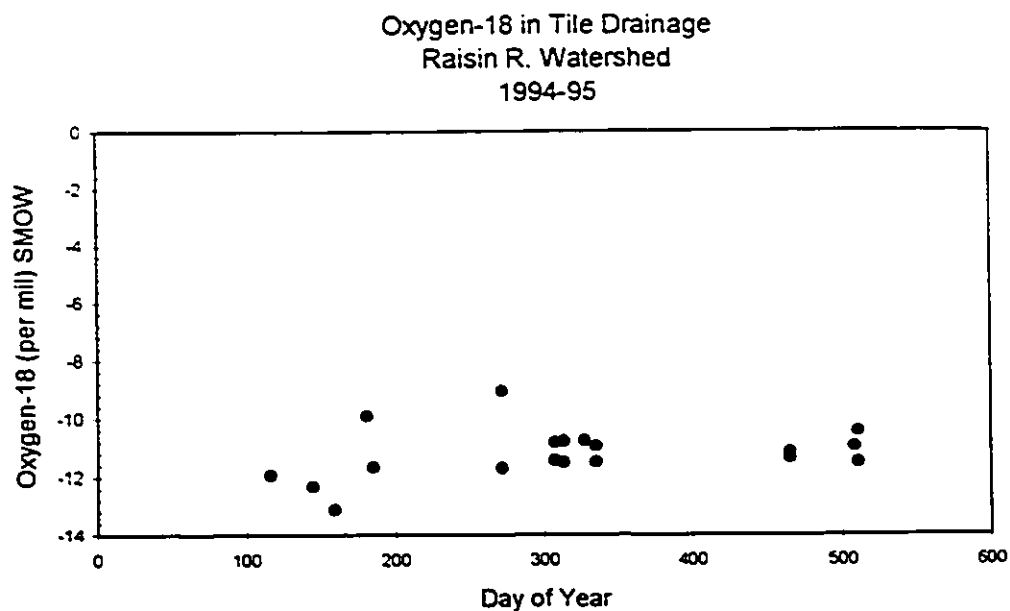


Figure 30. Delta Oxygen-18 vs Time in Tile Drainage Waters

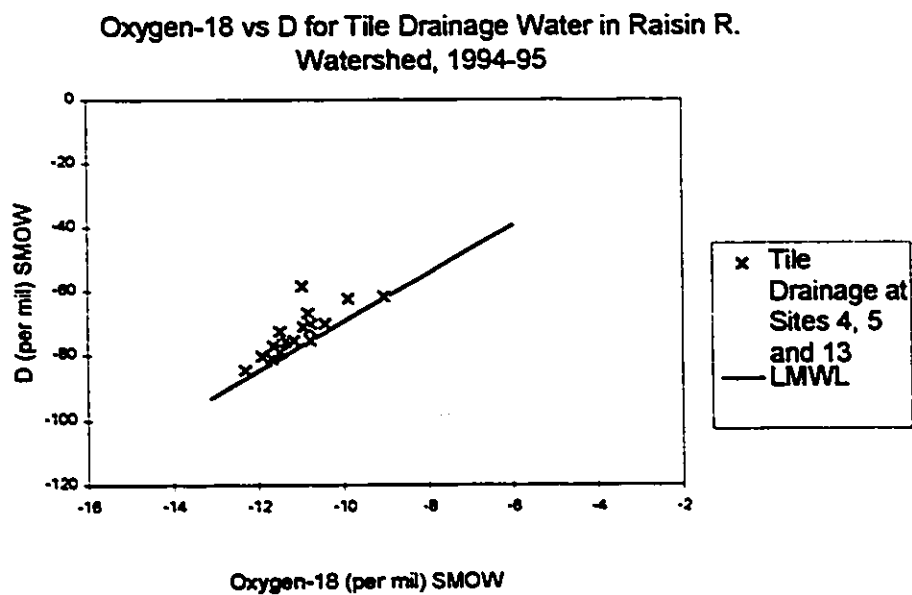


Figure 31. Delta Oxygen-18 and Deuterium Graph for Tile Drainage Waters

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 *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 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 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, 1997, in press). The ratio of the amplitudes, from plots of oxygen-18 in surface water and precipitation vs. time, 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):

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

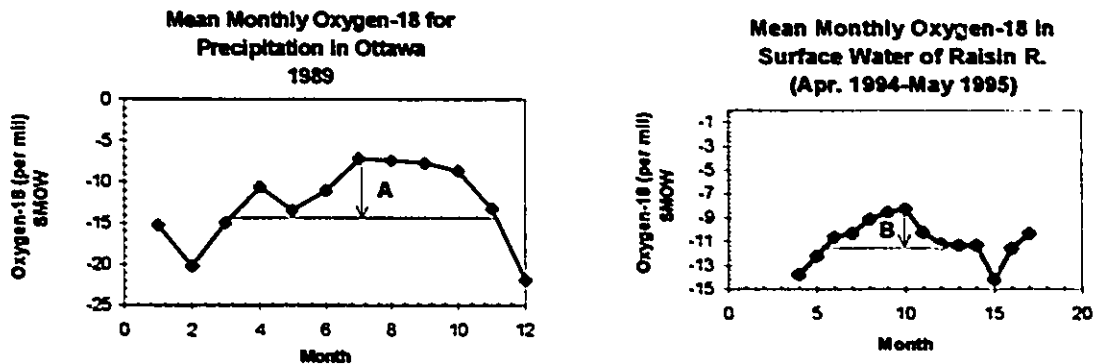


Figure 32. and Figure 33. Amplitudes of Delta Oxygen-18 Curves for Precipitation (A) and Surface Water (B)

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 32 and 33). A sample calculation and data is given in

Appendix 7. The *mean residence time* of meteoric water in the Raisin River watershed ($\sim 546 \text{ km}^2$) was estimated to be 4.06 months. 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 ($\delta^{18}\text{O}$, $\delta^2\text{H}$ - 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 , ^2H) 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 (same event discussed in Section 6.4). The isotopic concentrations of a rainfall sample collected on September 14 from site no. 1, (C_e), were the following: $\delta D = -26.4\text{‰}$ SMOW and $\delta^{18}O = -5.68\text{‰}$ 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 $\delta D = -26.6\text{‰}$ SMOW and $\delta^{18}O = -5.20\text{‰}$ 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: $\delta D = -65.1\text{‰}$ SMOW and $\delta^{18}O = -8.98\text{‰}$ 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 nos. 5, 6, and 7A, when discharge $Q = 0.071 \text{ m}^3\text{s}^{-1}$ (Q_i). The day of peak discharge was actually two days later, on September 17, 1995, where $Q = 0.079 \text{ m}^3\text{s}^{-1}$, but a water sample was not collected that day. Since discharge values for September 15 are similar to September 17 (a small difference of $0.008 \text{ m}^3\text{s}^{-1}$), these data were used for the calculations. The mean of isotopic results for the three water samples (C_i), is the following: $\delta\text{D} = -58.1\text{‰ SMOW}$ and $\delta^{18}\text{O} = -7.77\text{‰ SMOW}$.

Calculations produced an estimate that the pre-event component, Q_p , of total stream discharge resulting from the September 13 -14 storm was $0.045 (\pm 0.001) \text{ m}^3\text{s}^{-1}$. 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. This is considerably larger than the values of 35 and 22% calculated for low flow conditions using stream hydrographs (Section 6.1).

7.5 References

- Barth, J.A.C., (1996), Veizer, J. and Hall, G.E.M., (1996), "Geochemical Monitoring of the St. Lawrence River in the Cornwall Area", IREE, Ottawa.
- Craig, H., (1961), "Isotope Variations in Meteoric Water", Science, Vol. 133.
- Drever, J.I., (1982), The Geochemistry of Natural Waters, Prentice-Hall, N.J.
- Fritz, P., et al., (1987), "The Isotopic Composition of Precipitation and Groundwater in Canada", IAEA Symposium No. 299, Isotope Techniques in Water Resources Development, Vienna, March 1987, pp. 539-550.

Mean Residence Time:

- Burgman, J.O., Calles, B., and Westman, F., (1987), "Conclusions from a Ten Year Study of Oxygen-18 in Precipitation and Runoff in Sweden", Proceedings of a Symposium, Vienna, 30 March - 3 April, 1987, Organized by IAEA in cooperation with UNESCO on The Use of Isotope Techniques in Water Resources Development.
- Clark I., and Fritz, P., (1997) Environmental Isotopes in Hydrogeology, in press, CRC Lewis, New York, pp. 325.
- Kretz, R., (1985), "Calculation and Illustration of Uncertainty in Geochemical Analyses", Journal of Geological Education, Vol. 33, p. 40.
- Pearce, A.J., Stewart, M.K., and Sklash, M.G. (August 1986), "Storm Runoff Generation in Humid Headwater Catchments, 1. Where Does the Water Come From?", Water Resources Research, Vol. 22, No. 8, pp. 1263-1272.

Isotopic Hydrograph Separation:

- Fritz, P., Cherry, J.A., Weyer, K.U., and Sklash, M. (1976), "Storm Runoff Analyses using Environmental Isotopes and Major Ions", Interpretation of Environmental Isotope and Hydrochemical Data in Groundwater Hydrology, IAEA, Vienna, pp. 111-130.
- Fritz, P., (1981), " Stable Isotope Hydrology, Deuterium and Oxygen-18 in the Water Cycle, Chpt. 8: River Waters), Eds. Gat, J.R., Gonfiantini, R., IAEA Technical Report Series No. 210, Vienna.

Freeze, R.A., (1972), "Role of Subsurface Flow in Generating Runoff, 1. Baseflow Contributions to Channel Flow", *Water Resources Research*, Vol. 8, p. 609.

Freeze, R.A., (1974), "Stream-flow Generation", *Res. Geophys. Space Phys.*, Vol. 12, p. 627.

Gillham, R.W. (1984), "The Capillary Fringe and its effect on Water Table Response", *Journal of Hydrology*, Vol. 67, pp. 307-324.

Kendall, C., et al., (1995), "Isotope Tracers of Water and Solute Sources in Catchments", Chpt. 10 in Solute Modelling in Catchment Systems, ed. by S.T. Trudgill, John Wiley & Sons.

Kretz, R., (1985), "Calculation and Illustration of Uncertainty in Geochemical Analyses", *Journal of Geological Education*, V. 33, p. 40.

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

Sklash, M.G., Farvolden, R.R. and Fritz, P. (1976), "A Conceptual Model of Watershed Response to Rainfall, Developed through the use of Oxygen-18 as a Natural Tracer", *Canadian Journal of Earth Sciences*, Vol. 13, pp. 271-283.

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 a detailed look at the geochemistry of groundwater in the study area, the author refers readers to Cane (1996), and for 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. Inductively 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, and 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 23 of the 50 samples have greater 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 34 and 35).

Chebotarev's sequence indicates that the groundwater samples are from a shallow aquifers (or groundwaters that have recently been recharged) since they have high concentrations of HCO_3^- (generally $> 250 \text{ mg/L}$) 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 34). Several groundwater samples (site no. 12) are distinguishable as a chloride group (Figure 35). This might be an indication of discharge conditions or more likely some contamination from leaky septic systems. The Piper diagrams for tile drainage indicate considerable variability amongst the results (Figure 36). This is probably because each of the samples are from four different sites throughout the watershed, i.e. sample collection was insufficient for repeat analyses. A small number of rainfall samples

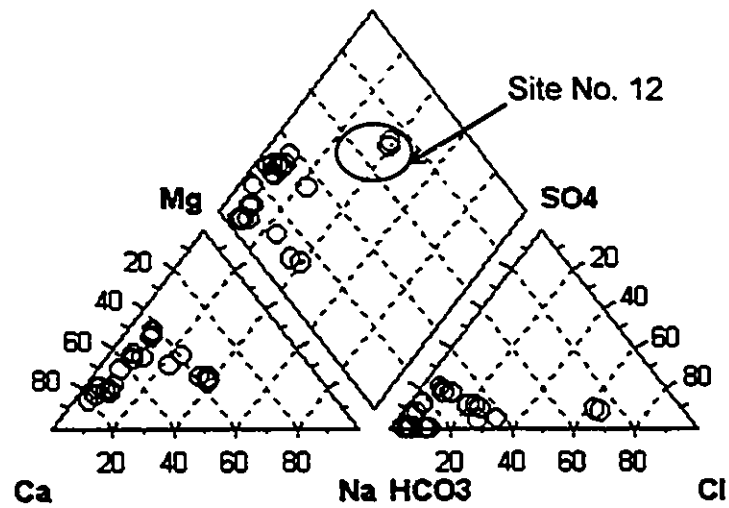
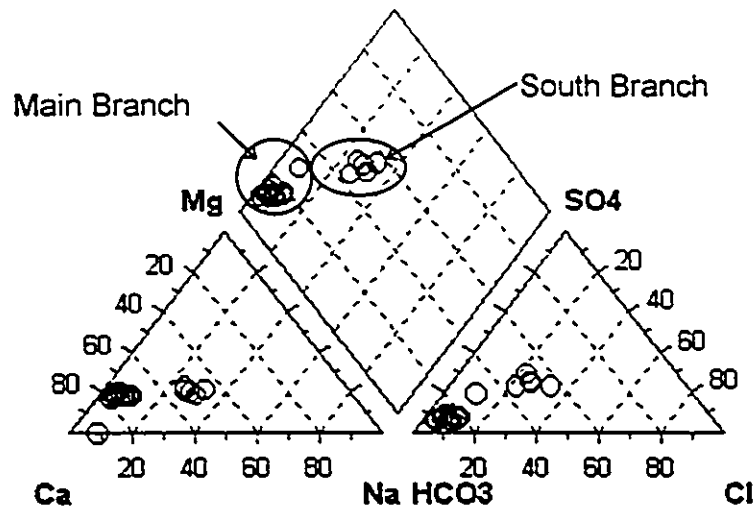


Figure 34. and Figure 35. Piper Plots of Geochemical Data from Surface Water (top) and Groundwater Samples (bottom)

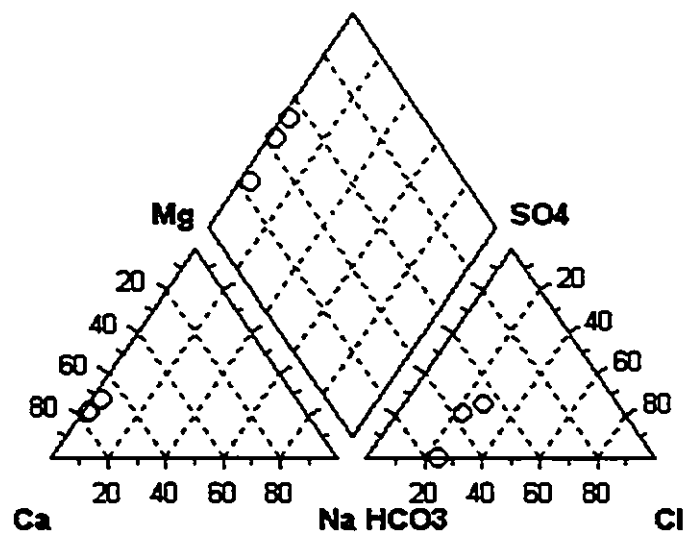
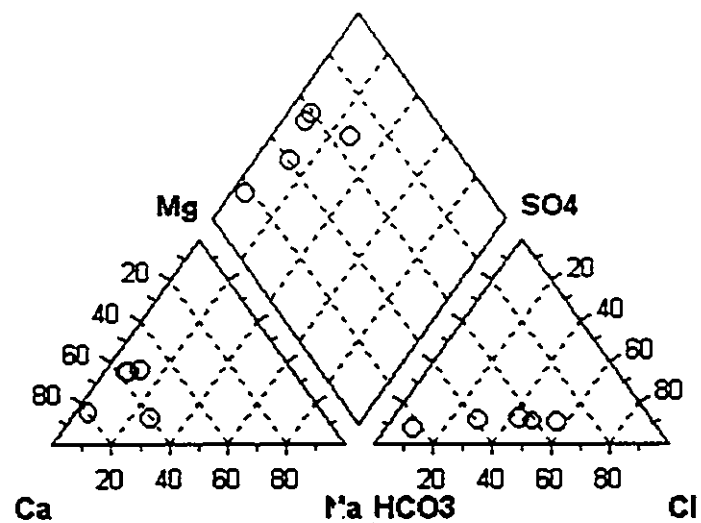


Figure 36. and Figure 37. Piper Plots of Geochemical Data from Tile Drainage (top) and Rain Water Samples (bottom)

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

8.3.1 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 when rejuvenating the exchange column, approximately once per month); inorganic fertilizers; road salt. Natural sources of Cl^- include marine clay and deeper bedrock porewaters. 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 could be from the KCl often used in inorganic fertilizers. This suggests that tile drains provide a short circuit path for rainfall to reach the Raisin River.

8.3.2 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. Other tile drainage sites did not exhibit noteworthy levels. The tile drainage leads directly to the river so this may have an impact on aquatic life (nitrates can contribute to 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. Possible sources of nitrates include fertilizers and organic wastes (eg., manure).

8.3.3 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 ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) 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.

8.3.4 Iron

An aesthetic objective of iron in potable water 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.

8.3.5 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. Two groundwater samples at site no. 12 which had high levels of chloride also had notable levels of sodium

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 or the Na^+ and Cl^- could be from the leaching of the marine clays in the area.

8.4 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 ($\text{CaMg}(\text{CO}_3)_2$) sedimentary rocks. The geochemical analyses also suggests the dissolution of gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and anhydrite (CaSO_4). The presence of Na^+ and Cl^- at some sites could also be the result of leaching from the overburden marine clay deposits.

8.5 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.

8.6 References

Back, W., (1966), "Hydrochemical facies and ground-water flow patterns in northern part of Atlantic Coastal Plain", U.S. Geological Survey Professional Paper No. 498-A, pp. 42.

Canadian Council for Resource and Environment Ministers (CCREM), (1984), Canadian Water Quality Guidelines, Environment Canada, Ottawa.

Cane, G., (1996), "Groundwater Quality and Contaminant Pathways in the Raisin River Agricultural Watershed; Susceptibility to Groundwater Contamination, Cornwall, Ontario", Master's Thesis, unpublished.

Chebotarev, I.I., (1955), "Metamorphism of natural waters in the crust of the weathering", *Geochim. Cosmochim. Acta*, Vol. 8. pp. 22-212.

Freeze, R.A., Cherry, J.A., (1979), Groundwater, Prentice-Hall, Inc., N.J.

Morgan, C.O., and Winner, M.D., Jr., (1962), "Hydrochemical facies in the 400 foot and 600 foot sands of Baton Rouge Area, Louisiana", U.S. Geological Survey Professional Paper No. 450-B, pp. B120-121.

Ontario Ministry of the Environment and Economy (OMOEE), (1993), "Ontario Drinking Water Objectives", For Your Information Publication, September 1993, Ontario.

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 $-9.82 \times 10^{-9} \text{ m}^3 \text{ m}^{-2} \text{ s}^{-1}$ (groundwater recharge from the river) to $2.23 \times 10^{-6} \text{ m}^3 \text{ m}^{-2} \text{ s}^{-1}$ (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 river stage, which in turn depends 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. The seepage meter/mini-piezometer and falling head permeameter/mini-piezometer 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 and clay 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 on average 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 effects 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 damping 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 a similar-sized 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 were 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, Sklash and Farvolden, 1979). Thus, groundwater quality should be taken into consideration when assessing surface water quality. Furthermore, it should be recognized that the geosphere provides a buffer zone to filter and attenuate contaminants.

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 dominated by 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).

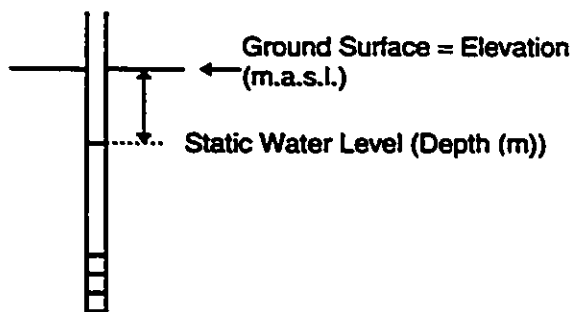


Figure 1. Definition of Surface Elevation and Static Water Level at a Water Well Location

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 statistical software, SPSS™) (Figure 2). The classes were defined by the changes in slope throughout the distribution of data.

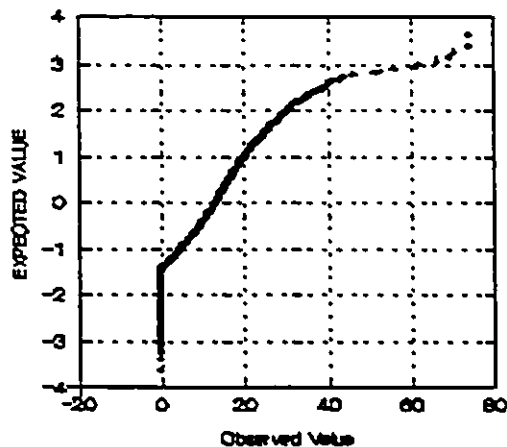


Figure 2. Normal Probability Plot for Overburden Depths (m)

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

Bonham-Carter, G.F., (1994), Geographic Information Systems for Geoscientists: Modelling with GIS, 1st Ed., Computer Methods in the Geosciences, Vol. 13, Pergamon/Elsevier Science, Ottawa, Ont.

Maps:

Dept. of Energy, Mines and Resources, 1980, Topographic Map of Ottawa, 31G, Edition 4, 1:250,000.

Terasmae, J., Mott, R.J., (1965) Surficial Geology, Cornwall, Ontario-Quebec, Map 1175A, Scale: 1:63,360 (Geology 1958-1959).

Williams, D.A., et al., (1985) , Paleozoic Geology, Cornwall-Huntingdon Area, Southern Ontario, Ontario Geological Survey, Map P.2720, Geologic Series - Preliminary Map, Scale: 1:50,000 (Geology 1981-1982).

Digital Data:

National Environment Satellite Data and Information Service, "Geophysics of North America" (1987): CD-ROM, United States Department of Commerce and National Oceanic and Atmospheric Administration, Users Manual Release 1.1, Boulder, Colorado, 80303 USA

Ontario Ministry of Environment and Energy, Environmental Monitoring and Reporting Branch, Drinking Water Section, Water Well Records, 1945-1984, Etobicoke, Ontario.

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 m³ 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 μ m 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.

