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Geological Survey of Canada
Bulletin 598

Canadian Groundwater Inventory: regional hydrogeological characterization of the Annapolis Valley aquifers

C. Rivard, D. Paradis, S.J. Paradis, A. Bolduc, R.H. Morin, S. Liao, S. Pullan, M.-J. Gauthier, S. Trépanier, A. Blackmore, I. Spooner, C. Deblonde, R. Boivin, R.A. Fernandes, S. Castonguay, T. Hamblin, Y. Michaud, J. Drage, and C. Paniconi

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Cover illustration
Landscape of the Annapolis Valley from North Mountain. 2008-176

Critical review
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PREFACE

The Annapolis-Cornwallis Valley Aquifer Study (ACVAS) was undertaken by the Geological Survey of Canada within the framework of the Canadian Groundwater Inventory, as part of its Groundwater Program. In order to warrant a sustainable use of groundwater resources and to protect their natural quality, the groundwater management needs rigorous scientific information and a complete and sound database. Through the compilation of existing data, fieldwork, data analysis, and interpretation, and modelling, a general understanding of the Annapolis Valley's aquifer system was obtained, providing valuable information to provincial and municipal authorities for the management of groundwater resources.

The Annapolis Valley is a major economic region of the province of Nova Scotia and its most important agricultural area. Since the last regional study published in 1968, significant changes in population and land use, as well as some droughts between 1996 and 2002, have put pressure on the water resources. A vast majority of the valley residents now relies on groundwater for domestic purposes, either from municipal wells or from private residential wells, mostly due to limited surface water supplies and their frequent poor quality during the summer.

This bulletin presents the current state of understanding of this regional hydrogeological system, along with the data and methodology used to characterize the various geological units and groundwater resources. Various documents, including reports, maps, databases, scientific papers, and theses, were compiled and their data structured into new databases.

This bulletin represents the third in the series of reports of assessments of regional-scale aquifers which are slowly populating the Canadian Groundwater Inventory. The ACVAS project also includes a highly colourful and graphical Hydrogeological Atlas presenting the main results and available data to provide a quick picture of hydrological, geological, and hydrogeological conditions in the valley.

The results of this study are aligned with a long-term mission to fill the knowledge gaps in the country's groundwater resources. This project benefited from multiple scientific and institutional collaborations, and is also well aligned with the Earth Sciences Sector's Groundwater Program and the vision of the Canadian Framework for Collaboration on Groundwater. I particularly wish to express my gratitude to Nova Scotia Environment for its great support in the development of this project and would like to congratulate the many stakeholders who contributed to this successful collaborative project.

Alfonso Rivera
Chief Hydrogeologist and Groundwater Program Manager
Earth Sciences Sector
Natural Resources Canada

PRÉFACE

L'Étude des aquifères de la vallée Annapolis-Cornwallis (ÉAVAC) a été entreprise par la Commission géologique du Canada dans le cadre de l'inventaire canadien des ressources en eau souterraine de son programme «Les eaux souterraines». Pour assurer une utilisation durable des ressources en eau souterraine et protéger leur qualité naturelle, la gestion des eaux souterraines doit s'appuyer sur de l'information scientifique rigoureuse et une base de données complète et fiable. Par la compilation des données existantes, des travaux de terrain, l'analyse et l'interprétation de données ainsi que la modélisation, cette étude a permis d'obtenir une connaissance générale du système aquifère de la vallée de l'Annapolis et de fournir aux autorités provinciales et municipales de précieux renseignements pour la gestion des ressources en eau souterraine.

La vallée de l'Annapolis est une région économique importante de la province de la Nouvelle-Écosse et sa plus importante région agricole. Depuis la dernière étude régionale publiée en 1968, des changements importants dans la population et l'utilisation des terres, ainsi que quelques périodes de sécheresse entre 1996 et 2002, ont exercé des pressions sur les ressources en eau. La vaste majorité des résidents de la vallée dépendent de l'eau souterraine pour leur approvisionnement, par l'intermédiaire de puits municipaux ou de puits résidentiels privés, en raison principalement d'un manque d'eau de surface et de la piètre qualité de celle-ci en période estivale.

Le présent bulletin décrit l'état actuel des connaissances sur ce système hydrogéologique régional, ainsi que les données et la méthode utilisées pour caractériser les différentes unités géologiques et les ressources en eau souterraine. Divers documents, dont des rapports, des cartes, des bases de données et des articles scientifiques ont été compilés, et leurs données ont été structurées dans de nouvelles bases de données.

Ce bulletin représente le troisième d'une série de rapports d'évaluation des aquifères régionaux qui viennent lentement enrichir l'inventaire canadien des ressources en eau souterraine. Le projet ÉAVAC s'accompagne également d'un atlas hydrogéologique couleur riche en figures, qui présente les principaux résultats et les données disponibles permettant de dresser un portrait des conditions hydrologiques, géologiques et hydrogéologiques dans la vallée.

Les résultats de cette étude s'inscrivent dans une mission à long terme visant à combler les lacunes dans les connaissances sur les ressources en eau souterraine du pays. Ce projet a bénéficié de multiples collaborations scientifiques et institutionnelles et s'harmonise en outre très bien avec le programme «Les eaux souterraines» du Secteur des sciences de la Terre et la vision du Cadre canadien de collaboration en matière d'eau souterraine. Je désire particulièrement exprimer ma gratitude à l'égard du ministère de l'Environnement de la Nouvelle-Écosse et féliciter les nombreux intervenants qui ont contribué au succès de ce projet concerté.

Alfonso Rivera
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Canadian Groundwater Inventory: regional hydrogeological characterization of the Annapolis Valley aquifers

Abstract

The Annapolis-Cornwallis Valley Aquifer Study was a regional hydrogeological study focusing on major aquifer units of the most important agricultural area of Nova Scotia. The study area covered 2100 km^2, and included sedimentary rocks of the Wolfville and Blomidon formations, as well as part of the North and South mountains bordering the valley. The surficial sediment cover is mainly composed of glacial tills, but sand and gravel units are also present in the eastern part of the valley. The main objectives of this project were to improve the general understanding of groundwater flow dynamics and to provide baseline information and tools for a regional groundwater resource assessment.

The main bedrock aquifers of the Valley are located in the Wolfville and Blomidon formations, which are composed of lenticular bodies of sandstone, conglomerate, shale and siltstone in variable proportions. The aquifers are often confined and the flow is topographically-driven. Their hydraulic conductivities are in the range of 10^{-6}to10^{-5} m/s. Good aquifers, though limited in extent, can also be found in the sand and gravel units, with hydraulic conductivities on the order of 10^{-4} m/s. Groundwater recharge was estimated to range between 115 and 224 mm/a over the entire study area. The vulnerability study showed that bedrock aquifers are typically less vulnerable than surficial aquifers, with the Wolfville Formation being the most vulnerable bedrock formation. Groundwater of the Valley is generally of good quality, although nitrate levels are of concern in several areas.

Résumé

L'Étude des aquifères de la vallée Annapolis-Cornwallis était une étude hydrogéologique régionale s'intéressant aux principales unités aquifères de la région agricole la plus importante de la Nouvelle-Écosse. La région à l'étude couvrait 2 100 km^2 et incluait les roches sédimentaires des formations de Wolfville et de Blomidon ainsi que des portions des montagnes du Nord et du Sud bordant la vallée. Les sédiments de surface sont principalement composés de tills glaciaires, mais des unités de sable et de gravier sont aussi présentes dans la partie est de la vallée. Les principaux objectifs de ce projet étaient d'améliorer la compréhension de la dynamique de l'écoulement de l'eau souterraine ainsi que de fournir des informations de base et des outils pour l'évaluation de la ressource en eau souterraine à l'échelle régionale.

Les principaux aquifères rocheux de la vallée sont situés dans les formations de Wolfville et de Blomidon, qui sont composées de strates lenticulaires de grès, de conglomérat, de shale et de siltstone dans des proportions variables. Les aquifères sont généralement confinés et l'écoulement est contrôlé par la gravité. Leurs conductivités hydrauliques sont de l'ordre de 10^{-6} à 10^{-5} m/s. Les unités de sable et de gravier constituent aussi de très bons aquifères, ayant une conductivité hydraulique moyenne d'environ 10-4 m/s, mais ont une étendue limitée. Une fourchette de 115 à 224 mm/a a été obtenue pour la recharge sur l'ensemble de la région à l'étude. L'étude de vulnérabilité a montré que les aquifères rocheux étaient typiquement moins vulnérables que ceux dans les sédiments de surface et que la Formation de Wolfville était la plus vulnérable des formations rocheuses. L'eau souterraine de la vallée est généralement de bonne qualité, mais les concentrations de nitrates sont préoccupantes à plusieurs endroits.

SUMMARY

A regional hydrogeological study of the Annapolis Valley, Nova Scotia, was conducted from 2003 to 2006 by the Geological Survey of Canada (GSC) with the help of many partners. The valley is located between the North and South mountains along the Bay of Fundy. It is a major economic region of the province and its most important agricultural area. Population growth, changes in land use, and recent droughts have put pressure on the water resources. Limited surface-water supplies, and their frequent poor quality during the summer, have made groundwater supplies increasingly appealing. More than 90% of the valley residents now rely on groundwater for domestic purposes, either from municipal wells or from private residential wells. At present, the majority of irrigation demands are supplied by surface water.

The study area covers 2100 km^2, and includes five watersheds, of which the largest are the Annapolis and Cornwallis watersheds. The valley is flanked to the south by metasedimentary and granitic rocks of the South Mountain, which form the highland region of central Nova Scotia, and to the north by basaltic rocks of the North Mountain cuesta. The valley floor is underlain mainly by sandstones of the Wolfville Formation and overlying shales and sandtones of the Blomidon Formation. The surficial sediment cover in the study area is mainly composed of glacial tills, but sand and gravel, as well as fine glaciolacustrine and marine sediments, are also present, reflecting the complexity of the Quaternary depositional history of this region.

The main objective of this project was to characterize and quantify the groundwater resources within granular and fractured aquifers of the valley, so as to improve the understanding of the hydrodynamic conditions and provide baseline information and tools to support management and protection programs. Both quantity and quality issues were addressed. Three M.Sc. degree theses were carried out to study specific issues in the valley: 1) on the vulnerability of the entire study area using the DRASTIC index, 2) on surface water/groundwater interactions, and 3) on groundwater nitrate contamination and vulnerability. The last two studies focused mainly on a representative local scale subwatershed called Thomas Brook, located on the western side of the Cornwallis watershed.

This bulletin presents the current state of understanding of this regional hydrogeological system, along with the data and methodology used to characterize the geological formations and groups. Various documents including reports, maps, databases, scientific papers, and theses were compiled and their

SOMMAIRE

Une étude hydrogéologique de la vallée de l'Annapolis en Nouvelle-Écosse a été réalisée de 2003 à 2006 par la Commission géologique du Canada (CGC), avec l'aide de plusieurs partenaires. Cette vallée est située entre les montagnes du Nord et du Sud, le long de la baie de Fundy. Elle constitue la plus importante région agricole et une des principales zones économiques de la province. La croissance de sa population, les changements dans l'utilisation des sols et de récentes sécheresses ont exercé des pressions sur les ressources en eau de la région. La quantité limitée d'eau de surface et la fréquente piètre qualité de celle-ci durant l'été ont rendu l'eau souterraine de plus en plus attirante. Plus de 90 % des résidents de la vallée utilisent actuellement l'eau souterraine pour leur approvisionnement à usage domestique, que ce soit par des puits privés ou des puits municipaux. À l'heure actuelle, la majorité de l'irrigation se fait avec l'eau de surface.

La zone à l'étude couvre 2 100 km^2 et inclut cinq bassins versants, dont les principaux sont ceux des rivières Annapolis et Cornwallis. La vallée est bordée au sud par les roches métasédimentaires et les roches granitiques de la montagne du Sud, qui forme les hautes terres de la partie centrale de la Nouvelle-Écosse, et au nord, par les roches basaltiques de la montagne du Nord (Basalte de North Mountain), qui présente un relief de cuesta. Le fond de la vallée est essentiellement constitué de grès de la Formation de Wolfville, sur lesquels reposent les unités de shale et de grès de la Formation de Blomidon. La couverture de sédiments de surface dans la région à l'étude est principalement composée de tills glaciaires, mais des unités de sable et de gravier, ainsi que des sédiments fins glaciolacustres et marins sont également présents, reflétant la complexité de l'histoire de la mise en place des dépôts quaternaires de cette région.

Le principal objectif de ce projet était de caractériser et de quantifier la ressource en eau souterraine des aquifères granulaires et rocheux fracturés de la vallée, de façon à améliorer la compréhension des conditions hydrodynamiques du système hydrogéologique et de fournir de l'information de base et des outils pouvant contribuer à l'élaboration de programmes de gestion et de protection de la ressource. Les questions de quantité et de qualité d'eau ont été abordées. Trois mémoires de maîtrise ont porté sur des problématiques spécifiques à la vallée, à savoir : 1) la vulnérabilité des aquifères de l'ensemble de la zone à l'étude, mesurée à l'aide de l'indice DRASTIC, 2) les interactions eau de surface/eau souterraine et 3) la contamination de l'eau souterraine par les nitrates et sa vulnérabilité. Les deux dernières études s'intéressaient essentiellement à un sous-bassin versant représentatif appelé «sous-bassin du ruisseau Thomas», situé dans la partie ouest du bassin de la rivière Cornwallis.

Ce bulletin présente l'état actuel des connaissances sur ce système hydrogéologique régional, avec les données et la méthodologie utilisées pour caractériser les formations et les groupes géologiques. Divers documents tels que des rapports, des cartes, des bases de données, des articles scientifiques, des thèses et des mémoires ont été compilés et leurs données structurées dans des bases de données. Ces

data structured into databases. Data essentially came from Nova Scotia Environment (NSE). they included well logs, well characteristics, pump test results, geochemistry, and some historical water-level data from monitoring wells. Fieldwork was carried out to gather additional data on stratigraphy, surficial-sediment history and architecture, hydraulic properties, fracturing, spatially distributed groundwater levels, and groundwater characteristics (including dating) in specific areas, to fill the main gaps in information coverage.

The climate of the valley can be described as semi-humid and temperate. Proximity to the Bay of Fundy and Atlantic Ocean prevents extreme temperatures, whereas protection provided by North and South mountains allows the valley to have the warmest temperatures and the second lowest annual precipitation in Nova Scotia. Lowlands of the valley proper have slightly warmer average temperatures, lower precipitation levels, and more frost-free days than highland areas. Annual total precipitation varies from 952 to 1468 mm in the study area, with an average of 1238 mm (and 1138 mm within the valley proper).

The main bedrock aquifers of the valley are located in the Wolfville and Blomidon formations and, to a lesser extent, in the North Mountain basalts. The Wolfville and Blomidon formations are composed of lenticular bodies of sandstone, conglomerate, shale, and siltstone in variable proportions. The Wolfville Formation is dominated by coarser grained facies, whereas the Blomidon Formation is characterized by more fine-grained strata. Variable hydraulic properties of the different strata imply that some bedrock units act as aquifers, whereas others behave like aquitards. Water-bearing fractures seem to be mostly associated with bedding planes gently dipping towards the Bay of Fundy. Conversely, the North Mountain basalts contain mainly vertical fractures that can provide good yields on a local basis only. The majority of fractures of all formations usually have a northeastern strike, aligned with the valley axis.

Because of this preferential fracturing and lenticular arrangement of beds, fractured aquifers of the study area can be locally anisotropic and highly heterogeneous, resulting in significant groundwater-flow channelling. Nevertheless, pumping tests from the database revealed that pumping wells generally behave as if they were in a porous media, with drawdown following a Theis-type curve. Based on these pumping tests, average hydraulic conductivities are 6.2×10^{-6}, 2.8×10^{-6}, and 5.2×10^{-7} m/s for the Wolfville, Blomidon, and North Mountain formations respectively. The hydraulic conductivity does not seem to decrease with depth. Aquifers of these formations are often confined.

données provenaient essentiellement du ministère de l'Environnement de la Nouvelle-Écosse Elles comprenaient des descriptions stratigraphiques, des caractéristiques de puits, des résultats d'essais de pompage, de la géochimie et des données historiques sur les niveaux d'eau dans des puits de surveillance. Des travaux de terrain ont été réalisés pour obtenir des données supplémentaires sur la stratigraphie, l'histoire de la mise en place des sédiments de surface et leur arrangement, les propriétés hydrauliques, la fracturation, les niveaux d'eau ponctuels spatialement distribués et les caractéristiques de l'eau souterraine (incluant de la datation) dans des régions spécifiques, pour combler les lacunes dans la couverture de l'information.

Le climat de la vallée peut être décrit comme humide et tempéré. La proximité de la baie de Fundy et de l'océan Atlantique préserve la vallée des températures extrêmes, tandis que la protection fournie par les montagnes du Nord et du Sud permet d'avoir les températures moyennes les plus chaudes et le deuxième plus faible taux de précipitations totales annuelles de la Nouvelle-Écosse. Les basses terres de la vallée ont des tempéra tures légèrement plus chaudes, de plus faibles précipitations et plus de jours sans gel que les hautes terres. Les précipitations totales annuelles varient de 952 à 1468 mm dans la zone à l'étude, avec une moyenne de 1238 mm (et de 1138 mm dans la vallée proprement dite).

Les principaux aquifères rocheux de la vallée sont situés dans les formations de Wolfville et de Blomidon et, dans une moins grande proportion, dans le Basalte de North Mountain. Les formations de Wolfville et de Blomidon sont composées de strates lenticulaires de grès, de conglomérat, de shale et de siltstone dans des proportions variables. Les faciès grossiers prédominent dans la Formation de Wolfville, alors que plus de strates à grain fin sont présentes dans la Formation de Blomidon. Les propriétés hydrauliques variables des différentes couches impliquent que certaines unités rocheuses agissent comme aquifères, tandis que d'autres se comportent comme des aquitards. Les fractures dans lesquelles l'eau circule semblent être principalement associées à des plans de litage ayant un pendage faible vers la baie de Fundy. À l'opposé, le Basalte de North Mountain contient surtout des fractures verticales, pouvant uniquement fournir de bons débits sur une étendue locale. La majorité des fractures de toutes les formations ont une direction nord-est, parallèle à l'axe de la vallée.

À cause de cette fracturation préférentielle et de l'arrangement lenticulaire des strates, les aquifères rocheux fracturés de la zone à l'étude peuvent être localement anisotropes et très hétérogènes, ce qui se traduit par un cheminement préférentiel de l'écoulement. Néanmoins, les essais de pompage tirés de la base de données ont révélé que les puits de pompage se comportaient comme s'ils étaient dans un milieu poreux, les rabattements suivant une courbe type de Theis. En se basant sur les résultats de ces essais de pompage, les conductivités hydrauliques moyennes sont de $6,2 \times 10^{-6}$, $2,8 \times 10^{-6}$ et $5,2 \times 10^{-7}$ m/s pour les formations de Wolfville, de Blomidon et de North Mountain respectivement. La conductivité hydraulique ne semble pas diminuer avec la profondeur. Les aquifères de ces formations sont souvent confinés.

The Quaternary sediments in the study area consist mostly of tills, ice-contact glaciofluvial sands and gravels, as well as glaciomarine and/or glaciolacustrine clays of variable thickness. Till is the most widespread glacial deposit, and is almost the only sediment present on both mountains. It presents different facies due to changes in glacial dynamics during deposition, but the nature of the underlying bedrock lithology is usually the predominant controlling factor. Since sandstone is the most widespread bedrock over the valley floor, the till is often sandy in this area. The major limiting factor for their productivity is their limited saturated thickness. Sand and gravel units are exploited in the eastern and middle parts of the valley, where sediments are thicker and coarser. The towns of Kentville and Wolfville have some of their production wells in these sand and gravel units. Hydraulic conductivities of sand and gravel units are by far the highest, being on average $1.3x10^{-3}$ m/s. Very few data were available to characterize till deposits. Their hydraulic conductivities were estimated using a Guelph permeameter; their values generally range from 10^{-7} to 10^{-4} m/s.

Preferential groundwater recharge occurs through vertical fractures of North Mountain basalts and on flat surfaces (i.e. in the valley) where sandy tills and sand and gravel units are present. The mean recharge rates estimated with the hydrograph-separation and the water-balance methods range between 250 and 360 mm/a for the entire valley. This potential recharge (infiltration) seems to largely overestimate the recharge to bedrock aquifers. The water-balance method was thus ‘corrected’ using estimated percentages of confined areas (indicating percentage of areas where recharge is impossible). The weighted average over the entire study area obtained with the corrected water-balance method range from 120 to 224 mm/a.

Values estimated for the hydrological budget are as follows: the annual recharge (i.e. what reaches bedrock aquifers) corresponds to 15.5% of the annual total precipitation (while the infiltration would represent 22%), whereas 31.5% is lost to surface runoff and 46.5% to evapotranspiration. According to available data, the minimum and maximum groundwater withdrawal would represent 5 and 70 mm/a when applied over the entire study area (i.e. 3 to 41% of the mean recharge, i.e. 172 mm/a). On a more local scale (e.g. small watershed scale), problematic conditions for streams and aquatic habitats could occur, as groundwater use may represent more than 50% of the recharge. Using mean total porosities and probable range of sandstone percentages for the Wolfville and Blomidon formations, and theoritical fracture porosities for both mountains, the storage was estimated to be on the order of 2300 mm for the upper 100 m of bedrock.

Les sédiments quaternaires dans la zone à l’étude consistent principalement en till, en sable et gravier fluvioglaciaires et en argile glaciomarine ou glaciolacustre d’épaisseurs variable. Le till est le sédiment glaciaire le plus répandus et est pratiquement le seul sédiment présent sur les deux montagnes. Il présente différents faciès dus à des changements de la dynamique glaciaire durant la sédimentation, mais la nature des roches sous-jacentes est habituellement le facteur dominant qui contrôle sa composition. Étant donné que le grès est la roche la plus répandue dans le fond de la vallée, le till est souvent sableux dans cette région. La contrainte majeure sur leur productivité est leur faible épaisseur saturée. Des unités de sable et de gravier sont exploitées dans l’est et le centre de la vallée, là où les sédiments sont plus grossiers et plus épais. Les municipalités de Kentville et de Wolfville ont certains de leurs puits de production dans ces unités de sable et de gravier. Les conductivités hydrauliques des unités de sable et de gravier sont de loin les plus élevées, étant en moyenne de $1,3x10^{-3}$ m/s. Peu de données sont disponibles pour caractériser les tills de cette région. Leurs conductivités hydrauliques ont été estimées en utilisant un perméamètre de Guelph; leurs valeurs varient entre 10^{-7} et 10^{-4} m/s.

La recharge des aquifères se produit préférentiellement par les fractures verticales du Basalte de North Mountain et sur les surfaces plates (c.-à-d. dans la vallée) aux endroits où des tills sableux et des unités de sable et de gravier sont présents. Les taux moyens de recharge estimés avec la méthode du bilan hydrique et la séparation d’hydrogramme sont de 250 et 360 mm/a pour l’ensemble de la vallée. Cette recharge potentielle (infiltration) semble surestimer largement la recharge aux aquifères rocheux. La méthode du bilan hydrique a donc été «corrigée» en utilisant des pourcentages estimés de zones à nappe captive (indiquant un pourcentage de la superficie où la recharge est impossible). La moyenne pondérée obtenue pour l’ensemble de la zone à l’étude avec la méthode du bilan hydrique corrigé varie de 120 à 224 mm/a.

Les valeurs estimées pour le bilan hydrique sont les suivantes : la recharge annuelle (c.-à-d. ce qui atteint les aquifères rocheux) correspond à 15,5 % des précipitations totales annuelles (tandis que l’infiltration représente 22 %), 31,5 % ruisselle en surface et 46,5 % se transforme en évapotranspiration. Selon les données disponibles, les débits pompés minimal et maximal représenteraient 5 et 70 mm/a respectivement lorsque appliqués à l’ensemble de la zone à l’étude (c.-à-d. de 3 à 41 % de la recharge moyenne, soit 172 mm/a). À une échelle plus locale (p. ex. sur un des petits bassins versants), des conditions problématiques pour les cours d’eau et les habitats aquatiques pourraient survenir étant donné que l’utilisation de l’eau souterraine peut représenter plus de 50 % de la recharge. En utilisant les porosités totales moyennes et des fourchettes de pourcentages probables de grès dans les formations de Wolfville et de Blomidon, ainsi que des porosités de fractures théoriques pour les deux montagnes, l’emmagasinement a été estimé être de l’ordre de 2300 mm pour les 100 m supérieurs du socle rocheux.

The bedrock potentiometric map was constructed from groundwater-level measurements; only the most recent existing data (of the last 10 years) and GSC field campaigns were used. This map, developed using kriging, shows that groundwater generally follows the topography: groundwater flows from the topographic highs of the South and North mountains to the main rivers located in the centre (lower part) of the valley floor. Groundwater levels are generally shallow, having a median depth of 6.1 m (although values vary from artesian-flowing conditions to depths that can reach more than 30 m).

A study using the DRASTIC methodology in combination with an overlay system in a geographic information system (GIS) was performed to generate maps of the intrinsic vulnerability to surface contamination of both bedrock and surficial aquifers. As expected, the results indicated that the bedrock aquifers tended to be significantly less vulnerable than the surficial aquifers, due to the shallow water depths, common confined conditions of the bedrock aquifers, and in places, high permeability of the sediments aquifers. In general, the aquifer units with the greatest production potential also correspond to higher potential to vulnerability, due to elevated values of hydraulic conductivity and recharge, and/or a flat topography (in the case of the valley floor). These areas alsocorrespond to the more populated regions and thus are areas where risk of surface contamination is highest.

Nevertheless, geochemical data indicate that the majority of wells located in the valley have water that does not exceed Health Canada drinking water guidelines. However, nitrates are of concern. Reported geochemical values show that elevated nitrate concentrations can be found in different areas of the valley, but are mostly concentrated in the eastern, more populated, portion of the valley. A random sampling of wells throughout the valley showed that 14.8% exceeded the 10 mg/L Canadian drinking water guideline. However, the percentage of tested wells exceeding the 1 mg/L background concentration probably provides a better picture of the groundwater degradation, as this threshold indicates wells already affected by anthropogenic activities (and thus a possible increase in the following years if corrective measures are not taken). Of the 290 wells available, 64.5% exceed this 1 mg/L background threshold. Using the Kings County database, 21% of the wells exceeded the 10 mg/L guideline and 80% exceeded the 1 mg/L threshold, but these wells were sometimes selected on purpose because of their suspected or known high levels of nitrate. However, the specific study in the Thomas Brook subwatershed, which used a random selection, found similar results. The presence of nitrates in both groundwater and surface water confirmed the hydraulic link between streams, surficial deposits and bedrock. Saltwater intrusion does not seem to be a major problem in the Annapolis Valley.

La carte potentiométrique des aquifères rocheux a été obtenue à partir des données de niveau d'eau dans les puits; seules les données les plus récentes des bases de données (des 10 dernières années) et des campagnes de terrain de la CGC ont été conservées. Cette carte, obtenue par krigeage, montre que l'eau souterraine suit généralement la topographie : l'eau s'écoule des hauts topographiques des montagnes du Nord et du Sud vers les principales rivières situées au fond de la vallée. Les niveaux d'eau sont généralement peu profonds, ayant une profondeur médiane de 6,1 m (les valeurs varient toutefois de conditions artésiennes à plus de 30 m).

Une étude utilisant la méthodologie DRASTIC en association avec un système d'information géographique (SIG) a permis de générer des cartes de vulnérabilité intrinsèque à la contamination de surface pour les aquifères rocheux et les aquifères dans les sédiments de surface. Comme on pouvait s'y attendre, les résultats ont indiqué que les aquifères rocheux tendent à être significativement moins vulnérables que les aquifères dans les sédiments de surface, en raison de la faible profondeur de la nappe, des conditions fréquentes de nappe captive des aquifères rocheux et de la grande perméabilité en divers endroits des sédiments des aquifères granulaires. En général, les unités aquifères ayant le meilleur potentiel production sont également celles qui sont les plus vulnérables, à cause de leurs valeurs élevées de conductivité hydraulique et de recharge, ou d'un relief plat (dans le cas du fond de la vallée). Ces secteurs correspondent aussi aux régions les plus populeuses et donc à des zones à plus haut risque de contamination de surface.

Néanmoins, les données géochimiques indiquent que la grande majorité des puits situés dans la vallée fournissent une eau dont les paramètres ne dépassent pas les normes de Santé Canada pour l'eau potable. Toutefois, les concentrations de nitrates sont préoccupantes. En effet, les données géochimiques disponibles montrent que des concentrations de nitrates élevées peuvent être mesurées en différents endroits de la vallée, mais qu'elles sont principalement localisées dans la partie est de la vallée, c'est-à-dire dans la partie la plus populeuse. Pour les puits échantillonnés aléatoirement dans la vallée, 14,8 % dépassaient 10 mg/L, la norme canadienne pour l'eau potable. Cependant, le pourcentage des puits testés excédant la concentration naturelle (bruit de fond) de 1 mg/L fournit probablement un meilleur portrait de la dégradation de l'eau souterraine, car ce seuil indique les puits qui sont déjà affectés par les activités humaines (et donc une augmentation possible dans les années à venir si aucune mesure correctrice n'est prise). Des 290 puits disponibles, 64,5 % dépassent ce seuil de 1 mg/L. En utilisant la base de données du comté de Kings, on trouve que 21 % des puits excédaient la limite de 10 mg/L et que 80 % dépassaient le seuil de 1 mg/L, mais ces puits étaient parfois délibérément choisis pour leurs teneurs élevées en nitrates, connues ou pressenties. Toutefois, l'étude spécifique sur le bassin versant du ruisseau Thomas, qui a utilisé une sélection aléatoire, a révélé des résultats similaires. La présence de nitrates dans les eaux souterraines et de surface a confirmé le lien hydraulique existant entre les cours d'eau, les sédiments de surfaces et le socle rocheux. L'intrusion d'eau salée ne semble pas être un problème majeur dans la vallée de l'Annapolis.

A three-scale conceptual model including regional, local, and point scales was used to schematically describe aquifers of the Annapolis Valley, to best illustrate the lenticular and layered Wolfville and Blomidon formations, and to integrate the knowledge acquired through this study. A regional groundwater-flow model was constructed in finite elements, based on the 3-D geological model. This model was run in steady state using saturated conditions, assuming that fractures and bedding planes are sufficiently connected to provide a relatively homogeneous flow system at the regional scale that could be mapped onto an equivalent porous medium. Modelling confirmed the estimated ranges of hydraulic conductivity and recharge values previously found. The recharge value over the entire study was found to be on the order of 115 mm/a. The fact that the modelled recharge lies in the lower range of the corrected water-balance values and is notably smaller than some of the values obtained using the hydrograph-separation method likely suggests that a large part of the infiltrated water is either evaporated, taken up by plants, or circulates as hypodermic flow in surficial sediments (or the first few metres of bedrock). Only about 50% on average would in fact reach bedrock aquifers. This result corroborates the percentage of confined wells estimated with high-technology tools (high-precision GPS and high resolution DEM generated using LIDAR) and is in agreement with the well developed stream network that can be observed across the entire study area, but that could not be represented in the regional model.