2.4

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

Table 1. 1994 Groundwater Seepage Flux Measurements

Day	Site #	Piez #	Head (cm)	Gradient	Direct Seepage ($m^3/m^2 \cdot s$)	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	2.26E-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	3.67E-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	0.080	NA	NA
271	1	3	3.35	0.067	8.60E-10	1485
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	1482
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 Mess. (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	-0.005	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	-0.80	-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	75	52	1.00	0.007	-8.14E-10	1580
243	75	52	1.00	0.007	NA	NA
266	75	52	-8.50	-0.077	-8.14E-10	1349
267	75	52	-2.40	-0.022	NA	NA
271	75	52	-0.70	-0.006	-9.81E-09	1573
272	75	52	-0.50	-0.005	NA	NA
243	8	63	7.50	0.068	1.06E-09	1191
244	8	63	8.80	0.060	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	0.035	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

2.9

Day	Site #	Piez #	Head	Gradient (l)	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	-0.056		-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 (l)	Mean K ^s (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	0.068		5.62E-09	NA	NA
619	2	10.5	12.0	0.061		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
606	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		1.66E-08	4.52E-09	1565
514	5	26	-2.8	-0.026		-8.43E-08	3.35E-09	1536

Day	Site #	Piez #	Head	Gradient (l)	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	6.36E-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	2.05E-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	1407
516	5	28	3.0	0.032		1.02E-07	2.29E-09	1321
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		1.46E-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 (l)	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 (f)	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	0.058		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 (l)	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 (l)	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	-0.066		-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 (l)	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 (f)	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 (ft)	Mean K _v (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	-26.0	-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 (l)	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 (l)	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	1363
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

	Site #	Piez #	Head	Gradient (l)	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		4.56E-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	0.025		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	1531
515	7.5	56	-8.0	-0.079		-1.57E-08	2.79E-09	1511
516	7.5	56	0.5	0.005		9.82E-10	1.39E-09	1392
517	7.5	56	7.0	0.069		1.31E-08	7.10E-09	1358
577	7.5	56	4.0	0.040		7.80E-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	0.003		1.18E-09	NA	NA

Day	Site #	Piez #	Head	Gradient (l)	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		-1.16E-08	NA	NA
646	7.5	56	-3.5	-0.035		-5.62E-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
571	7.5	57	29.5	0.173		3.42E-08	NA	NA
588	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	0.089		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 (l)	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	-0.068		-1.75E-08	NA	NA
511	7.5	59	-7.0	-0.054		-1.06E-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	0.083		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 (l)	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		5.68E-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		-2.36E-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

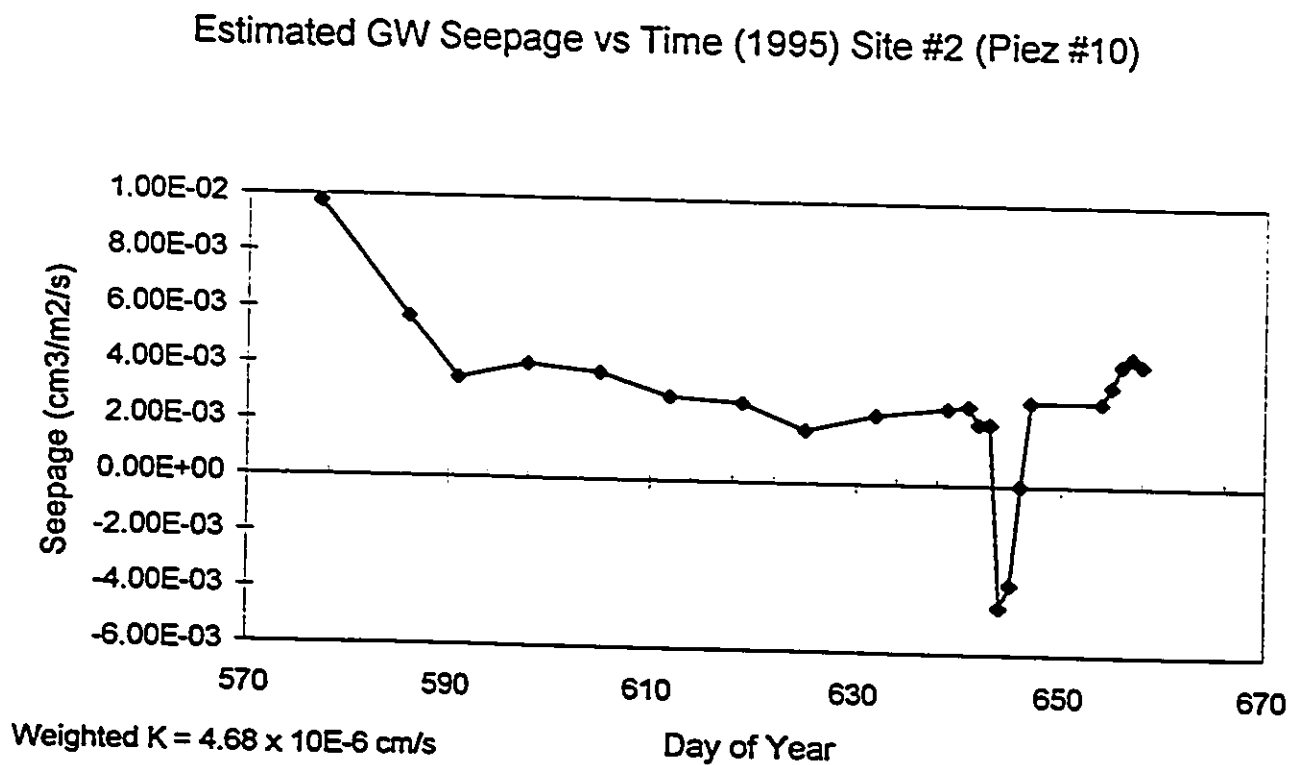
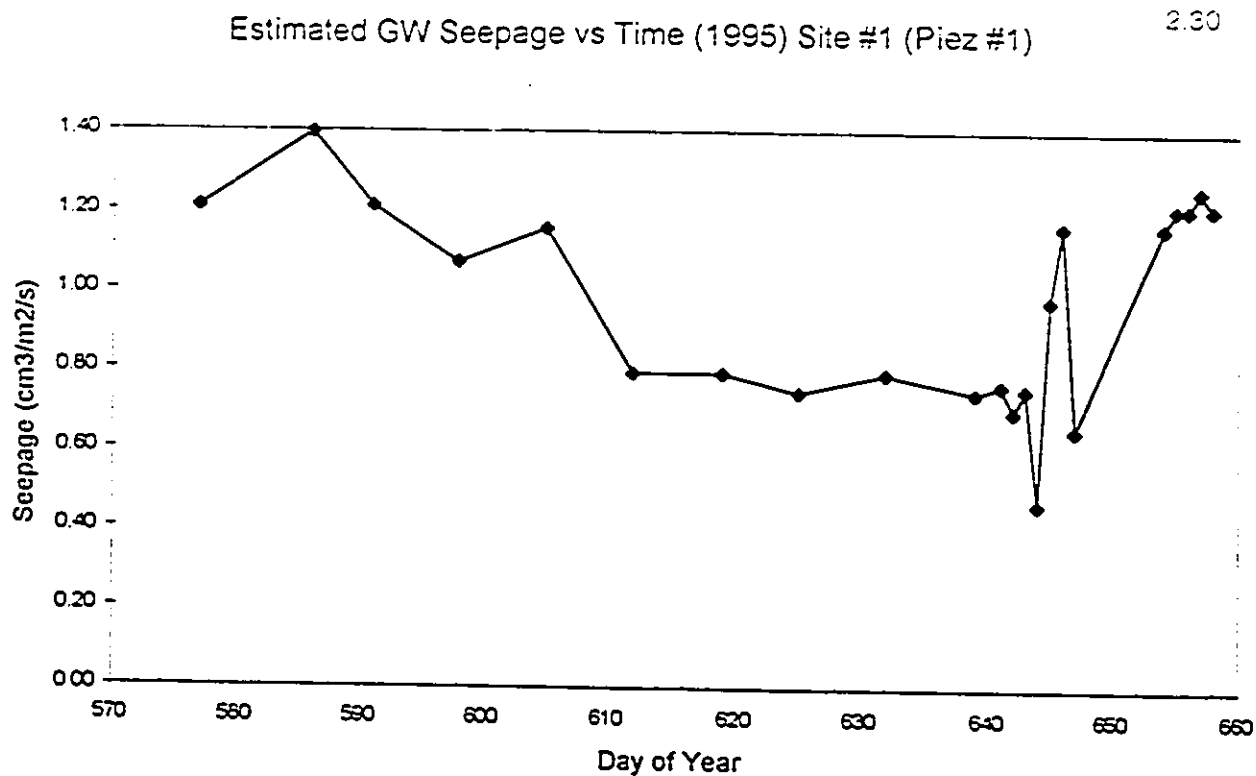
Day	Site #	Piez #	Head	Gradient (l)	Mean K [*] (m s ⁻¹)	Estimated Seepage (m ³ m ⁻² s ⁻¹)	Direct Seepage (m ³ m ⁻² s ⁻¹)	Total Time of Meas. (min)
655	2	64	3.0	0.025		1.30E-09	NA	NA
656	8	64	4.5	0.038		1.96E-09	NA	NA
657	8	64	6.0	0.050		2.61E-09	NA	NA
658	8	64	6.0	0.050		2.61E-09	NA	NA
530	11	69	28.0	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
596	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	1364
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
596	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 (l)	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		-6.57E-08	NA	NA
632	13	77	-2.0	-0.026		-1.14E-07	NA	NA
639	13	77	-0.5	-0.006		-2.66E-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 (l)	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	-0.015		-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	1366
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

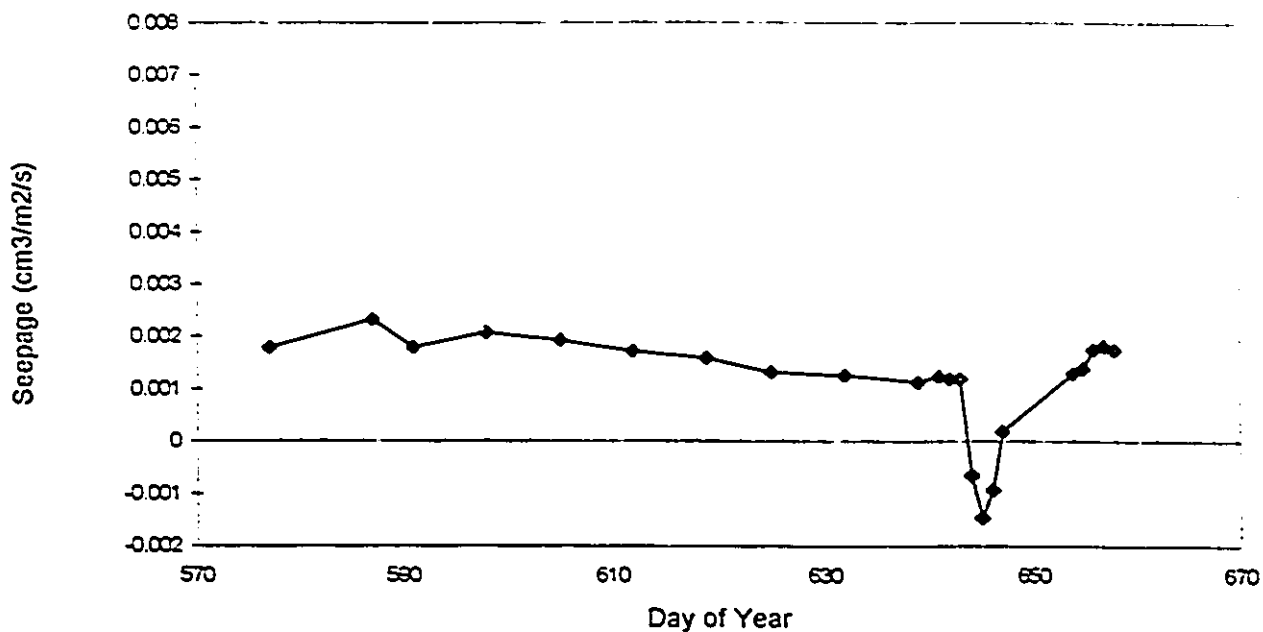
A2.5 Estimated Seepage Flux vs Time Figures for 1995

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

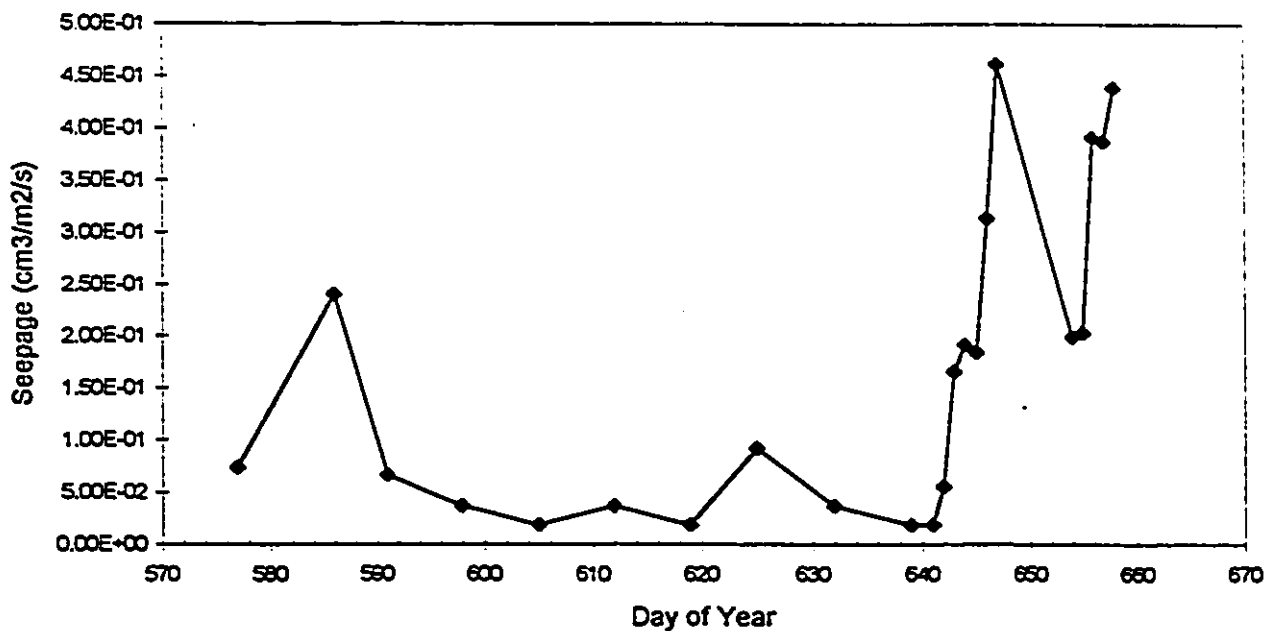


Estimated GW Seepage vs Time (1995) Site #2 (Piez #10.5)

2.31



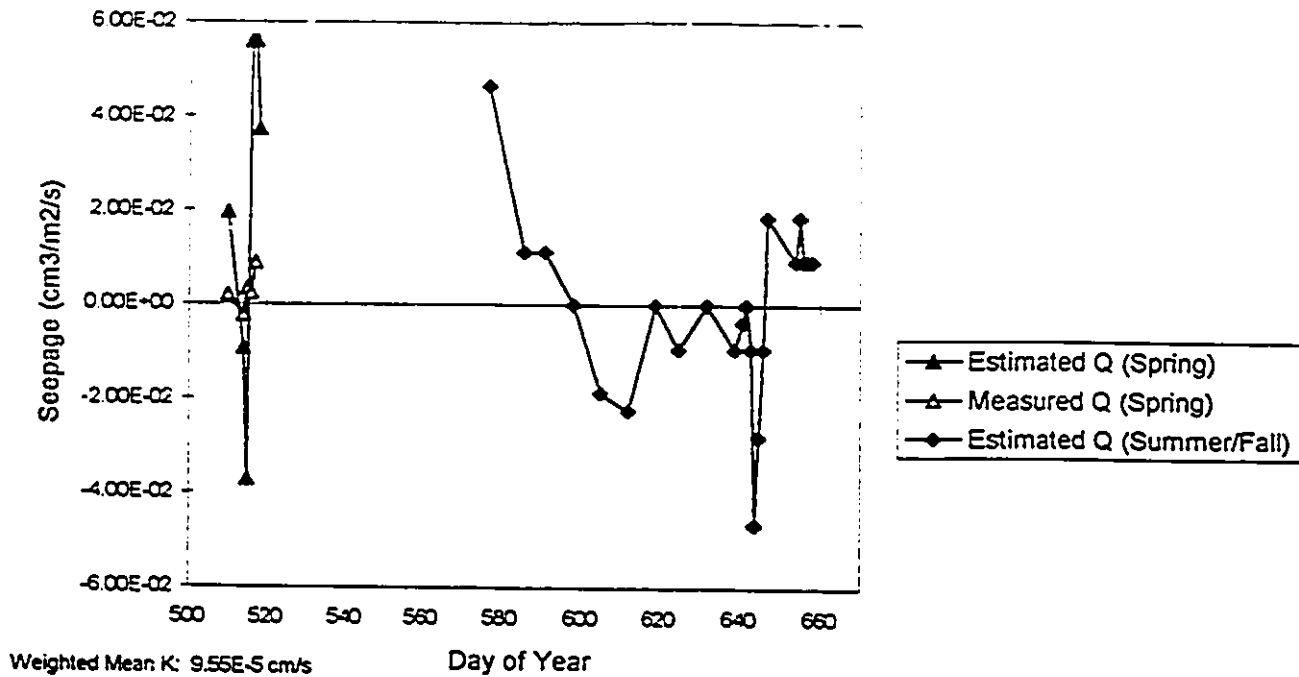
Estimated GW Seepage vs Time (1995) Site #3 (Piez #15)



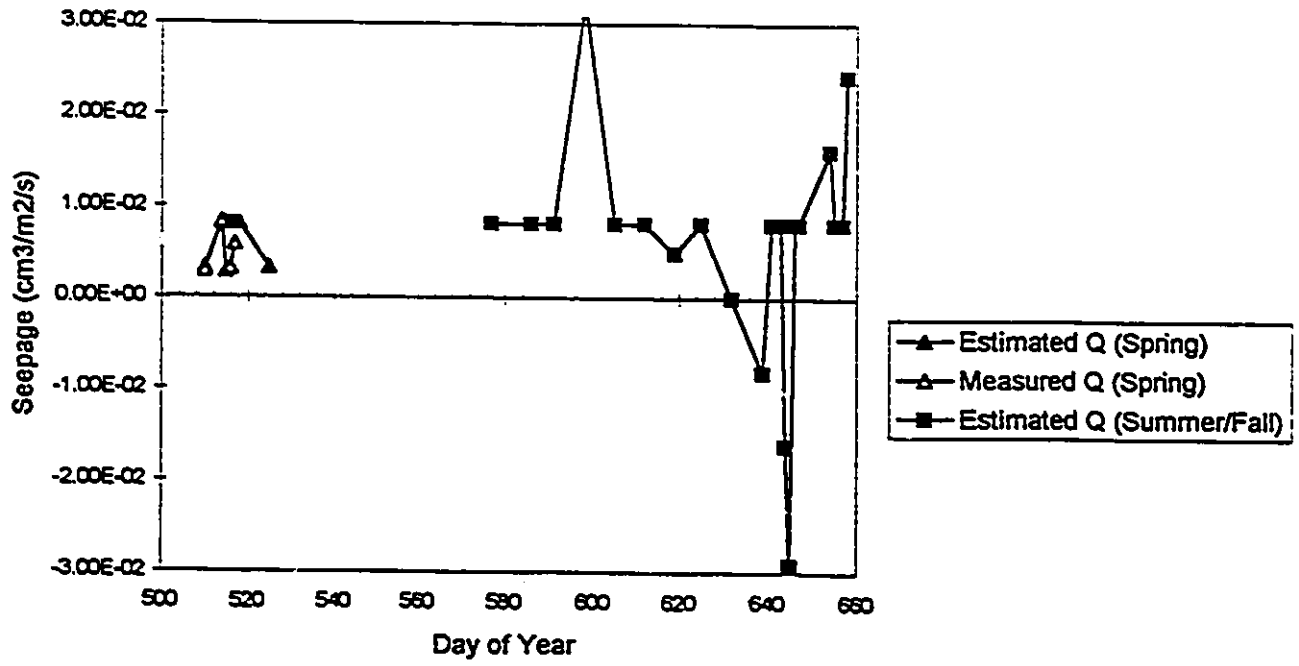
Weighted Mean K = 2.77×10^{-4} cm/s

Figures 5 and 6
 Estimated GW Seepage vs Time (1995)
 Site #5 (Piez #28) 1st Set

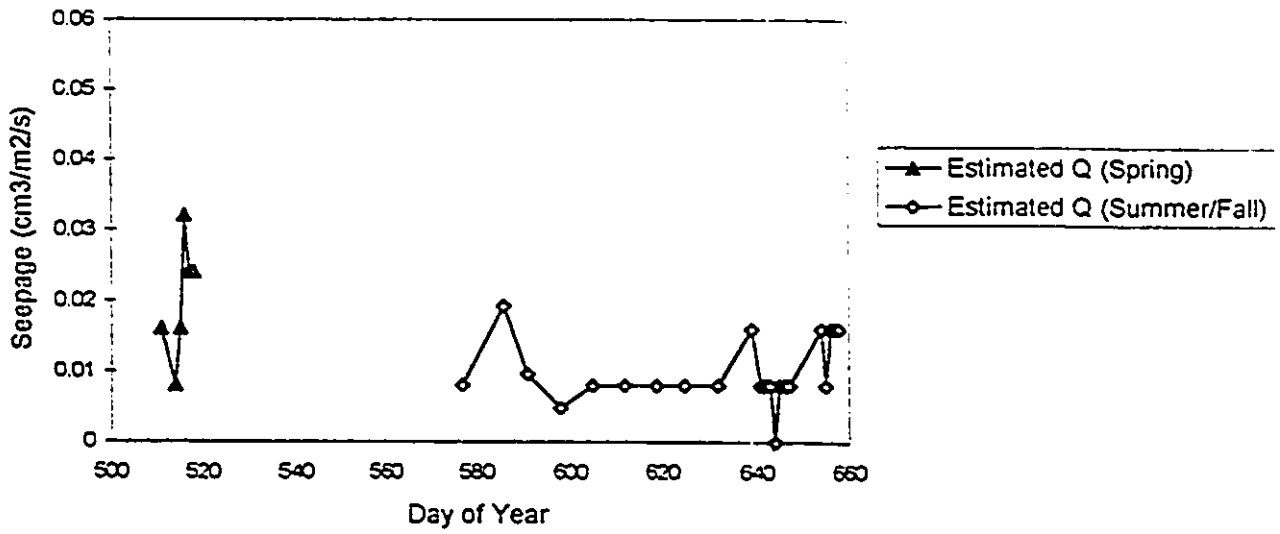
2.32



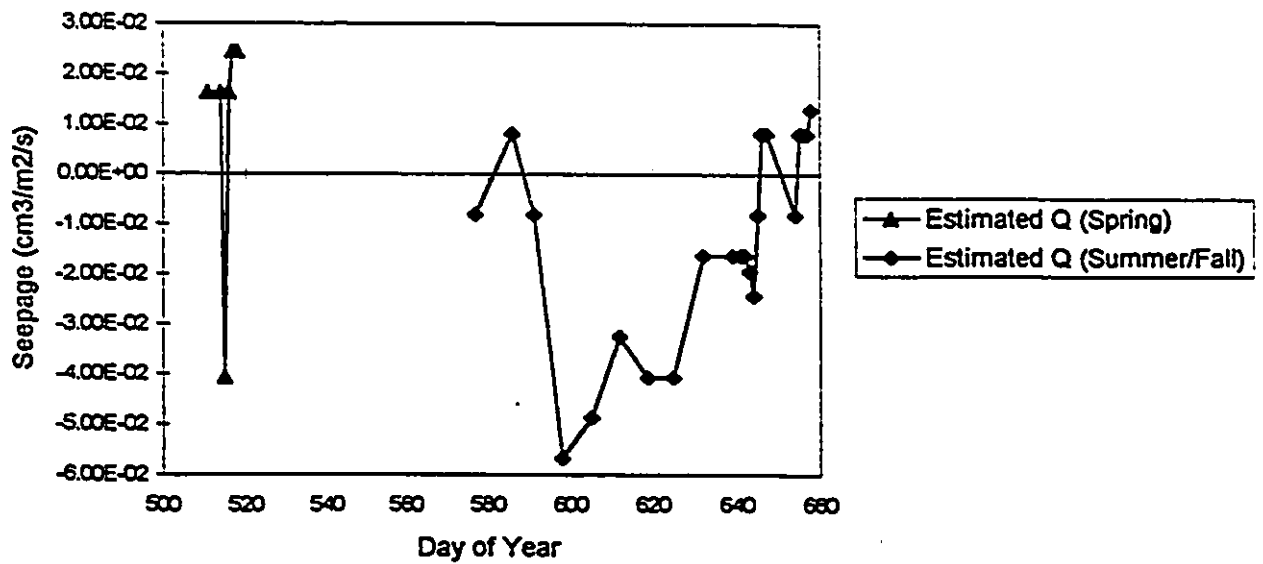
Estimated GW Seepage vs Time (1995)
 Site #5 (Piez #29) 1st Set



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

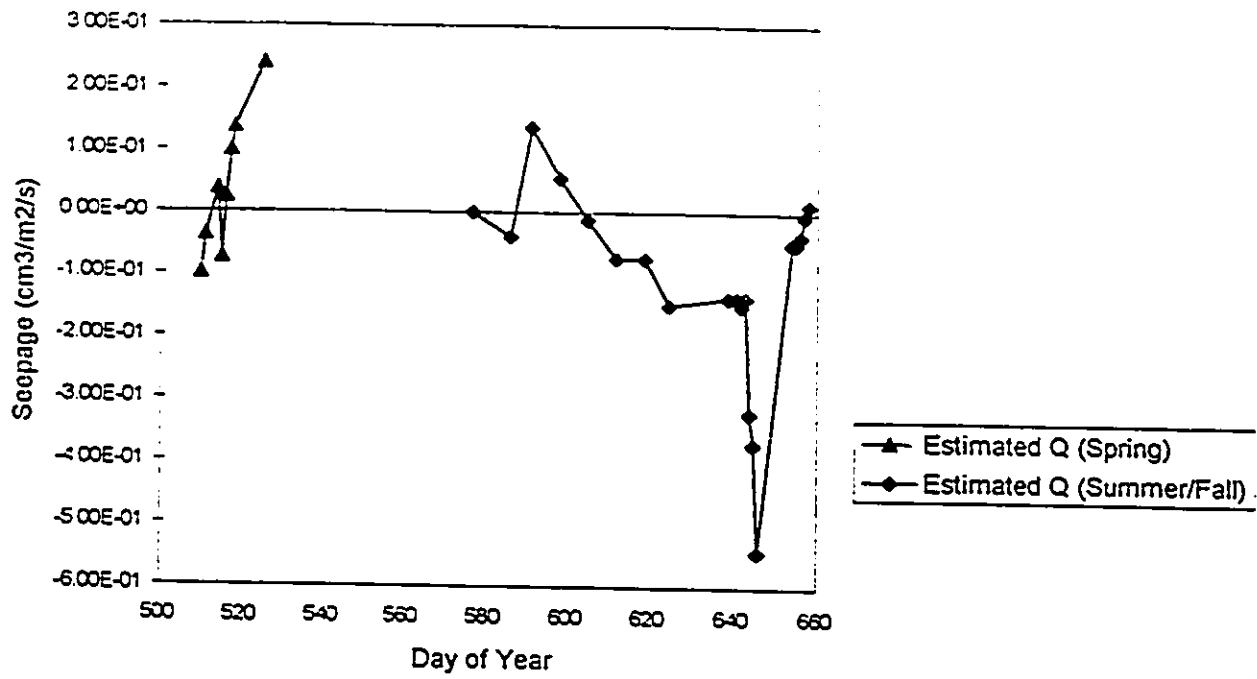


Estimated GW Seepage 1995
Site #5 (Piez #31) 2nd Set

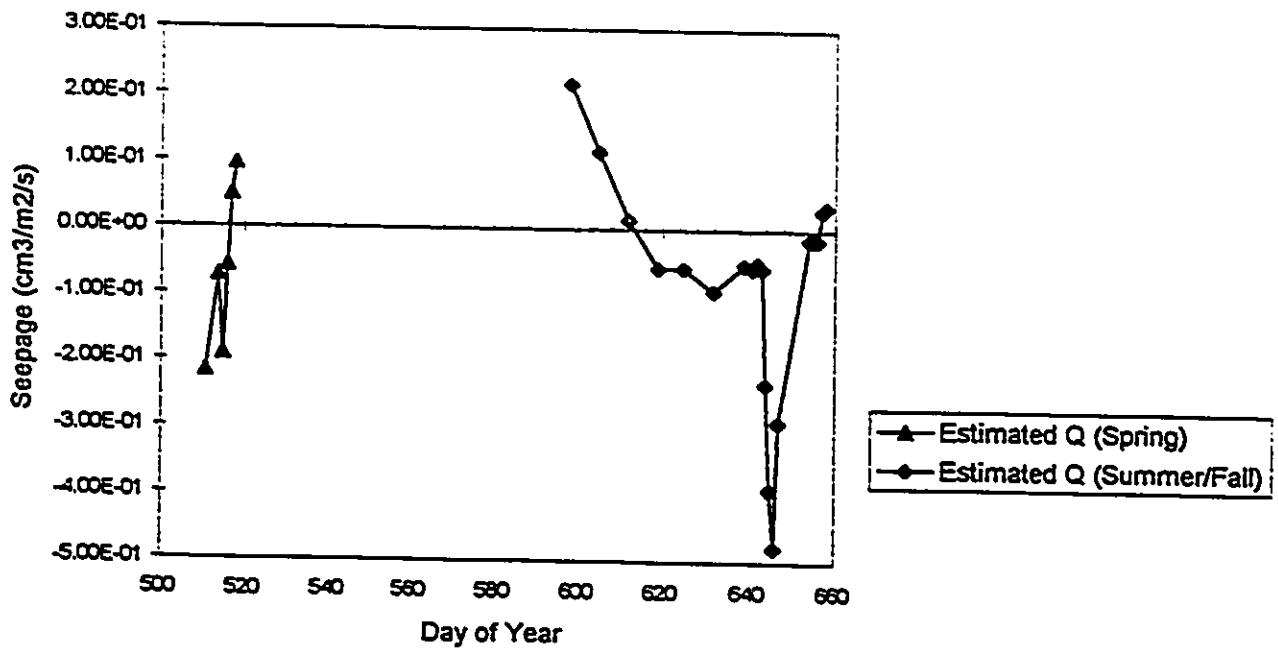


Estimated GW Seepage (1995) Site #5 (Piez #32) 2nd Set

2.34

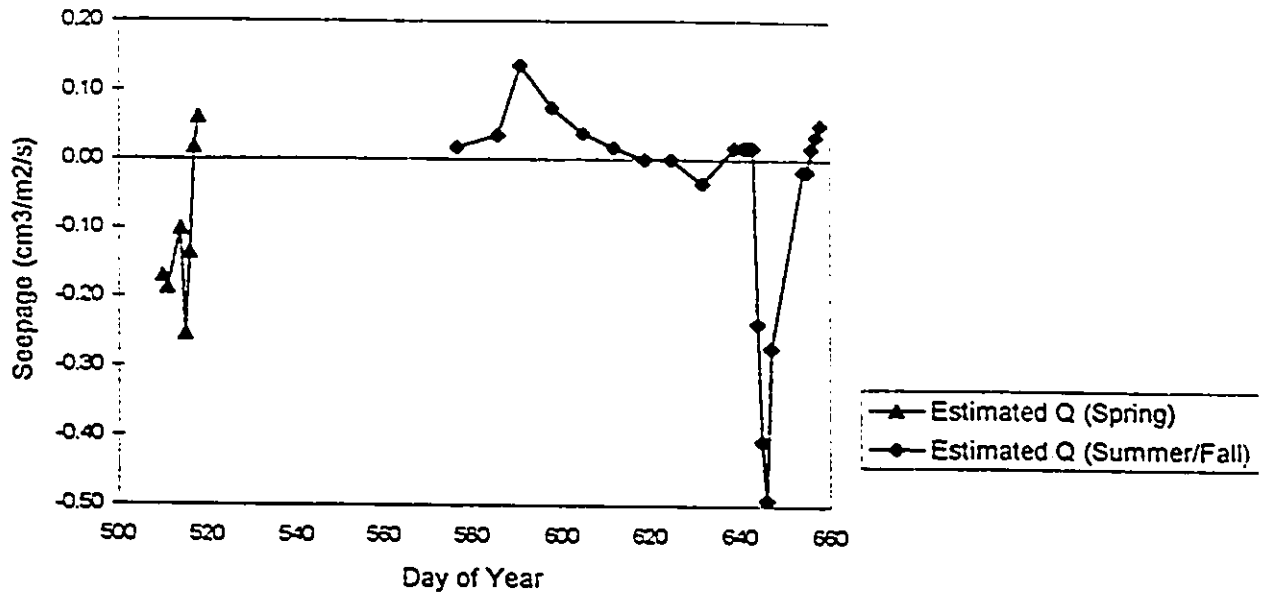


Estimated GW Seepage (1995) Site #5 (Piez #33) 2nd Set

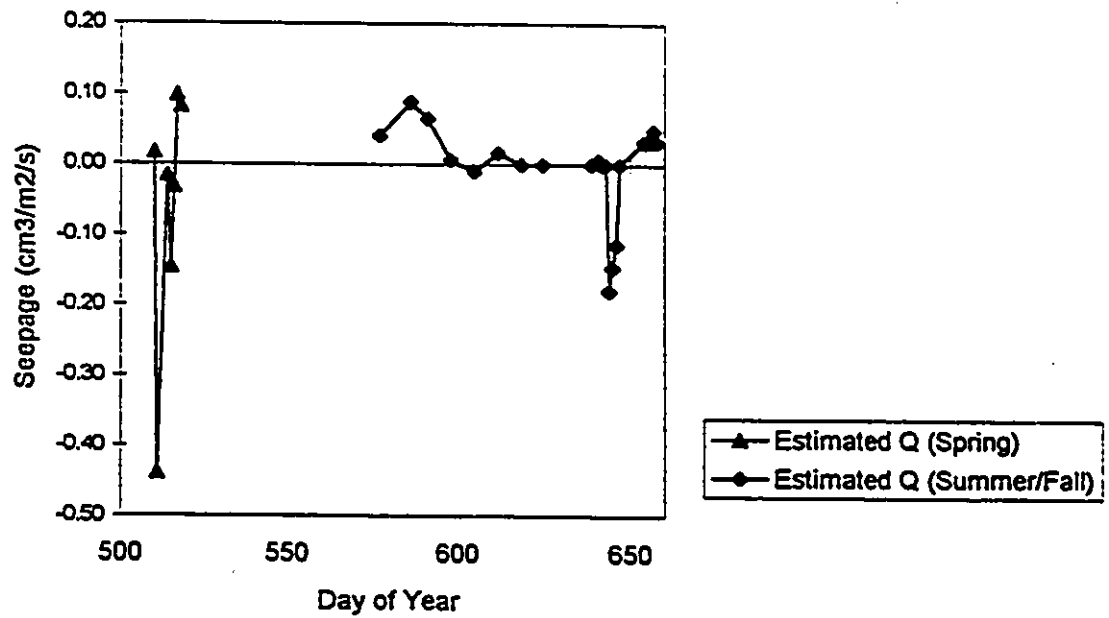


Estimated GW Seepage (1995) Site #5 (Piez #34) 2nd Set

2.35

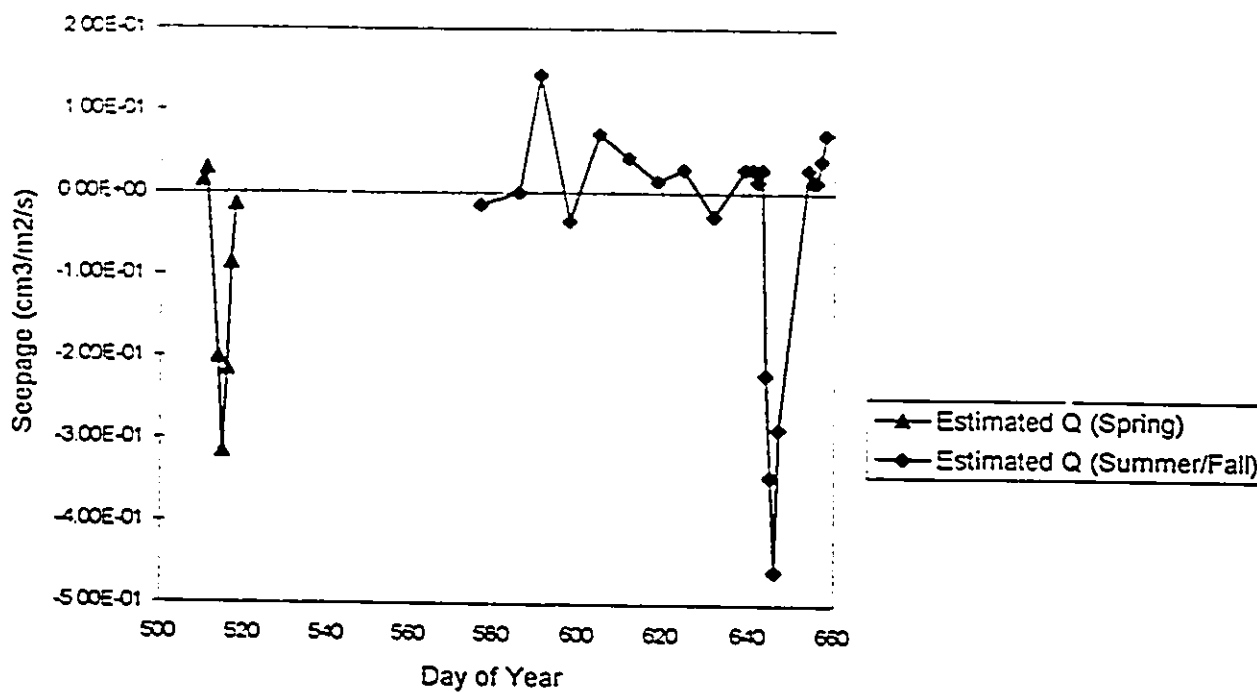


Estimated GW Seepage (1995) Site #5 (Piez #35) 3rd Set

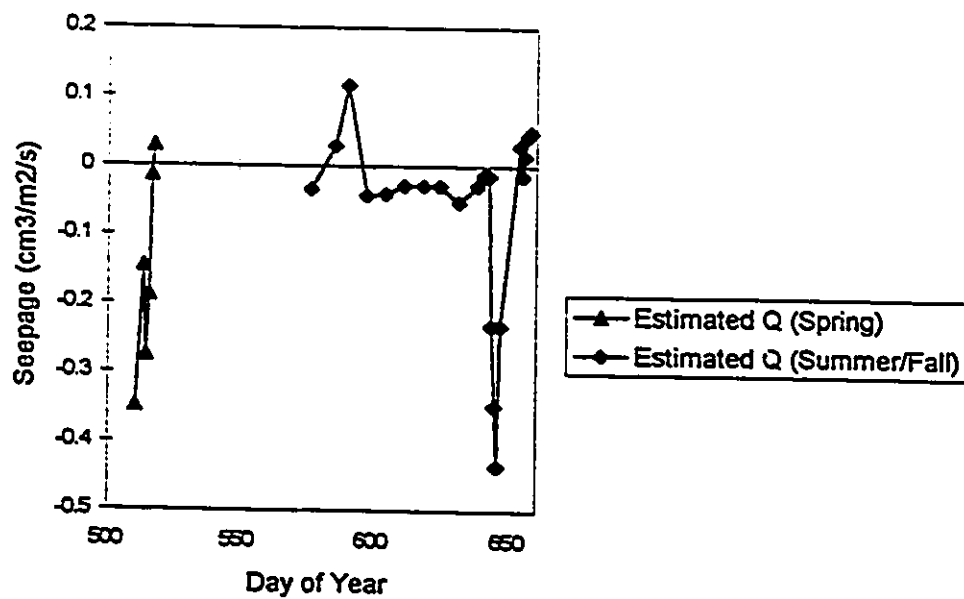


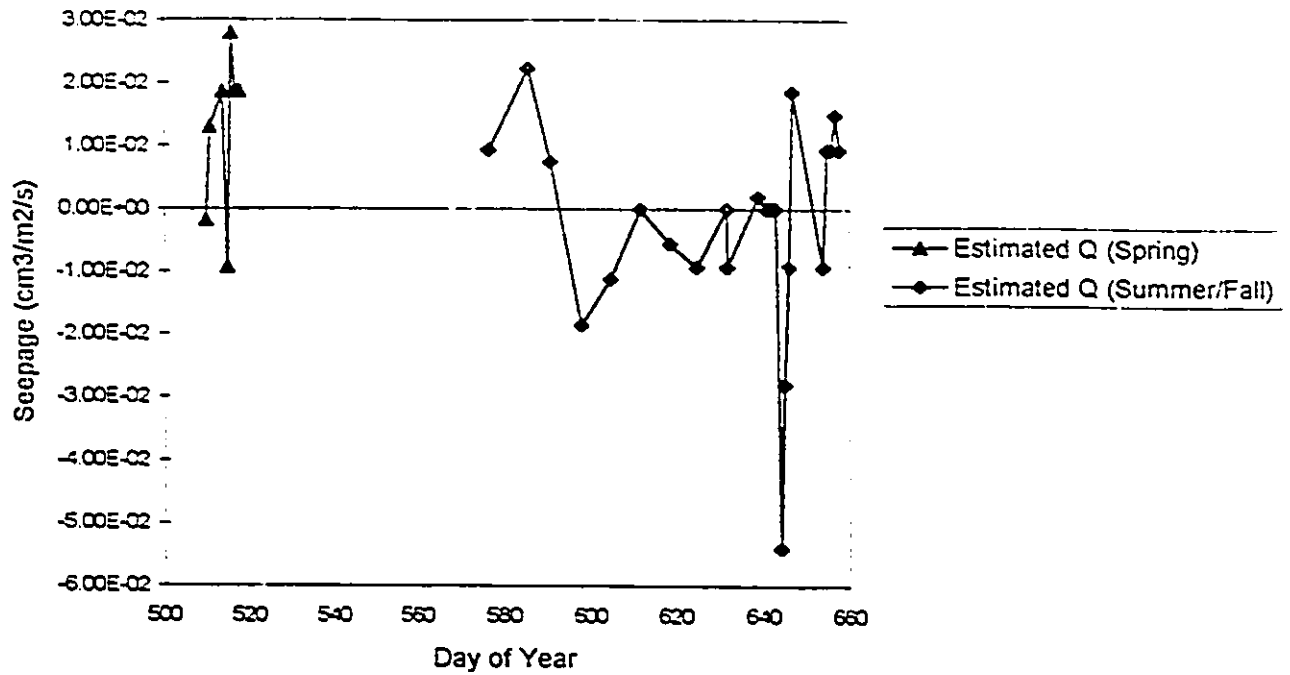
Estimated GW Seepage (1995) Site #5 (Piez #36) 3rd Set