To address the potential impacts of climate change in the Annapolis Valley, both historical data and future scenarios were employed. Annual baseflows estimated from Environment Canada gauging stations and groundwater levels from the provincial monitoring program showed that only one gauging station and one well had a significant decreasing trend. An additional well showed a decreasing trend for the month of August (considered one of the most critical for water supply and exploitation for this rural area). However, sampling series are probably too short to provide statistically significant results, even if a trend is present. More analyses should be performed in the future, when additional years will be available. A parallel project by Fernandes and Korolievich, on climate change and its potential impact on recharge, showed a decrease in recharge on the order of 33% in the valley over the next century, which is considerable. These findings should help to reinforce interest and confirm the importance of monitoring programs, especially those for monitoring wells. Since groundwater now constitutes the main water supply in the valley and withdrawals are likely to increase in future years, mainly for irrigation purposes, it would be important to be able to detect decreases in aquifer recharge and groundwater levels.

Un modèle conceptuel incluant les échelles régionale, locale et ponctuelle a été développé pour décrire schématiquement les aquifères de la vallée de l'Annapolis, de façon à illustrer le caractère lenticulaire et stratifié des formations de Wolfville et de Blomidon et à intégrer les connaissances acquises durant le projet. Un modèle numérique de l'écoulement souterrain à l'échelle régionale a été construit en éléments finis, en se fondant sur le modèle géologique 3D. Le modèle a été utilisé en régime permanent et dans des conditions saturées, en supposant que l'interconnexion des fractures et des plans de litage était suffisante pour produire un système d'écoulement relativement homogène à l'échelle régionale qui pouvait être représenté par un milieu poreux équivalent. La modélisation a validé les fourchettes estimées de conductivité hydraulique et les taux de recharge trouvés précédemment. La valeur de recharge obtenue pour l'ensemble de la zone à l'étude est de 115 mm/a. Le fait que la recharge modélisée soit près de la limite inférieure de la fourchette de valeurs obtenue avec la méthode du bilan hydrique corrigé et qu'elle soit nettement plus faible que celles trouvées avec la méthode de séparation d'hydrogramme, suggère qu'une bonne partie de l'eau infiltrée s'est évaporée, a été prélevée par les plantes ou circule sous forme d'écoulement hypodermique dans les sédiments de surface (ou les premiers mètres du socle rocheux). En moyenne, seulement 50 %, environ, atteindrait en fait les aquifères rocheux. Ce résultat corrobore le pourcentage de puits complétés dans des nappes captives estimé avec des technologies de haute précision (GPS haute précision et modèle altimétrique numérique haute résolution produit par lidar) et concorde avec le réseau hydrographique bien développé qui peut être observé dans l'ensemble de la zone à l'étude, mais qui ne peut pas être représenté dans le modèle régional.

Pour avoir une idée des impacts potentiels des changements climatiques dans la vallée de l'Annapolis, des données historiques et des scénarios futurs ont été utilisés. L'étude des débits de base annuels, estimés à partir des stations de jaugeage d'Environnement Canada, et des niveaux d'eau dans les puits de surveillance provinciaux a montré qu'une seule station de jaugeage et un seul puits présentaient des tendances à la baisse significatives. Un autre puits a montré une tendance à la baisse pour le mois d'août (considéré comme le mois critique pour l'approvisionnement et l'exploitation dans cette région rurale). Cependant, les séries temporelles sont probablement trop courtes pour fournir des résultats statistiquement significatifs, même si une tendance existe. Des analyses devraient donc être réalisées dans les années à venir, lorsque plus de données seront disponibles. Un projet parallèle de Fernandes et Korolievich sur les changements climatiques et leurs impacts potentiels sur la recharge a montré une diminution de la recharge de l'ordre de 33 % dans la vallée au cours des 100 prochaines années, ce qui est considérable. Ces résultats devraient aider à renforcer l'intérêt et à confirmer l'importance des programmes de surveillance, particulièrement en ce qui a trait aux puits de surveillance. Étant donné que l'eau souterraine est devenue la première source d'approvisionnement de la vallée et que le pompage augmentera probablement dans les années à venir, principalement pour les besoins d'irrigation, il serait important de pouvoir détecter toute baisse de la recharge des aquifères ou du niveau des nappes.

Through compilation of existing data, fieldwork, analyses, interpretation, and modelling, a general understanding of the Annapolis Valley's aquifer system has been obtained, including its geological hydrogeological, hydrological, and geochemical characteristics, thus providing valuable information to provincial and municipal authorities for the management of groundwater resources. This project generated several outputs, such as databases for stratigraphic logs, well characteristics and geochemistry, a three-scale conceptual model, geological and groundwater flow models, a water budget, vulnerability maps for both bedrock and surficial deposits, climate-change scenarios and their effects on aquifer recharge, and a Quaternary geology map at 1:100 000 scale, bringing a new interpretation and vision of the glacial-deglacial history of the region. Maps showing compiled and interpreted data, and major results regarding hydrogeology, geology, hydrology, and geochemistry of this project are presented in a companion atlas produced by the GSC.

Par la compilation des données existantes, des travaux de terrain, l'analyse et l'interprétation de données ainsi que la modélisation, une compréhension globale du système aquifère de la vallée de l'Annapolis a été obtenue, dont ses caractéristiques géologiques, hydrogéologiques, hydrologiques et géochimiques, fournissant ainsi aux autorités municipales et provinciales des informations utiles pour la gestion de la ressource en eau souterraine. Ce projet a généré plusieurs produits, tels que des bases de données pour les descriptions stratigraphiques, les caractéristiques des puits et la géochimie, un modèle conceptuel à trois échelles, un modèle géologique et un modèle de l'écoulement souterrain, un bilan hydrique, des cartes de vulnérabilité pour les aquifères granulaires et rocheux fracturés, des scénarios des changements climatiques et leurs effets sur la recharge, et une carte de la géologie du Quaternaire à l'échelle 1/100 000, apportant une nouvelle interprétation de l'histoire glaciaire et postglaciaire de la région. Un atlas d'accompagnement produit par la CGC fournit des cartes montrant les données compilées et interprétées, ainsi que les résultats les plus importants concernant l'hydrogéologie, la géologie, l'hydrologie et la géochimie de ce projet.

INTRODUCTION

A regional hydrogeological study of the Annapolis Valley, Nova Scotia, was undertaken by the Geological Survey of Canada within the framework of the national inventory of groundwater resources in Canada, which was suggested in the Canadian Framework for Collaboration on Groundwater (Rivera et al., 2003). Several collaborators actively participated in this project. This valley is located between the North Mountain and South Mountain along the Bay of Fundy. It is a major economic region of Nova Scotia and its most important agricultural area. It has an agricultural history dating back over 400 years, including Acadian settlers who had been preceded by Mi'kmaq populations.

Population growth, changes in land use, and recent droughts have put pressure on the water resources in the Annapolis Valley. Limited surface-water supplies and their sometimes poor quality have made groundwater increasingly appealing. Until recently, little was known about the groundwater resource and its properties, including aquifer/aquitard geometry, fracturing, recharge rates, and groundwater dynamics at the regional scale. The only significant regional hydrogeologic report for the Valley was published more than 35 years ago (Trescott, 1968).

The main objective of this project was to characterize and quantify groundwater resources within surficial and fractured aquifers, to improve the understanding of the hydrodynamic conditions of this key region of Nova Scotia. This three-year study (2003–2006) was intended to provide valuable information on groundwater and aquifer characteristics to support management programs, and the protection and sustainable development of this resource. Both quantity and quality issues were addressed.

The fieldwork associated with this project was the first significant regional-scale groundwater field program to be completed in the valley since the 1960s (Trescott, 1968), and has taken advantage of new technologies (e.g. borehole geophysics techniques, isotope analyses, remote sensing, GIS tools). In addition, the project included the development of regional geological and groundwater flow models.

Three M.Sc. degree thesis projects were carried out to study specific issues in the valley: 1) on the vulnerability of the entire study area using the DRASTIC index, 2) on surface water/groundwater interactions, and 3) on groundwater nitrate contamination and aquifer vulnerability. The last two studies focused mainly on a local-scale subwatershed called Thomas Brook. This subwatershed, north of Berwick, was selected because this area was considered representative of the valley in its geology and its rural activities, and because it had been studied by other organizations (mainly for surface water) since the year 2000.

This bulletin is divided into ten sections, the first being this introduction. The second section provides a description of the study area, and the third section is devoted to the methodology of the fieldwork and data analysis. In the fourth section, the bedrock and surficial geology are described. The fifth section presents hydraulic-property, recharge-rate, and total-porosity results obtained from new and existing data, while the sixth section provides the general hydrogeological context, including the bedrock potentiometric map. In the seventh section, an overview of the vulnerability study is provided, and the eighth section describes the groundwater chemistry, including results for nitrates and isotopes. The ninth section presents the conceptual and groundwater-flow numerical models. The tenth and last section provides an overview of the project results and some recommendations.

An atlas (Rivard et al., 2007) was produced as a complement to this bulletin, showing 51 maps and thematic plates for compiled and interpreted data, and major results regarding hydrogeology, geology and hydrology. Interested readers can find information on viewing or purchasing this atlas at: http://geopub.nrcan.gc.ca

ACKNOWLEDGMENTS

This multi-agency project was mainly funded through the Groundwater Program of the Geological Survey of Canada (J03 GW4200–05). This project also received support from Nova Scotia Environment (NSE), Agriculture and Agri-Food Canada (AAFC), and the Clean Annapolis River Project (CARP). NSE represented the primary source of information regarding geology, water wells, and groundwater quality and monitoring. The project benefited from the collaboration of INRS-Eau, Terre et Environnement (INRS-ETE), Université du Québec à Montréal (UQAM), Acadia University, the Centre of Geographic Sciences (COGS), Environment Canada, National Defence, Nova Scotia Department of Natural Resources (NSDNR), United States Geological Survey (USGS), Nova Scotia Agricultural College (NSAC), and Terry Hennigar of Terry W. Hennigar Water Consulting. Special thanks go to Mr. Ralph Stea of NSDNR, whose knowledge of the Quaternary deposits of the valley helped us throughout the project, and to local hydrogeologist Heather Cross of H.J. Cross Hydrogeo for her dedication to the characterization and protection of the valley groundwater resources and for her careful review of this document.

We also wish to thank all the municipalities, schools, and well owners involved in the fieldwork for their help. Finally, we would like to underline the valuable help and work provided by Tim Webster from COGS, and Bill Shaw from W.G. Shaw & Associates Ltd., as well as Stephen Hawboldt, Andy Sharpe, and Denise Sullivan from CARP.

DESCRIPTION OF THE STUDY AREA

The Annapolis Valley is a long narrow lowland extending from the Minas Basin to the Annapolis Basin along the south shore of the Bay of Fundy in Nova Scotia. The valley is about 100 km long and 10 to 15 km wide. The Annapolis Valley is flanked to the south by metasedimentary and granitic rocks of the South Mountain, which form the highland region of central Nova Scotia, and to the north by basaltic rocks of the North Mountain cuesta. The valley floor is underlain mainly by sandstones of the Wolfville Formation and overlying sandstones and shales of the Blomidon Formation. The rich and fertile soils, as well as its micro-climate, make the Annapolis Valley one of the three key regions in Canada for commercial fruit production, along with the Okanagan Valley in British Columbia, and the Niagara Peninsula in Ontario.

The Annapolis Valley was already identified as a high-priority area for hydrogeological research by the Nova Scotia Geoscience Needs Workshop in 1996. Indeed, population growth, intensive farming, and economic development of this valley have put high pressure on water resources. Moreover, several years of drought in the recent past have increased this pressure. In addition, agricultural practices have potential to create environmental impacts, such as groundwater contamination, depletion of waterways by irrigation, and pollution of water resources by nitrates, bacteria, and pesticides. Agricultural runoff containing fertilizers and pesticides can also have impacts on surface water bodies.

The best aquifers are found mostly in the fractured sandstones underlying the valley, and in the sand and gravel deposits in the eastern end of the valley. Groundwater represents the main source of water supply for private wells and municipal water supplies, and is also an important source of water for numerous aquatic habitats of the valley such as wetlands and streams.

Physiography and hydrography

The Annapolis Valley is located in the eastern portion of the Appalachian physiographic region, which extends from Newfoundland (Canada) to Alabama (U.S.A.). The location of the study area is shown on Figure 1. It encompasses approximately 2100 km^2 and includes 5 watersheds: Annapolis, Cornwallis, Canard, Habitant, and Pereau. The Annapolis River drains approximately 1600 km^2, and the Cornwallis River 375 km^2. The small watersheds of Habitant, Canard, and Pereau, all located at the northeastern end of the study area, together drain only 125 km^2. The Gaspereau watershed, south of the Cornwallis watershed, is not included in this study since its population is small and few environmental problems have been reported. The study area is included within Kings and Annapolis counties.

Topographic elevation in the South and North mountains rarely exceeds 250 m a.s.l., and riverbank heights in the valley vary from 0 m near the basins to 50 m a.s.l. at the watershed divides (Fig. 2). Because of the topography, only a small portion of North Mountain is included in the study area, while a very large portion of South Mountain is encompassed. At the eastern end of the valley, the land surface is gently undulating between the three rivers (subwatersheds being separated from each other by low ridges), terminating in abrupt cliffs at the Minas Basin (Thomas, 1974). Much of the lowland around the mouths of rivers is reclaimed tidal flats (dykeland). The minor relief on the valley floor creates local recharge and discharge areas. Thomas (1974) found that local topographic highs usually corresponded to areas with downward vertical gradients. Surface drainage along the south slope of North Mountain is unusual in that

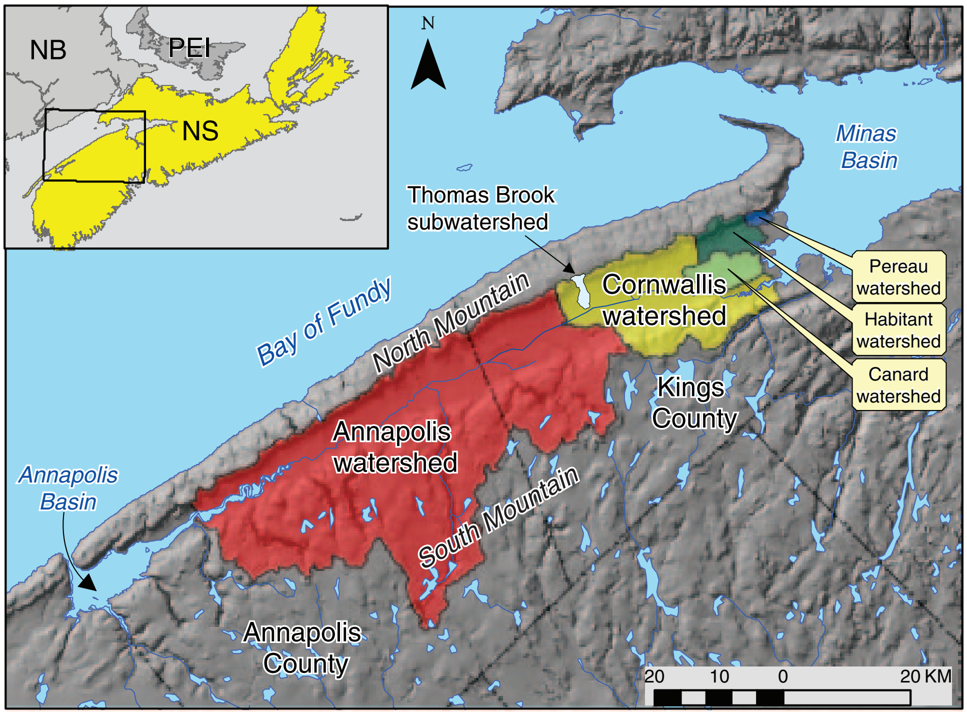


Figure 1. Location of the study area.

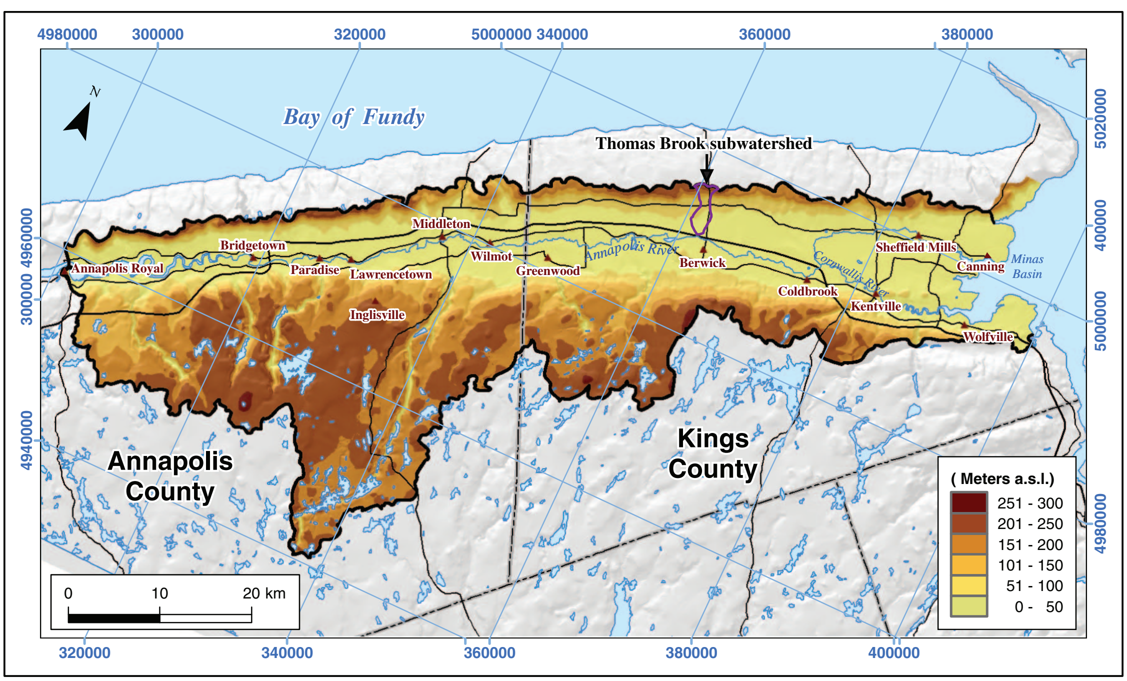


Figure 2. Topography of the study area (map in UTM co-ordinates, zone 20, Nad83).

streams with deeply incised gulleys flow down the slope, but disappear into the sand and gravel deposits of the valley (Thomas, 1974).

By the end of the nineteenth century, most of the forest in the valley floor had been cleared to accommodate agriculture (Blackmore, 2006). Still, most of the study area is forested due to North and South mountains, with approximately 68% forest-covered in Kings County and 82% in Annapolis County (Timmer, 2003). The study area comprises 1682 km of streams and contains 157 small to moderate size lakes and reservoirs (covering 68 km^2). Wetlands throughout the valley, especially along the main rivers (i.e. Annapolis and Cornwallis rivers) and the coast of the Minas Basin, have been extensively altered by dyking and infilling. Dykes have been used since Europeans began to settle in the Annapolis region in the early 17th century. It is estimated that 80% of the original salt marshes have been dyked or filled to create agricultural lands (Kings Community Economic Development Agency, 2000). Even so, numerous bogs, ponds and marshes are still present and provide excellent habitats for wildlife. Wetlands currently represent 4% of the study area.

The Bay of Fundy, and thus the Annapolis and Minas basins, are affected by high tides. Those of the Minas Basin are the highest in the world. The bay is ice-free year-round. The Bay of Fundy waters are cold and clear, while the Minas Basin waters are muddy and often warmer (Kings Community Economic Development Agency, 1998). Many of the valley's streams create estuaries as they empty into either of the Minas or Annapolis basins. The valley therefore comprises several tidal rivers, including the Annapolis, Cornwallis, Canard, Habitant, and Pereaux rivers. The Bay of Fundy shoreline consists of rocky beaches and basalt (erosion-resistant) cliffs of the North Mountain. The Minas Basin shoreline, composed of sandstone and shale from the Wolfville and Blomidon formations, erodes more easily.

The water divide between the Annapolis and Cornwallis watersheds is located near Berwick, where the Caribou bog occupies a quite large area (3.2 km^2). Westward from Paradise, the Annapolis River is a meandering watercourse through fine soils and with a low gradient down to the Annapolis causeway (Daborn and Daborn, 1991). This control structure was built in 1960–1961; it changed the well mixed estuary at the mouth of the Annapolis River into a stratified (salt wedge) estuary. The salt wedge extends to Bridgetown, as salt water is pushed upstream by the tide through the permanently open fishway and through holes in the causeway itself (Daborn and Daborn, 1991). Work to transform the causeway into a tidal station was completed in 1984. Hydroelectric power plants have operated in the Annapolis watersheds for over 75 years. For this purpose, as many as 47 dams have been placed on Annapolis River tributaries (Timmer, 2003). In the summer and early fall, electricity production is limited by lack of water and a need to maintain minimum water levels for fish population and habitat.

Five long-term gauging stations are available in the study area (stations 01DC003; 005; 006, and 007; and 01DD004 of Environment Canada, *see* Figure 9 for their location) with data extending discontinuously over 14 to 41 years. On an annual basis, streamflow generally peaks in April and the lowest values are recorded in August. However, multiple peaks related to rain or snow events are recorded throughout the year (*see* 'Hydrograph separation' section for more details).

Climate

The climate of the Annapolis Valley is moderate and can be described as semi-humid and temperate. The proximity to the Bay of Fundy and Atlantic Ocean prevents extreme temperatures. The moderating effect of the ocean and the climatic protection provided by North and South mountains allow the Annapolis Valley to have the warmest temperatures and the second lowest annual precipitation totals in Nova Scotia (Holmstrom and Thompson, 1989). Indeed, topography plays a major role in the climatic conditions, with the North and South mountains funnelling winds through the Valley and protecting it from winds blowing in directly off the Bay of Fundy and the Atlantic Ocean (Timmer, 2003).

Local climatic conditions within the valley are also heavily influenced by proximity to the Annapolis and Minas basins and by topographic elevations. Low-lying areas within a few kilometres of the water experience cooler summer temperatures (about 5°C cooler) and longer frost-free periods than other areas in the valley (Timmer, 2003). Lowlands of the valley proper have slightly warmer average temperatures, lower precipitation levels, and fewer frost-free days than highland areas.

Fifteen weather stations within or near the study area (Figure 3), for which data span 5 to 73 years, provide annual total precipitation varying from 952 to 1468 mm, with an average of 1238 mm, and 1138 mm within the valley proper. On average, between 15 and 25% of this precipitation falls as snow. Precipitation in the valley falls mostly during the autumn and total precipitation levels peak in December and January. The driest months are June and August. Monthly average temperatures range from –5 to +20°C, with more than 200 frost-free days (minimum temperature >0°C) per year. The mean annual temperature is approximately 6.5°C. The mean summer temperature is 15°C and the mean winter temperature is –2.5°C (Environment Canada, 2006). Flooding is an infrequent event in the area (Timmer, 2003).

Population and land use

The Annapolis Valley is rural, with towns and villages concentrated predominantly along the rivers. The valley contains one third of all the farmland in the province of Nova Scotia. The eastern end of the valley is the most urbanized. According to Statistics Canada (2007), 99 700 residents live

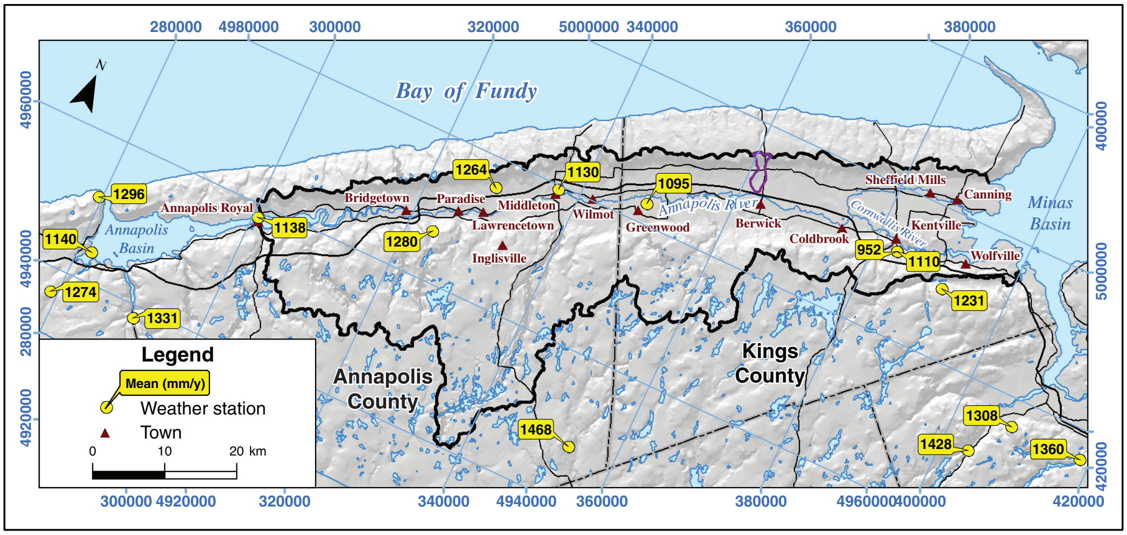


Figure 3. Location of the 15 weather stations located within or close to the study area, with annual average precipitation indicated for each station.

within the Annapolis Valley economic region, representing about 10% of the province's population. Kings County had one of the highest population growths in Nova Scotia over the last years (7.8% over the 1991–2001 period), while the population in Annapolis County declined (6.7% for the same period) (Timmer, 2003). The corridor between the community of Coldbrook and the Town of Wolfville contains 40% of the population of Kings County, and continues to grow faster than most other portions of the valley. It is expected that rural areas surrounding towns throughout the valley will continue to grow faster than the towns themselves (Timmer, 2003).

The region's economic base includes agriculture, tourism, and technology. One third of the provincial income from agriculture comes from Kings County (Kings Community Economic Development Agency, 1998). Major products include orchard fruits (mostly apples), cranberries, blueberries, chickens, vegetables, potatoes, turkeys, and hogs. Artificial drainage is needed to establish and maintain the soil due to poor natural drainage conditions. The importance of agriculture to the local economy is magnified by the extensive food processing industries located in the valley (Timmer, 2003). Other natural resource sectors such as fishing and forestry do not contribute significantly to the local or provincial economy (Kings Community Economic Development Agency, 1998).

METHODOLOGY

Data compilation

Various documents including reports, maps, databases, scientific papers, and theses were compiled and their data structured into databases using previously defined templates. Targeted information primarily consisted of well-log descriptions, well characteristics (such as depth, yield, static water level), weather and hydraulic data, water-chemistry data, as well as pump-test results and data related to monitoring wells. Databases essentially came from Nova Scotia Environment (NSE); they included well logs, well characteristics, pump-test results, geochemistry, and some historical water-level data. Other data received had to be digitized prior to being included in our databases. Some stratigraphic (mainly for surficial deposits) and geotechnical data were provided by Transportation and Public Works and National Defence (CFB Greenwood military base). A few stratigraphic logs were also obtained from municipalities of the valley, and various data were taken from Trescott's (1968) thesis (such as logs and spring locations). Weather and gauging-station data came from the Environment Canada (EC) website (http://climate.weatheroffice.ec.gc.ca/); in addition, their EC Envirodat database was used to complement the geochemical provincial databases. Table 1 summarizes the existing data compiled for the ACVAS project.

Fieldwork

Fieldwork was carried out every summer during the duration of this three-year project, but most of the work was conducted in 2004 and 2005. The purpose of this fieldwork was to fill the main gaps in information coverage, and to acquire information where no data were available, for example, installing piezometers to study groundwater/surface water (GW/SW) interactions.

Fieldwork activities were performed within the most important geological formations and surficial units from a hydrogeological point of view. They are described below. Significantly less hydrogeological data were acquired for the surficial deposit units since they are seldom used as aquifers in the Annapolis Valley. The selected sites for these activities are shown in Figure 4, and Table 2 summarizes the fieldwork performed.

Groundwater-level measurements

Water levels within domestic and municipal wells were measured during three summers (2003–2005) to obtain a regional estimate of the potentiometric surface across the study area. A total of 293 water levels were obtained, mainly from domestic wells. Forty-three (43) of these measurements were taken in surficial wells, while 242 were taken in bedrock wells (or correspond to springs). The remainder (eight wells) were indeterminate as to surficial or bedrock unit.

Six wells were equipped with dataloggers in order to record water levels every four hours during the project, to complement the provincial monitoring program. In 2003, wells in Wilmot (belonging to the province), Wolfville (belonging to the municipality), and Sheffield Farm (belonging to Agriculture and Agri-Food Canada) were selected. Due to malfunctioning of the datalogger in the Wilmot well during the first year, so a large part of that year's data was lost. In 2004, dataloggers were also installed in one of the Greenwood/Tremont municipal wells, and in two residential wells of the Thomas Brook subwatershed (TB 1-Malcolm and TB 2-Goode). Table 3 indicates the number of years and period covered for the different monitoring wells. The TB 2-Goode well was in use for domestic purposes.

Soundings

Soundings in Quaternary deposits and in the first few metres of rock were performed in June 2005 using a direct-push technique (Geotech 605D owned and operated by the Institut National de la Recherche Scientifique – Eau, Terre et

Table 1. Summary of existing data.

Data	Number
Description of wells from NSEL (location, depth, yield, etc.)*	12 820 wells (e.g. 11 379 static water levels)
Description of well stratigraphy from NSEL, Transportation and Public Works, National Defence, municipalities, and Trescott (1968)	12 891 well and borehole logs
Results of pump tests	157 within or slightly outside the study area, in approx. 50 'distinct' locations (further than 3 km)
Water sample analysis from NSEL and EC	1256 samples (e.g. 774 nitrate concentrations), with 327 distinct locations
Meteorological data from EC	15 stations within or close to the study area, 6 being inside the study area (5–73 year series)
Hydraulic data (stream hydrographs) from EC	7 gauging stations (1–40 year series)
Observation well hydrographs from NSEL	12 historical series, of which 4 had been digitized (5–30 year series)
* Note: the amount of information for each well varies.	