230

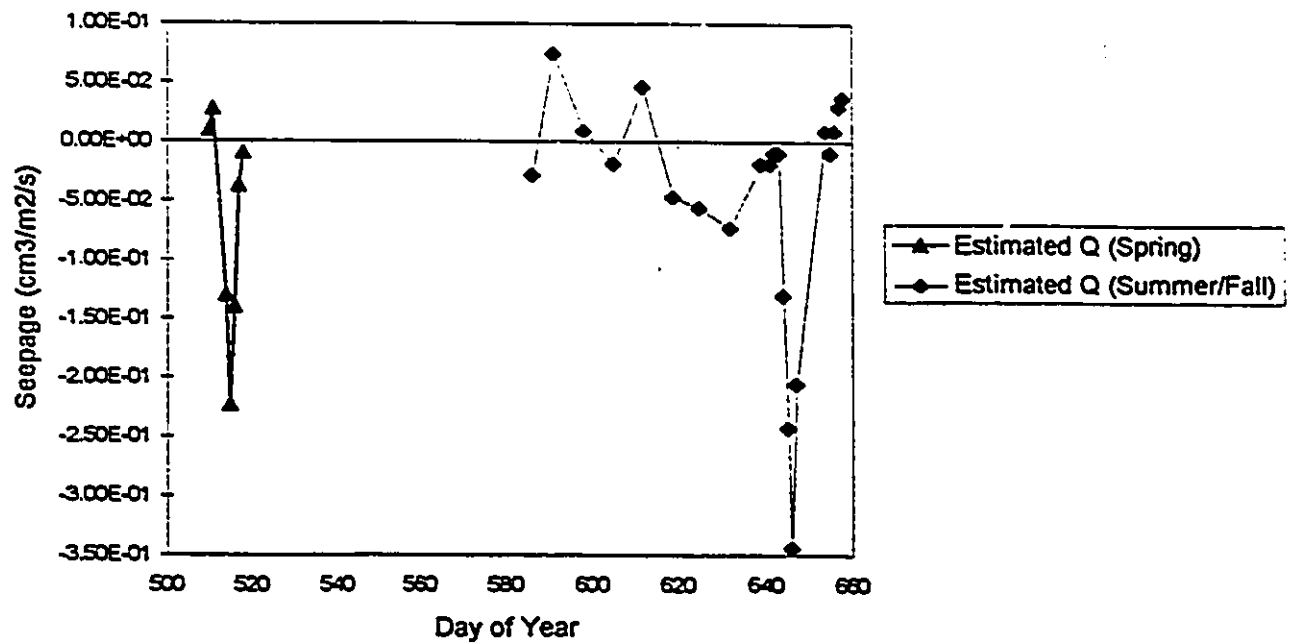


Estimated GW Seepage (1995) Site #5 (Piez #37) 3rd Set



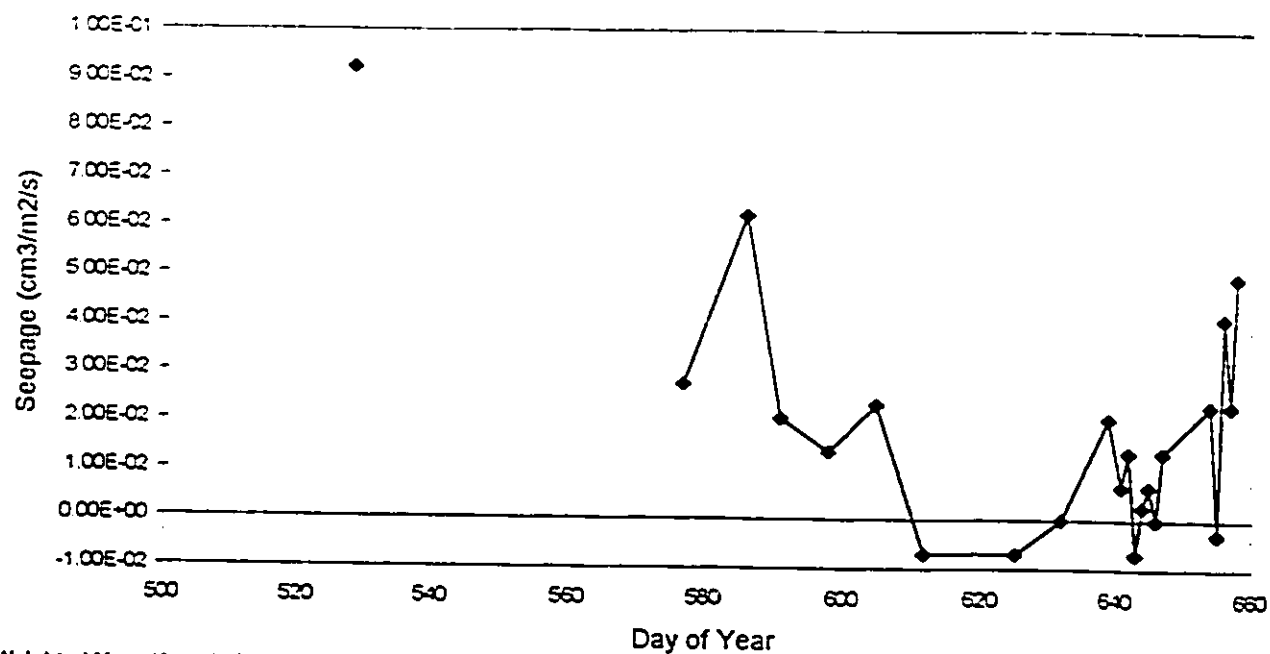


Estimated GW Seepage (1995) Site #5 (Piez #39) 3rd Set

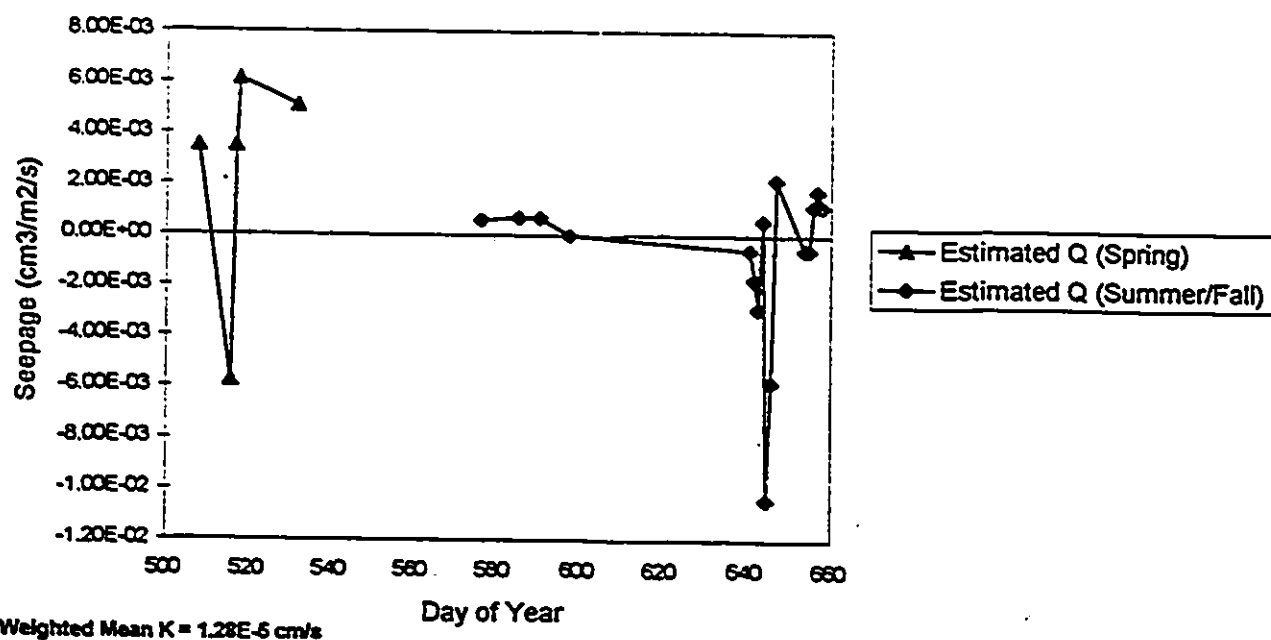


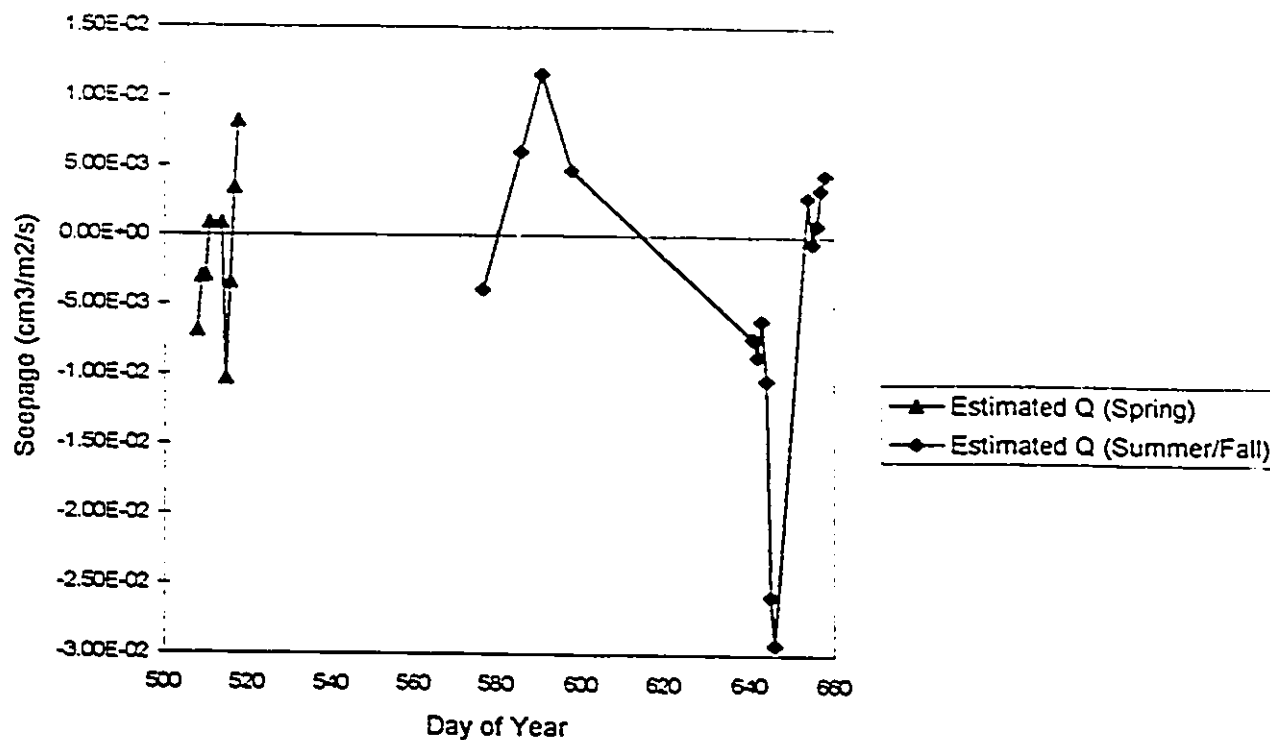
Figures 17 and 18 Estimated GW Seepage (1995) Site #7 (Piez #43)

236

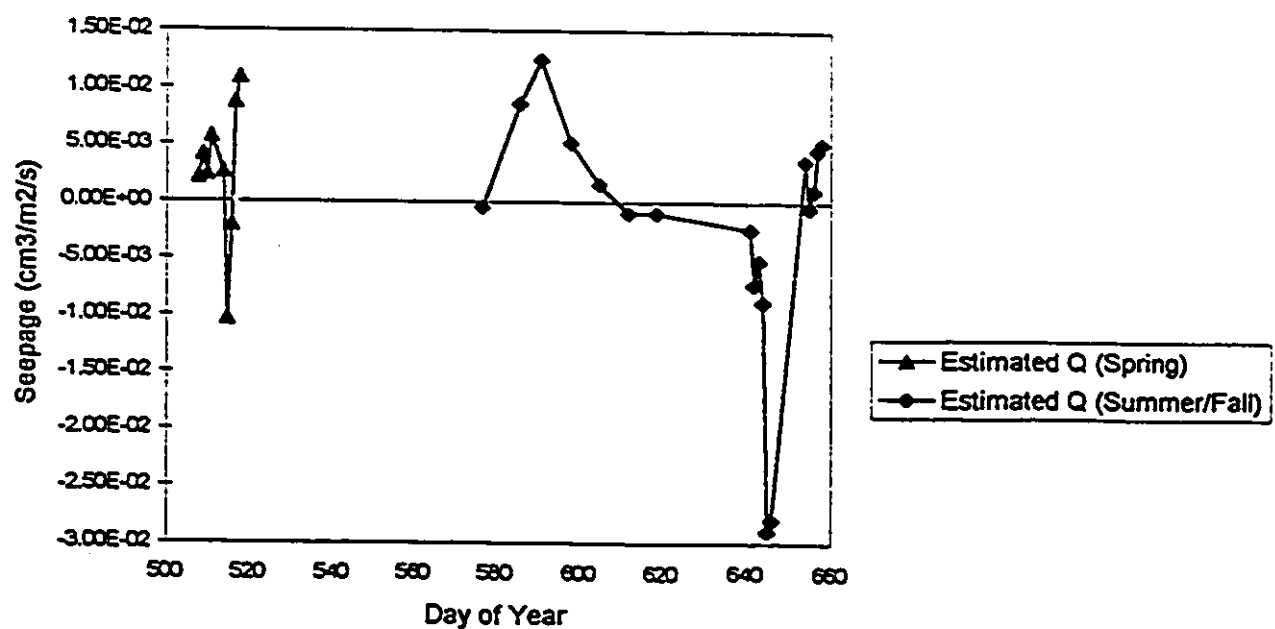


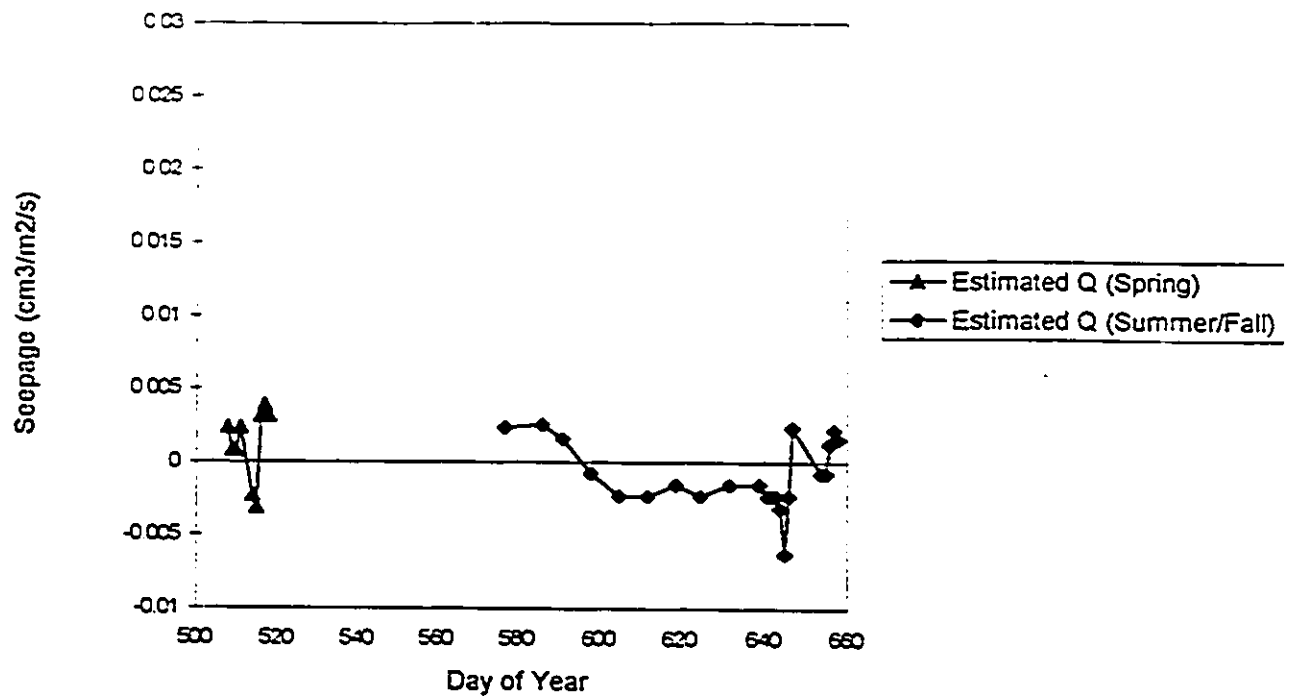
Estimated GW Seepage (1995) Site #7A (Piez #48) 1st Set



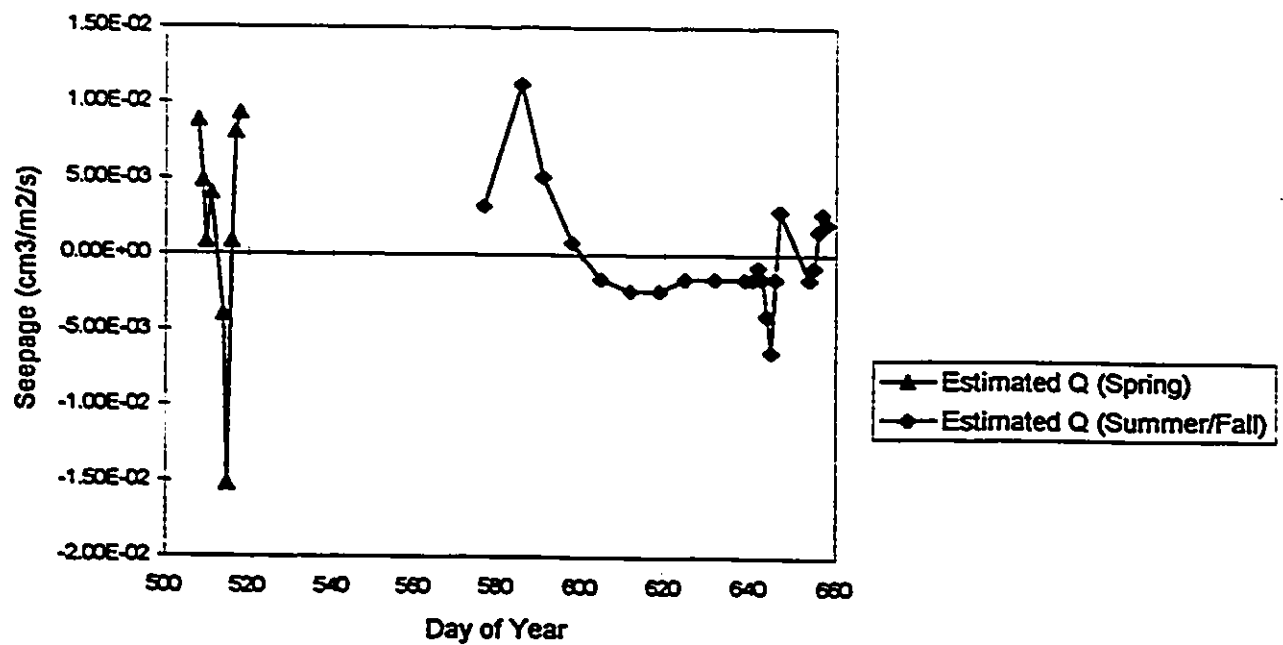


Estimated GW Seepage (1995) Site #7A (Piez #50) 1st Set





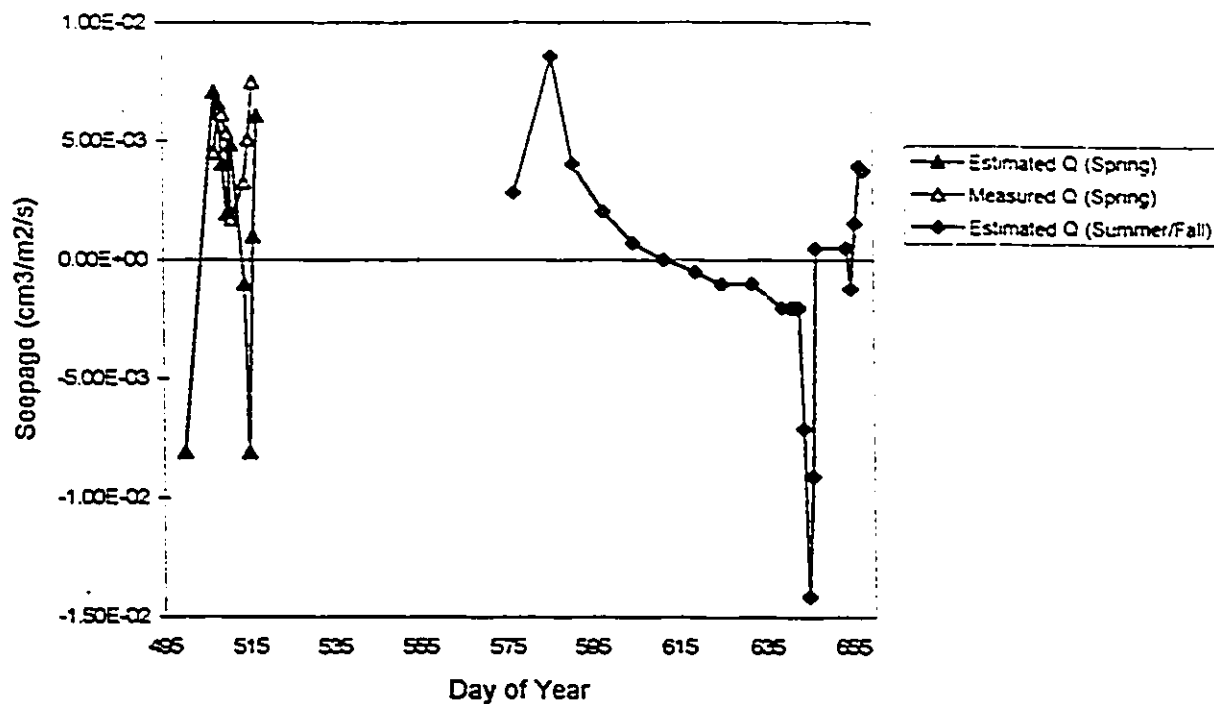
Estimated GW Seepage (1995) Site #7A (Piez #52) 1st Set



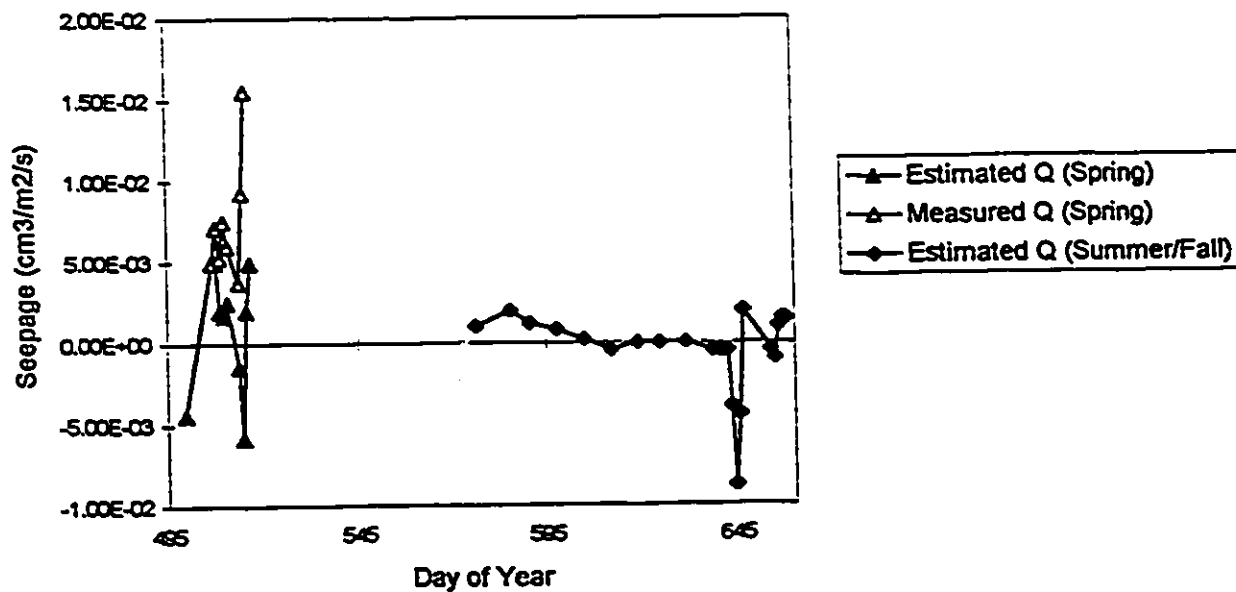
Figures 23 and 24

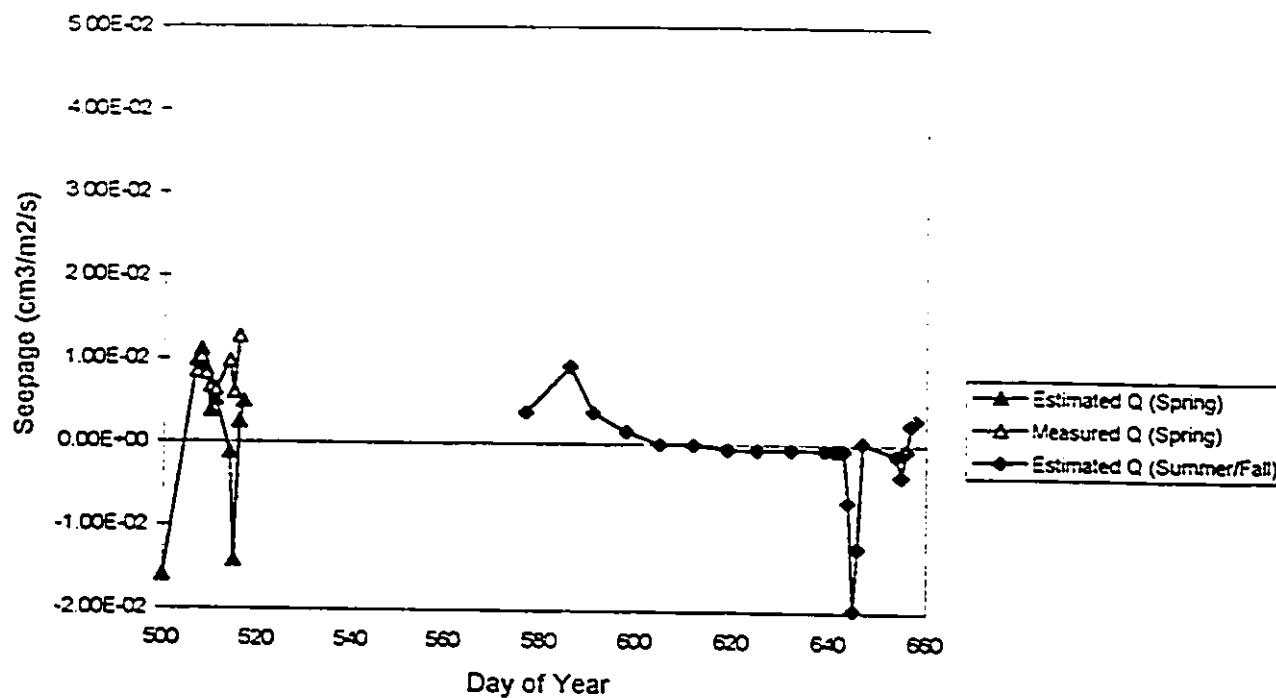
Estimated GW Seepage (1995) Site #7A (Piez #53) 2nd Set

241

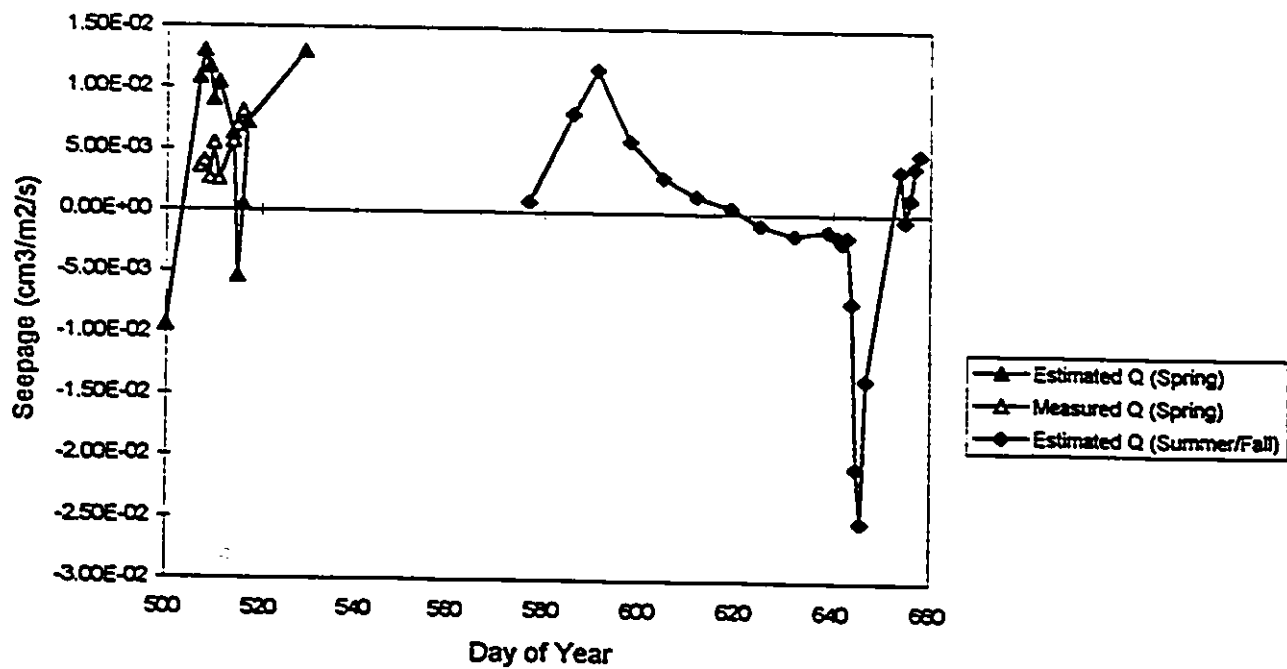


Estimated GW Seepage (1995) Site #7A (Piez #54) 2nd Set

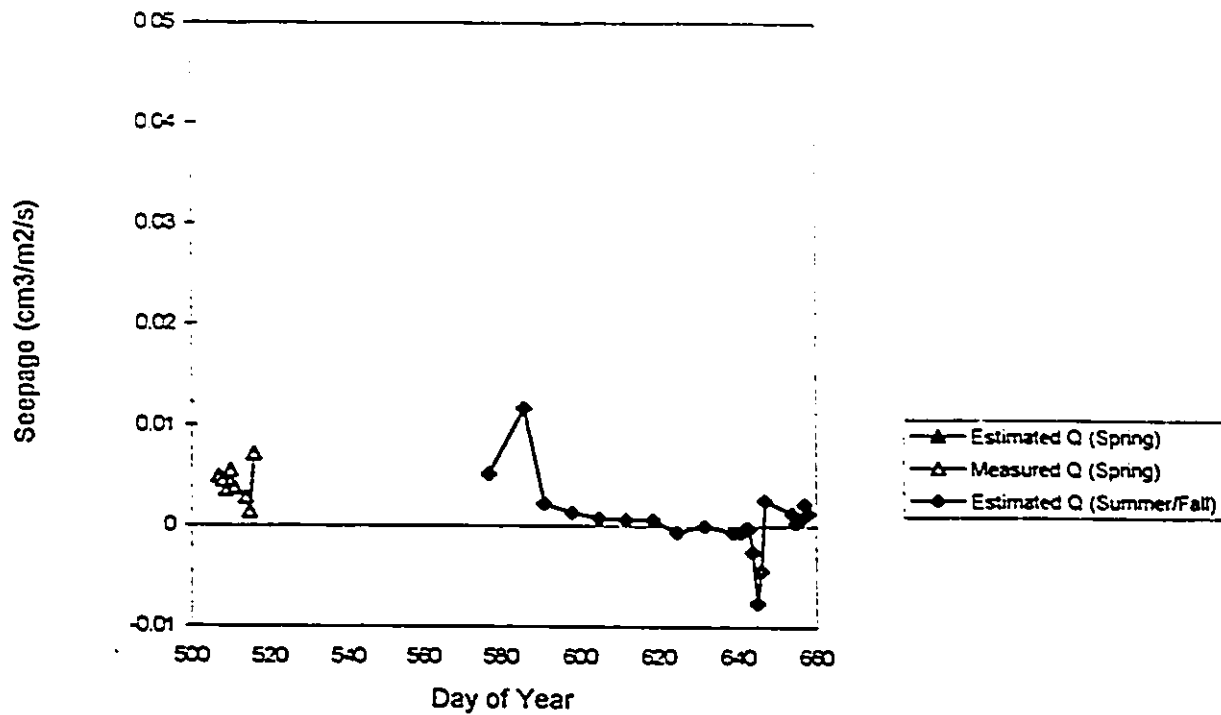




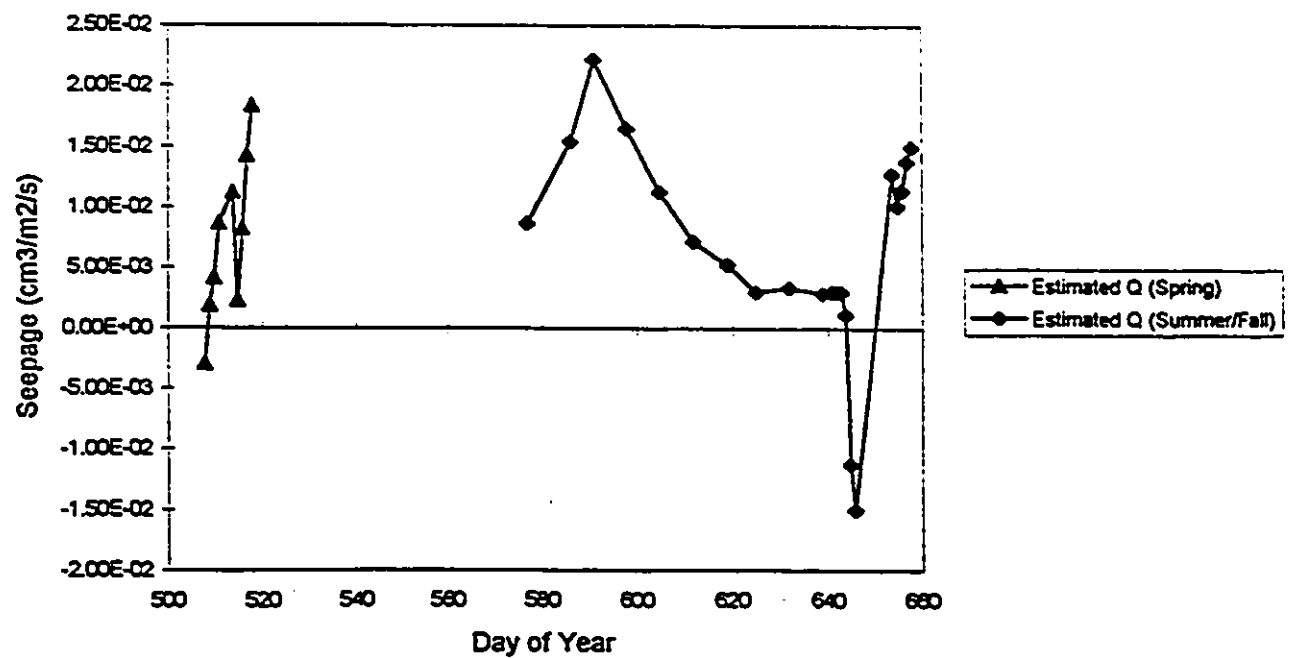
GW Seepage (1995) Site #7A (Piez #56) 2nd Set

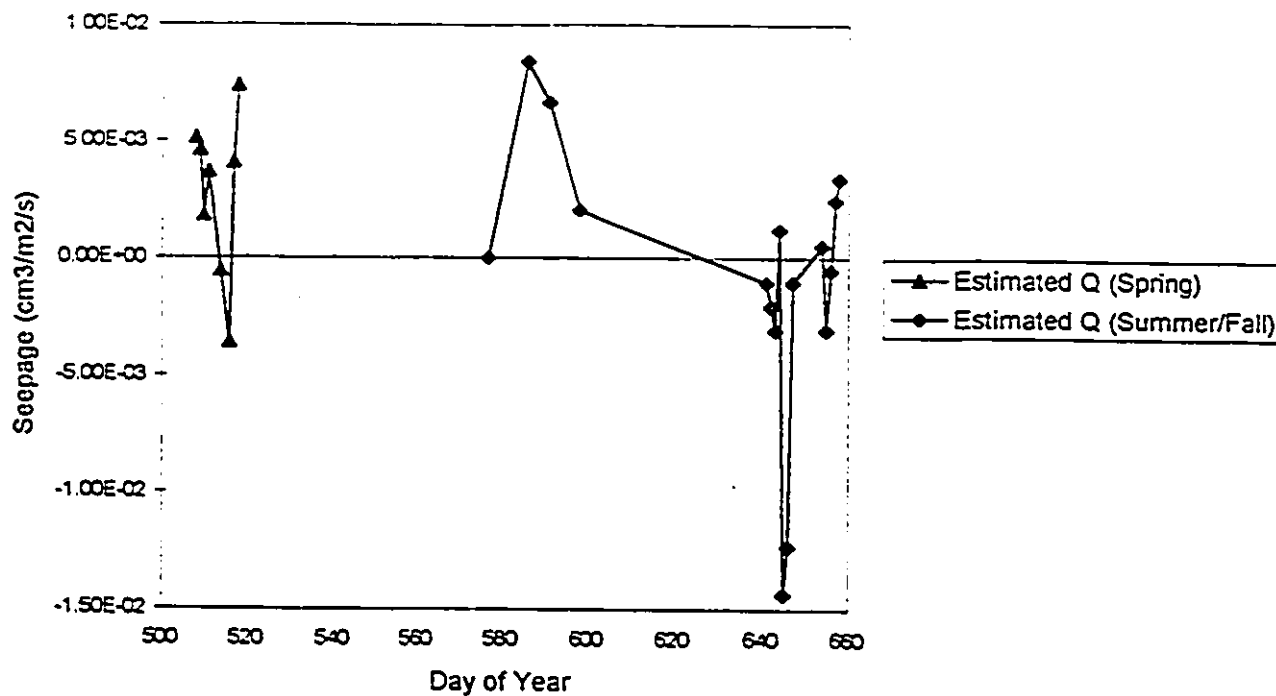


Estimated GW Seepage (1995)
Site #7A (Piez #57) 2nd Set

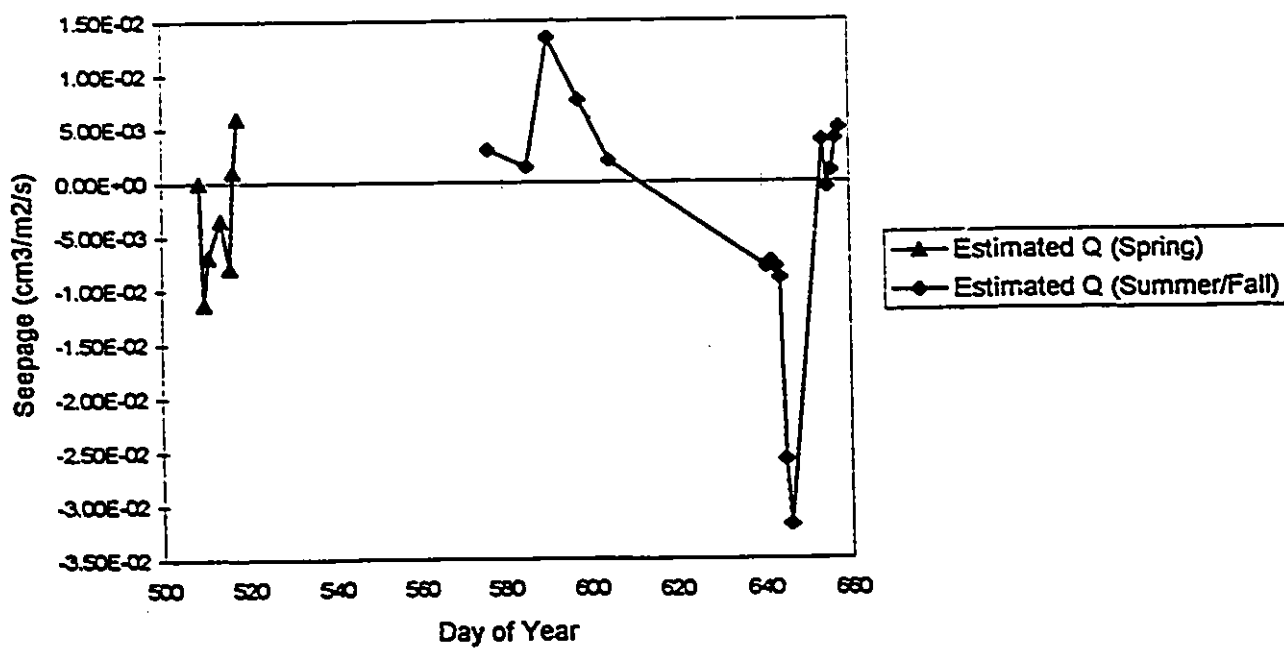


Estimated GW Seepage (1995) Site #7A (Piez #58) 3rd Set





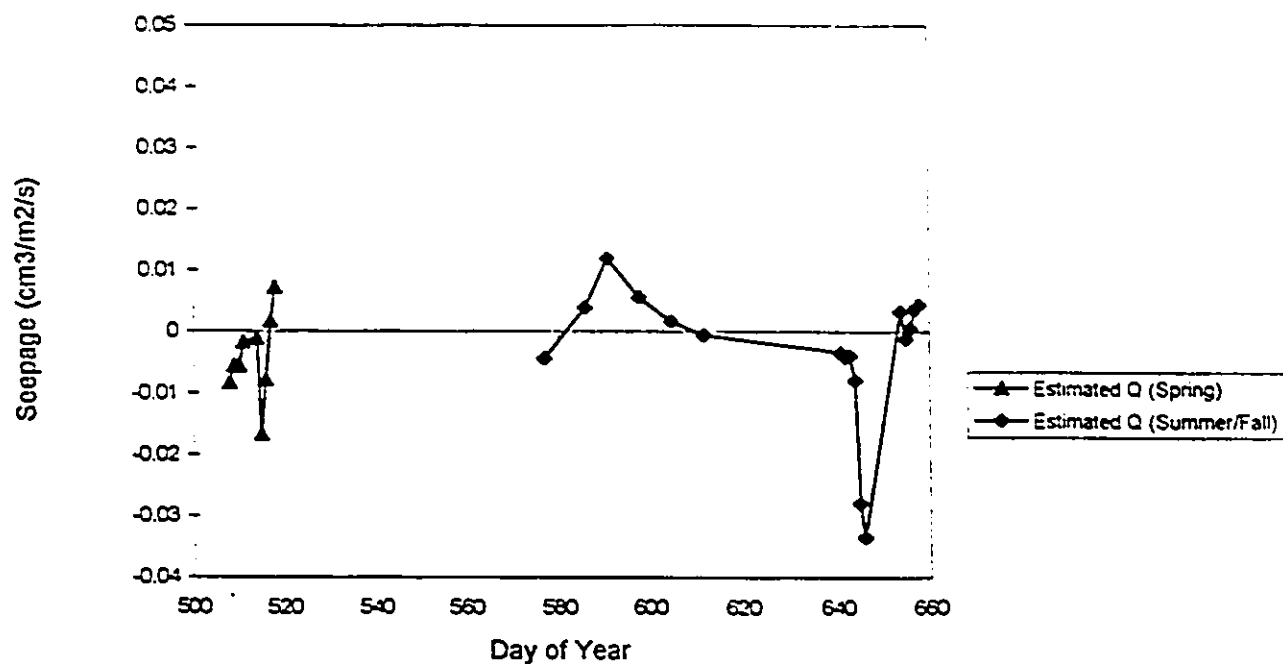
Estimate GW Seepage (1995) Site #7A (Piez #60) 3rd Set