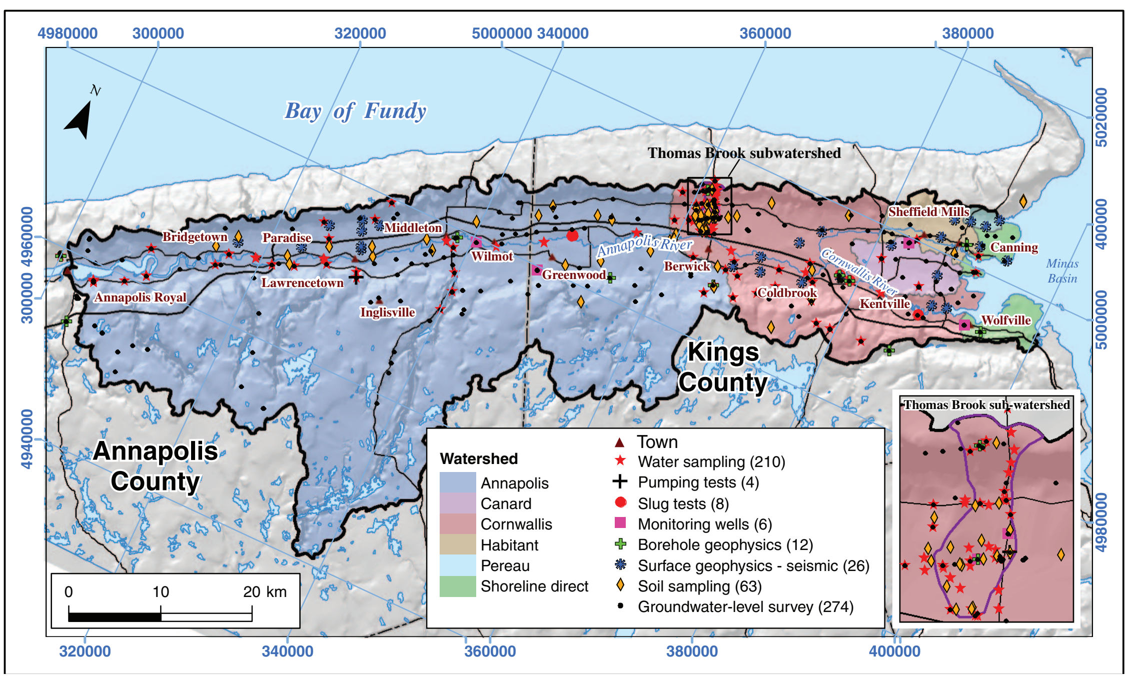


Figure 4. Location map of the study area showing investigated sites.

Table 2. Summary of acquired field data.

Category	Activity	Number of data locations	
		Fractured rock	Surficial deposits
Survey	Measurements of water levels in wells (293 sites)	242	43
	Quaternary survey (visited sites)	-	175 sites
	Nitrate profiling using a multi-parameter probe	14 wells	-
Monitoring	Installation of data loggers in wells	6	-
Soundings	Boreholes	-	17
	Installation of piezometers	6	7
Hydraulic testing	Pumping tests	4	-
	Slug tests	5	3
	Permeameter tests	-	110
	Packer tests	45 in 3 wells	-
	Riverbed permeability testing (using a seepage meter)	-	4 sites
Geophysics	Borehole geophysics	12 wells	-
	Seismic survey (26 lines)	-	-
	Ground-penetrating radar (≈2.6 km)	-	-
Analyses	Water for stable isotopes (δ^2H and $\delta^{18}O$; $\delta^{15}N$-NO_3 and $\delta^{18}O$-NO_3)	148 for H&O, 12 for nitrate	-
	Water for bacteria / nitrates / sulfates / and major ions	16/28/19/8	12/10/3/3
	Water for nitrate concentration index using a 'field kit'(Palintest)	20	6
	Soil – grain size	-	47
	Soil – total organic matter	-	18
	Soil porosity, bulk density, and water content	-	16
	Macrofossils (plant remains) / Microfauna	-	6 / 9
	Dating (tritium and ^{14}C in groundwater)	7	-
	Rock core samples (thin sections)	13	-
Remote sensing	Validation process (107 surveyed sites)	-	-

Table 3. Summary of GSC monitoring wells – period covered (UTMs are in Nad27 zone 20).

GSC monitoring wells*	X UTM (m)	Y UTM (m)	Number of years of data	Period covered
Greenwood/Tremont	347 284	4 979 363	2	07/2004–07/2006
Sheffield Farm (AAFC)	382 764	4 999 204	3	09/2003–07/2006
Wilmot*	339 952	4 979 299	2	06/2004–05/2006
Wolfville (Wickwire Rd)	392 024	4 993 592	3	06/2003–07/2006
TB 1 (Malcolm)	361 705	4 992 308	2	07/2004–07/2006
TB 2 (Goode)	362 151	4 993 282	2	07/2004–07/2006

* The Wilmot well was integrated into the provincial monitoring program in May 2006.

Environnement). This equipment can reach a maximum depth of 50 m and has two interchangeable spindles, enabling use of either rotation or percussion. The CPT (cone penetration test) drilling head, using percussion as the driving force, provides, among other things, a good idea of the stratigraphy, soil water pressure, and hydraulic conductivity of fine materials while conducting a dissipation test. The RPSS (rotopercussion sounding system) drilling head uses a hydraulic hammer and thus rotopercussion as the driving force. Measured parameters in this case permit the identification of encountered geological formations. This drilling head can be used for soft rocks, but is also very useful where gravel and blocks are encountered in surficial deposits, and to perform 'pre-holes' in the unsaturated zone within which a CPT can then be conducted.

Major differences were found between our results and well logs from the provincial databases. Based on existing data, 10 to 30 m of surficial deposits were expected in the southern part of the Thomas Brook subwatershed, but only 2 to 10 m were found. In the eastern part of the Annapolis Valley, where buried valleys had been suspected based on well logs showing up to 75 m of sediments, only 10 to 30 m could be found. Therefore, it was concluded that the compact till could not easily be differentiated from the very friable sandstone of the Wolfville Formation by standard drilling. Thus in this case, the CPT/RPSS method has proven to be helpful to distinguish between surficial deposits and bedrock.

For the Annapolis-Cornwallis Valley Aquifer Study (ACVAS) project, 17 holes were drilled, of which eight were in the Thomas Brook subwatershed. The others were drilled in the Middleton area (2), in the Green Acres area (3) north of the CFB Greenwood military base, and in the eastern part of the valley (3), where buried valleys had been suspected (*see* Fig, 4). The work performed included 6 CPT and 8 RPSS (in four sites), providing approximate stratigraphy and water contents. Results are presented in Appendix A. Eleven (11) soil samples were taken using Shelby tubes and plastic bags. Five slug tests were also performed (*see* 'Slug tests' section).

A total of thirteen piezometers were installed: seven in surficial deposits, the rest in the first few metres of bedrock. Eight were located in the Thomas Brook subwatershed, two in the Middleton area, and three in the Green Acres area. The characteristics of the boreholes are summarized below in the 'Stratigraphy and fracturing' section (*see* Table 5). Each piezometer was equipped with dedicated Waterra tubing and a foot valve, so as to be able to sample the water. However, some foot valves became clogged with fine particles, and most piezometers installed in surficial deposits yielded too little water and could therefore not be properly sampled.

Hydraulic testing

Hydraulic testing for the ACVAS project included long-term pump tests, slug tests, packer tests, and borehole flowmeter tests. The last testing technique is related to borehole geophysics and is thus described in the 'Borehole geophysics' section. River bed (or seepage) testing is also included in the present section, even though this activity is not specifically related to wells.

Slug tests

A slug test refers to an experiment where the water level in the well is disturbed for a few seconds to several minutes, either by injecting air or by removing a certain amount of water (e.g. using a bailer). This type of test is also well adapted to low-permeability rock, where pumping cannot really be performed due to the limited amount of water that can be extracted. These tests allow a quite good estimation of the aquifer hydraulic conductivity despite the fact that they are very local (within the range of a few m^2).

Slug tests were performed using two methods in different regions of the study area: compressed air (pressure) and a bailer. Water levels were measured using dataloggers every second until the water level had recovered to its static level. A total of 21 slug tests were conducted in bedrock wells, and four in surficial deposit or upper bedrock boreholes. However, during these tests, only five bedrock wells and three surficial wells responded well to these tests. Six bedrock wells appeared to be plugged (the pressure could not dissipate), and eight could not be interpreted.

Data were interpreted using the Bouwer and Rice (1976) or the Butler and Garnett (2000) method (Chapuis, 1999), depending on the hydraulic response. An example of calculation for the MN5-Kentville well is presented in Appendix B.

Pumping tests

In the summer of 2004, four long-term pump tests were conducted in different areas of the valley: Somerset (Berwick North), Canning, Lawrencetown, and at the Sheffield Farm belonging to AAFC (5 km north of Kentville). These long-term pumping tests, having pumping durations between 48 and 72 hours, were meant to estimate the hydraulic conductivity at the local scale (on the order of a couple of hundred metres).

Pump tests were interpreted using the Theis and Cooper-Jacob methods (Todd, 1980). Those two methods assume confined conditions and fully penetrating wells. For the Theis curve match, the software AQTESOLV™ by HydroSOLVE, Inc. was used. No observation-well response was available. Observation wells were either too far away to be influenced by the pumping or were too shallow in comparison to the pumping well (e.g. Sheffield Farm), and were thus not significantly affected (a few centimetres at most). Therefore, no storage coefficient could be obtained from for these tests.

Packer tests (multi-level slug tests)

Packer tests allow the estimation of hydraulic-conductivity profiles for sections with one or several fractures or for the matrix alone. Measurements of hydraulic conductivity (K) values using packer tests can range from 10^{-2} to 10^{-10} m/s. This technique seemed particularly appealing, since formations of the study area appeared to be quite heterogeneous vertically. The basic procedure for packer tests uses two or more packers to isolate a portion of the borehole. Depending on the application, the tested interval can vary from tens of centimetres to a few metres in length.

To investigate vertical hydraulic conductivity variability in the ACVAS project, slug tests were performed in three wells, using a straddle-packer system. Slug tests were performed by rapidly lowering the water level in the pipe string connected to the test interval and monitoring its recovery. Similarly to the slug tests, a pneumatic system (compressed air) was used to lower the water level and a pressure transducer served to monitor the recovery. This system has the advantage of being very accurate, especially in highly permeable horizons where the test duration may be less than a few seconds (Zurbuchen et al., 2002). However, in low-K horizons, it may take a few hours to recover the initial water level.

The investigated wells were: MW3–Granville Ferry and TB-Malcolm in the Blomidon Formation, and MW5–Kentville in the Wolfville Formation. These wells had all been studied previously using borehole geophysics. The Blomidon Formation was especially targeted as properties of this formation are less well known than those of the Wolfville Formation. For each of these wells, 3.7 m intervals were used to provide a good resolution of hydraulic conductivity in the profile with respect to the stratigraphic variations. Tests were generally repeated three times for each interval with different pressures as a measure of control on the data quality (Butler et al., 1996). Testing of each interval varied from half an hour to a few hours, depending on the permeability of the interval. For instance, the well MW3-Granville Ferry (100 m deep) took 3.5 days to investigate. Due to the degradation of the borehole walls, large packers (200–250 mm, 8–10 inches) had to be used for this 'initially' 150 mm (6 inch) well, and for some intervals adequate isolation of the section was not even possible. Hydraulic conductivities were calculated with the same method as for slug tests.

Permeameter tests

Because of the key role played by surficial-deposit units in aquifer recharge and protection against surface contamination, estimation of hydraulic conductivities was carried out using a Guelph permeameter in different areas of the valley. The Guelph permeameter is a constant head permeameter commonly used in field soil-permeability tests. A total of 89 tests were performed throughout the valley in 30 different soil types in the summer of 2004. In the summer of 2005, 28 additional tests were conducted at eight different sites located in the Thomas Brook subwatershed. About half of these tests provided negative results with the conventional 'two-head' procedure and thus had to be re-interpreted using the 'one-head' analysis applied to each of the two hydraulic heads (and then averaged, following instructions from SoilMoisture Equipment Corporation, 2005). The negative values apparently result from soil heterogeneity or when a root or stone is encountered. The location of these tested sites is presented in Figure 5.

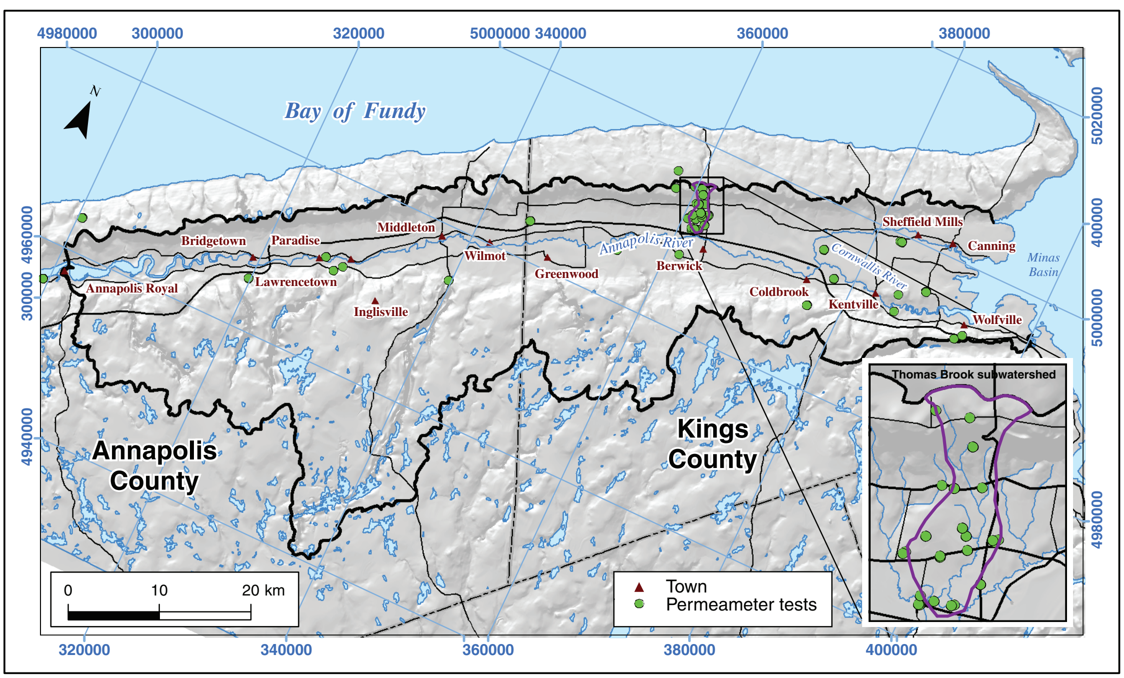


Figure 5. Location of the sites where permeameter tests were performed.

Soil permeability is the result of several factors, including soil composition, grain-size distribution, water content, degree of compaction, and soil-stress history. Soil units in the Annapolis Valley, for which hydraulic conductivity was to be estimated, were determined using soil maps from Kings and Annapolis counties (MacDougall et al., 1969). Representative soil types were chosen from these maps based on soil type, size of the soil unit, and accessibility of the location where samples could be taken.

A sample borehole was dug using an auger to a depth of at least 15 cm and at most 90 cm, depending on ease of digging and the height of each soil horizon. When a constant rate of fall of water in the reservoir had been achieved over three consecutive time intervals the test was considered complete. Three tests were performed for most sites; however in some locations, only two sample boreholes were completed due to difficulty in digging or to impermeable soils. Several soil types were tested in more than one location due to distance and differences in composition between sites of the same soil type.

Seepage meter

To measure the permeability of the Thomas Brook bed sediments and the groundwater flux across these sediments, a common measuring device called a seepage meter was used. This device consisted of a stainless steel open drum (diameter = 0.561 m (2′); height = 0.46 m (1.5′)) with a welded opening on the side to allow groundwater to escape. The drum was pushed into sediments until it was immersed. A plastic bag was connected to the opening via a tube to collect the flow as it left the drum (Fig. 6). The bag was initially filled with a certain amount of water, in order to minimize the amount of air and allow the measurement of either positive or negative fluxes. A drive point was installed next to the drum to estimate the vertical gradient. In the summer of 2005, six seepage-meter tests were conducted at four different sites along Thomas Brook. Measurements were replicated at various time intervals, varying between two and seven days. Although crude, this technique proved to be quite effective in the field, as Thomas Brook is narrow and the sediments do not contain blocks, allowing a good penetration of the drum.

Geophysics

Three types of geophysical work were conducted for the ACVAS project: borehole geophysics, near-surface (seismic) survey, and ground-penetrating radar. The last two techniques were used to obtain additional knowledge on the stratigraphy and depth of bedrock, while the first type was used to obtain information on, among other things, fracturing. For the definition of the stratigraphy, major problems were encountered, since the till of the valley could not be easily differentiated from the sandstone of the Wolfville Formation (*see* 'Soundings' section).

Borehole geophysics

In an effort to better understand the hydrogeological characteristics of the rock aquifers, comprehensive sets of geophysical logs were recorded in water wells specifically chosen because they penetrated one or two major geological formations of the Annapolis Valley. Geophysical logging operations included the use of caliper, natural gamma, electrical resistivity, acoustic televiewer, temperature, and fluid-resistivity logs, and flowmeter under ambient as well as pumping conditions. These logs were analyzed and interpreted in order to recognize important hydrogeological differences and similarities among rock types, from which a conceptual understanding of the regional hydrological system could be developed. In addition to information on the borehole geometry, logging results provide valuable general characteristics of formation properties, such as fracture frequency and orientation, the vertical distribution of transmissivity associated with each rock type, and individual flow

Figure 6. Seepage meter setting in Thomas Brook.

rate of water-bearing fractures. Geophysical logs are effective in recognizing individual rock formations. Indeed, each formation seems to have a unique combination of electrical-resistivity values and natural gamma activities from which it can be identified with some confidence. Each rock unit also has a unique fracture pattern associated with it that may be linked to stress history and its setting in an extensional rift basin.

Geophysical logs were obtained in 12 wells scattered throughout the region. These wells penetrate the five major rock formations or groups of the Annapolis Valley and their locations are shown in Figure 7. Data were obtained for the Wolfville Formation (Kentville wells MN5 and MN6; Canning well), the Blomidon Formation (Malcolm well; TW3-Granville Ferry well), the North Mountain basalt (Baiani well), granodiorite of the South Mountain (Jack well), and Meguma Group slate (Walsh well). Complementary packer tests were conducted at a few selected sites in order to confirm and refine the general observations. At times, data acquired using borehole geophysics represented the only information available on stratigraphy and potential yield. The information collected in the Annapolis Valley was interpreted within the structural context of the numerous similar sedimentary rift basins prevalent along the east coast of North America.

For the estimation of the vertical distribution of aquifer transmissivities, a pressure transducer and a flowmeter were introduced in the well, followed by a submersible pump. Using a constant pumping rate, the pressure and vertical fluid velocity (using the flowmeter) were monitored at selected depths, from the bottom up, once the drawdown had reached a (quasi) steady state. Transmissivities of individual productive zones were calculated assuming an ideal layered and stratified aquifer (Molz et al., 1989) using the Cooper-Jacob equation (Todd, 1980). The well's hydraulic conductivity was estimated by dividing the total transmissivity of the well, obtained from the summation of all individual values, by the saturated thickness of the open borehole. However, because of inherent resolution limitations of the flowmeter, this method can only measure transmissivities over roughly two to three orders of magnitude and can detect only the most permeable zones intersecting a well (Paillet, 1998).

Seismic survey

Shallow seismic-reflection/refraction test surveys were conducted in the summer of 2004 in different areas of the Annapolis Valley to determine whether seismic techniques could be used to delineate the bedrock surface and overlying stratigraphy. The seismic-reflection method is best suited for determining the depth to bedrock in areas where the surficial deposits are tens of metres thick, so the prime targets of these surveys were areas where borehole information suggested a substantial overburden thickness. Figure 8 shows the locations (centroids) of the 26 seismic test sites. The sites in the eastern portion of the Annapolis Valley were aimed at testing areas where overburden thickness was estimated (based on existing data) to be >30 m.

The initial objectives of this work were 1) to obtain an idea of the stratigraphy, 2) to evaluate the depth of surficial deposits and spatial extent of the suspected buried valleys in the eastern part of the study area, and 3) to delineate the clay

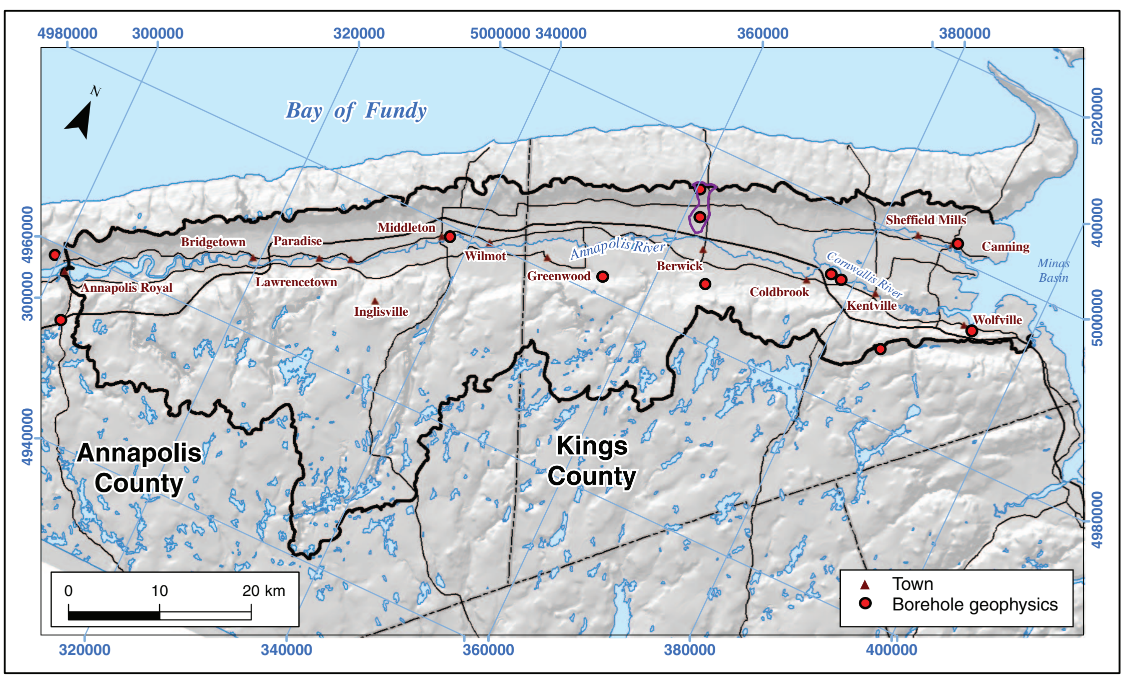


Figure 7. Location of wells investigated using borehole geophysics.

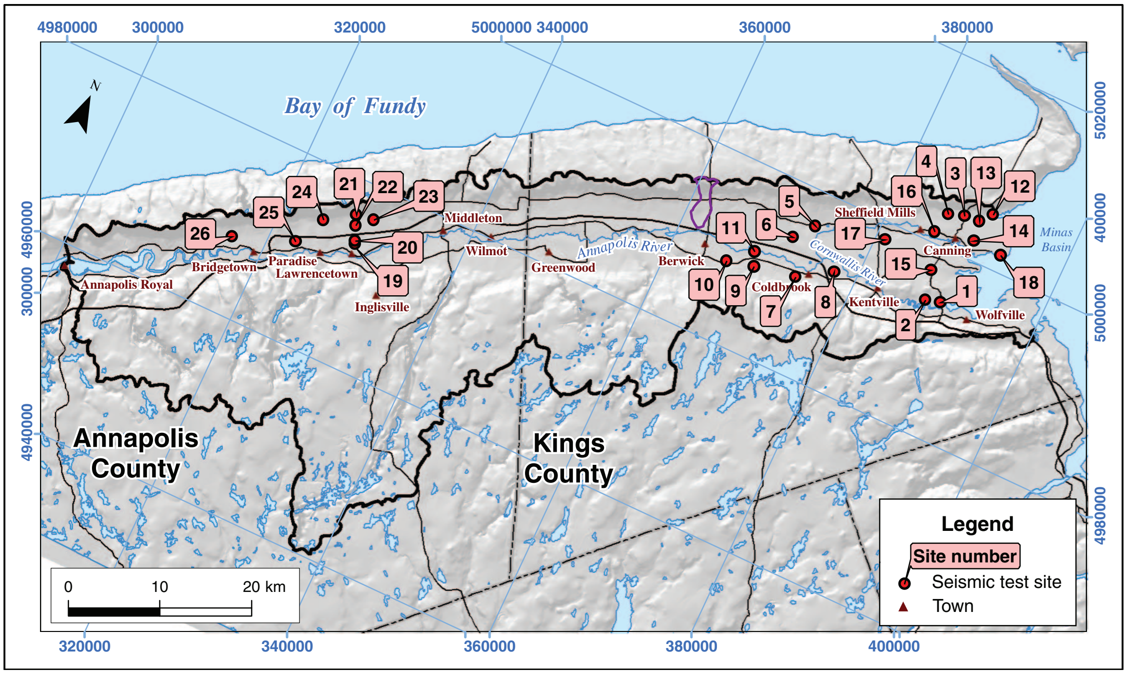


Figure 8. Locations of the 26 seismic test sites.

or fine-grained strata in the western portion of the valley. The shallow seismic-reflection surveys had been targeted to provide the following:

- detailed subsurface structural information (~10–>60 m depth);
- potential vertical and horizontal resolution on sub-metre to metre scale;
- depth to bedrock and stratigraphy of overlying sediments;
- 2-D structural information and means of evaluating lateral continuity of subsurface units, complementing available borehole information.

However, the data acquired in the test-site program did not provide sufficient information to reach the objectives of the geophysical work. In many cases, it was difficult or impossible to determine the depth to bedrock, and little information could be obtained on the stratigraphy of the overlying surficial deposits. Therefore, no follow-up seismic profiling was carried out as part of this project. Some results and discussion of the data obtained are presented in the 'Interpretation of Existing and Acquired Hydrogeological Data and Results' section and the report is presented in Appendix C.

Ground-penetrating radar

In 2005, ground-penetrating radar was also attempted in the eastern part of the study area in order to evaluate the depth to bedrock, where buried valleys were suspected, and to have some information on the sedimentary structures found in various sandy deposits. Surveys were performed using a pulseEKKO 100 system from Sensors and Software Inc. with 50 MHz frequency antennas and a 1000 V pulser. Measurements were made every metre with antenna separation of 2 m. Data retrieved from the various profiles were processed with built-in software (developed by Sensors and Software Inc.) using spatio-temporal filters.

Twelve ground-penetration radar lines (55 to 730 m long, for a total of 2.6 km) were conducted in the vicinity of Coldbrook, Greenwood, Kentville, and Canning, where the seismic survey could not provide information the previous summer. Again, this technique was limited in its application due to the similarity in the physical properties between the compacted till and the rotten sandstone unit underlying the majority of the visited sites. Thus, the resulting profiles could not show the depth to bedrock with a sufficient degree of certainty at most sites.

Water sampling

To improve the knowledge on groundwater age and potential sources, 189 samples from groundwater and surface water were taken for oxygen ($\delta^{18}O$) and deuterium ($\delta^{2}H$) content throughout the study area in 2004 and 2005. These samples were taken at 92 different sites, of which 16 correspond to surface water (three in the Cornwallis River, seven in the Annapolis River, and six in the Thomas Brook). Of the 92 sites, 40 wells were visited three times during the year (summer, fall-winter and spring) and four wells only twice. Surface-water samples were taken three times. Sites were selected based on their uniform spatial distribution across the study area as much as possible. Locations of the visited sites are presented in the 'Geochemistry' section.

In the Thomas Brook subwatershed, water samples were also taken within the framework of the M.Sc. theses on surface water/groundwater (SW/GW) interactions and migration of nitrates in groundwater in 2005. In all, 42 samples were taken for NO_3 and 21 for SO_4 concentrations, 28 samples for bacteria, and 15 for major ions (including Ca, Cl, Fe, Mn, Mg, Na, NO_3, HCO_3, and SO_4), either in wells or in Thomas Brook. Electrical conductivity and chlorides were measured in situ with a MiniTroll 9000 data-logging probe in 17 wells and three sites on the brook; and pH was measured in situ with a YSI Inc. probe in six bedrock wells, six springs, one pond and five sites on the brook. In addition, several samples were acquired for nitrate, and hydrogen and oxygen isotopes. A total of 61 samples were taken for $\delta^{18}O$ and $\delta^{2}H$; 26 were taken during the summer, 17 in December, and 18 in March (in addition, eight samples from the regional survey of 2004–2005 were located in this study area). Of the 61 samples, five sites were dedicated to surface water of Thomas Brook. Twenty-eight samples were also taken for $\delta^{15}N$-NO_3 and $\delta^{18}O$-NO_3, and only the five sites devoted to surface water were re-sampled twice (fall-winter and winter-spring campaigns). Samples taken in December were not appropriately identified and were not analyzed. Measurements of nitrate profiles in 14 wells have also been conducted using a multi-parameter probe (InSitu Inc. Mini-Troll 9000).

Seven water samples were taken in the different geological formations of the Annapolis Valley in July 2006 for dating using carbon 14 and tritium. Samples were sent to the University of Toronto (^{14}C) and University of Waterloo (for tritium). Five samples were taken in the Thomas Brook subwatershed in the North Mountain (from two wells), Blomidon (from a well and a spring) and Wolfville (from a well) formations, one in a deep well tapping the Blomidon Formation in Granville Ferry, and one south of Berwick in the Meguma Group slate. All these wells correspond to open holes and their characteristics will be provided in the 'Water dating' section.

Soil sampling

Numerous soil samples were acquired during Quaternary surveys, of which 46 were used for grain-size analyses across the study area, including 16 for the Thomas Brook subwatershed. Eleven samples were analyzed for their total organic matter. Six samples were analyzed for macrofossils (plant remains) and nine for macrofauna.

Eighteen undisturbed small samples had initially been taken for obtaining retention curves ($K(\psi)$ and $\theta(\psi)$ curves, where ψ is the pressure head) for the M.Sc. thesis on nitrate contamination and vulnerability. However, they were too small to fit in the pressure chambers. Therefore, these small samples were used to obtain three parameters: the soil natural water content (θ), the total porosity (n), and the bulk density (ρ).

Quaternary survey

As part of this regional hydrogeological characterization project, the Quaternary successions have been reinvestigated. Detailed mapping in the valley was necessary to clarify aspects of its complex glacial-deglacial history. It was also crucial to understand the 3-D architecture of the surficial deposits, as it directly affects groundwater recharge and natural protection of bedrock aquifers. Indeed, sandy material will allow more recharge to bedrock aquifers, while clayey-silty units will protect them from surface contamination. To improve our understanding and to be able to complete a 1:100 000-scale map of Quaternary deposits, aerial photos (scale 1: 40 000) were studied and Quaternary surveys were conducted in 2004 and 2005. During fieldwork, representative units, outcrops, interbedded organic units, and more problematic areas identified from aerial photos were targeted to verify known glacial movements or to infer new ones. A total of 175 sites were visited throughout the Annapolis Valley, from which 130 stations have been created in the project Web site. After this field validation, interpreted aerial photos were scanned and digitized. The information (symbols, contacts, etc.) was then transferred to ArcInfo® where the surficial-deposit map was constructed incorporating a digital elevation model (DEM), the legends, and surroundings. These data and the knowledge acquired were also used to build a 3-D geological model for the valley, including surficial deposits and bedrock, which served as a basis for the 3-D groundwater flow model.

Data analysis

Re-interpretation of existing pumping tests

When available, pumping test results from the NSE database were re-interpreted. About a quarter of these pump tests had raw data available, and another half had at least drawdown-versus-time graphs (semi-log or log-log) that could be reviewed. New interpretation results were generally close to previously reported results, but a few re-interpretations provided significant changes.

To obtain additional data on aquifer properties, transmissivities were estimated using drawdown and pumping rate values collected by drillers, usually during the development of the well immediately after its construction. The specific capacity (C_s)corresponds to $C_s = Q/s_{max}$, where Q is the pumping rate and s_{max} is the maximum recorded drawdown. An estimation of the transmissivity T (in m^2/s) can be obtained from the iteration of the Cooper-Jacob equation (Todd, 1980, p. 129):

$$T = \frac{Q}{s} \cdot \frac{2.3}{4\pi} \log\left[\frac{2.25 \cdot T \cdot t}{S \cdot r^2}\right] \quad (1)$$

where Q is the pumping rate (m^3/s), s is the drawdown (m), t is the time (s), S is the storage coefficient and r is the well radius (m). This equation assumes laminar flow and, therefore, it may underestimate aquifer transmissivity if there are turbulent head losses at the pumping well. Since Q/s often decreases with time during a pumping test, the Cooper-Jacob equation usually provides a better estimate of the transmissivity value than the specific capacity alone (Nastev et al., 2004). The transmissivity is then calculated iteratively, assuming a value for the unknown storage coefficient. However, the logarithm in the equation limits the influence of this parameter. An average S value of $2x10^{-4}$ for bedrock wells and $2x10^{-3}$ for surficial wells, estimated using results from the pumping test database, were used in this case.

Some constraints had to be imposed in order to eliminate as much as possible erroneous data and to apply the method only when hypotheses are realistic. Therefore, all the wells for which the maximum drawdown was larger than a third of the initial saturated aquifer thickness were eliminated. This condition was used so as to satisfy the 'confined' hypothesis of the Theis equation, but also to avoid wells where sparse fracturing could influence the aquifer response (Nastev et al., 2004). In addition, a minimum duration of 4 hours was imposed. To be able to use this approximation, the following data also had to be available: static water level, well depth, drawdown, pumping rate, and duration. Out of the 12 830 data records included in the Nova Scotia Well-log database, only 55 could be used after the screening. Thus, 55 transmissivity values (53 for bedrock and two for surficial aquifers) were added to the values obtained using long-term pump tests, resulting in a better spatial coverage.

A verification using the pump test database was made, to see if this process was applicable for this study area. A hundred and two (102) values of K obtained from specific capacities and from pump tests were plotted on a log-log graph. The power regression line provided a satisfactory coefficient of $R^2 = 0.82$. This method is thus believed to provide good 'soft' information, but should not be considered as reliable as pumping test results. These additional values only provide estimates, or orders of magnitude, which can give an indication of the aquifer transmissivity in an area where no other information is available.

Groundwater recharge

Aquifer recharge is defined in a general sense as the amount of infiltrated water reaching the saturated zone, thus representing the net contribution to an aquifer. Several techniques are available to estimate groundwater recharge, including groundwater fluctuations, hydrograph separation, hydrological budgets, and modelling. Each method has its own advantages and drawbacks, related to factors such as scale, hydrogeological conditions, and the reliability of available parameters (Lerner et al., 1990). The range of recharge rates estimated using various approaches can thus be large. Uncertainties in each approach underscore the need for application of multiple techniques to increase the reliability of recharge estimates (Scanlon et al., 2002).

In the ACVAS project, all approaches listed above were used to obtain a reliable range that is representative of the regional scale, or at least of a large area. Groundwater fluctuations were also used to obtain estimates of specific yields. Recharge estimates obtained from modelling are presented in the 'Conceptual and Numerical Models' section.

Hydrograph separation

Hydrograph separation methods are intended for the analysis of daily streamflow record in a basin where it can reasonably be assumed that nearly all groundwater discharges to the stream, except for the part that is lost to evapotranspiration near the stream, and where regulation and diversion of flow can be considered negligible. River hydrographs reflect two very different types of contributions from the watershed: 1) the peaks, which are mainly delivered to the stream by surface runoff and subsurface stormflow, are the result of a fast response to short-term changes; and 2) the baseflow, which is delivered to the stream by deeper groundwater flow, is the result of a slow response to longer term changes in the groundwater flow system (Freeze and Cherry, 1979). Therefore, the baseflow, which only plays a small role during a storm event, generally supports the stream flow in the absence of rain and during dry periods (especially the summer). The groundwater recharge rate over an entire watershed thus roughly corresponds to the baseflow measured at the outlet of the watershed, divided by the watershed area for a given period (month or year). All separation methods suffer from a lack of real knowledge of the movement of water through the watershed and of the 'feeding' groundwater horizons.

Three methods were used in this study, two based on a filter (Chapman, 1991; Eckhardt, 2005) and the other on a graphical approach (Recess/Rora, developed by the USGS, Rutledge, 1998). The Chapman (1991) method belongs to 'one-parameter' approaches, while the Eckhardt (2005) method is a 'two-parameter' approach. The latter was implemented in a parallel project on climate change and its potential impacts on recharge (Fernandes and Korolievich, unpub. rept., 2006). The Recess/Rora method was selected because another graphical method tested in Rivard et al. (2003) provided poor results.

Chapman (1991) suggested an improvement to the filter developed by Nathan and McMahon (1990), which necessitated several passages (iterations) in order for the baseflow not to exceed the river flow at the end of the recession curve (end of runoff). The improved filter by Chapman (1991) is the following:

$$Q_k = \frac{3\alpha - 1}{3 - \alpha} Q_k - 1 + \frac{2}{3 - \alpha}\left(Y_k - \alpha Y_k - 1\right) \quad (2)$$

where Y_k is the streamflow on day k, Q_k the base flow on day k and α is a parameter that was usually taken between 0.925 and 0.95.

The Eckhardt (2005) filter, provided in the WHAT tool (Lim et al., 2005), is a generalization of one-parameter filters:

$$Q_k = \frac{a}{1+C} Q_{k-1} + \frac{C}{1+C} Y_k, \qquad (3)$$
$$\text{with } C = \frac{(1 - a)\,BFI_{max}}{1 - BFI_{max}}$$

Its two parameters are the recession constant (a), which can be estimated in a recession analysis, and the value of the maximum baseflow index (BFI_{max}) that can be determined by using an automated recession curve analysis.

The Recess/Rora graphical method (Rutledge, 1998) is based on the principle that, in many cases, individual recession curves can be compiled, providing an average characterization of the flow called the master recession curve (MRC). According to Nathan and McMahon (1990), recession rates are strongly influenced by the antecedent conditions of the system, and thus the MRC would represent the most probable recession scenario under a given condition. The Rutledge (1998) method is a semi-automated procedure, that 1) uses a repetitive interactive technique for selecting several periods (segments) of continuous recession, 2) determines a best-fit equation for the rate of recession as a function of log Q using a recession index[1], and 3) uses the coefficients of this equation to derive the MRC, a second-order polynomial expression of time versus log Q. A recession-curve displacement method is used to estimate the recharge for each peak in the streamflow record. Since the streamflow at the beginning of the recession period is mostly related to surface runoff, the corresponding data should not be used and a critical time is defined, based on the recession index. Hence, the MRC is applied after this critical time.

Ten gauging stations are listed within, or very close to, the study area. These stations have histories of recorded data varying from eight to 45 years, and half of them have records dating back to 1915–1916 (although measurements were stopped between 1919 and 1946). Watershed areas vary widely, from less than 9 km^2 to 1020 km^2. Only three stations have data up to 2007, of which one was only initiated in 2000. Therefore, only four stations appeared to be of interest for this study. They are: 01DC005, 01DC006, 01DC007, and 01DD004. However, stations 01DD005 and 01DC001 were kept as no other stations were available at both ends of the valley. Station 01DC003 was also kept despite the fact that the station was closed in 1949, as the series spans 34 years. Locations of these stations are illustrated in Figure 9. Only the three stations with the most usable data (01DC005, 01DC007, and 01DD004) were kept for the graphical method as this method requires several important rain events to be representative. The Eckhardt (2005) method was applied only to gauging station 01DC007, which is the station that covers the largest drainage area (64% of the Annapolis watershed).

River hydrographs have also been obtained from Agriculture and Agri-Food Canada (AAFC) and Nova Scotia Agricultural College (NSAC) for five stations located on Thomas Brook. Data were, however, usually available only from May or late April to October. The only station having a nearly complete year is the downstream station 5, at the watershed outlet, for 2005.

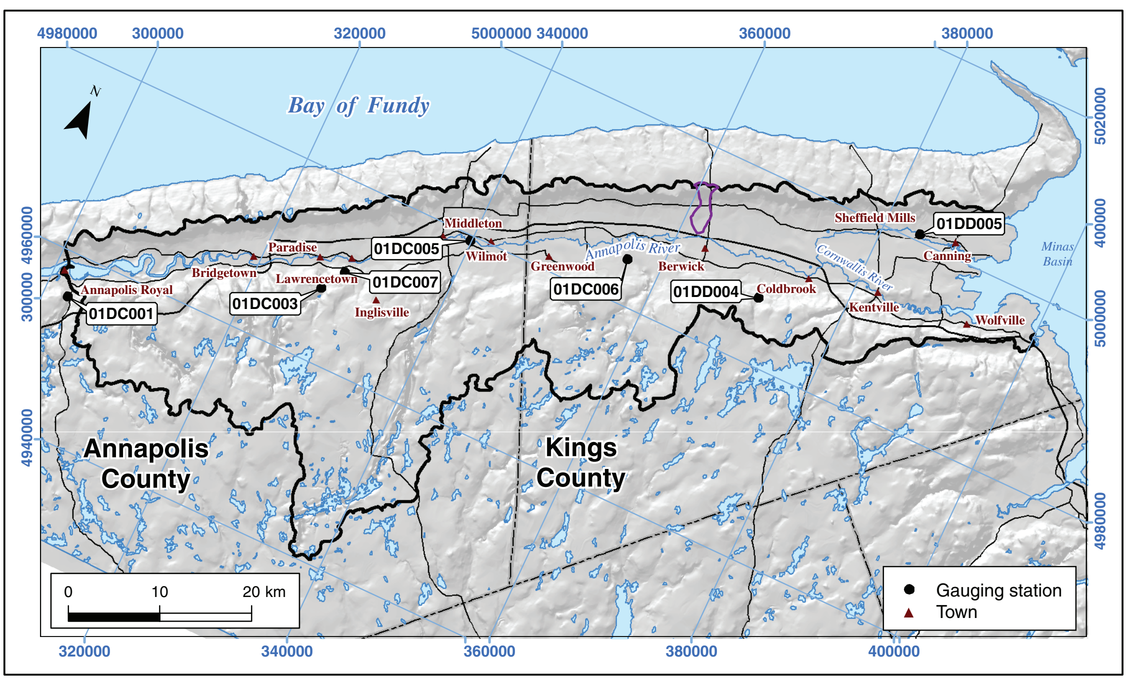


Figure 9. Locations of gauging stations of interest in the study area.

[1] The recession index (K) corresponds to the time per log cycle of streamflow recession and is defined to be linearly related to log Q. In step 2, the recession indexes of each nearly linear segment of recession periods are used to determine the best linear fit of the 'global' recession index.

Water-balance method

The general formulation of the hydrological budget used to evaluate the aquifer recharge (*W*) in the ACVAS project is:

$$W = (P - R) - ETR - \Delta RAS \quad (4)$$

where P is precipitation (mm), R is surface runoff (mm), ETR is real evapotranspiration (mm), and Δ RAS is the variation of the available water in soils for the plants (mm).

The period for this hydrological budget was selected according to the availability of the daily measurements for precipitation and temperature parameters. Two weather stations were selected at first for their long and continuous series: 1) Greenwood-8202000 at the centre of the valley, and 2) Springfield-8205200 on South Mountain (slightly outside the study area). However, first runs confirmed that the second station was not representative enough of the valley conditions (but rather typical of the highlands) and was thus rejected. Several other stations were available, but their historical series were much shorter and the missing daily measurements were too numerous for the 'statistical filling' (using statistical regression) to be realistic. However, comparison between incomplete temporal series and the selected station (Greenwood) in different areas showed that the latter was reasonably representative of other stations in the study area.

The period used for the estimation of recharge extended from 1983 to 2002 (20 years). The hydrological budget was calculated on a daily basis. Only the potential evapotranspiration (ETP) was estimated on a monthly basis (due to the method used), before being downscaled to a daily basis for the rest of the calculations.

Runoff was estimated based on the Soil Conservation Service (SCS, United States Department of Agriculture, 1985) method modified by Monfet (1979). Indeed, modifications implemented by Monfet allow a more reliable estimation of runoff in watersheds that have a short concentration time (for instance watersheds with abrupt slopes or of a limited size). Its application requires collecting data on a daily basis. The SCS method allows the prediction of the volume of water flowing as runoff down to a stream, following a major rain event. The SCS method was originally developed to get an evaluation of this parameter throughout the United States. Therefore, the watersheds used were quite large, and not quite representative of the eastern Canada conditions. In his study, Monfet (1979) modified the SCS method based on Quebec conditions. It was hypothesized that the Quebec conditions were fairly close to those of the Maritimes. Validation of the curves confirmed that these modifications significantly improved the estimates compared to the original SCS method results. Indeed, a run performed using a small subwatershed within the Annapolis Valley provided very similar values of runoff to those obtained using the hydrograph-separation approach, while the original SCS method provided results that were much too small.

The SCS method needs the following information: soil characteristics, land use, hydrological conditions (quality of the vegetation with respect to the runoff potential), prior conditions of soil humidity, and slope. Soil characteristic classes were selected according to their drainage quality (infiltration capacity), based mainly on the soil texture and thickness reported on the soil maps (Soil Landscapes of Canada, 2005), and by calibration using values obtained with the hydrograph-separation method. Indeed, because of the difficulty of making correspondences between the drainage quality from the soil maps and the soil classes of the SCS method, an adjustment by trial and error had to be performed to find the classes. This adjustment took into account:

- the runoff/precipitation ratio estimated using river hydrograph separation on some limited river segments;
- the limited thickness of Quaternary deposits in many areas (0–5 m).

Soils were generally classified as thin and/or poorly drained.

A 'poor' hydrological condition was used in order to favour runoff, based on the study area features. Indeed, the study area appears to be poorly drained, as many lakes and peatlands are present. Classes for slopes were determined using the digital elevation model (DEM) from Geomatics Canada. Once classes were determined, a SCS number was attributed to each cell. Based on precipitation and the SCS curve number modified by Monfet, runoff was evaluated. To simplify the calculation snow precipitation was considered instantaneously available, although melting occurs only four to eight times on average per winter due to the valley microclimate. Slope classes were selected based on the DEM. The SCS method provides numbers for the various combinations of soils, soil covers, hydrological conditions, and slopes (Monfet, 1979).

Potential evapotranspiration (ETP) was estimated with the Thornthwaite method, using monthly averages for the air temperature and the latitude of the weather station. The daily real evapotranspiration (ETR) values were estimated by taking the minimum between ETP and the infiltration plus the ready available supply prior to the day of the estimation (RAS_{prior}, *see* Appendix D for more details). Parameters required for the RAS coefficient (variation of the available water in soils for the plants) were determined from the soil and land use maps (and coefficients taken from tables of a publication from the South Jersey Research Conservation and Development Council, Inc.:

http://www.sjrcd.org/ag/effective_root_zone.htm.)

The spatial resolution was 500 m × 500 m over the whole study area. This size was selected to obtain a reasonable number of cells without losing precision on each parameter. A numerical code was developed in C++ to automate the process.

Specific yields

The inherent difficulty of estimating recharge using well hydrographs resides in the determination of the specific yield (Healy and Cook, 2002). Since no reliable data for the latter was available, groundwater fluctuations were used instead to obtain specific yield estimates based on previously found recharge rates. The equation allowing the calculation of the recharge (W) from groundwater fluctuations is:

$$W = S_y \cdot \Delta h / \Delta t \qquad (5)$$

where S_y is the specific yield (equivalent to the drainage porosity, ne) and Δh is the groundwater-level variation over a given period Δt. This method is applicable for unconfined aquifers only, and is best suited for wells having shallow water tables with large fluctuations (Healy and Cook, 2002). It is based on the premise that rises in groundwater levels in unconfined aquifers are attributable to recharge water reaching the water table. The groundwater-level variation Δh is set equal to the difference between the peak of the rise and low point of the extrapolated antecedent recession curve at the time of the peak. The extrapolation of the antecedent recession curve is the trace that the well hydrograph would have followed in the absence of precipitation.

Out of the 11 monitoring wells available in the Annapolis Valley, only the five wells tapping surficial aquifers were considered unconfined, since bedrock aquifers are often confined in this area and no data confirming their condition was available. These wells are: Coldbrook (1965–1994), Greenwood (1980–2001), Wilmot (1966–1995; 2004–2006), Wolfville 1 (1969–1990), and Wolfville 3 (1971–1995). However, not all years could be used, as many missing data 'holes' are present in these historical series, and the Wolfville 3 well, due to influence of tides, had to be put aside.

The estimation of water-level variation Δh was automated in Excel, using the Posavec et al. (2006) code, since the traditional manual method has the drawback of being time-consuming and subjective. The Posavec et al. (2006) method is based on the automated definition of a master recession curve (MRC), similar to the Rutledge (1998) method for stream hydrograph separation (see 'Hydrographic separation' section). This method utilizes the matching strip method, whereby individual recession segments are plotted and adjusted horizontally until they overlap in the main parts. The MRC is thus constructed by fitting a model function to the set of individual segments to obtain the best fit, adding one segment at a time to the previous 'composite' segment. Recession curves are initially rank-sorted from the highest to the lowest according to the initial value of each linear segment. The Posavec et al. (2006) method offers five different linear and nonlinear (logarithmic, exponential, second-order polynomial, and power) regression models to adjust automatically the recession segments to their proper position in the MRC.

Rock porosity analysis

Area porosity percentages for thin sections of the Blomidon Formation and the Wolfville Formation were evaluated using samples from the GAV-77–2 drill core located close to Greenwood (in the middle of the valley). The core is over 580 m in length, was spudded into the North Mountain basalt, and penetrated about 60 m into the Wolfville Formation. In this core, the Wolfville Formation consists primarily of massive, horizontally laminated, fine- to medium-grained sandstone and mudstone, with minor coarsening-upwards sequences. Conversely, the Blomidon Formation consists of red, calcareous, massive mudstone and associated minor fine- to medium-grained sandstone, interpreted as playa lake deposits. For the Blomidon Formation thin sections, an attempt was made to sample the sandier facies and one typical fine-grained mudstone was also sampled. For the Wolfville Formation, both finer grained and coarse-grained sandstone samples were obtained.

Porosity percentages for minimum, maximum, and average values were determined using image manipulation and analysis techniques. Poor penetration of the dyed mounting medium was observed in several examples and thus the porosity could in these cases only be determined for a small portion of the thin section. Theoretical volume porosity values were also provided for comparative purposes. Area determinations were converted to volume determinations using both a cubic and rhombohedral packing model, providing a more realistic portrayal of the range of actual porosity volumes inherent in the samples. The morphology and spatial distribution of porosity development can be evaluated using these images, and anisotropy can be observed.

Thin sections were digitally scanned to get a very high resolution, true-colour digital image of the thin section. The resultant images were exported in .tiff format to maintain image quality, and then imported into Corel PhotoPaint (version 9) and were 'masked'. Using the masking function, the pore space in the images was made completely black and the background white. These images were then exported in .jpg format, which dramatically reduced their data size but maintained image resolution. Subsequently, the .jpg images were opened using UTHSCSA ImageTool Version 2.0 Alpha 3, and then converted to a grey-scale image. This was done to simplify the discrimination process as grey scale uses a linear scale of 256 shades in which quantification of a binomial distribution (pores or not pores) is easily made.

As area porosity percentages are not adequate for investigating fluid-movement dynamics, volume estimates of the porosity were calculated. Mathematically, the maximum area porosity possible for perfectly spherical, cubically packed sandstone is 21.5%, whereas the maximum volume porosity is 47.6%. Therefore if the area porosity percentage is known, the corresponding theoretical maximum volume porosity can be estimated by multiplying it by 2.22. To obtain the minimum estimated volume porosity percentage, it is necessary to assume that rhombohedral packing has taken place. Following the same reasoning outlined above, spherically packed sandstone will theoretically have minimum volume porosity of

25.9%. Thus given the area porosity calculated for each thin section, the estimated volume porosity can be calculated by multiplying by 1.21. *See* Spooner (unpub. rept., 2006) for more details.

GEOLOGICAL CONTEXT

The overall bedrock geology of the Annapolis Valley is relatively well known and its architecture is considered to be rather simple compared to neighbouring areas. In contrast, the surficial geology of this area is very complex and, aside from certain limited areas, had only been the subject of a 1:500 000 scale mapping. It was thus decided to put emphasis on these surficial sediments and their deposition history in order to develop a 1:100 000 scale map coverage for the entire study area.

The most recent regional bedrock geological maps date back to Taylor (1969) and Smitheringale (1973) (though a recent compilation by Keppie (2000) is available). The structural geology, stratigraphy, and tectonic history of the Bay of Fundy Basin were compiled by Wade et al. (1996). Despite the relative simplicity of the valley's geological setting, local- to regional-scale characterization of bedrock units and aquifer/aquitard sequences are poorly known in this area. Using existing data (bedrock maps and well database), near-surface bedrock cross-sections were prepared and percentages of major rock types found in wells were estimated in order to better characterize bedrock lithologies throughout the valley. Regional- and local-scale structures such as faults and major fracture sets, which potentially could have a significant impact on groundwater flow patterns, have not been studied in detail and thus represent an evident drawback to the overall understanding of this area. However, most regional faults documented in bedrock maps of the study area are restricted to the Paleozoic rock succession and do not appear to affect the Mesozoic rocks underlying the Annapolis Valley.

A 3-D geological model was built for the valley, including bedrock and a simplistic surficial deposit layer (*see* 'Three-dimensional geological model' section). This model served as a basis for hydrogeological numerical modelling.

Bedrock

The bedrock units of the Annapolis Valley were deposited within the Fundy Rift basin, which constitutes the largest and northernmost of nine major Triassic rift basins that are preserved onshore along the Appalachian Belt, from South Carolina to Nova Scotia (Manspeizer, 1981; Brown and Grantham, 1992). These Triassic/Jurassic basins are related to the early stages of rifting and basin formation that eventually led to the opening of the Atlantic Ocean. These rock sequences unconformably overlie a collage of Paleozoic rocks which relate to the Appalachian Orogen (Greenough, 1995; Wade et al., 1996).

The Fundy Basin represents a half-graben, bounded to the north by a major syn-sedimentary, south-dipping, listric normal fault system (Cobequid-Chedabucto fault system and other correlative structures beneath the Bay of Fundy). This basin covers an area of about 16 500 km^2, primarily beneath the waters of the Bay of Fundy. The sedimentary sequence is wedge-shaped, thickening and dipping northward toward the Cobequid-Chedabucto Fault, and displays an asymmetric sedimentary-facies distribution consistent with the evolution of half-graben rift segments. For a more detailed review of the geological setting and lithostratigraphy of the Annapolis Valley, refer to Hamblin (2004).

Paleozoic

Paleozoic rocks form the South Mountain highland and the basement beneath Triassic rocks in the Valley. Cambrian to Devonian metasedimentary and Late Devonian granitic rocks (South Mountain Batholith) are dominant in the South Mountains. Southwest of Wolfville, the latest Devonian to Carboniferous sedimentary units of the Horton Group are encountered directly under surficial deposits (Fig. 10). The Lower Paleozoic units comprise the Meguma Group (including the Goldenville and Halifax formations), as well as the Kentville, New Canaan, Torbrook and White Rock formations that are included in the Annapolis Supergroup. The Meguma Group's youngest unit, the Halifax Formation (Lower Ordovician), covers a large region in the southeastern part of the study area and is composed of interbedded slate, siltstone, and quartzite (Trescott, 1968). In the eastern part of the valley, the Meguma Group is unconformably overlain by the Horton Group, which consists in its upper part of shale with interbedded grit and sandstone. Strata are lenticular and crossbedded, typical of Maritimes Basin units. The cross-section A–A′ near Middleton, adapted from Trescott (1968) is presented in Figure 11.

Mesozoic

The Mesozoic rocks of the valley include the Triassic-Jurassic Fundy Group, underlying the valley proper and forming North Mountain. The contact between the deformed Paleozoic rock sequences and the overlying Fundy Group is a high-angle angular unconformity. Locally, a nonconformity characterizes the unconformable contact between the stratified rocks of the Wolfville Formation and the underlying Devonian intrusive rocks (and contact aureole) of the South Mountain Batholith. Although speculated from geophysical data and the morphology of the Annapolis Valley (Keppie, 1977; Zietz et al., 1980), there is no direct evidence for a single, south-bounding regional fault at the contact between the Fundy Group and the Paleozoic rock units to the south of the Annapolis Valley. There are, however, indications that multiple, small, down-to-north faults do occur and offset the unconformable contact between the two rocks sequences (Wade et al., 1996).

The Fundy Group rocks have a stratigraphic thickness varying between 2 and 10 km (increasing northward). The strata dip to the north at approximately 4 to 12°. In Nova Scotia, the Fundy Group comprises, in ascending order: the Wolfville, Blomidon, North Mountain, Scots Bay, and McCoy Brook formations. The upper two formations do not occur in the study area. In the Annapolis Valley, rocks of the Fundy Group outcrop along the North Mountain and near the Minas Basin. Small outcrops are also commonly found along the Annapolis and Cornwallis rivers. The Triassic sediments of the Wolfville and Blomidon formations have a gradational contact, forming a conformable succession.

The Wolfville Formation represents the most important bedrock aquifer of the Annapolis Valley. The Blomidon and the North Mountain formations can also be tapped, but usually with less success (however, few wells have been tested in these formations). Overall, formations of the Fundy Group are fining-upward individually, as well as collectively, so that the higher porosities should be found in lower portions of the group, although higher-order fining-upward cycles of the two main formations and better tracturation may concentrate aquifer potential at certain stratigraphic levels (Hamblin, 2004). More-detailed descriptions of the Wolfville, Blomidon, and North Mountain formations than those presented here are summarized in Hamblin (2004).

Wolfville Formation

The Wolfville Formation, which underlies most of the valley floor, is composed of reddish, thickly bedded, medium- to coarse-grained, arenitic to subarkosic sandstone, with subordinate pebbly and conglomeratic beds whose clasts are derived from the adjacent metamorphic and granitic highlands. Figure 12 shows a typical example of the Wolfville sandstone. The Wolfville Formation is remarkable for its heterogeneity (Crosby, 1962; Taylor, 1969). It is an interbedded and intertonguing complex of crudely stratified rocks of continental (primarily fluvial) origin, typically in lenticular beds. Large-scale crossbedding is present in some locations. Conglomerate units are particularly common near

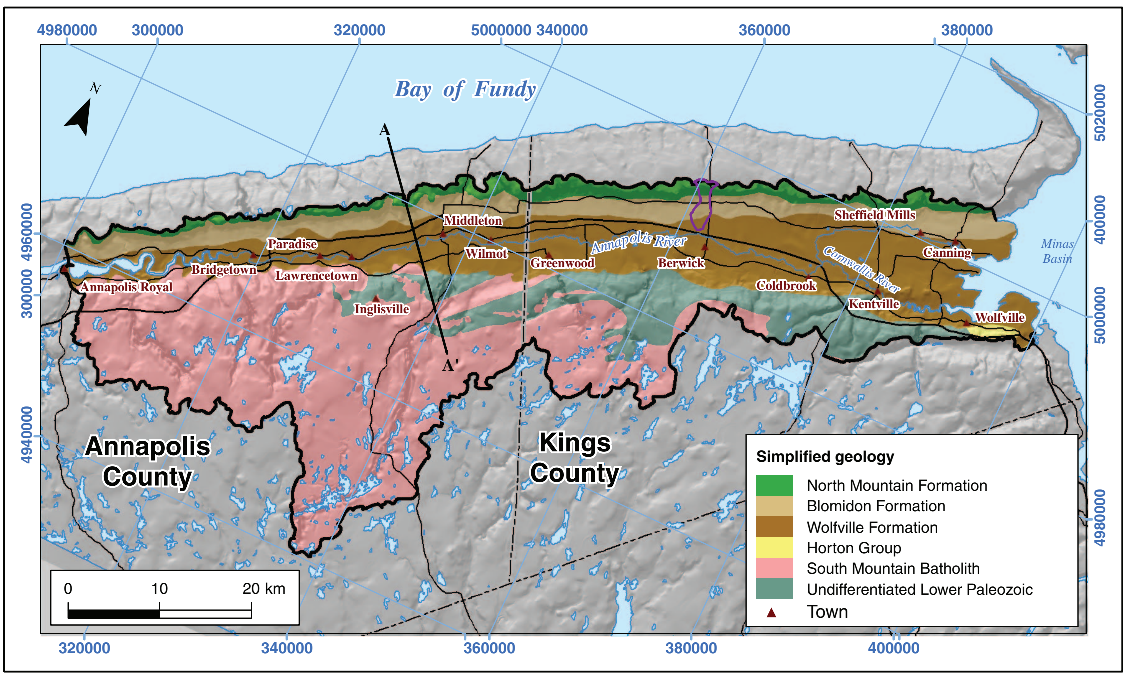


Figure 10. Simplified version of the bedrock geology map by Keppie (2000). The complete map is presented in the atlas on Plate 2.1. Cross-section marked on figure is shown on Figure 11.