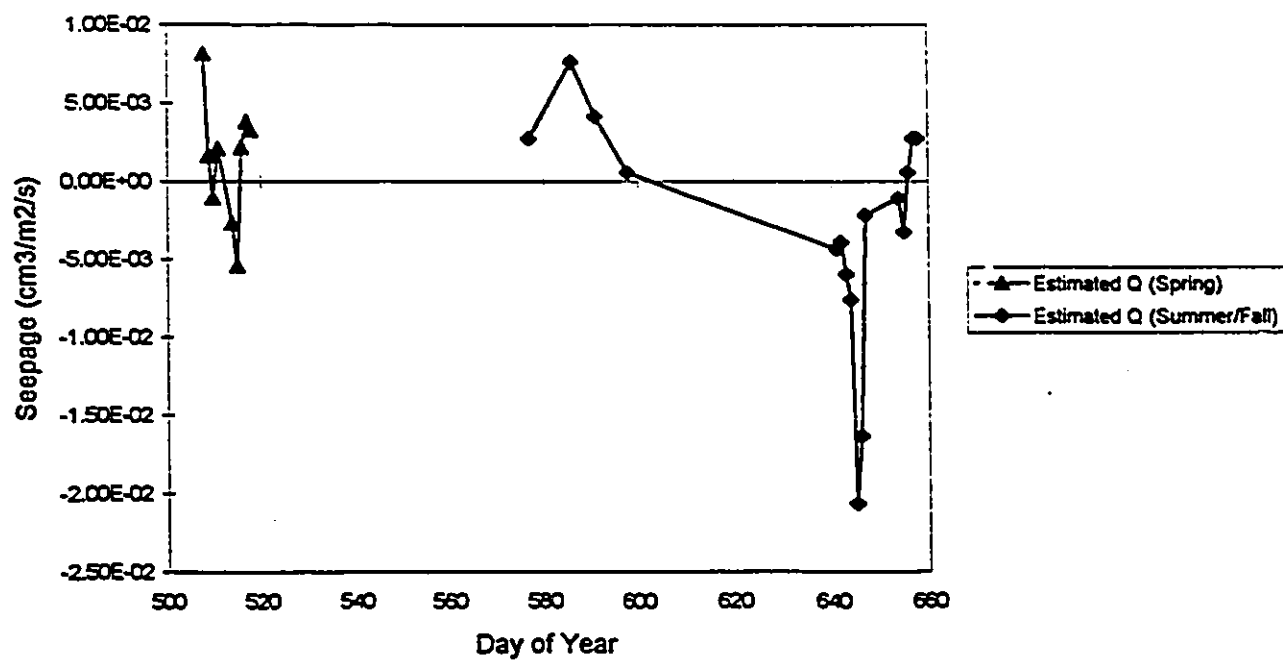
Figures 31 and 32

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

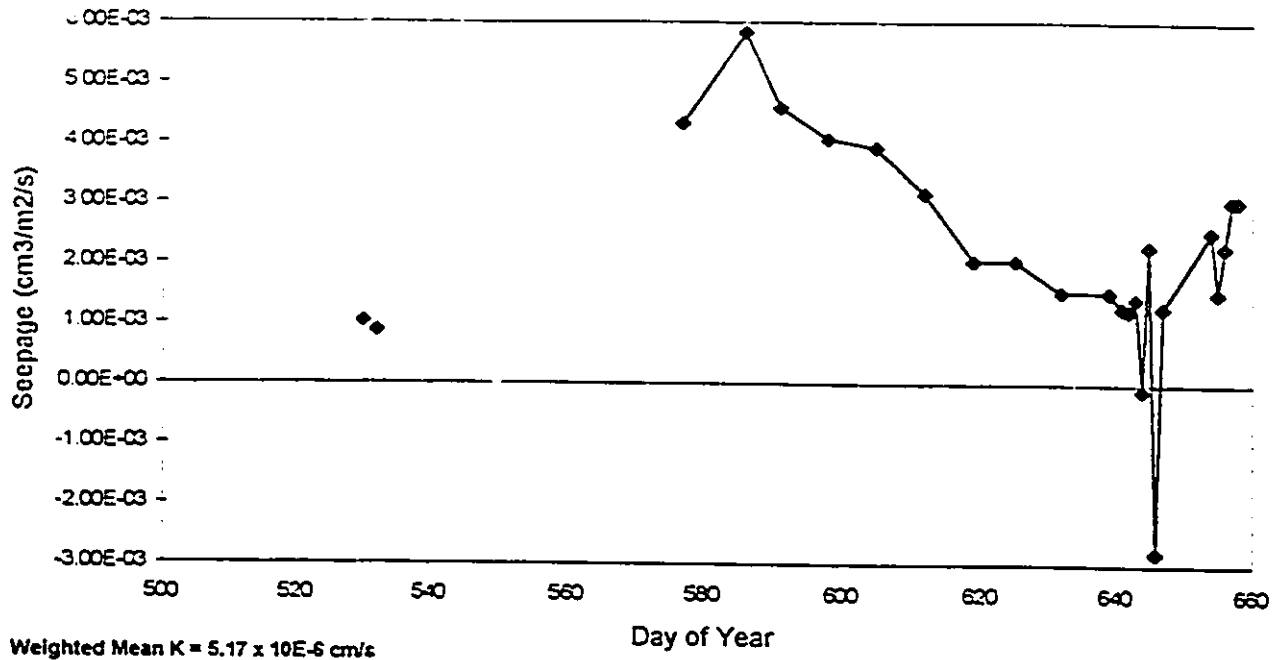
2-45



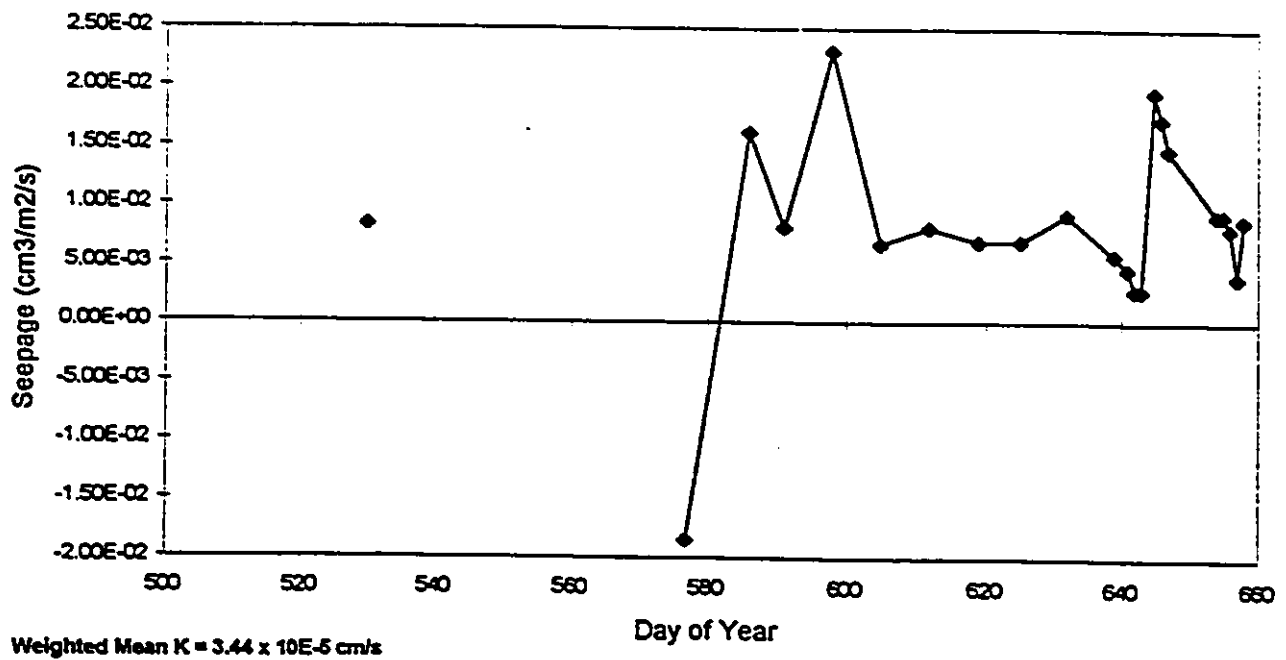
Estimated GW Seepage (1995) Site #7A (Piez #62) 3rd Set



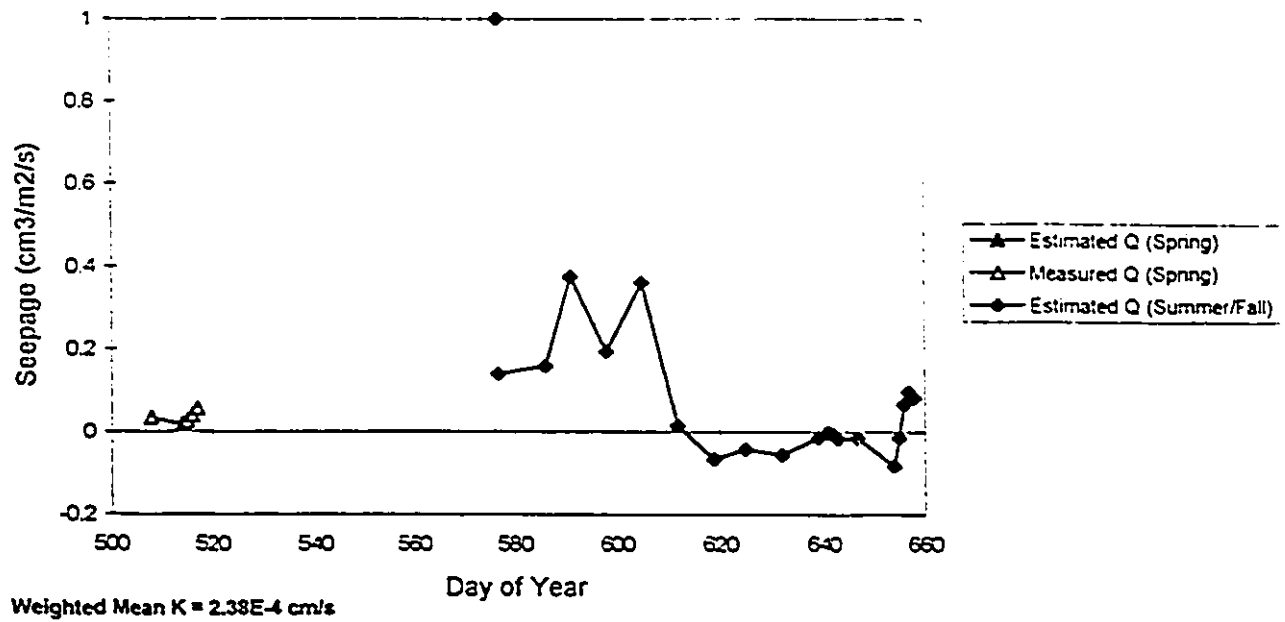
Estimated GW Seepage (1995) Site #8 (Piez #64)



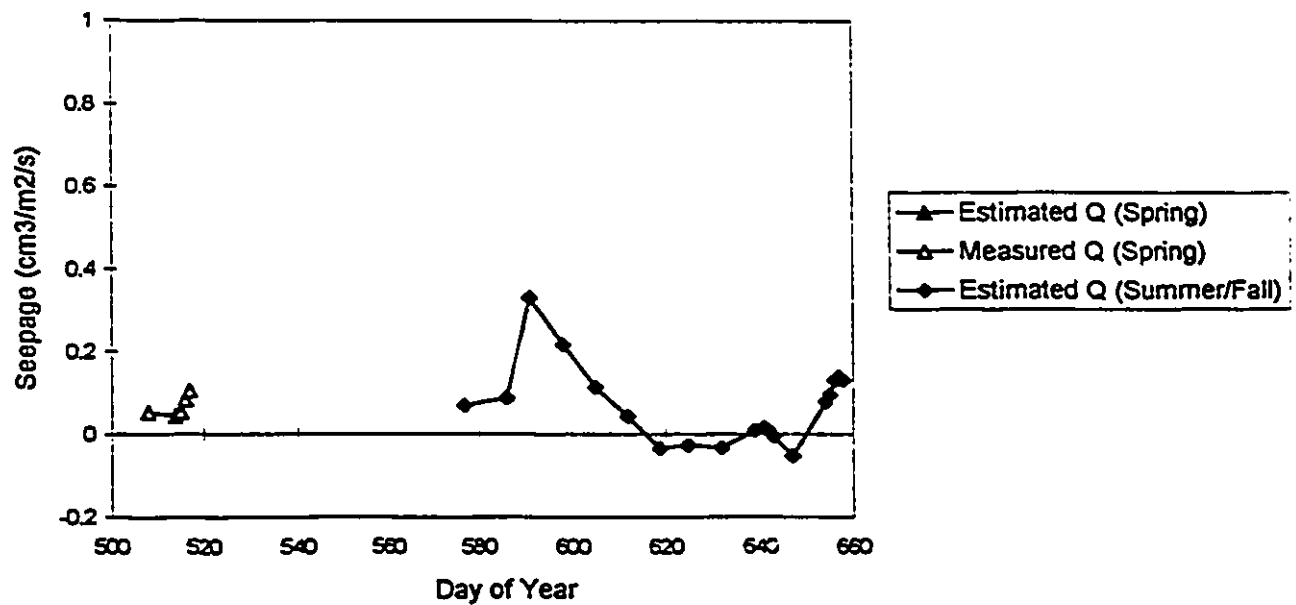
Estimated GW Seepage (1995) Site #12 (Piez #73)



Estimated GW Seepage (1995)
Site #13 (Piez #77)

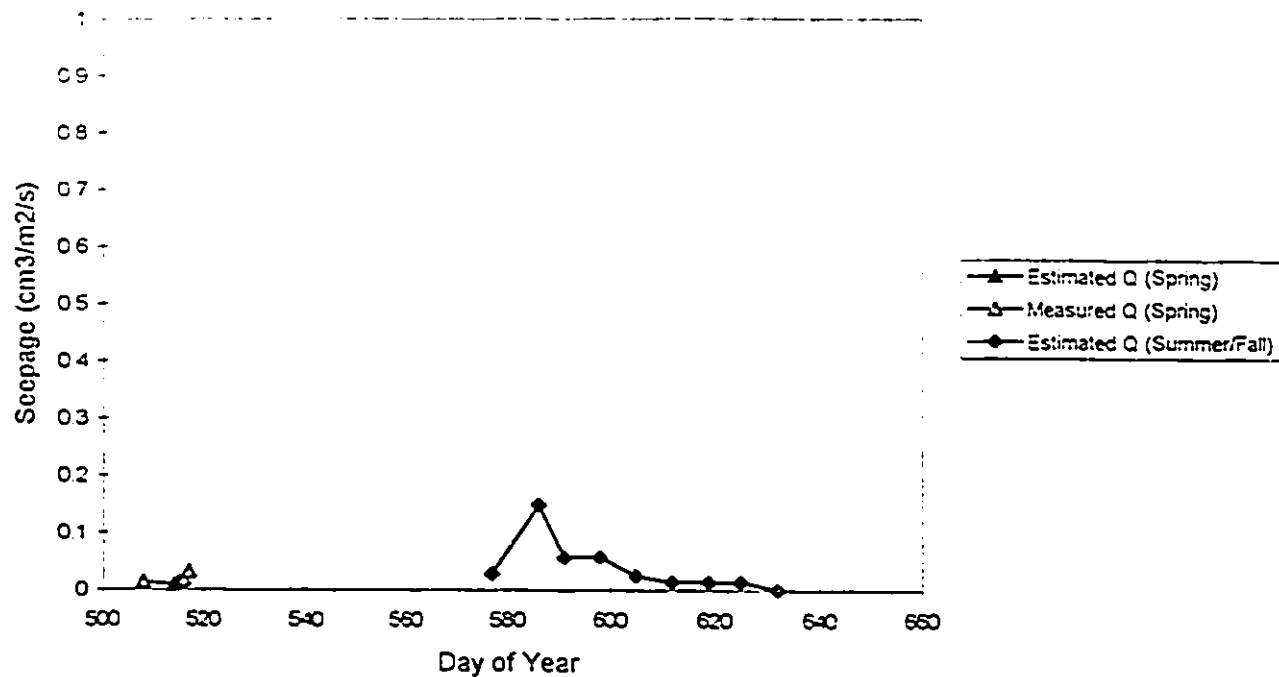


Estimated GW Seepage (1995)
Site #13 (Piez #78)

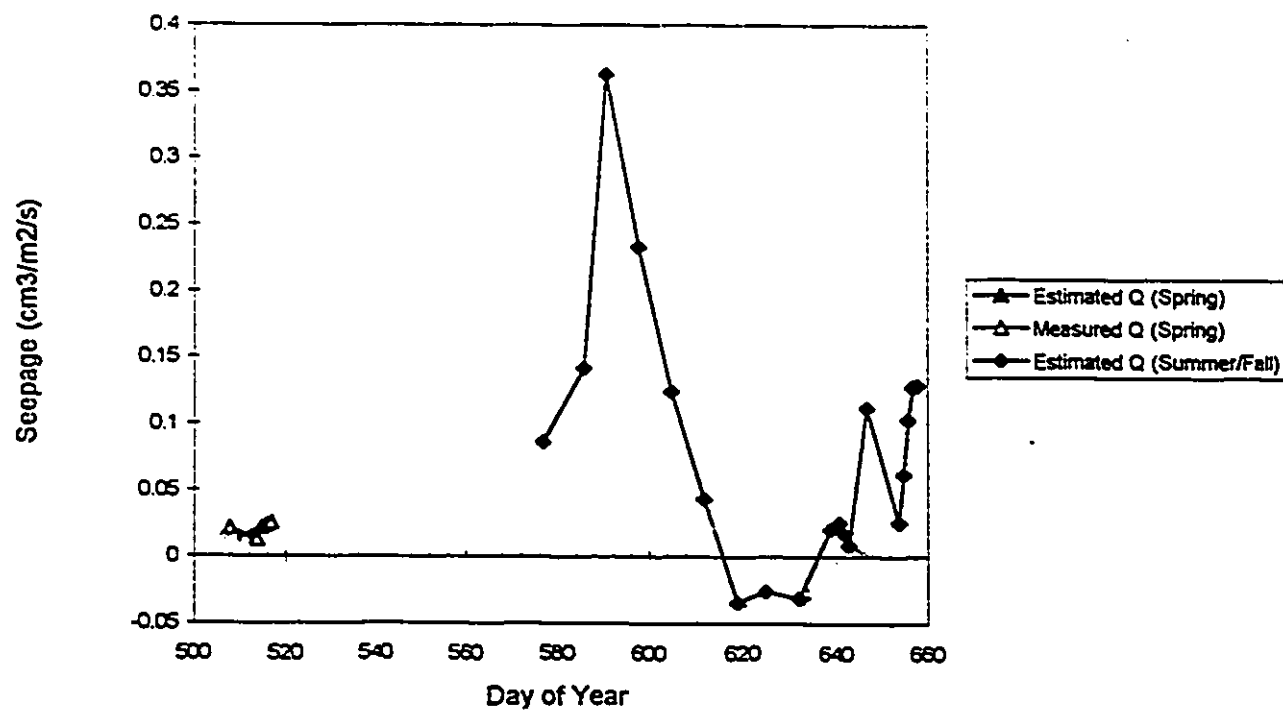


GW Seepage (1995) Site #13 (Piez #79)

245



Estimated GW Seepage (1995) Site #13 (Piez #80)



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	0.63088	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	6.925038	0.003772

ERROR 0.003488 77 0.000046

Site No. 13:

TYPES

DAY

Est

DEP VAR: SEEPAGE N: 25 MULTIPLE R: 0.656 SQUARED MULTIPLE R: 0.430

ANALYSIS OF VARIANCE

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

Seepage Measurements ($\text{m}^3/\text{m}^2\text{s}$) - Spring 1995 Seepage Meters (SM): 1 to 5					
Day ⁵	SM1	SM2	SM3	SM4	SM5
Site no. 5					
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^{-8}
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 hierarchical 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:

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

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 ³ m ⁻² s ⁻¹))							
R1	R2	R3	R4	R5			
0.014	0.010	0.012	0.015	0.022			
UNIVARIATE AND MULTIVARIATE REPEATED MEASURES ANALYSIS							
<u>BETWEEN SUBJECTS</u>							
SOURCE	SS	DF	MS	F	P		
SITES	0.011	2	0.005	7.489	0.010		
ERROR	0.007	10	.729987E-03				
<u>WITHIN SUBJECTS</u>							
SOURCE	SS	DF	MS	F	P	G-G	H-F
temporal	0.001	4	.251027E-03	7.830	.9E-04	0.010	0.005
temporal*SITES	0.002	8	.259956E-03	8.994	.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	.899482E-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
 72.0000000 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
TIMES	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	654 to 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 ($10^{-6} \text{ m}^3 \text{ m}^{-2} \text{ s}^{-1}$) or ($\mu\text{m s}^{-1}$)

h/l = hydraulic gradient (hydraulic head (m)/length (m))

Sample Calculation of K

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

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

$$m = \sqrt{\frac{k_h}{k_v}} \approx 1 \quad (\text{Lee and Cherry (1978)})$$

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:

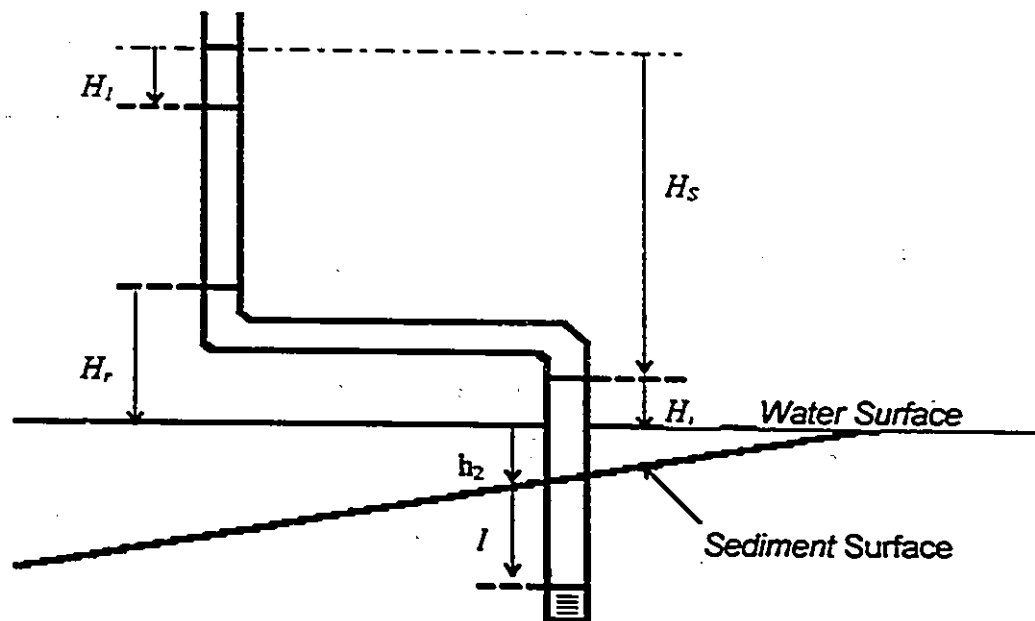


Figure 1. Falling Head Permeameter/Piezometer Apparatus

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 = $H_s + H_r - H_i$

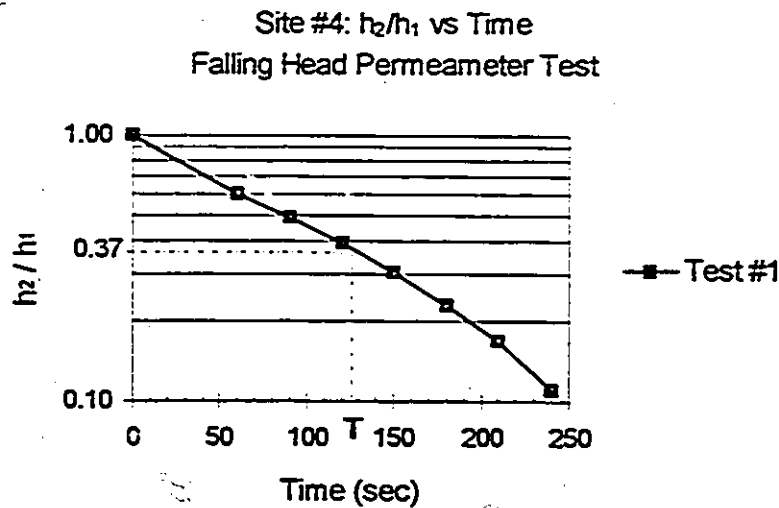


Figure 2 - Sample Plot of Slug Test Data, used to determine Time Lag, T

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,

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

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, $H_f = 142$ cm;

$$h_1 = 152.5 + 47 - 0.5 = 199 \text{ cm}$$

$$h_2 = 152.5 - 142 + 47 - 0.5 = 57 \text{ cm}$$

$$K_h = \frac{(0.5)^2 \ln\left(2 * \frac{1*10}{0.6}\right)}{8*10*(26.41)} * \ln\left(\frac{199}{57}\right) = 5.19 \times 10^{-9} \text{ m s}^{-1}$$