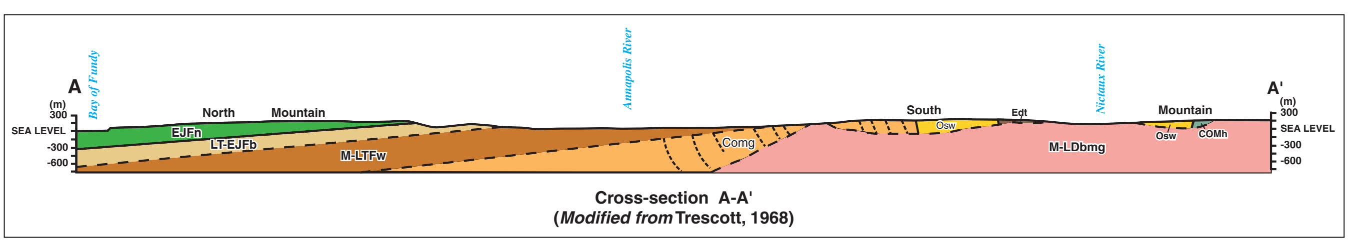


Figure 11. Cross-section A-A′ near Middleton shown in Figure 10, adapted from Trescott (1968). The legend is shown in Figure 10. Formation designations are from the bedrock geology map (Plate 2.1 of the atlas, Rivard et al., 2007).

Figure 12. Wolfville Formation at Kingsport, cliff erosion.

the base of the Wolfville and may constitute 10% of Wolfville rocks (Crosby, 1962; Smitheringale, 1973). Cut-and-fill channelling, and lens-like beds that pinch out laterally over 10 to 100 m are common, as are ripples, mud cracks, and parting lineation. Near the surface, the sandstones and conglomerates are poorly cemented, but they become more consolidated with increasing depth (Thomas, 1974).

Deposition occurred in alluvial fan, fluvial, and aeolian environments, and an overall fining-upward succession is evident (Tanner, 2000). In the Annapolis Valley, fluvial/alluvial paleocurrent data suggest sediment transport (and therefore, linear sandstone aquifer body trends) toward the northwest. The Wolfville Formation unconformably overlies the Lower and Upper Paleozoic rocks which form the deformed basement in the area, and thicknesses of the Wolfville Formation up to 833 m have been reported (Crosby, 1962; Taylor, 1969). Wolfville rocks have been assigned a Late Triassic age. The strata generally dip 5 to 10° northwest toward the Bay of Fundy. Although numerous minor northeast-trending, steeply dipping normal faults occur in the Wolfville Formation, there is no evidence for a large, basin-bounding fault on the south side of the Fundy Rift, suggesting a half-graben asymmetry.

Most fluvial sandstone samples are mineralogically low-rank greywacke (eastern Annapolis Valley), high-rank greywacke (western Annapolis Valley), arkose and orthoquartzite (eastern Annapolis Valley and north shore of Minas Basin), and are texturally submature to mature, and subangular to well rounded (Hamblin, 2004). Calcium carbonate cement ranges from 0 to 55% and averages 14% (Klein, 1962). If aeolian sandstones are present, they should be mineralogically and texturally more mature.

Blomidon Formation

The Late Triassic Blomidon Formation occurs along the southern flank of North Mountain. It conformably overlies (gradational contact) the Wolfville Formation and has a paraconformable contact with the overlying volcanic rocks of the North Mountain Formation. This formation comprises the same lithological types as the Wolfville Formation, but finer grained beds are usually more abundant, especially in its upper section. Figure 13 presents an example of sandy shale from this formation. Gypsum lenses are also common. The Blomidon Formation represents a paleoenvironment that alternated between arid and wet conditions, with the climate becoming progressively wetter from the latest Triassic to earliest Jurassic time (Webster, 2005). Structural and sedimentary features indicate lacustrine and playa/mudflat environments of deposition (Thomas, 1974).

Figure 13. Shales of the Blomidon Formation, near Cape Blomidon, along the Minas Basin.

The Blomidon Formation consists of up to 363 m of sandy mudstone with silty layers interbedded with muddy sandstone (Crosby, 1962; Smitheringale, 1973; Mertz and Hubert, 1990). A significant component of laterally extensive sandstone beds (scour-based, sandy channel units) can also be encountered, especially at the base of the formation. Thick-bedded, siltstone-dominated strata and graded bedding have been identified in the eastern part of the valley. Channelization and crossbedding are common in the western part. The formation can be traced laterally for 150 km northeastward along the Annapolis Valley. In terms of water supply, this formation could be classified as a ‘variable’ aquifer, since its hydraulic potential can vary greatly from place to place.

According to literature, the bulk of Blomidon rocks (70–75%) comprise reddish-brown to greyish-red, poorly sorted sandy mudstone and siltstone beds up to 3 m thick of playa/mudflat origin (Hubert and Hyde, 1982). The remaining portion is made of reddish- or greenish-grey, fine- to coarse-grained sandstone, poorly to moderately sorted, and texturally immature. Mineralogically, the sandstones include low-rank greywacke (western Annapolis Valley), arkose and orthoquartzite (eastern Annapolis Valley), with micaceous matrix averaging 8% and sparry calcite cement averaging 15%, and minor gypsum (Klein, 1962; Mertz and Hubert, 1990).

Strata are arranged into numerous 2 to 12 m fining-upward cycles (attributed to autocyclic channel avulsion or fault-induced subsidence on the adjacent fan), which are in turn arranged into a number of tectonically controlled, fining-upward or coarsening-upward megacycles (attributed to rejuvenation and erosional degradation of the adjacent fault highland, Klein, 1962; Mertz and Hubert, 1990). Near the surface, the sediment is cut by fractures which are stained with manganese oxides (Thomas, 1974). The strata dip 5° NW. The Blomidon Formation is also assigned a Late Triassic age and spans about 20 Ma of time (Hamblin, 2004).

North Mountain Formation

The distinctive, dark-coloured, resistant Early Jurassic North Mountain Formation overlies the Blomidon Formation. It consists of a series of massive and amygdaloidal basalt flows, which form the prominent North Mountain escarpment along the northern side of the valley. The geochemical and isotopic signatures of the tholeiitic basalt flows are very similar to others in the eastern North America flood basalt province and indicate that they were formed during the initial period of extrusion at the time of rifting (Webster, 2005). These North Mountain basalts are cut by north- to northeast-trending faults and fractures that exhibit dextral displacement (Webster, 2005). The cuesta has an angle generally varying between 30 and 45°. Thicknesses up to 427 m have been recorded for this formation (Crosby, 1962). Coastal outcrops are generally good.

A Ph.D. thesis study conducted at Dalhousie University (Webster, 2005) used LIDAR technology, complemented with field observations, to generate a high-resolution DEM in order to study topographical differences and to better define previously identified contacts of three flow units. It was found that each flow unit has distinct topographic signatures visible on the LIDAR-DEM, as well as chemical and physical (e.g. grain-size and structure) properties that result in different resistances to erosion and fracturing patterns. The lower flow unit (LFU) forms the cuesta of the valley; it consists of a thick (40–150 m) massive single flow that shows columnar jointing (Figure 14). The middle flow unit (MFU) conformably overlies the LFU, and consists of multiple thin flows that are highly vesicular and amygdaloidal; it is thus less resistant to erosion than the other two flow units. The upper flow unit (UFU) conformably overlies the MFU, outcrops along the shore, and consists of 1 to 2 massive flows that appear to have a good resistance to erosion. There is no evidence of pillows within any of the flow units. Ring structures present in the LFU were identified, sometimes relocated, and re-interpreted to be a result of the interaction between the partially solidified lava and surface or shallow groundwater based on morphology, petrology, and geochemical data. Indeed, glacial erosion would have excavated the highly fractured cone material, leaving the more resistant dike and quenched melt to form protruding ring structures.

First-order statistical analysis of major rock units

Lithological descriptions in logs of shallow wells that penetrated bedrock provided some information on the overall lithological types of the two main formations of the valley. A series of 10 959 descriptions of bedrock well intervals, totalling 555.7 km from 6 908 wells, were extracted from the database in order to calculate the percentage of main lithological types. Wells were assigned to the formation that they penetrate at surface. The interval descriptions were first analyzed and filtered in order to only obtain the main lithological types. For example, a silty sandstone interval was classified as sandstone. Similar and equivalent descriptions of rock types (in terms of grain size) were grouped (e.g. mudstone, shale, and slate). When two lithologies were provided for an interval (e.g. sandstone and shale), 60% of the interval length was assigned to the first rock type, 40% for the second. If three lithologies were given, the partition of the interval length was as follows: 50%, 30% and 20% for the first, second, and third type, respectively.

The results are as follows:

- Wolfville Formation: 66% sandstone, 29% shale, 4% granite, and 1% siltstone. The granite comes from the bottoms of wells on the southern side of the valley that have perforated the Wolfville contact within the South Mountain Batholith. If granite intervals are removed from calculation, we obtain 69% coarser grained lithologies (sandstone and conglomerate) and 31% finer-grained lithologies (shale and siltstone).
- Blomidon Formation: 74% sandstone, 25% shale, 1% siltstone.

Almost identical numbers were obtained for a similar analysis that was performed using only the wells selected for drawing the cross-sections (Rivard et al., 2007, Plate 2.2) in order to test their representativeness. These results are quite surprising, since the Blomidon Formation is generally described in the literature as containing more fine-grained layers than the Wolfville Formation. This is in part due to the simplified information contained in the provincial databases, but also likely due to the fact that fine-grained strata are more easily eroded and result in depressions of the bedrock topography, now filled with surficial deposits. More-resistant coarser-grained strata are therefore preferentially occurring at depth. More importantly, however, is that the Blomidon Formation has been suggested to be generally coarser grained on the southern side of the Minas Basin and along the Annapolis Valley compared to the northern side of the basin where the frequency and thickness of mudstone beds increases (Klein, 1962; Mertz and Hubert, 1990; Tanner, 2000). The results of our detailed well analysis are a clear indication that, indeed, the Blomidon Formation in the valley contains a larger percentage of sandstone (and therefore a significantly better aquifer potential) than was expected based on the literature review (summarized in Hamblin, 2004). This important new data allows fresh interpretations with notable implications for groundwater assessment. This coarser grained nature of the Blomidon is interpreted to be a result of the location of the Annapolis Valley 1) overlying the stratigraphically lowest part of the Blomidon Formation, and 2) being in close proximity to the original Triassic sediment source area of South Mountain. This could also be partly attributable to the fact that only logs of the most 'interesting' wells are probably kept in databases.

Quaternary

The Quaternary geology and geomorphology of the Annapolis Valley present a high degree of diversity associated with the major depositional systems of glacial settings. Their interactions often result in a series of genetically-related contemporaneous or time-transgressive deposits partly overlying other deposits of different origin and age. Details on the surficial sediments of the entire Annapolis Valley were only available at the 1:500 000 scale (Stea et al., 1992). In addition, parts of the western (Stea and Kennedy, 1998) and the central Valley (Hickox, 1962) were available at the 1:50 000 scale and a portion of the eastern valley had been mapped at the 1:63 360 scale (1 mile = 1 inch, Trescott, 1968).

The 1:100 000 surficial geology map (Paradis et al., 2006) allowed the clarification of several aspects of the Annapolis Valley's glacial-deglacial history, and hence of the 3-D architecture of the surficial deposits. The following subsections follow in part from this improved understanding.

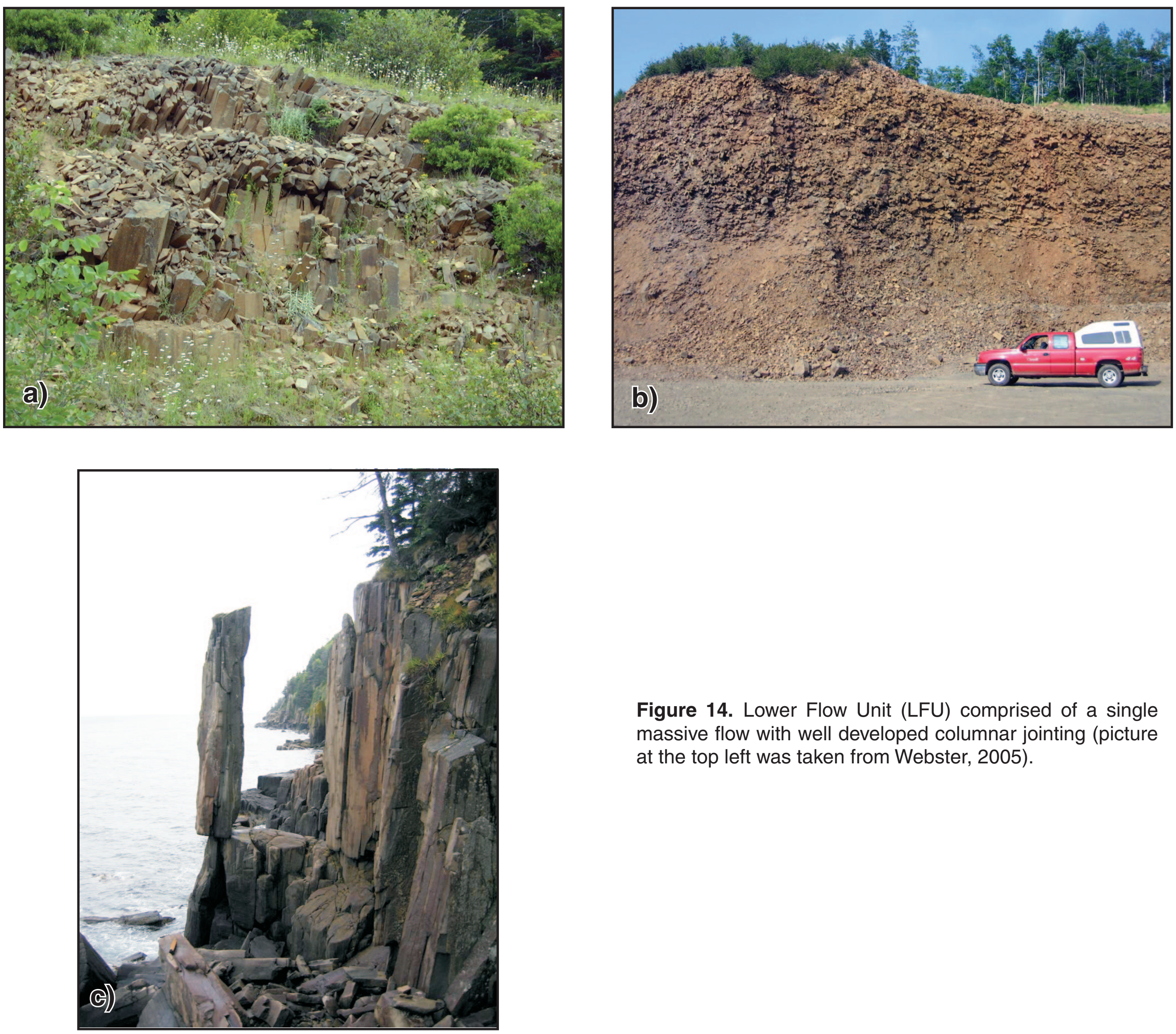


Figure 14. Lower Flow Unit (LFU) comprised of a single massive flow with well developed columnar jointing (picture at the top left was taken from Webster, 2005).

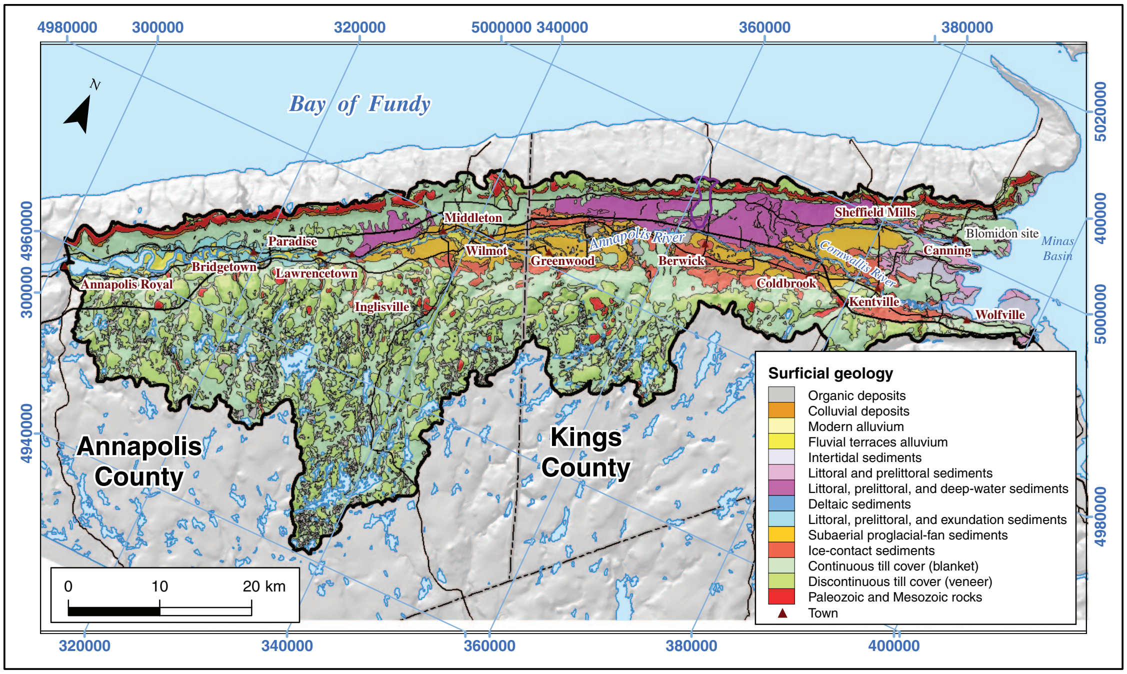


Figure 15. 1:100 000 surficial geology map of the study area (the detailed map is presented in the atlas on Plate 3.1, Rivard et al., 2007).

Figure 15 shows the simplified Quaternary map. The complete map can be found in the atlas (Rivard et al. 2007, Plate 3.1), as details could not be included in this figure.

High-resolution (ca. 4 m) laser altimetry (LIDAR) DEM was used to examine metrics of similarly-sized catchments that have been modified by glaciation (Webster, 2005). Stream-incision depths were related to the variability of the flow unit's resistance to erosion and interpret the dominant processes involved for each flow unit (e.g. abrasion, plucking). Results demonstrated that the till cover is a primary factor in catchment evolution.

Glacial dynamics

The Annapolis Valley has had a complex glacial-deglacial history (Bolduc et al., 2005) that relates to the overall regional story of Nova Scotia (*see* Stea, 2004 for a complete review of ice flows in the Maritimes during the Quaternary). While the valley must have been affected by early Wisconsinan glacial advance (Caledonia phase), we only see evidence for this older flow from some east-southeast-trending striae. Therefore, what appears to be the first, dominant ice-flow event in the valley is the southward Escuminac phase, which is generally associated with the Late Wisconsinan glacial maximum. The Scotian phase (ice-flow reversal following thinning of the ice sheet) and the Chignecto phase (late-glacial ice streaming) are both well represented by glacial striae, dispersal of erratics, and the orientation of landforms. During glacial retreat, proglacial lakes were dammed to at least 80 m a.s.l. in the central and eastern part of the valley, while the western part was connected to the Bay of Fundy via Digby Neck. A prolonged period of climatic warming and ice-retreat postdating the Chignecto phase was followed by an abrupt and pronounced phase of climatic cooling dated just before 11 ka (Collins Pond Phase – Younger Dryas). During a relative sea level lowstand at –30 to –60 m at 11 ka, glaciers were reactivated, and a series of proglacial lakes were blocked along the southern and western edges of the Minas Basin. This lacustrine paleoenvironment is well documented at the Blomidon site and at other sites within the Minas Basin.

New ice-flow orientations were recorded at 13 sites in the area, on slates and granites on South Mountain, and on North Mountain basalts. The rare and weathered outcrops on the valley floor are not very good at preserving striae. All together, through the years, striae have been measured by different authors in the Annapolis Valley area at a total of 67 sites. Three main ice-flow orientations were measured. The oldest one clusters at 110 and 160°, the intermediate between 305 and 350°, and the youngest around 240°. We suggest the first cluster can be further separated to attribute the more eastward striae to Caledonia-phase ice, and the more southern striae to Escuminac phase. The second cluster represents migration of Scotian-phase ice, and the third cluster is Chignecto-phase ice. Figure 16 summarizes the identified iced-flow orientations in the valley and Figure 17 presents examples of ice-flow striae found in different areas of the study area.

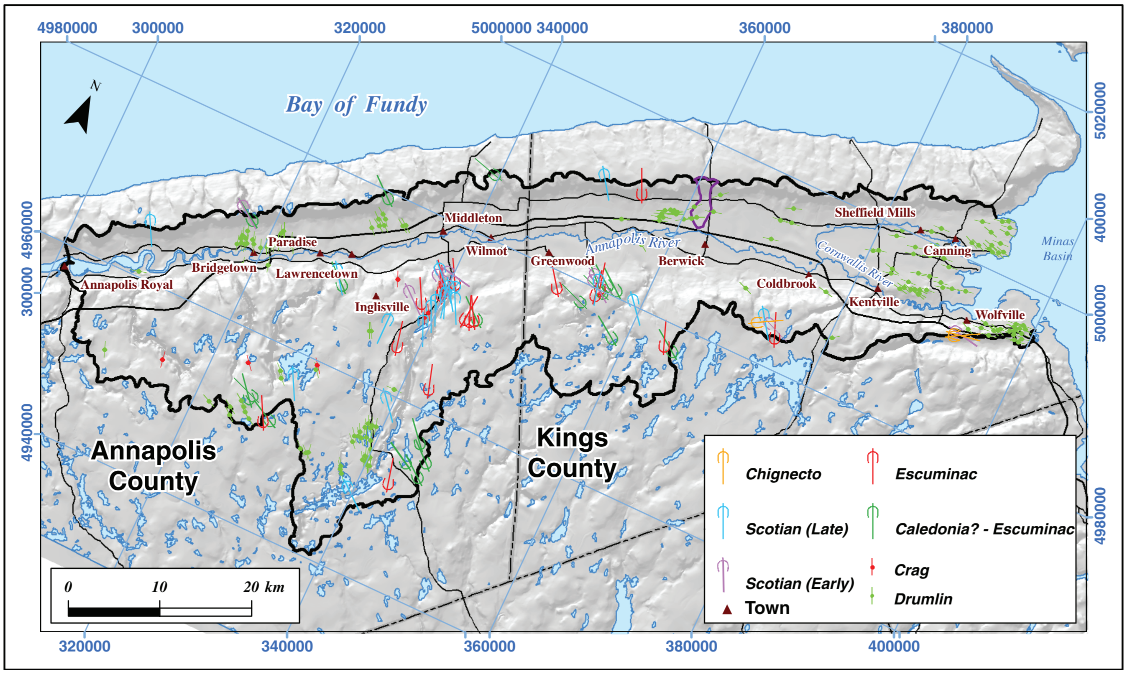


Figure 16. Ice-flow orientations recorded in the Annapolis Valley.

Figure 17. Striae associated with either Caledonian or Escuminac ice flow (**a**, **b**1, **c**1), Scotian ice flow (b2), and Chignecto ice flow (c2).

Caledonia-phase ice

The first (oldest) ice movement toward the east-southeast (110°) can be associated with the Wisconsinan glacial advance Caledonia phase (75 000–30 000 years BP). This flow pattern relates to an extensive ice sheet that eroded the tops of all highlands areas in Maritime Canada. Mature tills (overconsolidated, matrix rich – McCarron Brook Till, Hartlen Till, Milford Till; cf. Williams et al., 1985) are linked to this east and southeast flow through till fabrics and provenance studies (Rampton et al., 1984; Pronk et al., 1989; Lamothe, 1992). This ice flow appears to have lasted most of the Wisconsinan (Stea, 2004).

Escuminac-phase ice

The second oldest ice movement toward the south-southeast (160°) can be associated with the late-glacial maximum Escuminac phase (20 000 years BP). A red muddy till sheet (Lawrencetown Till) is associated with this movement, the provenance of which is partly local (erosion of the red Triassic Fundy Group bedrock) and partly from the Carboniferous red beds of New Brunswick, Prince Edward Island, or the Magdalen Shelf. This late Wisconsinan Escuminac phase appears to have crossed the 300 m high Cobequid and Caledonia Highlands, all the way to the continental shelf edge, partly as ice-streaming. In the valley, this phase is recorded on outcrops on both the North and South mountains, but not on the soft rocks of the valley floor.

Scotian-phase ice

Due to rapid thinning of the ice sheet during late glacial time, Nova Scotia-based ice caps began to flow independently during the Scotian phase (18 000 years BP) and ice-flow reversals occurred over certain areas. The event is recorded by northwest-trending striae (280–350°) on South Mountain, as well as by the presence of South Mountain erratics on North Mountain. The large span of recorded directions (70°) of this ice flow can probably be explained by the migration of the ice dispersal centre from east-central Nova Scotia to west-central Nova Scotia. A grey till was also formed by this northward flow as the ice eroded South Mountain granites. The Beaver River Till is found extensively as a discontinuous 2 to 3 m sheet over South Mountain. The debris were transported to at least the edge of North Mountain, where it was found above the red till of the previous Escuminac and Caledonia Phase tills. Southeastward-oriented striae were found in erosional stratigraphic relationship with the northwestward-oriented striae at two locations. They clearly indicated age relationships between these phases: flow to the south followed by flow to the north. South-north-oriented streamlined landforms on the valley floor west of Middleton are interpreted by Webster (2003) as having been formed by the Scotian ice flow.

Early deglaciation

As climatic conditions warmed, ice retreated and the isostatically depressed western Annapolis Valley underwent marine inundation via Digby Neck northwest of Annapolis Royal. This interpretation is backed by the discovery of shell-bearing clays in the Middleton area (Bailey, 1898). However, these clays were not seen in the course of this work, and the shells remain undated. Stratigraphic reconstructions suggest that these clays, interpreted by Hickox (1962) as estuarine clays, are overlain by a fluvioglacial sequence of very late glacial age. Their presence, however, requires that the ice retreated from the area to an unknown location east of Middleton. Complete deglaciation of the valley is unlikely, as there is no evidence of early marine inundation in the eastern valley.

The presence of these shell-bearing clays is a puzzle in the paleogeographic reconstructions of the valley that needs further investigation. The quarry in which these clays were apparently found is at 15 m a.s.l. (Hickox, 1962) and the highest marine shorelines in the area are found at about 30 m a.s.l., at the same elevation as those found in the Bay of Fundy (Stea and Kennedy, 1998). If the clays are estuarine as suggested by Hickox (1962), they were of a surprisingly good quality to allow for brick-making. Where these fit in the general glacial-retreat story is still open to discussion. Buried organic layers have been documented in some stream sections near Bridgetown (Stea and Kennedy, 1998), but have yet to be dated. We assume that their presence suggests that the climate improved substantially before deteriorating during the Younger Dryas (Mott, 1994), as is indicated by other buried peat layers south of Middleton (11,200 ± 100 y BP, E. Nielsen *in* Lowdon and Blake, 1975). This climatic deterioration promoted the growth of local ice caps that blocked the surface drainage and led to the development of proglacial lakes in front of the re-advancing glaciers. The final ice flow recorded in the valley associated with westward ice streaming is contemporaneous to the Chignecto ice streaming phase.

Chignecto-phase ice

If the youngest ice flow is contemporaneous with the Chignecto phase (13 000 years BP), then it records westward flow from an ice-dispersal centre located in the Cobequid Highlands of central Nova Scotia. Ice accumulated in the Minas Basin and was forced to flow on either side of North Mountain, a major ice stream developing in the Bay of Fundy while a smaller one was entrained parallel to it in the Annapolis Valley. West-trending landforms on the valley floor and a few scattered westward striae observed on the flanks and top of the surrounding mountains are evidence of this ice flow.

The ice stream progressed to about the location of Middleton, where westward striae are found as well as late eskers oriented westward. It is believed that the proglacial lake that developed in front of the advancing ice stream drained through some deeply incised valleys north of Middleton into the Bay of Fundy, the sediments producing what is known as the Margaretsville delta (Stea et al., 1992). The ice continued to pile up and finally overtopped North Mountain. Kame deposits mark the final position of the ice on North Mountain. There is no evidence that the ice advanced any further west than Middleton. Final deglaciation started, and some proglacial lakes developed between the ice margin to the south and the southern flank of North Mountain.

Because the ice did not readvance any further than Middleton, and drainage is to the southwest, proglacial lakes could not be blocked in the Annapolis Royal area. Sediments attributed to a glaciolacustrine episode near Bridgetown (Purdy, 1951) are, in our view, best reinterpreted as paramarine in origin. These sediments may be contemporaneous with or younger than the buried marine clays at Middleton. Because these sediments are found below 30 m, which is the maximum marine limit in the Bay of Fundy (Stea and Kennedy, 1998), we believe that there was a connection between the Annapolis Basin and the open ocean via Digby Neck. The influence of fresh meltwater was, however important, as the connection to the ocean was narrow. Denser marine waters probably sank to the bottom of the basin while the surface layer was brackish to fresh. The use of the term paramarine, after Occhietti (1980), emphasizes that the conditions were neither truly marine, nor truly freshwater. There is evidence of the extension of this paramarine basin eastward to Middleton, where shorelines carved in till are clearly visible at 30 m a.s.l.

Between Middleton and Greenwood, an ice dam must have been present, impeding drainage to the west and allowing the formation of a proglacial lake in the upper reaches of the Annapolis Valley. The shoreline of this lake, at about 80 m a.s.l., is recognized on the southern flank of North Mountain. The lack of equivalent shorelines on South Mountain suggests that the lake was in contact with the ice during its entire duration. Rhythmites were found in an active sand pit near Coldbrook, clearly indicating the relationship between the underlying fluvioglacial sediments and the glaciolacustrine sediments above. We also recognize a nearshore facies that superficially resembles a silty pebbly till. This is similar to those sediments associated with the paramarine basin in the Lawrencetown-Middleton area. We believe this unit was misidentified by Trescott (1968) as till because of the numerous pebbles, some striated, found at the surface (Fig. 18a). When this material is exposed in sections, it consists of massive silty clays without pebbles (Fig. 18b). We think the pebbles are the result of wave washing of the adjacent tills on North Mountain or protruding streamlined landforms, as well as deposition by ice rafting.

The lake itself could have initially drained on ice toward Annapolis Royal basin and perhaps even all the way to the open ocean via Digby Neck or toward the Bay of Fundy as no outlets are found at 80 m elevation. A lower outlet toward Minas Basin is cut at 50 m elevation in the till flanking North Mountain. Final collapse of the ice drained the lake completely and allowed marine waters to invade the lower reaches of the Cornwallis, Canard, Pereau, and Habitant rivers. Marine clays occupy all areas below 15 to 20 m a.s.l. These must have been estuarine environments that even today would be subjected to tidal processes if the rivers had not been dyked.

Younger Dryas

A prolonged period of climatic warming and ice retreat postdating the Chignecto phase was followed by an abrupt and pronounced phase of climatic cooling dated just before 11 ka (Collins Pond Phase – Younger Dryas). During a relative sea-level lowstand at −30 to −60 m at 11 ka, glaciers

Figure 18. Glaciolacustrine sediments **a)** Field exposure showing pebbles at the surface, **b)** Section exposure showing the silty nature of the deposit.

were reactivated, and a series of proglacial lakes were blocked along the southern and western edge of the Minas Basin. This lacustrine paleoenvironment is well documented at about 30 sites within Nova Scotia and immediate surroundings, with glaciogenic deposits overlying organic beds. The Blomidon site, located at an elevation of 30 m a.s.l. on the southeast slope of North Mountain overlooking the Annapolis Valley and Minas Basin, is one of them. This site shows a basal silty diamicton (till) overlain by sand containing organic seams in its upper part. A peat layer 20 to 40 cm thick that grades upward into silt and clay with organic seams is overlain by up to 2 m of sand with gravelly and silty layers (Stea et al., 1992). The sand has normally graded beds, some of which are faintly ripple laminated.

Three radiocarbon dates were obtained from the organic unit. The basal 3 cm produced a date of 11 700 ± 110 BP and the top 2 cm a date of 10 600 ± 90 BP. An intermediate date on pollen changes was 11 200 ± 100 BP (Stea et al. 1992). Based on the detailed pollen analysis, Mott and Stea (1993) have interpreted the Blomidon site as follows. Following deglaciation prior to 11 700 BP, first silty clay and then peat began to accumulate in a shallow, wet depression on the seaward-sloping plain. The sedge meadow and surroundings supported abundant willow growth as seen by the pollen and by twigs found throughout the peat. Shrub birch then became dominant in the area as spruce trees began to arrive. By 11 200 BP, spruce formed open woodlands, followed by reversion to a shrub birch, then to a willow- and herb-dominated environment, indicating a subsequent climatic cooling. Mineral input increased after 10 600 BP and eventually buried the site with sand, the genesis of which is equivocal.

Following the 2005 fieldwork, six samples of unconsolidated material were sent for identification of macroscopic plant remains (Larouche, unpub. rept., 2006). Three samples represented the glaciomarine environment from the western part of the Annapolis Valley (Annapolis River area): one of them was from the paleo-proglacial-lakes of the central Annapolis Valley (Lawrencetown-Greenwood sector) and two were from the Blomidon site. Except for the peat sample from Blomidon, no contemporaneous plant remains were identified. Nine samples of unconsolidated material were sent for microfaunal analyses (Guilbault, unpub. rept., 2006). Of the nine samples, four represented the glaciomarine environment from the western part of the Annapolis Valley (Annapolis River area); four were from the paleo proglacial lakes of the central Annapolis Valley (Lawrencetown-Greenwood sector) and one was from the Blomidon site, above the peat. After analysis, no significant micro fauna was found in any of the samples. It is therefore impossible to discriminate the origin of the different water bodies as being marine or lacustrine, but the sparsity of organic remains, macroscopic or microscopic, favours the lacustrine-environment hypothesis. This is very important for the Blomidon site. Based on our general knowledge of the paleoenvironment of the different sites around the Minas Basin, we can assume that following the abrupt and pronounced phase of climatic cooling dated just before 11 ka, glaciers formed and readvanced during the Younger Dryas in Nova Scotia (Fig. 19). This readvance caused the ponding of short lived paleo-proglacial lakes at different places around the Minas Basin, and the Blomidon site is characteristic of such a site.

Final deglaciation and recent landscape

After the Younger Dryas, ice completely retreated from the Minas Basin as climate improved to today's conditions. Rise in sea level to modern day, combined with the exceptional tidal range in the Bay of Fundy, is responsible for

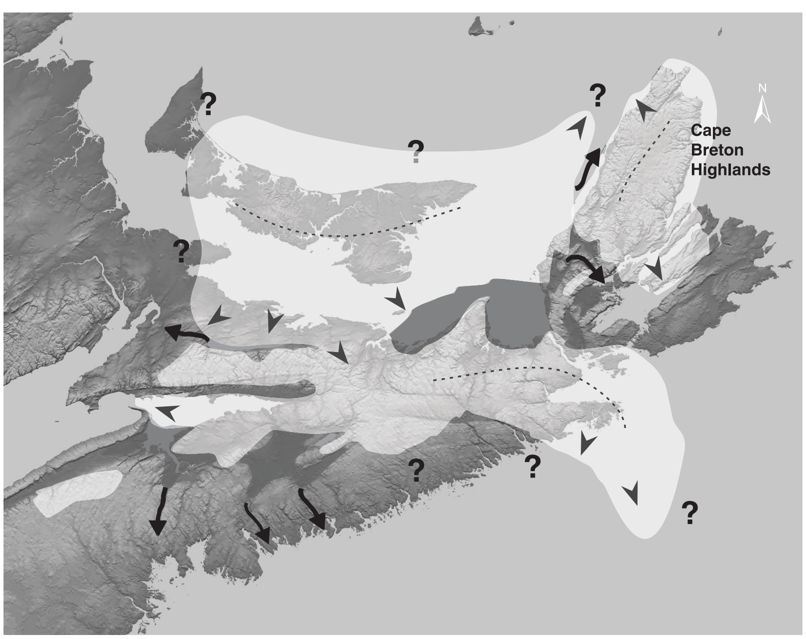


Figure 19. Reconstruction of Younger Dryas ice margins in the Gulf of St. Lawrence and environs. Light-shaded areas are ice sheets; dark-shaded areas represent ice marginal glacial lakes, and arrows meltwater spillways. Modified from Stea and Mott (2005).

inundation of the lowlands along the major rivers draining the valley. As aforementioned, modern settlement in the 17th century by the Acadians modified the landscape by dyking the lowlands to reclaim farmland.

Sediment distribution and composition

The Quaternary sediments in the study area consist mostly of tills, ice-contact glaciofluvial sands and gravels, and glaciomarine and/or glaciolacustrine clays of variable thickness. Till is the most widespread glacial deposit, but the largest mass of glacial materials may be of glaciofluvial origin (Trescott, 1968). The till composition is the result of the different ice-flow phases described above, and is also related to the underlying bedrock lithology. Deposits are thinner in the upland areas (rarely exceeding 10 m), and thicker in the valley (up to 20 m). However, they could reach 60 m in some bedrock depressions. Most of the surficial sediments were deposited during the last glacial/deglacial episode.

Available previous work (e.g. Hickox, 1962; Trescott, 1968; Stea and Kennedy, 1998), as well as limited recent investigations, suggests the presence of west-trending glaciofluvial morphosequences consisting of ice-contact and proglacial deposits. Across the valley and from east to west, kames, kame terraces, and eskers grade into, and are partly overlain by, outwash plain and outwash fan sediments. The latter sediments are in turn interfingered with more distal, and thus finer-grained, glaciolacustrine/glaciomarine sediments in the Bridgetown area. The morphosequences of ice-contact and outwash sediments imply that the late glacial westward ice-flow phase (Chignecto Phase) extended to the area of Middleton.

In particular, the middle and eastern portions of the Valley are generally covered by ice-proximal/ice-contact sandy sediments. However, some ice-contact deposits are also present along secondary depressions near the Minas Basin, in many of the tributary valleys along South Mountain, and scattered along North Mountain (Trescott, 1968). In general, the sediments are sandier and better sorted in the centre of the valley, whereas gravel and boulders are found along the flank of South Mountain (Trescott, 1968). An extensive outwash plain occupies much of the central part of the valley between Berwick and Lawrencetown. Outwash sediments usually consist of well stratified and crossbedded fine-grained to coarse-grained sand.

As is often the case, eskers appear to be controlled by depressions in the bedrock. Available data indicate that till is frequently lacking along these depressions, suggesting that meltwater eroded most of the pre-existing glacial sediments along these narrow conduits. Kames and other ice-contact deposits are closely associated spatially with eskers, forming complex and sometimes large and continuous glaciofluvial ridges in the eastern part of the valley. This likely implies controlled deposition, reflecting former subglacial, englacial, and supraglacial debris concentrations, crevasse patterns, and/or drainage systems.

Glaciolacustrine rhythmites have recently been observed in an active sand pit near Coldbrook. At that location, they overlie ice-contact deposits, but, because of the sand extraction activities, it is unknown whether they were overlain by any other sediments. Their regional extent and paleogeographic significance are still poorly understood. They could be related to a local ice-dammed lake or to a more extensive lake that covered part of the eastern side of the valley. Available data tend to indicate a limited extent. Large areas of the valley floor are covered by a silty clay of glaciomarine origin (west of Lawrencetown) or glaciolacustrine origin (north of Berwick). The ends of the valley are dominated by intertidal sediments that are no longer active, due to the dyking system.

Surficial deposits of the study area are generally not good aquifers, even when sand is dominant, as they are thin, except in the eastern part of the Annapolis Valley. Indeed, the saturated thickness of the thicker sand units is usually not important. Nevertheless, surficial deposits have a key role in the hydrogeology of the valley, both for aquifer recharge and vulnerability to contamination. In particular, the glaciolacustrine silty-clayey units that act as protective layers against surface contamination (but also hinder infiltration), were investigated, because their lateral and vertical extents were not well known. The area covered by glaciolacustrine fine-grained sediments is more or less 150 km^2 between Centreville and Greenwood, on the north side of the valley. Observed thicknesses are of a few metres, and borehole information suggests maximum thickness of less than 10 m.

The surficial 'story' is supplemented by limited subsurface information. From preliminary geomodelling using archival borehole data performed in the first year of the project, thicknesses of up to 60 m had been found in certain areas in the eastern part of the valley, and buried valleys with good aquifer potential were thus suspected. These areas were therefore the targets of geophysical investigations and rotopercussion sounding system (RPSS) soundings. However, both techniques found evidence of sediment depths reaching at most 30 m, but usually less (10–15 m). The model was thus modified accordingly (*see* Fig. 21). The stratigraphy in those areas remains uncertain, due to similar velocities between the altered bedrock (Wolfville Formation) and the local till, making it hard to distinguish them using seismic methods. The altered bedrock being very soft, as has been documented in surface exposures south of Greenwood, conventional drilling may describe the unit as 'sand' rather than bedrock.

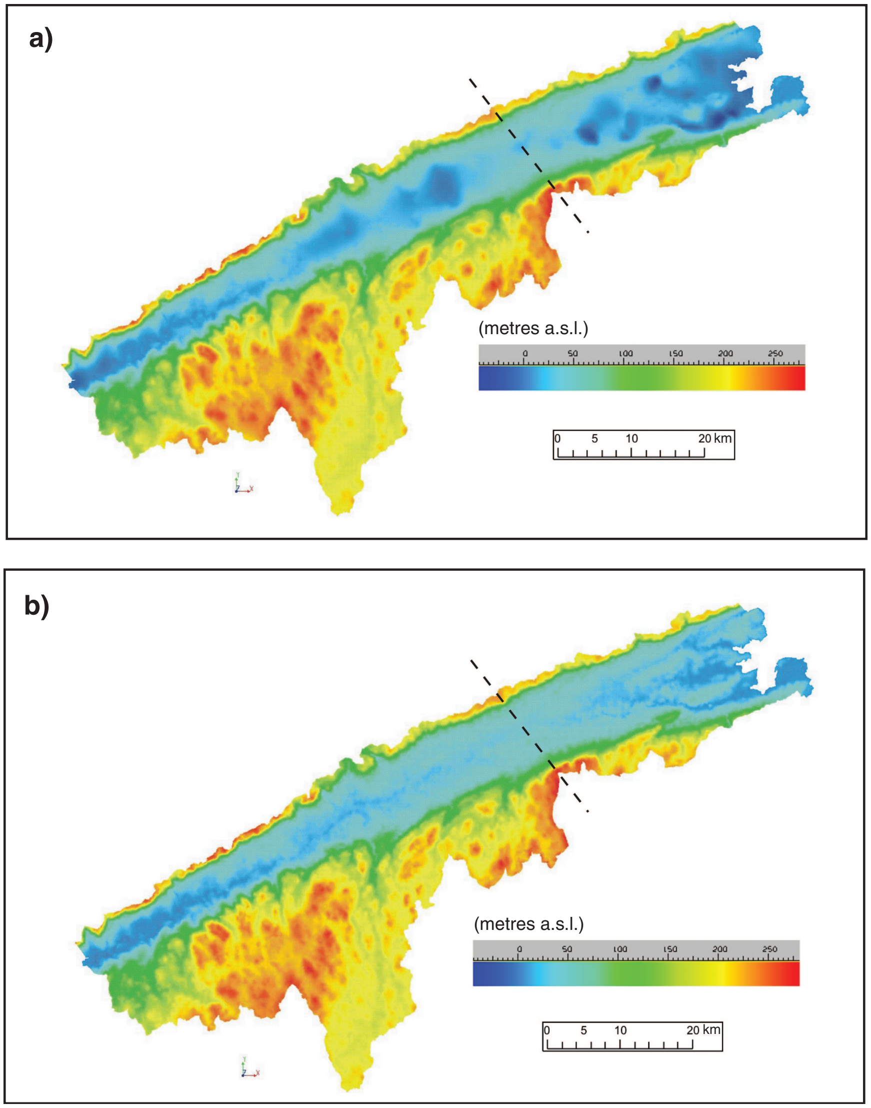


Figure 20. Bedrock topography model **a)** and present-day digital elevation model **b)**. Both are colour-coded with the same parameters. The dashed line on each model is the approximate location of the boundary between the Annapolis and the Cornwallis watersheds. Note that this has not changed substantially from preglacial **a)** to modern **b)** time.

Three-dimensional geological model

A 3-D geological model was developed, integrating map information from Keppie (2000), Trescott (1968), and Paradis et al. (2006). It also integrated log information from Nova Scotia Environment (NSE), Department of Transportation and Public Works and Nova Scotia Department of Natural Resources (NSDNR), as well as constraints from our own borehole data. Because the quality of the information from well logs directly influences the modelling, the well-log database was screened for accuracy of location and of stratigraphic information.

Wells from NSE (groundwater observation wells from the monitoring network), the Department of Transportation and Public Works, and NSDNR are located with fair precision using information contained in the original reports. Those were kept for the 3-D geological modelling. However, wells from the NSE water well database are georeferenced to the centrepoint of a 1 km^2 grid. Therefore, even after cleaning the database, there are often many (up to 25) boreholes or wells with the same geographical co-ordinates. Because of the highly variable nature of the well descriptions at any one location (including depth to bedrock) and due to time constraints, these well descriptions were only used as guides when no other information was available.

Another major problem with the database came from the log descriptions. During drilling, it may be difficult to differentiate bedrock from unconsolidated sediments. The very soft Wolfville Formation is often described in well logs as 'sand,' and there are no criteria that could systematically be used to distinguish this Mesozoic sand from a Quaternary sand. Those well descriptions that indicated 'sand' between two bedrock units were thus not used for geomodelling, and the remaining wells (170) were critically analyzed to make sure they were properly used.

The original goal was to produce a 3-D model for the entire valley, including stratigraphic information for bedrock and surficial sediments. Upon working with the archival data, and for the reasons stated above, it became clear that less than 20% of the well data could be used to construct the model, and that there was not enough stratigraphic information in the Quaternary sequence to build a meaningful model of this unit. Therefore, the regional model shows a thin layer of Quaternary deposits, the sediment types derived directly from the surficial geology map, without any stratigraphy. Locally, where some stratigraphic information was available or where reasonable interpretations could be made, the model was fully developed in the Quaternary sequence (e.g. in the Thomas Brook subwatershed).

The first step in developing the geomodel was to reconstruct the top of bedrock, regardless of the formation (Fig. 20a). This was done using the reliable wells that were kept after screening the database. The digital elevation model (DEM, Figure 20b) from NASA (90 m cells) was used to

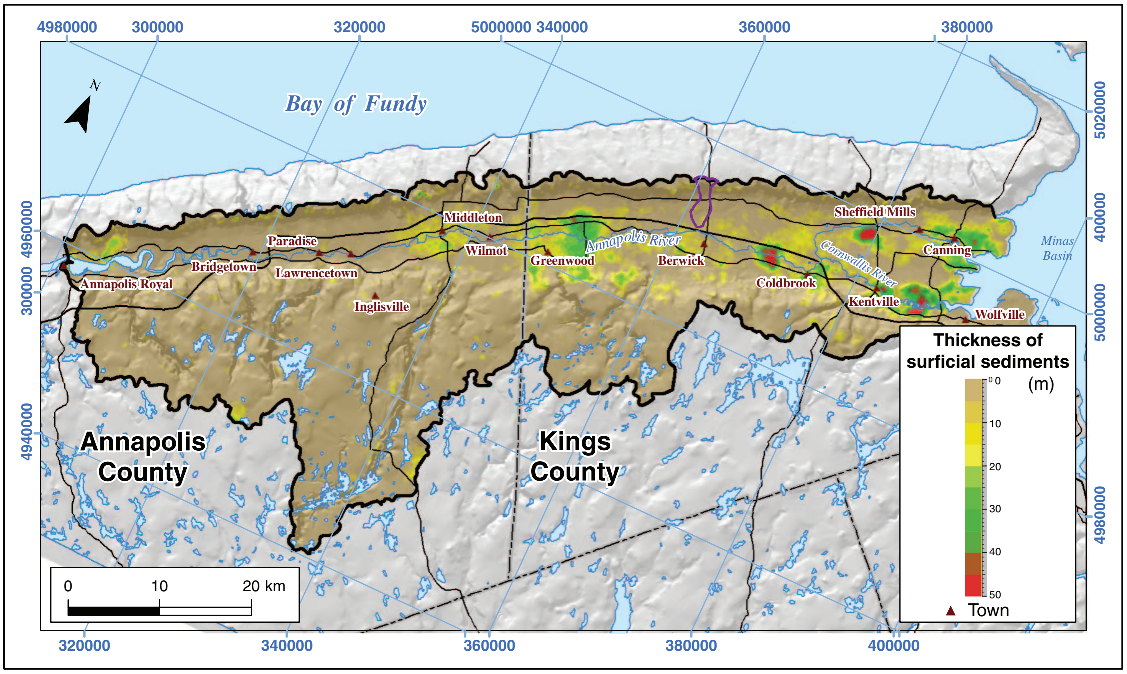


Figure 21. Distribution of the Quaternary sediment thickness, from less than 5 m (tan colour) to more than 50 m (red colour).

register the altitude of the wells. Constraints on the bedrock surface were applied to honour well and outcrop data, and to make sure that the surface is not projecting above the DEM. As expected, the bedrock surface morphology mimics the surface morphology, i.e. higher elevation on both North and South Mountains and lower elevations in the axis of the valley. A comparison between the bedrock topography and the DEM (Fig. 20a and b) shows that the wide, preglacial Annapolis Valley is characterized by circular to oval depressions, down to –45 m a.s.l. in the area of New Minas and –35 m a.s.l. west of Canning. Bedrock elevations near Annapolis Royal are slightly higher, −15 to −20 m a.s.l. The modern watershed between the Annapolis and the Cornwallis rivers is located above the preglacial watershed as shown in Figure 20.

Subtracting the bedrock surface from the DEM gives the thickness of Quaternary sediments (Fig. 21). Sediment thickness reaches 65 m west of Canning, but is typically less than 5 m over the entire study area. Depressions in the bedrock surface have been infilled by glacial and postglacial sediments such that the thicker surficial sediments are located over those bedrock depressions with no surface expression. An exception to this is in the Kentville/Wolfville axis that corresponds to a sediment accumulation not directly above a bedrock depression. Geophysical testing usually did not confirm thick sediment sequences, even where they were suspected from the original geomodelling. This suggests that thicknesses were likely overestimated due to low borehole density in some areas and because Quaternary sediments and weathered sandstone often cannot be reliably distinguished in boreholes. There do not appear to be any significant buried valleys, but locally, infilled bedrock depressions containing sand and gravel can represent a good aquifer potential. Indeed, the towns of Wolfville and Kentville use these surficial sediments as part of their water supply (with reported well depths of 30 to 50 m).

Polygons from the surficial geology map (Paradis et al., 2006) were imported into the geomodel and moulded onto the DEM. Quaternary sediment thickness was attributed to each unit from the geomodel. In targeted areas, stratigraphy was added to allow local modelling.

Figure 22 presents the 3-D models with and without surficial sediments. Triassic units in this model are dipping toward northwest at an angle generally ranging from 3 to 7°, which is within the reported range for these units (*see* ‘Bedrock’ section). However, internal dip and structures are not modelled in the Horton Group, and Lower Paleozoic rocks are undivided. The modelled vertical thickness of the Wolfville Formation ranges from 0 to about 1150 m under the North Mountain, in agreement with reported values (<833 m, Hamblin, 2004). However, the geometry is mainly inferred and extrapolated and is affected by the modelling process itself. For example, the modelled thickness of the Wolfville Formation is controlled by a set of constraints and by the geometry of the underlying units which are subject to modifications as additional data become available. Folds and faults are not represented, as they are not well known in the area and could not be represented appropriately (*see* ‘Bedrock’ section for details on the bedrock geology).

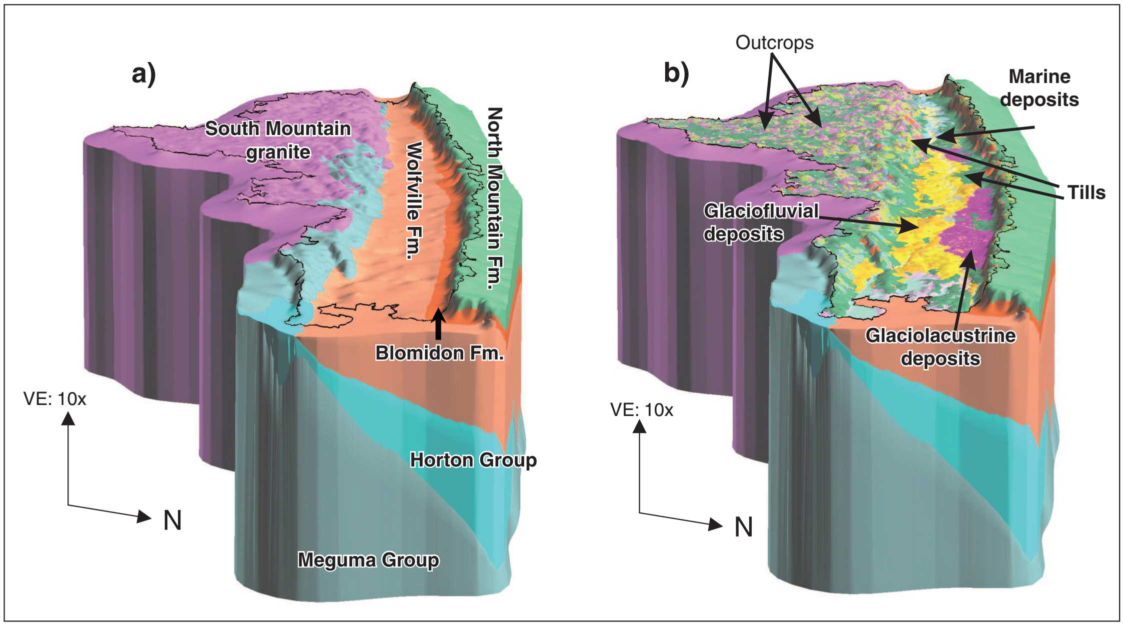


Figure 22. 3-D geological models **a)** of the bedrock and **b)** with surficial sediments. Vertical exaggeration is 10X.

INTERPRETATION OF EXISTING AND ACQUIRED HYDROGEOLOGICAL DATA AND RESULTS

This section describes results obtained from the analysis and interpretation of both fieldwork and existing data. Results are presented as either tables, graphs, or figures. Maps developed to summarize the geological and hydrogeological knowledge using the results obtained in this section are presented in the following sections or in the atlas (Rivard et al., 2007).

Data from fieldwork

Fieldwork performed over this three-year project included the following activities: groundwater-level surveys, CPT/RPSS soundings, geophysics, hydraulic testing, and sampling (*see* 'Methodology' section for description). The results obtained were added to the database and have contributed significantly to the general understanding of this hydrogeological system.

Groundwater-level survey

Water levels measured in wells located in the study area vary from artesian flowing conditions to depths that can reach more than 30 m (especially on North Mountain). The median groundwater level depth is 6.1 m. However, it varies according to the geological formation (*see* Table 26 in 'Hydrogeological context' section). Groundwater elevation was calculated by subtracting the groundwater depth from the topographic (Z) elevation plus the casing length above the ground (when available). A potentiometric map of the bedrock was produced through kriging using a spherical variogram with a correlation length of 12 km, a sill (roughly corresponding to the variance of the data) of 3750, and no nugget. A considerable amount of information on groundwater depths was available from provincial databases, but a high level of uncertainty is attached to this data, mostly because static water levels are often measured immediately after the well construction. Moreover, interannual and interdecadal fluctuations can be quite large. For this reason, only data of the last 10 years (1996–2005) from the provincial database were retained, giving more weight to our water-level survey data. This also avoided dealing with long-term fluctuation patterns or trends. In addition, since in the provincial database the type of well (dug or drilled) is not always indicated, wells for the bedrock potentiometric map were selected only if an indication of fracture depth was reported or if the well depth was at least 2 m below the Quaternary sediment thickness. Wells with a groundwater elevation smaller than −5 m were removed. This threshold (–5 m) was chosen since it corresponds to the DEM precision. Finally, null static water levels were attributed to wells with a reported 'overflowing' indication. All wells were used without discrimination regarding their depths, since most residential wells are probably open in the bedrock from directly under the surficial deposits to the bottom of the well. Therefore, the development of this map included 1667 wells from the NSE well-log database, 91 from the NSE pump-test database, 197 springs reported in Trescott (1968), and 242 wells from the GSC field campaigns (mostly residential wells). A map generated using only deeper wells (drilled deeper than 50 m, 720 in all) indicated, though contours were not as precise, a similar pattern to that using all wells, suggesting that deeper wells are also in hydraulic connection with major rivers. The potentiometric map is presented in the 'Hydrogeological context' section and on Plate 5.5 of the atlas (Rivard et al., 2007).

A potentiometric map of the surficial sediments could not be obtained, as very few wells (approximately 10%) use water from these deposits due to the thin Quaternary cover in most of the valley. In addition, many dug wells are not included in the NSE database since they are very old (often built before 1930) or have not been constructed by drillers. Thus, data from only 144 wells were available for the entire valley. Many houses that used to be hooked up to dug wells have had to drill a new well into bedrock in the past 10 years. During the GSC piezometric survey, many dug well owners reported a water-level decline during the summer of sometimes more than 1.5 m (5 ft), and some dry wells. This reported fluctuation seems to be in agreement with the historical series of monitoring wells in Wilmot, Coldbrook, and Wolfville (*see* below). Nevertheless, no decreasing trend has been observed in these monitoring wells (*see* 'Monitoring wells and historical trends' section). The groundwater depletion (when wells went dry) could thus be due to local pumping changes (more wells with an increasing demand). However, monitoring wells and gauging stations are all located close to the valley floor, and many residents who have had to have another well constructed are located on both sides of the valley, on the South and North mountains or the mountain flanks.

CPT/RPSS soundings showed that a water table could be found in the surficial deposits only in the two southern sites of the Thomas Brook subwatershed, where surficial deposits are thicker. In the other four sites, the groundwater level was found in the first few metres of bedrock. A comparison of water levels in piezometers and surrounding bedrock residential wells tended to show that a downward hydraulic gradient was present in the middle of the subwatershed (approximately corresponding to the location of the Blomidon Formation), whereas no vertical gradient was apparent in the southern portion (for more details *see* Gauthier, 2009). This piece of information was further corroborated by the nitrate-concentration analyses, which showed that higher values were found in the middle of the subwatershed, while low concentrations were observed in the southern part (*see* 'Geochemistry' section). The downward hydraulic gradient could likely be due to the presence of a discontinuos finer grained strata in the upper portion of the Blomidon Formation that acts as a semiconfining layer, which still allows dissolved contaminants to penetrate deeper into the bedrock at some places. In the southern part of the subwatershed, the underlying bedrock belongs to the Wolfville Formation, comprising mainly sandstone; the absence of vertical gradients is thus not surprising. This suggests that groundwater in this area flows mainly in a north-south direction in agreement with the bedrock potentiometric map (*see* below).

Uncertainties related to the geographical location of the wells add to the inherent uncertainty of their static water elevation (topographic elevation minus static groundwater level). This makes conclusions regarding hydraulic connections difficult using provincial databases. An attempt to compare water levels in bedrock and in streams was made using only GSC piezometric campaign stations. Figure 23 illustrates schematically the differences in levels that could be encountered in a hypothetical sequence of the Blomidon or Wolfville formations.

Stations that were within 100 m of a stream (readings were made from a 1:50 000 scale map) were selected, and a comparison of water levels was made only when LIDAR and high precision GPS elevations were available (therefore when a precision of 2 m or less was available). Only 45 stations met these criteria. They showed that both water levels (stream and groundwater elevations) usually have a few metres of difference. Indeed, 52% had a difference in elevation of 2 m or more, 35% had a difference larger than 3 m, and 19% had a difference larger than 5 m. From these data alone, it could not be concluded whether or not each bedrock well is confined. Nevertheless, it provides another indication that a large percentage (52%) of bedrock wells seems to have a significant vertical-gradient difference, suggesting common confined conditions. Few data on groundwater within surficial sediments are available over the area. However, the well developed stream network suggests that water circulating in this layer is mainly flowing in an east-west (or vice-versa) direction toward tributaries of main rivers, while the groundwater circulating into bedrock is usually flowing in a north or south direction toward major rivers in the middle of the valley. Based on contamination evidence (mainly by nitrates), surficial sediments and streams appear to be hydraulically connected to bedrock aquifers in many areas.

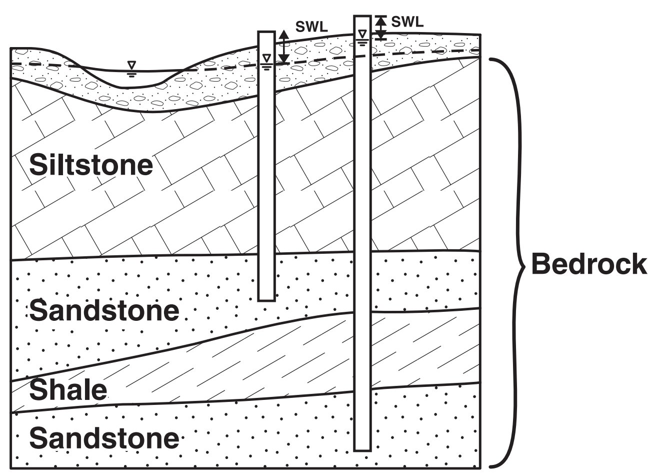


Figure 23. Schematic illustration of differences in water elevations between surface water and groundwater in a hypothetical sedimentary rock sequence.