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

$$H_0: \mu_1 = \mu_2$$

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 $\ln K$ measurements 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 :

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

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 PIEZ	DATES BRANCHS	SITE SGEOLS	METHOD K	SETS LNK
-------------	------------------	----------------	-------------	-------------

C:\SYSTATW5\FILES\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

21.000	38.000	24.000	25.000	26.000	27.000
29.000	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: 199 MULTIPLE R: 0.966 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	8.362	8.045	0.1×10^{-14}
ERROR	146.618	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 $1.039 (\ln K)^2 \text{ m s}^{-1}$ 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:

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

where i is the method number. The weight, w , of each K value is 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:

$$\text{Weighted Mean } K = \frac{\sum [(23 \times 10^{-3}) (5)] + [(138 \times 10^{-3}) (3)]}{\sum (5+3)} = 196 \times 10^{-3} \text{ ms}^{-1}$$

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	3.78E-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	til	1.29E-07	-15.86
215	94.08.03	6	1	"2 of 1st"	40	north	til	2.39E-06	-12.94
216	94.08.04	6	1	"3 of 1st"	41	north	til	2.22E-06	-13.02
221	94.08.09	6	1	"1 of 1st"	39	north	til	2.02E-07	-15.41
530	95.06.14	6	2	"3 of 1st"	39	north	til	5.19E-06	-12.17
530	95.06.14	6	2	"3 of 1st"	39	north	til	1.03E-05	-11.48
530	95.06.14	6	2	"3 of 1st"	39	north	til	9.25E-06	-11.59
223	94.08.11	7	1	"1 of 1st"	42	main	til	4.57E-07	-14.60
223	94.08.11	7	1	"2 of 1st"	43	main	til	2.49E-07	-15.21
223	94.08.11	7	1	"3 of 1st"	44	main	til	8.42E-07	-13.99
223	94.08.11	7	1	"4 of 1st"	45	main	til	2.92E-07	-15.05
223	94.08.11	7	1	"5 of 1st"	46	main	til	2.65E-07	-15.14
528	95.06.12	7	2	"1 of 1st"	42	main	til	3.50E-06	-12.56
528	95.06.12	7	2	"1 of 1st"	42	main	til	3.21E-06	-12.65
528	95.06.12	7	2	"1 of 1st"	42	main	til	2.09E-06	-13.08
528	95.06.12	7	2	"1 of 1st"	42	main	til	2.06E-06	-13.09
528	95.06.12	7	2	"1 of 1st"	42	main	til	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

Day	Date	Site	Method	Set	Piez	Branch	Surficial Geology	K (m/s)	LnK (m/s)
507	95.05.22	7.5	1	"4 of 2nd"		55 main	sand/siclay	4.04E-08	-17.02
507	95.05.22	7.5	1	"5 of 2nd"		56 main	sand/siclay	6.73E-08	-16.51
508	95.05.23	7.5	1	"1 of 2nd"		52 main	sand/siclay	1.50E-07	-15.71
508	95.05.23	7.5	1	"2 of 2nd"		53 main	sand/siclay	2.66E-07	-15.14
508	95.05.23	7.5	1	"3 of 2nd"		54 main	sand/siclay	1.33E-07	-15.83
508	95.05.23	7.5	1	"4 of 2nd"		55 main	sand/siclay	4.17E-08	-16.99
508	95.05.23	7.5	1	"5 of 2nd"		56 main	sand/siclay	6.21E-08	-16.59
509	95.05.24	7.5	1	"1 of 2nd"		52 main	sand/siclay	2.64E-07	-15.15
509	95.05.24	7.5	1	"2 of 2nd"		53 main	sand/siclay	3.70E-07	-14.81
509	95.05.24	7.5	1	"3 of 2nd"		54 main	sand/siclay	1.72E-07	-15.58
509	95.05.24	7.5	1	"4 of 2nd"		55 main	sand/siclay	3.24E-08	-17.25
509	95.05.24	7.5	1	"5 of 2nd"		56 main	sand/siclay	8.23E-08	-16.31
510	95.05.25	7.5	1	"1 of 2nd"		52 main	sand/siclay	2.03E-07	-15.41
510	95.05.25	7.5	1	"2 of 2nd"		53 main	sand/siclay	4.65E-07	-14.58
510	95.05.25	7.5	1	"3 of 2nd"		54 main	sand/siclay	1.93E-07	-15.46
510	95.05.25	7.5	1	"4 of 2nd"		55 main	sand/siclay	7.22E-08	-16.44
510	95.05.25	7.5	1	"5 of 2nd"		56 main	sand/siclay	1.58E-07	-15.66
514	95.05.29	7.5	1	"1 of 2nd"		52 main	sand/siclay	4.79E-08	-16.85
514	95.05.29	7.5	1	"2 of 2nd"		53 main	sand/siclay	2.07E-07	-15.39
514	95.05.29	7.5	1	"3 of 2nd"		54 main	sand/siclay	1.05E-07	-16.07
514	95.05.29	7.5	1	"4 of 2nd"		55 main	sand/siclay	7.23E-07	-14.14
514	95.05.29	7.5	1	"5 of 2nd"		56 main	sand/siclay	9.31E-08	-16.19
515	95.05.30	7.5	1	"1 of 2nd"		52 main	sand/siclay	1.18E-07	-15.95
515	95.05.30	7.5	1	"2 of 2nd"		53 main	sand/siclay	2.44E-07	-15.23
515	95.05.30	7.5	1	"3 of 2nd"		54 main	sand/siclay	2.14E-07	-15.36
515	95.05.30	7.5	1	"4 of 2nd"		55 main	sand/siclay	2.91E-07	-15.05
515	95.05.30	7.5	1	"5 of 2nd"		56 main	sand/siclay	7.51E-08	-16.40
516	95.05.31	7.5	1	"1 of 2nd"		52 main	sand/siclay	1.84E-07	-15.51
516	95.05.31	7.5	1	"2 of 2nd"		53 main	sand/siclay	3.02E-07	-15.01
516	95.05.31	7.5	1	"3 of 2nd"		54 main	sand/siclay	2.08E-07	-15.38
516	95.05.31	7.5	1	"4 of 2nd"		55 main	sand/siclay	2.33E-07	-15.27
516	95.05.31	7.5	1	"5 of 2nd"		56 main	sand/siclay	3.73E-08	-17.10
517	95.06.01	7.5	1	"1 of 2nd"		52 main	sand/siclay	1.46E-07	-15.74
517	95.06.01	7.5	1	"2 of 2nd"		53 main	sand/siclay	4.06E-07	-14.72
517	95.06.01	7.5	1	"3 of 2nd"		54 main	sand/siclay	2.41E-07	-15.24
517	95.06.01	7.5	1	"4 of 2nd"		55 main	sand/siclay	1.15E-07	-15.98
517	95.06.01	7.5	1	"5 of 2nd"		56 main	sand/siclay	9.56E-08	-16.16
529	95.06.13	7.5	2	"2 of 2nd"		53 main	sand/siclay	1.16E-07	-15.97
529	95.06.13	7.5	2	"2 of 2nd"		53 main	sand/siclay	2.47E-07	-15.21
529	95.06.13	7.5	2	"2 of 2nd"		53 main	sand/siclay	2.47E-07	-15.21
529	95.06.13	7.5	2	"4 of 2nd"		55 main	sand/siclay	6.04E-09	-18.92
529	95.06.13	7.5	2	"4 of 2nd"		55 main	sand/siclay	6.04E-09	-18.92
532	95.06.16	7.5	2	"1 of 1st"		47 main	sand/siclay	8.43E-08	-16.29
532	95.06.16	7.5	2	"1 of 1st"		47 main	sand/siclay	2.21E-08	-17.63
532	95.06.16	7.5	2	"1 of 1st"		47 main	sand/siclay	2.21E-08	-17.63
243	94.08.31	8	1	"1 of 1st"		62 main	sand/siclay	1.85E-08	-17.75
243	94.08.31	8	1	"2 of 1st"		63 main	sand/siclay	3.43E-07	-14.89
243	94.08.31	8	1	"4 of 1st"		65 main	sand/siclay	5.69E-08	-16.68
251	94.09.08	8	1	"1 of 1st"		62 main	sand/siclay	1.35E-08	-18.12
251	94.09.08	8	1	"2 of 1st"		63 main	sand/siclay	1.52E-07	-15.70
251	94.09.08	8	1	"3 of 1st"		64 main	sand/siclay	3.25E-08	-17.24
251	94.09.08	8	1	"4 of 1st"		65 main	sand/siclay	1.22E-07	-15.92
251	94.09.08	8	1	"5 of 1st"		66 main	sand/siclay	2.90E-08	-17.35
586	95.08.09	8	2	"2 of 1st"		63 main	sand/siclay	2.28E-08	-17.60
586	95.08.09	8	2	"2 of 1st"		63 main	sand/siclay	2.28E-08	-17.60
586	95.08.09	8	2	"2 of 1st"		63 main	sand/siclay	2.28E-08	-17.60
293	94.10.20	11	1	"3 of 1st"		69 south	strsnd/siclay	6.24E-07	-14.29
293	94.10.20	11	1	"4 of 1st"		70 south	strsnd/siclay	6.24E-07	-14.29
293	94.10.20	11	1	"5 of 1st"		71 south	strsnd/siclay	8.65E-07	-13.96
530	95.06.14	11	2	"3 of 1st"		67 south	strsnd/siclay	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/siclay	6.45E-08	-16.56
530	95.06.14	11		2 "3 of 1st"		67 south	strsnd/siclay	6.45E-08	-16.56
293	94.10.20	12		1 "1 of 1st"		72 south	mclay/silt	7.9E-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	95.05.29	13		1 "3 of 4"		79 south	strsnd/siclay	1.21E-06	-13.62
508	95.05.29	13		1 "1 of 4"		77 south	strsnd/siclay	2.81E-07	-15.09
508	95.05.29	13		1 "2 of 4"		78 south	strsnd/siclay	7.54E-07	-14.10
508	95.05.29	13		1 "3 of 4"		79 south	strsnd/siclay	1.22E-06	-13.62
508	95.05.29	13		1 "4 of 4"		80 south	strsnd/siclay	6.27E-07	-14.28
508	95.05.29	13		1 "1 of 4"		77 south	strsnd/siclay	1.94E-06	-13.15
508	95.05.29	13		1 "2 of 4"		78 south	strsnd/siclay	3.99E-06	-12.43
508	95.05.29	13		1 "3 of 4"		79 south	strsnd/siclay	8.60E-07	-13.97
508	95.05.29	13		1 "4 of 4"		80 south	strsnd/siclay	1.86E-07	-15.50
515	95.05.30	13		1 "1 of 4"		77 south	strsnd/siclay	9.59E-07	-13.86
515	95.05.30	13		1 "2 of 4"		78 south	strsnd/siclay	2.13E-06	-13.06
515	95.05.30	13		1 "3 of 4"		79 south	strsnd/siclay	2.15E-06	-13.05
515	95.05.30	13		1 "4 of 4"		80 south	strsnd/siclay	8.27E-07	-14.01
515	95.05.30	13		1 "1 of 4"		77 south	strsnd/siclay	6.43E-06	-11.95
515	95.05.30	13		1 "2 of 4"		78 south	strsnd/siclay	1.72E-06	-13.27
515	95.05.30	13		1 "3 of 4"		79 south	strsnd/siclay	3.51E-07	-14.86
516	95.05.31	13		1 "1 of 4"		77 south	strsnd/siclay	8.54E-06	-11.67
516	95.05.31	13		1 "2 of 4"		78 south	strsnd/siclay	5.82E-06	-12.05
516	95.05.31	13		1 "3 of 4"		79 south	strsnd/siclay	8.68E-07	-13.96
516	95.05.31	13		1 "4 of 4"		80 south	strsnd/siclay	5.85E-07	-14.35
516	95.05.31	13		1 "1 of 4"		77 south	strsnd/siclay	5.86E-07	-14.35
516	95.05.31	13		1 "2 of 4"		78 south	strsnd/siclay	3.67E-06	-12.52
516	95.05.31	13		1 "3 of 4"		79 south	strsnd/siclay	4.69E-07	-14.57
516	95.05.31	13		1 "4 of 4"		80 south	strsnd/siclay	2.78E-07	-15.10
517	95.06.01	13		1 "1 of 4"		77 south	strsnd/siclay	1.25E-06	-13.59
517	95.06.01	13		1 "2 of 4"		78 south	strsnd/siclay	5.69E-06	-12.08
517	95.06.01	13		1 "3 of 4"		79 south	strsnd/siclay	1.09E-06	-13.73
517	95.06.01	13		1 "4 of 4"		80 south	strsnd/siclay	5.12E-07	-14.48
517	95.06.01	13		1 "1 of 4"		77 south	strsnd/siclay	1.15E-06	-13.68
517	95.06.01	13		1 "2 of 4"		78 south	strsnd/siclay	7.18E-06	-11.84
517	95.06.01	13		1 "3 of 4"		79 south	strsnd/siclay	7.43E-07	-14.11
517	95.06.01	13		1 "4 of 4"		80 south	strsnd/siclay	5.50E-07	-14.41
532	95.06.16	13		2 "3 of 4"		79 south	strsnd/siclay	4.39E-06	-12.34
532	95.06.16	13		2 "3 of 4"		79 south	strsnd/siclay	5.16E-06	-12.17
532	95.06.16	13		2 "3 of 4"		79 south	strsnd/siclay	1.42E-05	-11.16
532	95.06.16	13		2 "3 of 4"		79 south	strsnd/siclay	2.65E-06	-12.84
532	95.06.16	13		2 "3 of 4"		79 south	strsnd/siclay	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 as 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:

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

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

$$Q_{tp} = \int_0^{\infty} Q_o dt = \frac{K_1 K_2}{2.3}$$

where Q = river discharge, K = recession constant

($K_1 = Q$ at $t = 0$ (or Q_o); and $K_2 = t$, when $Q = 0.1K_1$)

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 ($\text{m}^3 \text{s}^{-1}$), 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_p 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):

$$AGD = \int_0^t Q_o dt = \left[\left(\frac{Q_o t_1}{2.3} \right) - \left(\frac{-\frac{Q_o t_1}{2.3}}{10^{1/4}} \right) \right]$$

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

$$BS = (Q_p - AGD)_{\text{At end of recession}}$$

Groundwater recharge (GR) between recessions is calculated by subtracting *baseflow storage* from the previous recession from Q_p .

$$GR = Q_p - BS$$

A5.2 Sample Calculations

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

The *total potential groundwater discharge*, Q_p is:

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

Actual Groundwater Discharge (AGD) is:

$$AGD = (5.259 \times 10^6) - \frac{5.259 \times 10^6}{10^{\frac{96}{756}}} = 5.157 \times 10^6 \text{ m}^3$$

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

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

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

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

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 m². The *actual groundwater discharge* (AGD , calculated in section A5.2, above) was divided by the *total area* to obtain an estimate of seepage flux, q (the groundwater discharge per unit area, A , of the river bed, per unit time, t):

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

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)

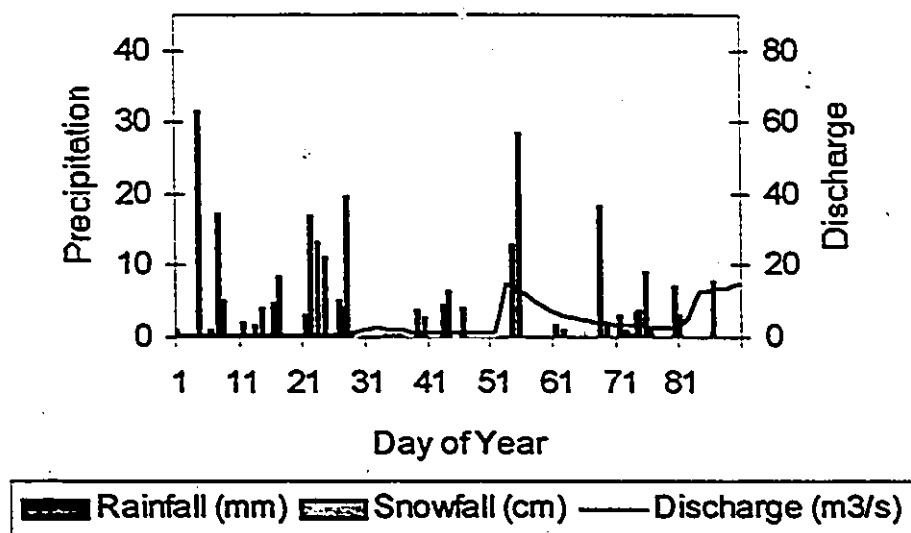


Figure 1.

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

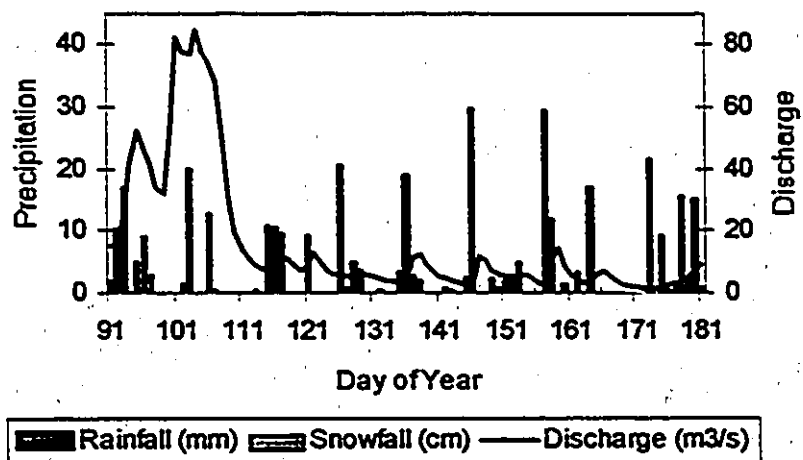


Figure 2.

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

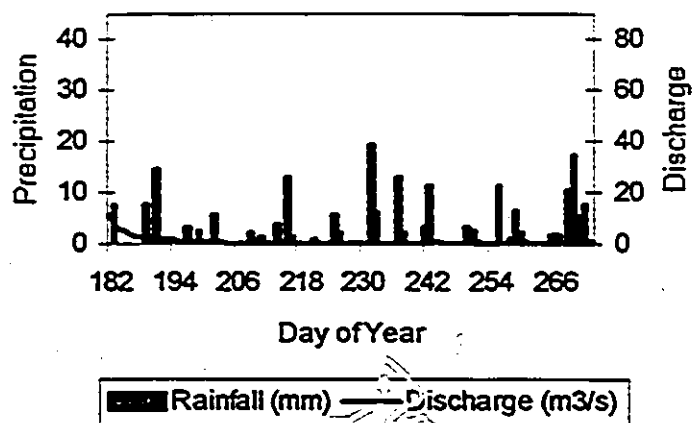


Figure 3.

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

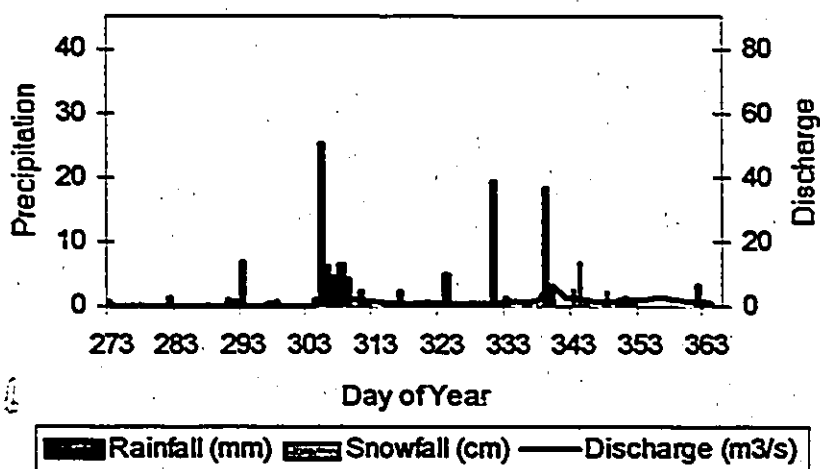


Figure 4.

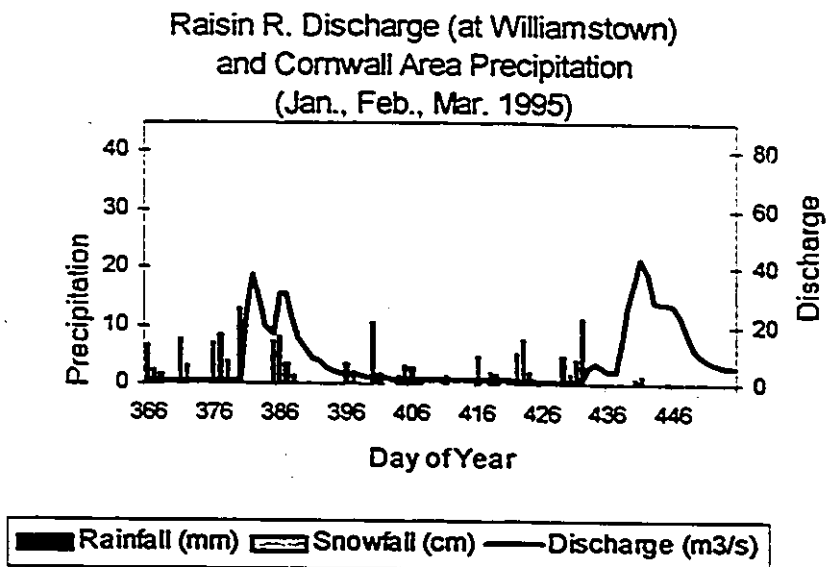


Figure 5.