Groundwater-level monitoring

Table 4 presents the characteristics of the GSC monitoring wells. Of the four monitoring wells for which more than one year of data are available, only one taps a surficial aquifer (Wilmot). Two of the three bedrock wells (Sheffield Farm and Wolfville) have relatively low annual variations (on the order of 1 m or less). The Greenwood/ Tremont well has larger annual variations, on the order of 1.5 m, similar to the Wilmot well. Figure 24 presents fluctuations of the Wolfville–Wickwire Road well from August 2003 to June 2006. It is difficult to tell if these bedrock wells tap confined (or semi-confined) aquifers, due to poor knowledge of the stratigraphy and because no long-term pump test was conducted. However, the Wolfville well does not seem to be influenced by precipitation events (*see* Figure 24); daily fluctuations could rather be attributed to nearby pumping or barometric variations. Due to relatively small fluctuations over the short-term (rain events) and year-round basis, the Sheffield Farm well likely taps a confined aquifer. In addition, the pump test carried out in this well indicated a 'confined' type of behaviour. Figure 24 indicates relatively low levels for the summer of 2003, similar to the Greenwood/Tremont and Wolfville wells. Monitoring-well hydrographs are presented in Appendix E. One well located in the Thomas Brook subwatershed (Goode) is influenced by daily residential pumping. The Sheffield Farm is also used occasionally for irrigation during the growing season by AAFC.

Stratigraphy and fracturing

Soundings

Table 5 summarizes the location and depths of boreholes, as well as the unit and depth at which a piezometer was installed. Samples taken during CPT/RPSS soundings

Table 4. Summary of GSC monitoring wells – average annual fluctuation.

Monitoring well	Type of aquifer / formation	Well depth (m)	Reaction to rain events?	Average annual fluctuation (m)
Greenwood/Tremont	Fractured (Wolfville)	66.1	N	1.5
Sheffield Farm (AAFC)	Fractured (Wolfville)	61.0	N	1
Wilmot	Surficial / sand	6.0	Y	1.5
Wolfville (Wickwire Rd.)	Fractured (Wolfville)	20.0	N	1
TB1-Malcolm	Fractured (Blomidon)	31.3	Y	< 1
TB2-Goode	Fractured (Blomidon)	25.9	N	1

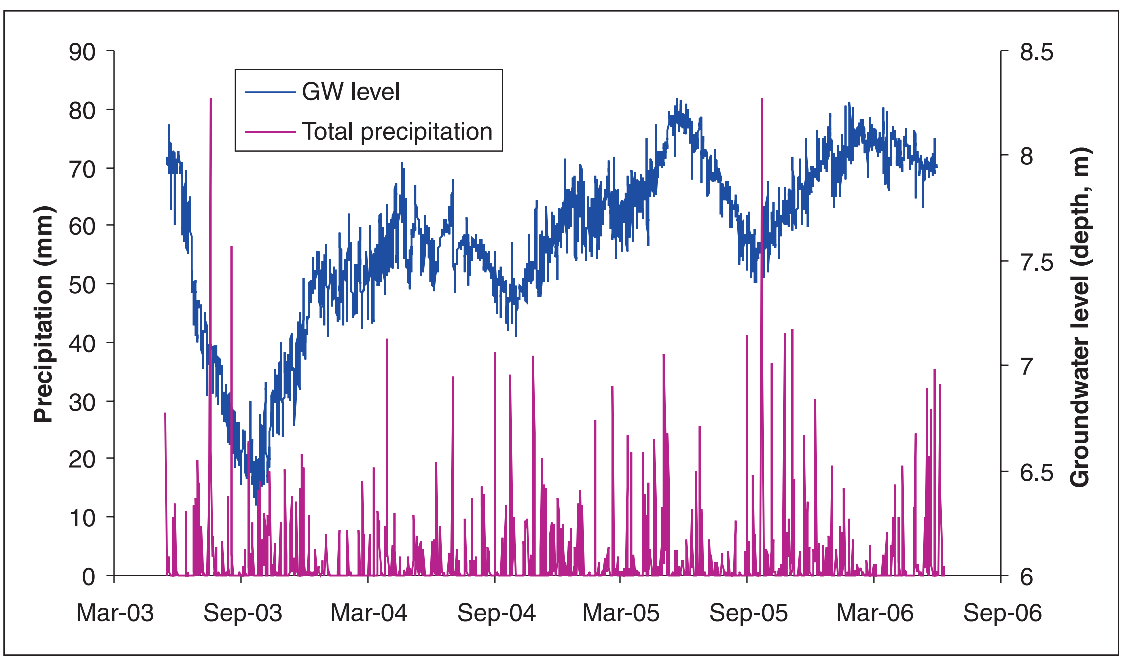


Figure 24. Fluctuations of water levels in the Wolfville-Wickwire Road well, Kings County, together with total precipitation from the Kentville weather station.

Table 5. Summary of boreholes and piezometers (UTMs Nad 83, Zone 20).

Site ID	Location	X in UTM (m)	Y in UTM (m)	Z (m)	Total depth (m)	Piezometer** / depth (m)
05AVMG0001A 05AVMG0001B	TB* - Malcom's field	362125	4991003	28.5	16.5	SD / 8.5 UB / 16.5
05AVMG0002A 05AVMG0002B	TB - Andrew Morse's field	361599	4991385	31.2	7.0	SD / 5.0 UB / 7.0
05AVMG0003	TB - Lindsay Kinsman's field near Brooklyn St.	360949	4991685	44.9	4.0	UB / 4.0
05AVMG0004	TB - Lindsay Kinsman's field on Chute Rd	360640	4992232	56.9	12.5	UB / 12.5
05AVMG0005	TB - Harry Morse's field	361350	4992480	47.7	10.0	UB / 9.0
05AVMG0006	TB - Malcom's house	361657	4992284	44.3	8.0	UB / 7.5
05AVMG0007	Kentville (close to the Michelin plant)	369156	4989459	31.7	7.0	None
05AVMG0008	Webster's Farm (east of Waterville)	369277	4990534	33.5	12.0	None
05AVMG0009	Kentville (Seven Bridges)	377640	4992750	16.3	12.0	None
05AVMG00010	Middleton well field	337589	4978870	12.5	6.5	SD / 5.0
05AVMG00011	Middleton well field	337607	4978923	11.6	4.5	SD / 4.5
05AVMG00012	Green Acres	349098	4984273	22.7	16.0	SD / 13.5
05AVMG00013A 05AVMG00013B	Green Acres	349124	4984376	24.8	17.0	SD / 12.0 SD / 4.5
05AVMG00014	Webster's Farm (east of Waterville)	369313	4991255	18.7	32.0	None

* TB : Thomas Brook subwatershed.
** SD: Surficial deposits ; UB: Upper part of the bedrock

confirmed that the till covering a large part of the study area is very compact, so that the semi-consolidated sandstone of the Wolfville Formation could easily be mistaken for till. Thomas (1974) had already pointed out the fact that in some places, the till is loosely cemented and cannot easily be distinguished from weathered sandstone in the eastern part of the valley. The 17 boreholes invalidated the surficial-deposit thickness data obtained from provincial databases, suggesting much smaller values.

The drilling performed using a percussion (Pionjar) drill in a peatland (Annapolis Valley Peat Moss, close to the water divide between the Annapolis and Cornwallis watersheds) provided samples for grain-size analysis at various depths (down to 9.4 m). This work indicated that below the peat layer, a sandy silt layer could be found, followed by a relatively thick (>3 m) silty stratum, likely producing a quite impermeable barrier, keeping the water level high in the peat and impeding water exchange between the bedrock and water circulating in the peat. This is similar to findings in the Beauséjour Peatland (New Brunswick) previously studied by Carrier (2003).

Borehole geophysics

Borehole geophysical logging was conducted at 12 wells in the Annapolis Valley. The investigated wells are listed, along with their major characteristics, in Table 6. Figure 4 ('Methodology' Section) presents their locations. The downhole measurements revealed that each geological formation has its own characteristic structural and hydrological properties. Values of electrical resistivity and natural gamma activity were obtained in every well, helping to distinguish between individual rock units. Investigated wells showed that sandstones of the Wolfville and Blomidon formations have the highest hydraulic conductivities (~ 10^{-5} m/s), basalts have intermediate values (~ 10^{-6} m/s), and slates and granites have the lowest hydraulic conductivities ($\leq 10^{-8}$ m/s). Table 7 summarizes average values found for each geological formation or group.

The Annapolis Valley represents the southeastern extension of the Minas Rift Basin, one of 20 exposed Mesozoic basins found along the northeastern coast of North America (Fig. 25). Field studies previously conducted in two of these basins, the Newark Basin in New Jersey and New York (Morin et al., 1997; 2000) and the Hartford Basin in Connecticut and Massachusetts (Stone et al., 1996), determined that the primary regional aquifers were composed of sedimentary rocks that shared similar hydrogeological characteristics. These rocks were found to contain two orthogonal fracture sets through which groundwater flow was controlled and confined: 1) subhorizontal bedding-plane partings associated with softer, more compliant rocks (mudstones, siltstones), and 2) subvertical joints associated with the brittle fracturing of harder sandstones subjected to tectonic forces (Morin and Savage, 2003).

Blomidon Formation

The two wells investigated in the Blomidon Formation were predominantly composed of sandstones; very few siltstone and shale beds were encountered; contrasting with the reported general composition of Blomidon rocks (usually dominated by fine-grained rocks). Careful examination of the televiewer logs reveals that these sandstones also have two orthogonal fracture sets, again typical of what has been observed at the two other basins. This fracture distribution is depicted in the rosette (dip direction) and lower-hemisphere stereographic plots shown in Figure 26; a televiewer image showing the intersection of these two features is presented in Figure 27. A statistical analysis of fracture orientations, computed by means of a Bingham axial distribution (Mardia, 1972), was performed on this data set. Magnitudes of the eigenvalues, λ, and eigenvectors (strike and dip) are listed in Table 8. The value of λ is normalized to 1.0 and is considered to be a measure of the relative concentration of poles associated with a statistically significant fracture set. The eigenvector represents the orientation of a representative fracture plane within that set. The results presented in Table 8 indicate that bedding planes are the primary fracture set ($\lambda = 0.68$) and that these, on average, dip gently (~12°) to the northwest. Joints/fractures form a secondary set ($\lambda = 0.23$) that dips steeply (~78°) to the southeast. Both sets strike subparallel to the axis of the valley.

The overall transmissivity of each well and the vertical distribution of the fracture transmissivity were determined by the flowmeter/pumping technique (Morin et al., 1988; Molz et al., 1989) wherever wells were accessible and conditions were favourable for pumping, logging, and measuring drawdown simultaneously. Results of these tests are presented in Figures 28 and 29 for the TW3-Granville Ferry well and the Malcolm well, respectively. These diagrams illustrate that transmissive zones in Blomidon sandstones are numerous and are interspersed throughout the formation. These permeable intervals are often located at the intersection of bedding planes and joints (*see* Figure 27).

Table 6. General information where geophysical logs were recorded.

Well ID	Total depth (m)	Casing depth (m)	Formation	Lithology
Canning #3	118.7	10.7	Wolfville	Sandstone, siltstone
Middleton	55.3	6.4	Wolfville	
Kentville – Ind. Park*	17.1	17.1*	Wolfville	
MN5-Kentville	100	34.8	Wolfville	
MN6-Kentville (7-Bridges)	49.9	15.9	Wolfville	
Malcolm	31.3	6.7	Blomidon	Shale, siltstone
TW3-Granville (Ferry)	100	15.2	Blomidon	
Baiani	66.2	11.0	North Mountain	Basalt
Walsh	199.2	5.5	Meguma Gr.	Slate
Wolfville TW-1	62.2	6.1	Horton/Meguma Gr.	Shale, sandstone / slate
Jack	163.4	18.0	Meguma/Batholith	Slate / Granite
Annapolis Royal	56.7	2.3	Batholith	Granite

* This well was cased along its entire depth, thus inhibiting most downhole measurments.

Table 7. Average values of electrical resistivity, natural gamma activity, and hydraulic conductivity for each rock formation.

Unit (number of investigated wells)	Resistivity (Ω-m)	Gamma activity (cps)	Hydraulic conductivity (m/s)
Wolfville sandstones (4)	75	65	1.3×10^{-4}
Blomidon sandstones (2)	100	110	6.7×10^{-5}
North Mountain basalts (1)	200	35	1.2×10^{-6}
South Mountain granites (2)	500	150	1.2×10^{-8}
Meguma Group slates (2)	250	170	6.7×10^{-9}

Wolfville Formation

Wolfville sandstones are softer and less cemented than the Blomidon sandstones, as indicated by their lower electrical resistivity and lower natural gamma activity (Table 7). Examination of televiewer logs reveals that they contain a large number of subhorizontal bedding planes, but that they show a marked paucity in subvertical joints/fractures (Fig. 30). This is reflected in the rosette and stereographic diagrams shown in Figure 31 and by the attendant fracture statistics listed in Table 9, where shallow dipping (~ 13°) bedding planes form the predominant fracture set (λ = 0.80). This probably suggests that these rocks were too compliant to undergo brittle failure when subjected to regional tectonic forces as did the Blomidon sandstones, but were more likely to deform by grain-to-grain displacement. Orientations of bedding planes in both sandstone units are very similar (Tables 8 and 9).

The vertical distribution of fracture transmissivity in Wolfville sandstones could only be determined in one well (MN5-Kentville well); results are presented in Figure 32. Although the overall transmissivity of this well integrated over its entire depth is similar in magnitude to those

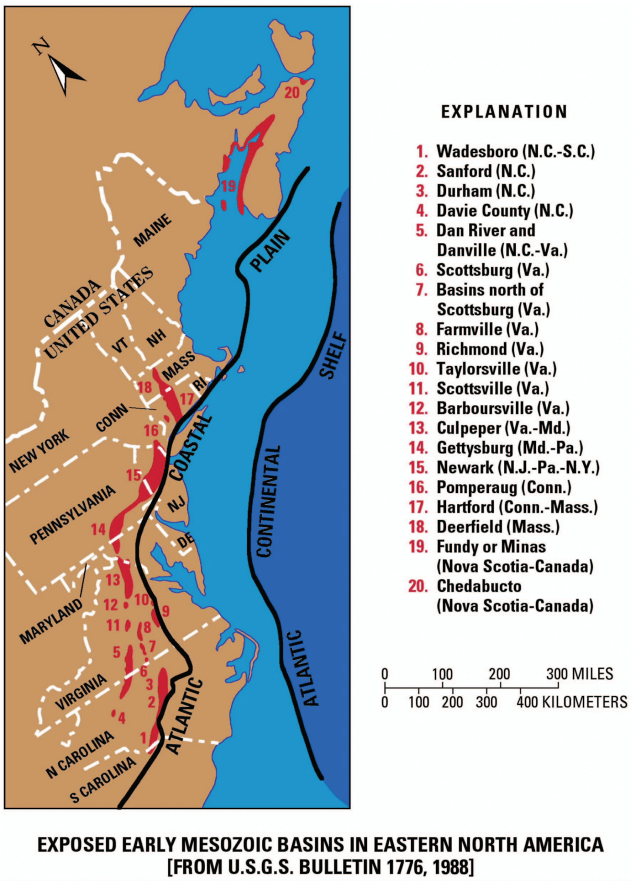


Figure 25. Locations of 20 Mesozoic basins along the eastern coast of North America (*from* Froelich and Robinson, 1988).

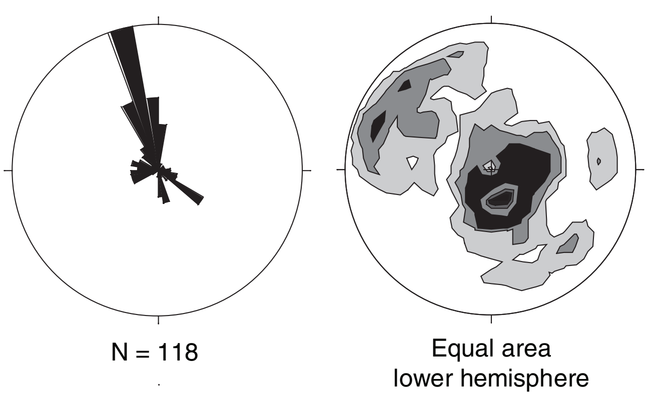


Figure 26. Rosette (dip direction) and stereographic diagram of fracture planes intersecting Blomidon sandstones.

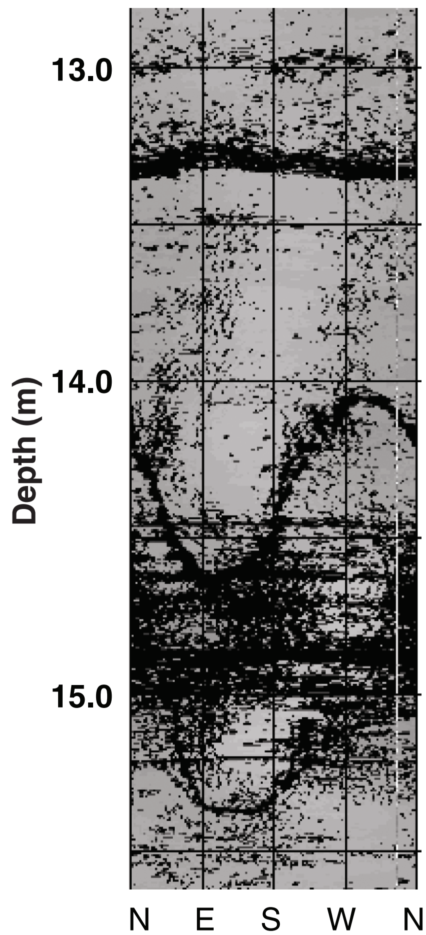


Figure 27. Magnetically oriented televiewer image of borehole wall in Blomidon sandstone showing both subhorizontal bedding planes (around 13 m deep) and subvertical fractures (around 14–15 m deep).

Table 8. Fracture statistics for Blomidon sandstone.

Eigenvalue λ	Eigenvector	
	Strike	**Dip**
0.68	58.0°	12.5°
0.23	220.3°	78.1°
0.09	311.1°	86.3°

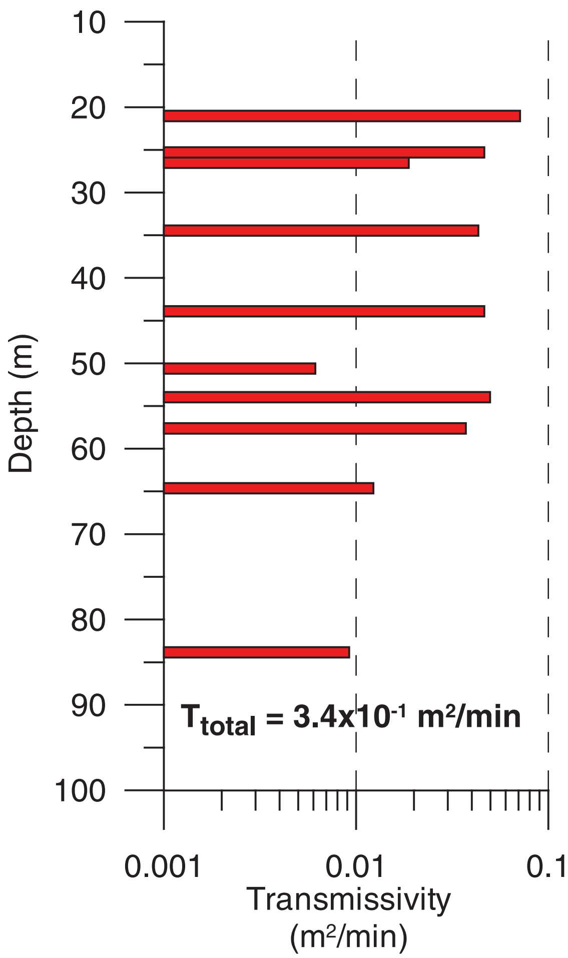


Figure 28. Vertical distribution of fracture transmissivity in the TW3-Granville Ferry well.

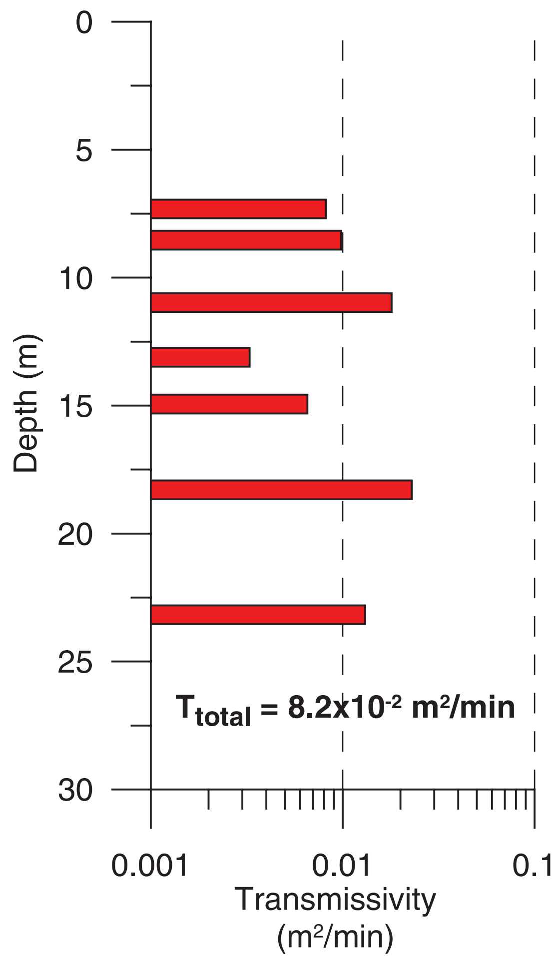


Figure 29. Vertical distribution of fracture transmissivity in the Malcolm well.

determined in the Blomidon sandstone wells, the vertical distribution of this transmissivity is significantly different. There are only a few distinct intervals from which this permeability originates as opposed to many more in the Blomidon sandstones (Fig. 28 and 29). The MN5-Kentville well depicts two such zones across 80 m of open hole (Fig. 32), whereas wells in the Blomidon formation depict almost 10 times as many per unit depth. It appears that the lack of vertical fractures in the Wolfville sandstones does not diminish its overall transmissivity (Table 7), but that this transmissivity is now limited spatially to only a few highly permeable bedding plane partings. We could thus hypothesize that the Wolfville sandstones are more anisotropic in terms of vertical versus horizontal flow paths than the Blomidon sandstones, based on these observations. In both wells tapping the Blomidon Formation, bedding planes are the primary fracture set ($\lambda = 0.68$; Table 8) but subvertical fractures are pervasive and, consequently, $T_{horiz} > T_{vert}$. However, in the MN5-Kentville well (Wolfville sandstones), $T_{horiz} >> T_{vert}$ because of the lack of these joints. It must be noted that only one well could be pumped in the Wolfville Formation and two in the Blomidon Formation, and that sandstone was the primary if not the only rock type encountered in these investigated wells. However, fine-grained strata are supposed to be common in the Blomidon Formation and their presence would significantly increase the overall vertical anisotropy.

North Mountain basalts

Geophysical measurements were obtained in only one basalt well (Baiani well) located above a steep cliff with a 220 m elevation relief to the valley below. Basalt is distinguished from all other rock units in this study by its very low gamma activity (Table 7). Most fractures in basalt, as identified from the televiewer images, are very steep and define two conjugate fracture sets that strike parallel to the valley axis. Attendant rosette (dip direction) and stereographic diagrams are shown in Figure 33 and fracture statistics are presented in Table 10.

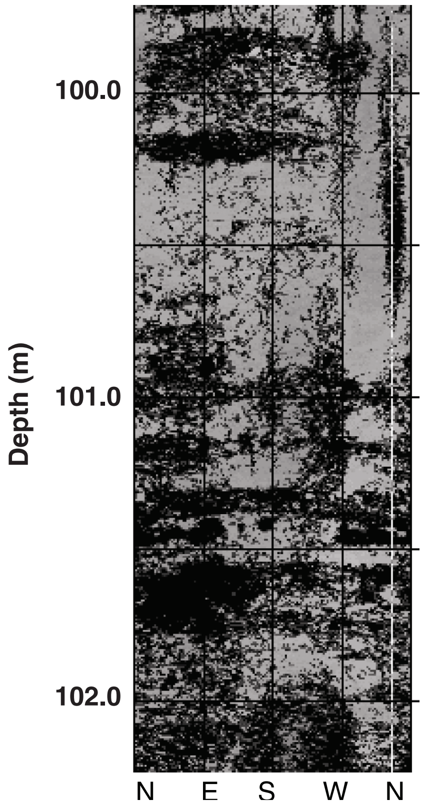


Figure 30. Magnetically oriented televiewer image of borehole wall in Wolfville sandstones showing numerous subhorizontal bedding planes but no subvertical fractures.

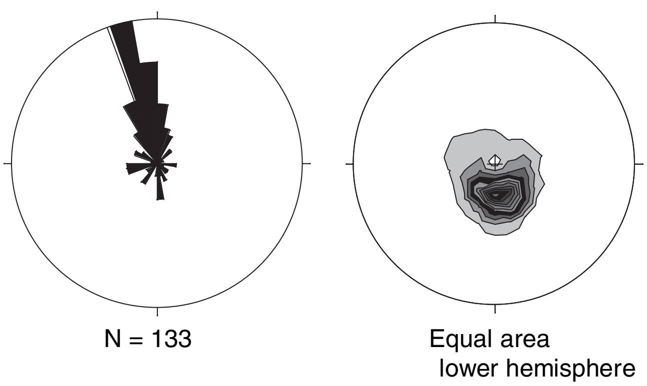


Figure 31. Rosette (dip direction) and stereographic diagram of fracture planes intersecting Wolfville sandstones.

Table 9. Fracture statistics for Wolfville sandstones

Eigenvalue	Eigenvector	
	Strike	Dip
0.80	71.1°	13.1°
0.13	270.9°	77.6°
0.07	180.0°	85.7°

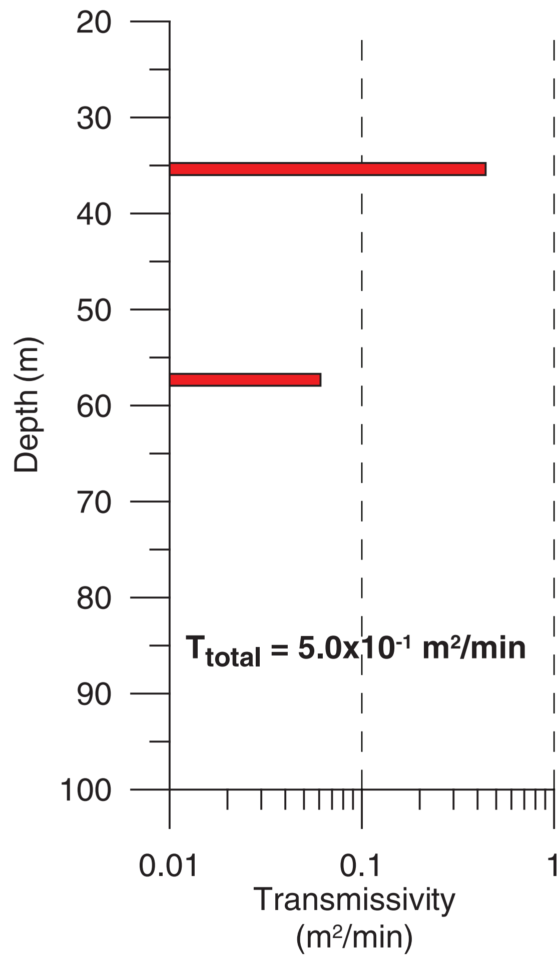


Figure 32. Vertical distribution of fracture transmissivity in the MN5-Kentville well.

The Baiani well penetrated through a basalt cap approximately 60 m thick and then intercepted underlying Blomidon sandstones. This lithological change is clearly delineated by the natural gamma log (Fig. 34) and is also recognized in the resistivity profile, the caliper log, and the televiewer images. A flowmeter/pumping test was conducted in this well and it was anticipated that the transmissive interval would be confined exclusively to the permeable sandstones underlying the basalt. However, several productive zones were also identified in the basalt and these are depicted in Figure 35. Within the context of this study, the magnitude of the hydraulic conductivity of the basalt is intermediate (Table 7).

The permeable fractures in the basalt can be precisely identified by examining the vertical transmissivity distribution (Fig. 35) and then locating the corresponding productive zones in the televiewer images. In this way, the permeable fractures can be distinguished from the general fracture population. This process is illustrated in the stereographic diagram presented in Figure 36. The lower-hemisphere plot presents the same directional data shown in Figure 33, but it is now constructed only from the poles to the fracture planes rather than processed with smoothing contours. The crosses represent individual fracture planes intersecting the well and the stars locate those fractures recognized to be permeable. The permeable fractures form a cluster that identifies a group of planes that roughly share a common orientation. They strike east-northeast–west-southwest, parallel to both the valley axis and the cliff face, and dip steeply (~ 65°) to the south-southeast and into the valley.

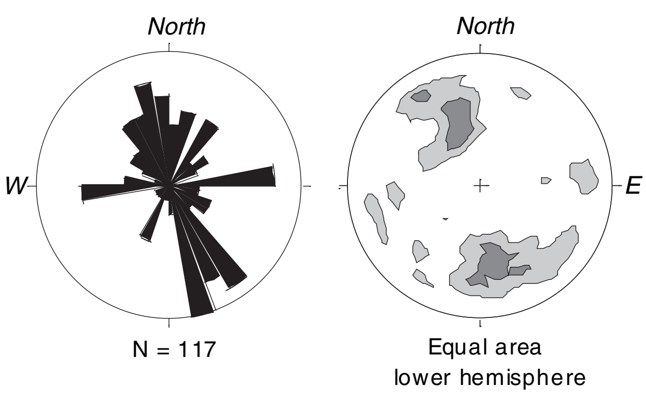


Figure 33. Rosette (dip direction) and stereographic diagram of fracture planes intersecting basalt.

Table 10. Fracture statistics for basalt.