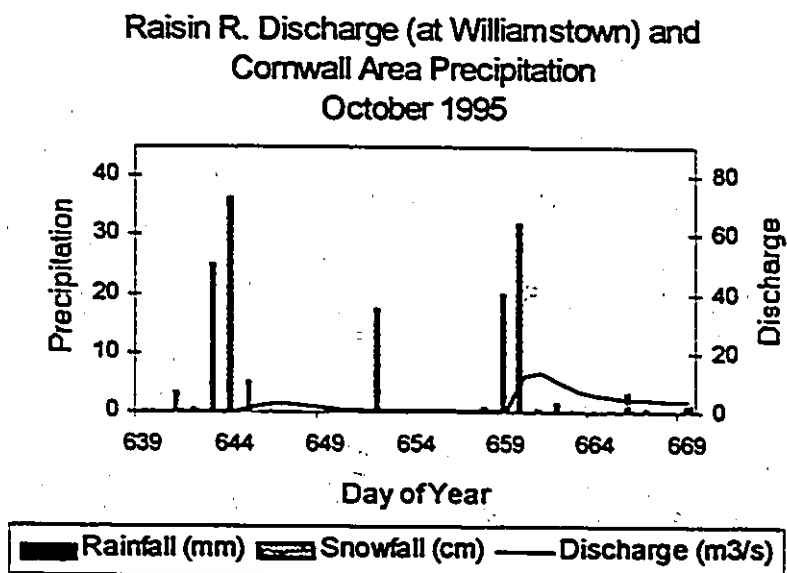


Figure 6.

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)

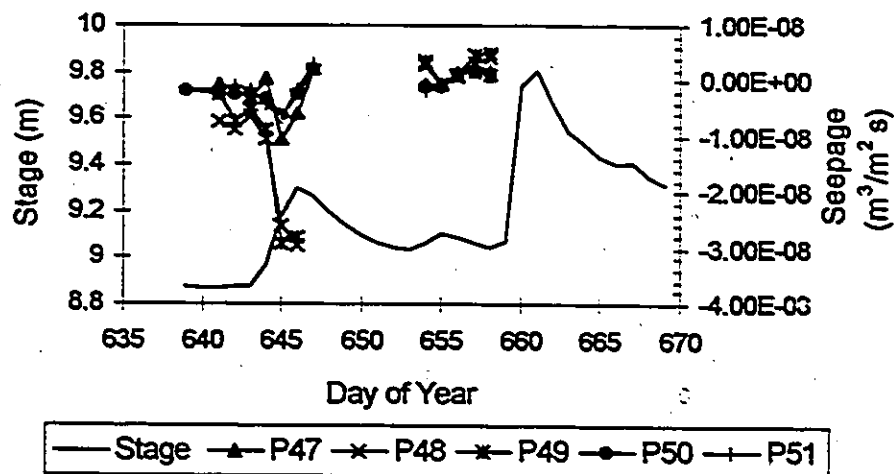


Figure 7.

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

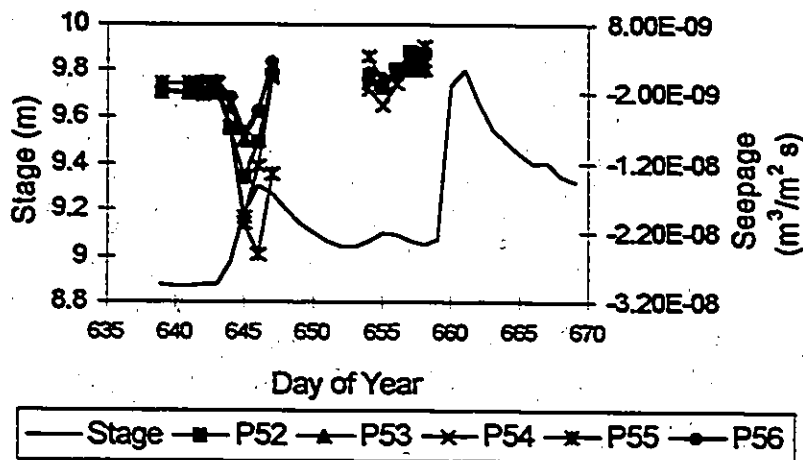


Figure 8.

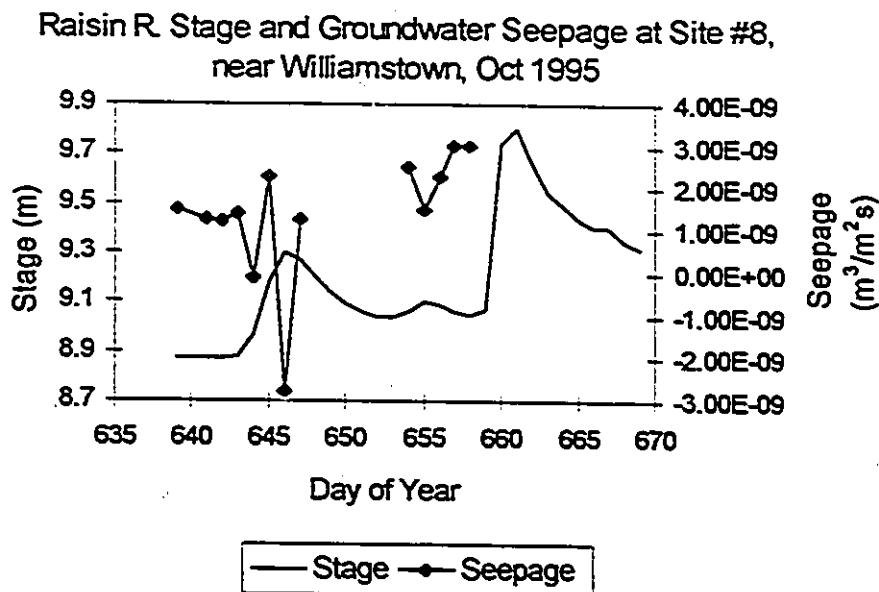


Figure 9.

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 $0.045 \text{ m}^3 \text{ s}^{-1}$ 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.

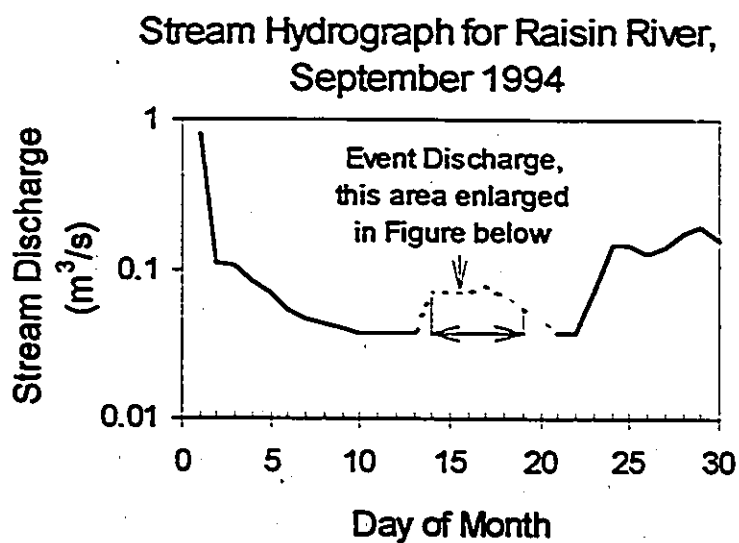


Figure 10. Stream Hydrograph of Raisin River Discharge, September 1994

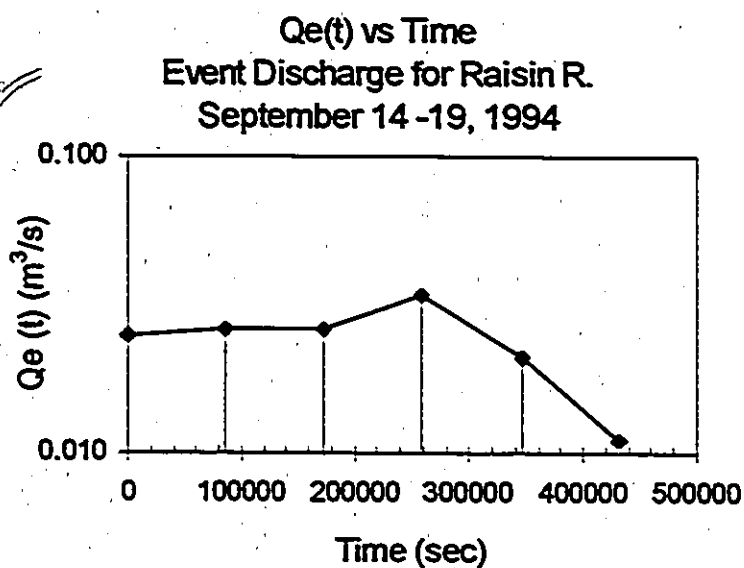


Figure 11. Event Discharge (t) vs. t for September 14, 1995 Storm Event

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 $\pm 0.10\%$ (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 $\pm 1.5\%$ (equal to 2s).

For example:

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

where M = slope and B = intercept

A6.3 References

Clark, I., Fritz, P., (1997); Environmental Isotopes in Hydrogeology, In Press, CRC Lewis, pp. 325.

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 represents 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
289	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	-68.5
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
	258/94.09.16	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	-11.07	-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
	268/94.09.23	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
	218/94.08.03	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	-66.8
	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

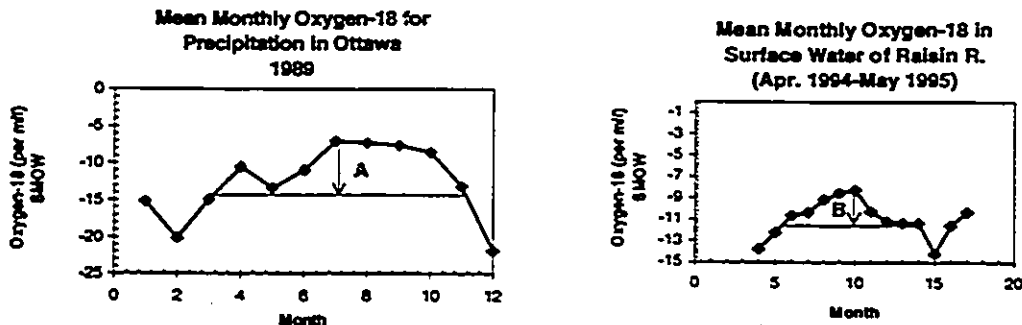


Figure 1. and 2. Amplitudes of Oxygen-18 Curves for Precipitation and Surface Water

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

Pearce et al. (1986):

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

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.

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

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

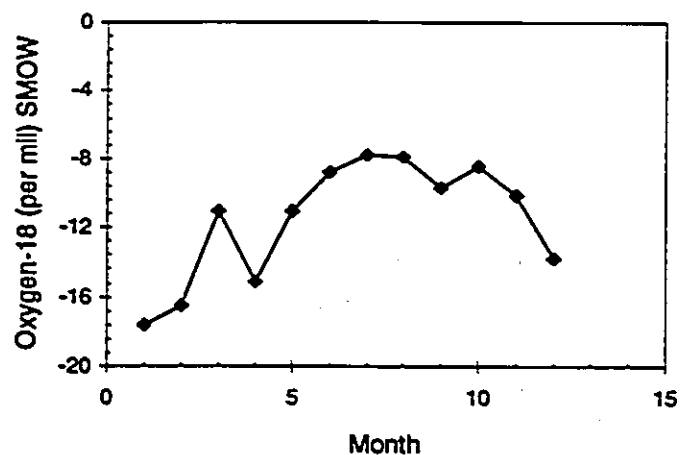
Table 1. Monthly Isotope Values for Precipitation in Ottawa, 1989 to 1994

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

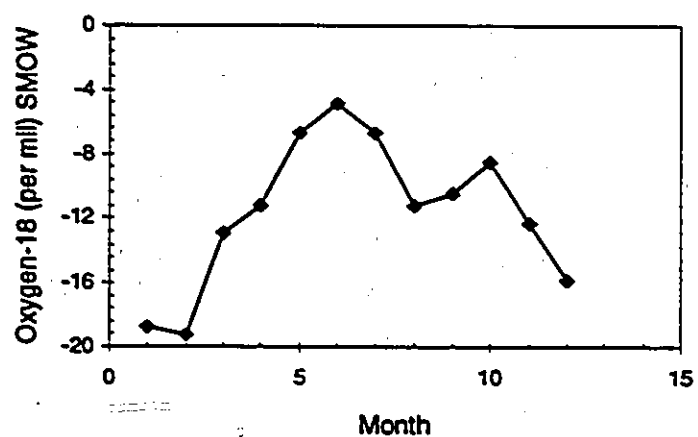
Year	Month	Precip (mm)	Oxygen-18 (per mil)	Deuterium (per mil)
1992	1	61.0	-17.21	-122.2
1992	2	78.2	-18.80	-134.6
1992	3	97.6	-15.50	-107.2
1992	4	51.4	-16.04	-122.3
1992	5	63.8	-8.21	-53.8
1992	6	57.8	-8.88	-61.3
1992	7	186.3	-10.05	-71.2
1992	8	105.0	-8.04	-62.3
1992	9	76.6	-7.01	-41.1
1992	10	48.8	-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)

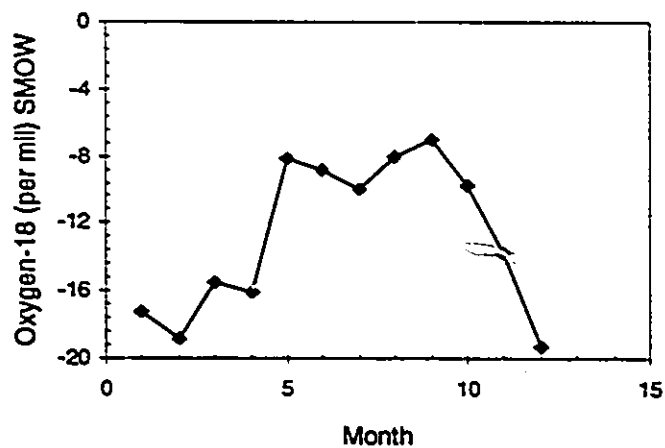
Mean Monthly Oxygen-18 in Precipitation
Ottawa, 1990



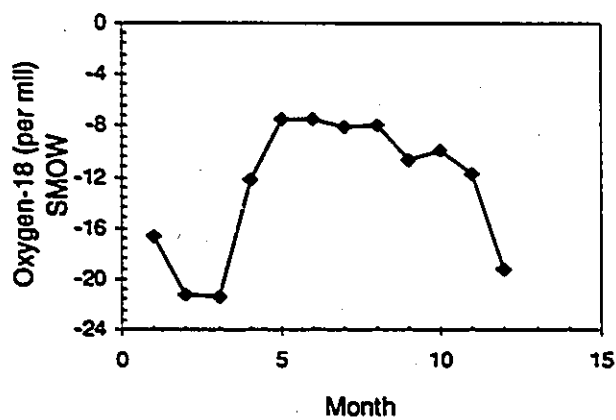
Mean Monthly Oxygen-18 in Precipitation
Ottawa, 1991



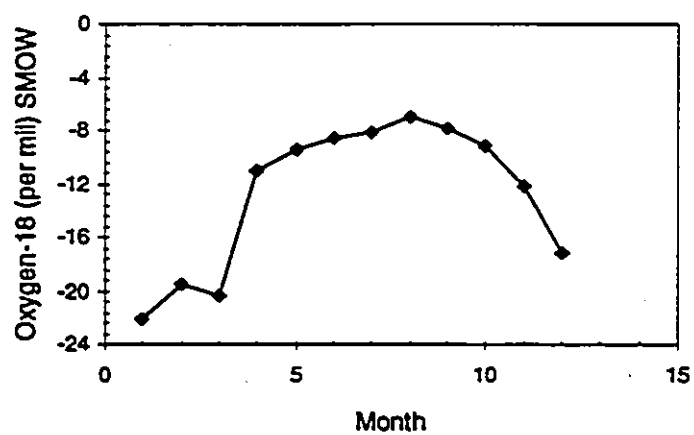
Mean Monthly Oxygen-18 in Precipitation
Ottawa, 1992



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:

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

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	TYPES
-----	---	-----------	------	-------

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					

TYPES

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
TYPES	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
TYPES
    D          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
TYPES	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	-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: DELTA180 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: DELTA180 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	2.0234	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 ($m^3 s^{-1}$)

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:

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

Therefore,

$$\frac{Q_p}{Q_t} = \frac{0.045}{0.071} = 0.63 \text{ which shows that 63\% of total stream discharge is composed of pre-storm water (i.e. groundwater).}$$

A8.2 Uncertainty (expressed as variance) of Q_p

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

$$s_{Q_p}^2 = \left(\frac{\partial Q_p}{\partial Q_i} \right)^2 s_{Q_i}^2 + \left(\frac{\partial Q_p}{\partial C_i} \right)^2 s_{C_i}^2 + \left(\frac{\partial Q_p}{\partial C_e} \right)^2 s_{C_e}^2 + \left(\frac{\partial Q_p}{\partial C_p} \right)^2 s_{C_p}^2$$

where:

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

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:

$$\begin{aligned} \frac{\partial Q_p}{\partial C_e} &= \frac{\partial}{\partial C_e} \left(\frac{Q_i C_i}{C_p - C_e} \right) - \frac{\partial}{\partial C_e} \left(\frac{Q_i C_e}{C_p - C_e} \right) \\ &= \left[\frac{(C_p - C_e) \left(\frac{\partial (Q_i C_i)}{\partial C_e} \right) - Q_i C_i \left(\frac{\partial (C_p - C_e)}{\partial C_e} \right)}{(C_p - C_e)^2} \right] - \left[\frac{(C_p - C_e) \left(\frac{\partial (Q_i C_e)}{\partial C_e} \right) - Q_i C_e \left(\frac{\partial (C_p - C_e)}{\partial C_e} \right)}{(C_p - C_e)^2} \right] \\ &= \left(\frac{Q_i C_i}{(C_p - C_e)^2} \right) - \left(\frac{Q_i (C_p - C_e) + Q_i C_e}{(C_p - C_e)^2} \right) \\ &= \left(\frac{Q_i C_i - Q_i (C_p - C_e) + Q_i C_e}{(C_p - C_e)^2} \right) \\ &= \left(\frac{Q_i}{(C_p - C_e)^2} \right) (C_i - C_p + C_e - C_e) = Q_i \left(\frac{(C_i - C_p)}{(C_p - C_e)^2} \right) \end{aligned}$$

and,

$$\begin{aligned}
 \frac{\partial Q_p}{\partial C_p} &= \left(\frac{\partial}{\partial C_p} \left(\frac{Q_i C_i}{C_p - C_e} \right) \right) - \frac{\partial}{\partial C_p} \left(\frac{Q_i C_e}{C_p - C_e} \right) \\
 &= \left[\frac{\left((C_p - C_e) \frac{\partial (Q_i C_i)}{\partial C_p} \right) - \left(Q_i C_i \frac{\partial (C_p - C_e)}{\partial C_p} \right)}{(C_p - C_e)^2} \right] - \left[\frac{\left((C_p - C_e) \frac{\partial (Q_i C_e)}{\partial C_p} \right) - \left(Q_i C_e \frac{\partial (C_p - C_e)}{\partial C_p} \right)}{(C_p - C_e)^2} \right] \\
 &= \left(-\frac{Q_i C_i}{(C_p - C_e)^2} \right) - \left(-\frac{Q_i C_e}{(C_p - C_e)^2} \right) \\
 &= \frac{-Q_i C_i + Q_i C_e}{(C_p - C_e)^2} = Q_i \left(\frac{C_e - C_i}{(C_p - C_e)^2} \right)
 \end{aligned}$$

Thus:

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

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

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

and therefore:

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

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

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

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

$$\begin{aligned} s_{Q_p}^2 &= \left[\left(\frac{-7.77 - (-5.68)}{-8.98 - (-5.68)} \right)^2 (2.5 \times 10^{-7}) \right] + \left[\left(\frac{0.071}{-8.98 - (-5.68)} \right)^2 (0.0025) \right] \\ &+ \left[\left((0.071) \left(\frac{-7.77 - (-8.98)}{(-8.98 - (-5.68))^2} \right) \right)^2 (0.0025) \right] + \left[\left((0.071) \left(\frac{-5.68 - (-7.77)}{(-8.98 - (-5.68))^2} \right) \right)^2 (0.0025) \right] \\ &= 1.88 \times 10^{-6} (\text{m}^3\text{s}^{-1})^2 \end{aligned}$$

$$\begin{aligned} s_{\left(\frac{Q_p}{Q_t}\right)}^2 &= \left(\frac{Q_p}{Q_t}\right)^2 \left(\frac{s_{Q_p}^2}{Q_p^2} + \frac{s_{Q_t}^2}{Q_t^2} \right) \quad (\text{From Kretz, 1985}) \\ &= \left(\frac{0.045}{0.071}\right)^2 \left(\left(\frac{1.88 \times 10^{-6}}{(0.045)^2} \right) + \left(\frac{2.5 \times 10^{-7}}{(0.071)^2} \right) \right) = 3.93 \times 10^{-4} = 0.04\% \end{aligned}$$

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 1. Number and Type of Samples Analysed for Geochemistry

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

Table 2. 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 3. 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	10.8	NA
3	94.11.03	rain	7.1	36.6	0.0	0.0	2.9	0.01	0.2	0.7	15.4
3	94.11.16	rain	2.0	23.7	2.2	5.3	NA	NA	NA	NA	NA

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 (%)
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
11	94.11.09	surface water	60.0	263.4	4.3	88.6	72.6	0.03	40.9	17.7	6.6

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 (%)
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 4. 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
	Na ⁺	0.18	0.41	0.257	56

Water Type	Ion	Min (mg/L)	Max (mg/L)	Mean (mg/L)	C.V. (%)
	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