Eigenvalue	Eigenvector	
	Strike	Dip
0.40	67.5°	79.2°
0.36	186.0°	21.8°
0.24	333.8°	71.3°

This correlation between fracture orientation and transmissivity has been recognized in several studies when local stress conditions are evaluated (e.g. Barton et al., 1995; Savage and Morin, 2002). The state of stress produced by a sharp cliff face has been examined theoretically by Savage (1993; 1994) and results show that a lack of buttressing and gravitational support opposing the cliff produces extensional forces perpendicular to the wall. In the case of Annapolis Valley, this condition is exacerbated by principal tectonic stresses that are compressional and that strike east-northeast–west-southwest (Zoback and Zoback, 1989), in alignment with the valley axis. Thus, the combination of gravitational stresses produced by topography superimposed upon regional tectonic stresses tends to pull apart the near-vertical fractures in the basalt that strike parallel to the valley axis. This, in turn, tends to enhance the permeability of these preferentially oriented planes. A cross-section of the Annapolis Valley (i.e. the topography with a large vertical exaggeration) through the town of Berwick and near the Baiani well is presented in Figure 37.

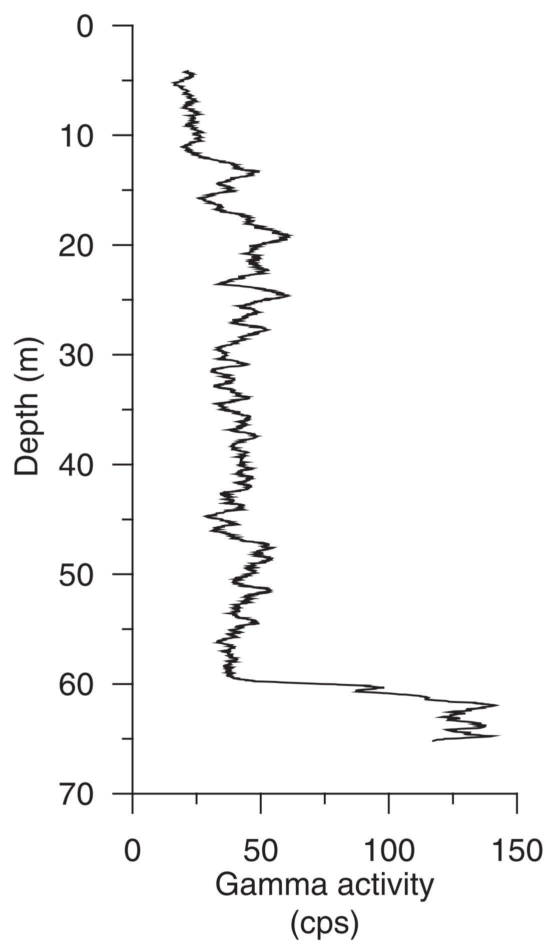


Figure 34. Natural gamma log recorded in Baiani well showing contact between basalt above and sandstone below at 60 m.

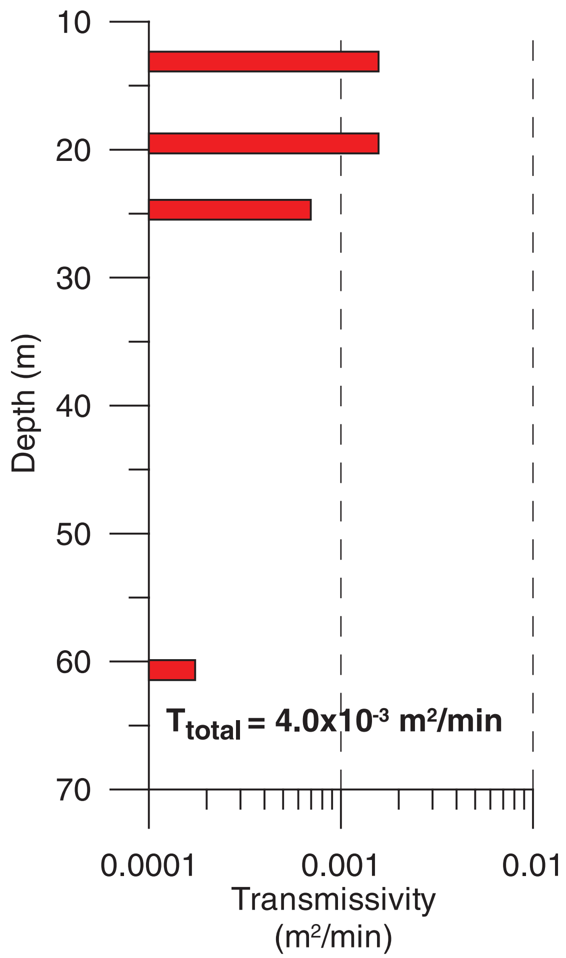


Figure 35. Vertical distribution of transmissivity in the Baiani well.

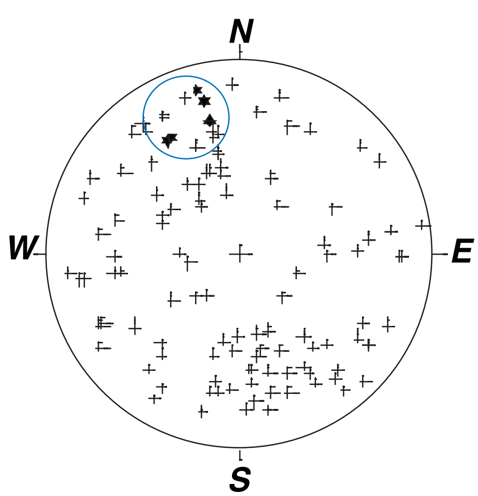


Figure 36. Stereographic diagram (poles to planes) of individual fractures (crosses) and permeable fractures (stars) intersecting the basalt well. Stars form a cluster shown within circle.

These conditions probably only apply to the southern side of the North Mountain Formation, and correspond to the lower flow unit (LFU) characterized by columnar jointing. According to local drillers, vertical fracturing in the basalts, and especially in the cuesta, is so 'severe' in some areas that wells sometimes collapse during drilling or a couple of days after drilling. This extensively fractured basalt (117 planes observed over 54 m) is nevertheless rarely very permeable, since subhorizontal fracture interconnectivity is not well developed. Only three water-bearing fracture zones were identified in the basalt and one at the basalt-Blomidon sandstone contact.

Topography and gravity-induced effects cause fractures that are preferentially oriented within the regional stress field to be more prone to opening, and thus more permeable than other fractures having less optimum orientations (Morin et al., 2006). Therefore, in the case of the Annapolis Valley, steeply dipping fracture planes close to the cuesta and parallel to the valley axis would be more likely to provide larger quantities of water than elsewhere in the basalt cap. The tensional stress state, resulting in vertical fracture opening, is a product of both gravitational stresses due to topography and lateral spreading due to a contrast in Poisson's ratios between rock formations (basalt/Blomidon sandstone). Therefore, once water flows down a vertical fracture, it can sometimes move horizontally into basalts, but only in the direction of the valley axis. Both vertical and horizontal flows can be large in that direction which is along the strike of the permeable fractures.

South Mountain granites

Geophysical measurements were conducted in one granodiorite well (Jack well). These rocks are distinguished from the other formations by their high values of both electrical resistivity and gamma activity (Table 7). This was a relatively deep well (162 m), especially for a residential well, and the temperature profile was particularly interesting (Fig. 38) because it showed evidence of short-term seasonal temperature fluctuations near the surface (e.g. Ingersoll et al., 1954) superimposed upon a long-term warming trend (e.g. Chisholm and Chapman, 1992) that may be related to land use during the past 100 years.

Fractures in this well were numerous and a majority of them ($\lambda = 0.73$) were steeply dipping (~ 59°) to the southeast, striking roughly parallel to the valley axis but dipping away from it. Rosette (dip direction) and stereographic plots representing these directional data are presented in Figure 39 and statistical information is listed in Table 11.

A flowmeter/pumping test conducted in this well was not totally successful because of the lack of water production. Only about 1.5 L was produced from a small fracture at the 134 m depth under about 14 m of drawdown and an upper limit on the overall well hydraulic conductivity is estimated to be roughly 10^{-8} m/s.

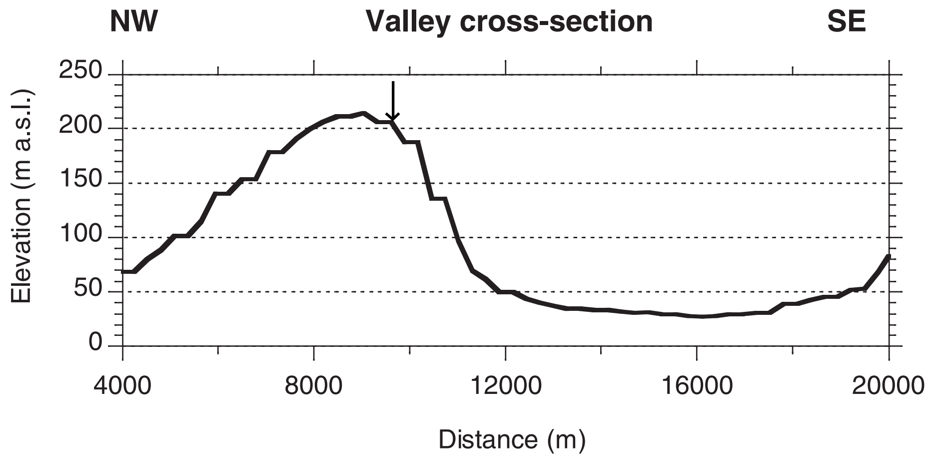


Figure 37. Cross-section of Annapolis Valley near the town of Berwick. Basalt well is located at the top southern edge of cliff (shown by the arrow). Vertical exaggeration is 20x.

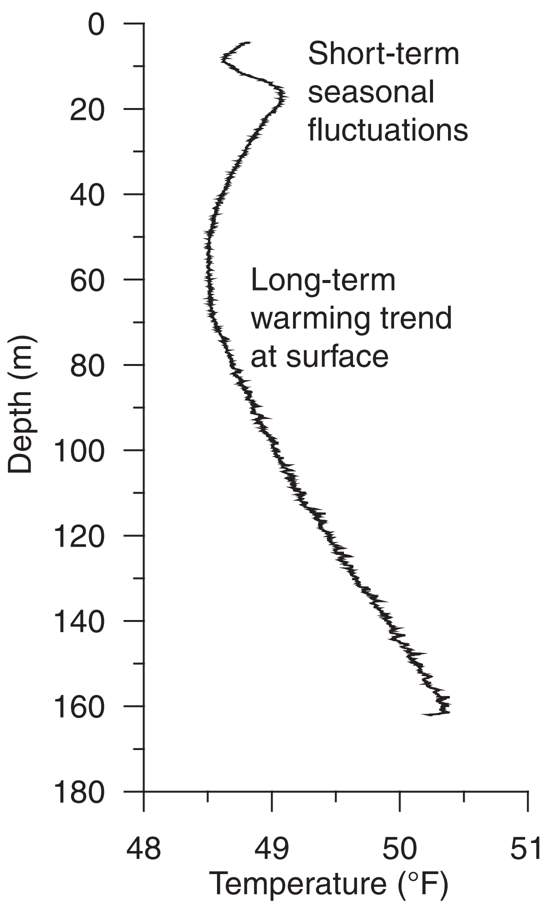


Figure 38. Temperature profile in Jack well.

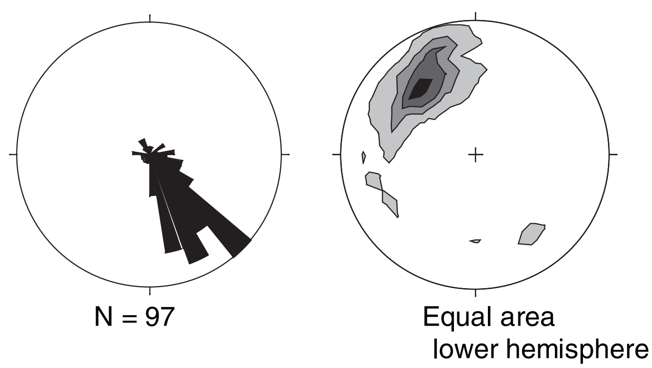


Figure 39. Rosette (dip direction) and stereographic diagram of fracture planes intersecting granodiorite.

Table11. Fracture statistics for the granite well.

Eigenvalue λ	Eigenvector	
	Strike	Dip
0.73	233.9°	59.3°
0.16	124.1°	60.3°
0.11	359.8°	45.4°

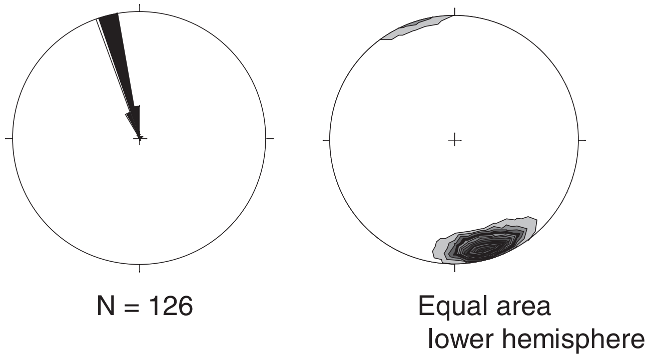


Figure 40. Rosette (dip direction) and stereographic diagram of fracture planes intersecting slate.

Meguma Group slates

Geophysical measurements were obtained in one well penetrating slate (Walsh well). This rock has particularly high gamma activity (Table 7). Fractures were numerous in this well and almost all of them ($\lambda = 0.95$) were dipping steeply (~79°) to the northwest, again striking subparallel to the valley axis but, unlike the granodiorite fractures, dipping toward the valley. Rosette (dip direction) and stereographic diagrams representing these directional data are presented in Figure 40 and statistical information is provided in Table 12.

A flowmeter/pumping test performed in this well was unsuccessful, as no detectable amount of water could be extracted even when drawdown exceeded 15 m. Within the context of this study, this slate well and the granodiorite well both fall into the category of very low hydraulic conductivities (Table 7).

Table 12. Fracture statistics for slate.

Eigenvalue λ	Eigenvector	
	Strike	Dip
0.95	73.9°	79.2°
0.04	170.7°	58.4°
0.01	327.3°	33.8°

Seismic survey

The near-surface geophysics survey included 26 seismic tests sites: 18 sites in the eastern part of the Annapolis Valley, where the main objective of the survey was to confirm the presence of suspected buried valleys; and eight sites in the Lawrencetown area, to delineate the extent of fine-grained layers (Fig. 8, section 3). At each test site a suite of five or more seismic records were acquired using a source-receiver geometry. Several issues were identified during the ACVAS project, including low velocity of the upper bedrock unit (2000 to 2400 m/s), similarity between the velocity of till and that of the bedrock, and dry, sandy surface conditions (resulting in poor coupling of seismic energy into the ground), as well as shallow bedrock. For these reasons, data from only a few of the 26 investigated sites could be interpreted. Results obtained at sites 1, 2, 4, 7, 18, and 22 are presented in Appendix C.

The seismic surveys were nevertheless able to provide some velocity estimates on the overburden stratigraphy and approximate depth to bedrock information in a few areas. Bedrock depth estimates that could be made are generally on the order of 10 to 30 m, in agreement with CPT/RPSS soundings and ground penetrating radar carried out as part of this project. No data acquired during this survey was able to confirm the buried valley hypothesis, as occurrences of thick overburden (>50 m) suggested by some borehole data were not found. However, these thick surficial deposit occurrences could be quite limited in extent, and not precisely located, as borehole locations are often only specified to within a 1 km^2 grid. As well, the main suspected buried valley occurs in a highly urbanized corridor (Kentville/Port Williams/Wolfville), where it was difficult to find locations to conduct the seismic surveys. The summary of information acquired at each seismic test site is provided in Table C-1 of Appendix C.

Hydraulic properties of the bedrock

Slug tests

Data from the five successful slug tests performed in bedrock wells were interpreted using the Bouwer and Rice (1976) or the Butler and Garnett (2000) method, depending on the hydraulic response. Hydraulic conductivity (K) values obtained are presented in Table 13 (*see* Appendix B for an example of calculation).

The K value obtained for the Malcolm well is quite high for the Blomidon Formation, but this well is only drilled into sandstone and is located very close to the Wolfville Formation boundary. The four wells tapping the Wolfville Formation show reasonable values for this formation, with a geometric mean of 7×10^{-6} m/s.

Pumping tests

The interpretation of the pumping test data was done using both the Theis and Cooper-Jacob methods (Kruseman and de Ridder, 2000; Todd, 1980). These two methods assume confined conditions and a fully penetrating well. However, they are commonly used in various contexts more or less deviating from these ideal conditions. For the Theis curve match, the software AqteSolv™ was used. Two of the wells reached a steady-state condition after a few minutes due to the fact that available pumps were not powerful enough for the tested aquifers. No observation well data could be used for any of the tests, since the wells either reacted abnormally or were too far away to be influenced by the pumping wells. Therefore, no storage coefficient could be estimated.

Table 13. Results of slug tests in bedrock (UTMs Nad 83, Zone 20).

Well ID	X (UTM)	Y (UTM)	Z (m)	Formation	Borehole depth (m)	Method*	K (m/s)
Malcolm	361 705	4 992 308	42.3	Blomidon	31	B + P	1.8×10^{-5}
Greenwood / Tremont	347 284	4 979 363	28.8	Wolfville	66.1	P	1.6×10^{-4}
Memorial Park	386 933	4 992 424	21.1	Wolfville	61.2	P	2.3×10^{-6}
MN5-Kentville	378 619	4 992 642	11.0	Wolfville	134**	P	1×10^{-6}
MN6-Kentville (Seven-Bridges)	377 384	4 992 793	16.5	Wolfville	122**	P	5.2×10^{-6}

* B: bailer; P: pneumatic;
** Initial total depth when drilled.

Table 14. Results of pump tests (UTMs in Nad 83, zone 20).

Well ID	X (UTM)	Y (UTM)	Z (m)	Formation	Depth (m)	Duration (h)	K (m/s)
Somerset School	362 424	4 992 853	43.1	Wolfville	35	48	2×10^{-5}
Sheffield Farm	382 764	4 999 204	19.9	Wolfville	61	71	2×10^{-5}
Canning #3	388 565	5 001 662	27.5	Wolfville	118.7	24	7×10^{-6}
Village of Lawrence-town (granite well)	329 746	4 970 291	78.2	Granites	59.8	72	2×10^{-5}

Some problems occurred during all four pumping tests, either with the pumping well and/or observation wells. In particular, the drawdown at the Somerset school stopped increasing only 10 minutes after the beginning of the test. Since the well had a 150 mm (6″) casing, only one pump could be introduced and its rate was much too low for the well capacity. Therefore, conventional methods could not be used for the interpretation of the test and only an estimate of the transmissivity was obtained using the specific capacity ($C_s = Q/s_{max}$, where s_{max} is the maximum drawdown) and the Cooper-Jacob equation ('Data analysis" section). A positive boundary effect, probably corresponding to the influence of a nearby (~ 400 m) brook (either Thomas or Fisher, located east and west from the pumping well), was recorded after approximately 11 hours. The drawdown at the Canning well also stabilized rapidly (after 100 minutes, likely because the aquifer is very productive), and showed tidal influence.

The well located in Lawrencetown taps the South Mountain granite, and the two observation wells (separated by 5 m) are located in sandstone of the Wolfville Formation. One observation well was pumped continuously during the test. The wells seem to have responded to the pumping of the granite well nine hours after the start of the test, with a maximum additional drawdown of about 3 m at the end of the pumping period. However, the groundwater level did not recover, while the flow rate of the sandstone well never increased. Indeed, the groundwater level in both observation wells did not show any recovery, even 32 hours after the granite well pump was shut off. We thus concluded that these two wells were not in hydraulic connection with the granite well, and that this additional drawdown was attributable to nearby pumping. In the case of the Sheffield Farm well, the response from the available eight piezometers was not straightforward. They did not respond quickly to the pumping test (except for one) and drawdown versus time curves showed numerous anomalies. In addition, the maximum recorded drawdown was 25 cm. These piezometers could not, therefore, be used for interpretation. This is likely due to the fact that piezometers are less than 10 m deep (in comparison with the 61 m deep pumping well), and to the frequent aquifer/aquitard layering present in the sedimentary rocks of the Fundy Group. A positive boundary effect, likely corresponding to the influence of the pond located 2 km southeast from the pumping well, was recorded after approximately 18 hours.

Table 14 presents pumping-test characteristics along with the results, reported as the mean hydraulic properties obtained using the geometric mean of available data (from pumping and recovery at all pump and observation wells). Values of average hydraulic conductivity range between 7×10^{-6} and 2×10^{-5} m/s, indicating a good hydraulic potential. These pumping tests provided evidence that these fractured aquifers behave like an equivalent porous media as they followed normal Theis type curves.

Hydraulic conductivity values again correspond well to known properties of the Wolfville Formation (geometric mean of 10^{-5} m/s). However, the value for the Lawrencetown well is remarkably high for a well tapping granite rocks. According to the Lawrencetown superintendent of Public Works, this type of elevated value is not uncommon in the area. Due to the low-K matrix of the granite, this suggests that the fracture network is very well developed in this region.

Packer tests (multi-level slug tests)

Two of the three wells investigated using packers (TW3-Granville Ferry and Malcolm) intercept the Blomidon Formation, usually containing interbedded siltstone and shale beds within sandstone, and the last well (MN5-Kentville) taps the Wolfville Formation, mostly composed of sandstone and conglomerate. The length of each interval was 3.7 m, and the number of sections per well depended on its total depth (from 6 to 22).

Pneumatic slug tests were performed in all sections. For each isolated section, 2 to 4 tests were conducted to verify if the hydraulic head and hydraulic conductivities (K) were independent of the applied head, and if there was development of a skin effect. The interpretation was performed using the Bouwer and Rice (1976) method for isolated sections having moderate to low K values, while the methods of Butler and Garnett (2000) were used for high K value sections. Two sections showed an underdamped response (one in TW3 and the other in MN5) and were interpreted using the Butler and Garnett (2000) method; five showed hydraulic short-circuits, of which two (one in TW3 and the other in MN5) could not be interpreted. Short circuits can result from a poor contact between the packers and the borehole wall (due to wall irregularities) or from a connection of the isolated section to the rest of the well through fractures. Other sections showed standard overdamped responses, and were interpreted with the Bouwer and Rice method (1976). The summary of hydraulic head and conductivity profiles for each well is presented in Appendix F.

For the TW3–Granville and MN5–Kentville wells, two distinct zones were observed in both hydraulic head and conductivity profiles. Hydraulic-head results suggest an upward gradient for the MN5 and TW3 wells, indicating confined conditions, whereas for the Malcolm well, an absence of vertical flow suggested an unconfined condition. These conclusions are in agreement with borehole-geophysics observations. The two distinct zones observed in the hydraulic conductivity profile of the TW3 well (with packer tests) indicated that the transmissive part is located in the lower part of the well (last 65 m has values ranging from 10^{-6}–10^{-4} m/s), whereas the well protection is ensured by an aquitard having a lower K value (10^{-7}-10^{-6} m/s) in the upper part. However, these lower K values were not detected by borehole geophysics. The MN5 well do not seem as heterogeneous as the borehole geophysics suggests, investigating only major water bearing fractures. Elevated K values were found in the first few metres (10^{-3} m/s for the first interval), while moderate K values were found in the rest of the well (7×10^{-6} m/s on average). The Malcolm well seemed to be the most homogeneous, with values ranging from 3×10^{-6} and 3×10^{-5} m/s, with a moderate mean K value of 1.3×10^{-6} m/s.

Generally speaking, zones of very high hydraulic conductivity (>10^{-5} m/s) correspond to rocks dominated by fracture flow or weakly consolidated sandstone (as in the case of MN5-Kentville), whereas zones of lower hydraulic conductivity (<10^{-5} m/s) indicate the presence of few fractures. The major water-bearing zones identified by the geophysical logs usually coincided with high hydraulic-conductivity values as determined from packer tests. It is interesting to note, however, that the flowmeter-derived values of T are consistently greater than the slug-derived values (with a variable difference). Packer tests provide the intrinsic K value of the formation (aquifer) across a broad range of hydraulic conductivities, whereas profiles estimated by borehole geophysics with the flowmeter/pumping technique determine the flow rate corresponding to individual fractures, which may be a function of several fracture characteristics such as aperture, hydraulic connectivity, and frequency. In addition, discrepancies between the two methods may also be accounted for by inadvertent packer inflation over a permeable fracture, by leakage around packers, or by an inadequate calibration of the flowmeter.

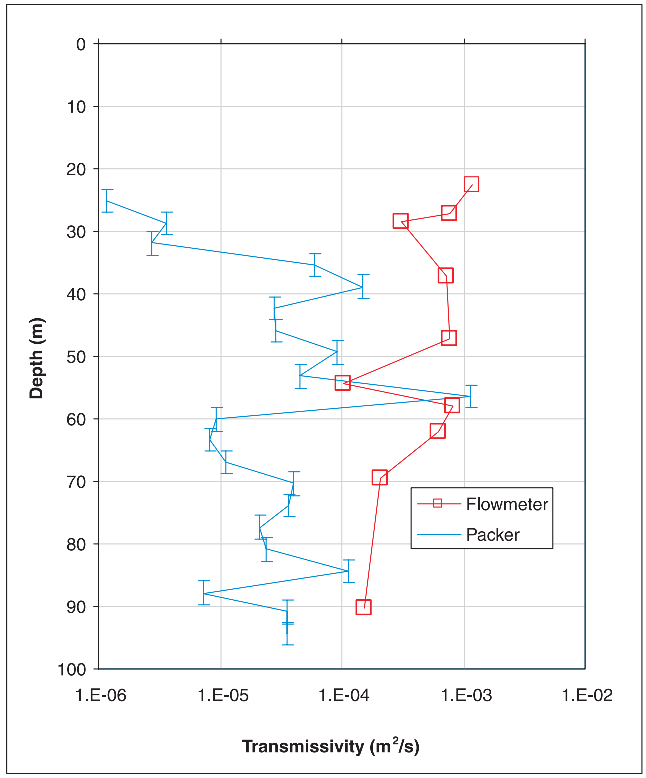


Figure 41. Comparison between results of borehole flowmeter-pumping tests and multi-level slug tests (packer tests) for the TW3–Granville Ferry well.

Several zones of high transmissivity identified from the results of geophysical logging also showed high values with the packer tests. In addition, overall transmissivities of the three investigated wells are very close. However, several discrepancies can be observed along the vertical profiles. Figure 41 presents combined results for the TW3-Granville Ferry well. The lower values detected by the packer tests in the well's upper part (first 4 sections) do not appear in the borehole geophysics profile. The overall hydraulic conductivities

Table 15. Results of packer tests (UTMs in Nad 83, zone 20).

Well ID	X (UTM)	Y (UTM)	Formation	Depth (m)	Intervals used (m)	K_H *(m/s)	K_H/K_V*
TB-Malcolm	361705	4992308	Blomidon	32	6	1.6×10^{-5}	2
MN5-Kentville	378619	4992642	Wolfville	100	16	8.5×10^{-5}	44
TW3-Granville Ferry	299523	4958797	Blomidon	108	21	2.4×10^{-5}	10
* $K_H = \Sigma(K_i \cdot b_i) / \Sigma b_i$; $K_V = \Sigma b_i / \Sigma(b_i/K_i)$							

Table 16. Comparison of hydraulic conductivities obtained using different methods (UTMs in Nad 83, zone 20).

			Method - K (m/s)			
Well ID	X (UTM)	Y (UTM)	Slug test	Pumping test	Packer test (K_H)	Borehole geophysics
TB-Malcolm	361705	4992308	1.8×10^{-5}	-	1.6×10^{-5}	4.3×10^{-5}
MN5-Kentville	378619	4992642	1.6×10^{-4}	-	8.5×10^{-5}	8.3×10^{-5}
TW3-Granville Ferry	299523	4958797	-	-	2.4×10^{-5}	5.7×10^{-5}

are: 5.7×10^{-5} m/s for borehole geophysics and 2.4×10^{-5} m/s for packer testing (see Tables 15 and 16). From the 22 tested intervals, 10 intervals from the lower portion (sections 5 to 22) had elevated K values ($\geq 10^{-5}$ m/s) and are thus likely located in fractured sandstone. The lower K values obtained in the first four sections of the well ($<10^{-6}$ m/s) probably indicate zones of siltstone and shale with very few fractures, whereas intermediate values (found in the lower section) probably indicate zones of sandstone with few or no fractures.

Table 15 presents results of horizontal and vertical hydraulic conductivities for the three wells, along with the K_H/K_V ratio, and the number of intervals tested. The anisotropic ratio varies from 7 to 39, with an average (geometric mean) of 14. However, the K_H/K_V ratios do not seem to be representative of the strong aquifer/aquitard layering known to occur in the Blomidon, and to a lesser extent, in the Wolfville formations. The investigated wells were mostly drilled into sandstones and differences seen among various intervals are likely more related to the presence or absence of fractures within sandstones, and to the size of the matrix grains. Moreover, the estimated K_H/K_V ratios are a function of the distance between the packers. However, as this distance is larger than the stratigraphic changes, these ratios tend to be underestimated. Overall hydraulic conductivities obtained from the different methods are compared in Table 16. Only three wells were investigated using more than one method and were thus included. No pumping tests were conducted in these wells.

The overall hydraulic conductivity values estimated using slug tests, packers, and borehole geophysics are in good agreement for the three wells, being within an order of magnitude (*see* Table 16). Unfortunately, no long-term pumping test results can be used for comparison. Considering the limitations and differences in these three approaches, these results are very satisfactory. Differences among values can be attributed to the measurement resolution (e.g. detection by the flowmeter of only the more permeable zones intersecting the well), well conditions, and methods of analysis.

Results from packer tests and borehole flowmeter-pumping tests show that even if they cannot be compared over single intervals (due to differences in measurement types), they can be very informative, and overall values seem to be representative. The packer system successfully measured the hydraulic conductivities of the less transmissive zones (these intervals were below the resolution limitations of the flowmeter/pumping method and were not detected), and thus allow the calculation of K_H/K_V ratios. The hydraulic conductivity of the intact rock matrix would possibility be on the order of 10^{-8} m/s, based on values measured in other regions in the Maritimes where similar sandstones can be found (Rivard et al., 2008).

Hydraulic properties of the surficial deposits

Areas with both high and low hydraulic conductivities (K) are important to identify because they either correspond to preferential recharge zones, as well as pathways for contaminants (high K), or they can be areas of flooding with heavy rainfall and where contaminants are less likely to enter the aquifer (low K). For the surficial sediments, permeameter tests allowed the estimation of the soil hydraulic conductivity across the valley and a few slug tests were also performed during the CPT/RPSS soundings work. Since most surficial sediments in the valley are composed of till, results from grain-size analysis could not provide K values by methods such as that of Hazen (*see* Fetter (2001), section 4.4.3), which requires sandy material.

Hydraulic conductivity (K) measurements performed on the same soil type in different locations usually yielded similar hydraulic conductivities when using the Guelph permeameter. Results are presented in Appendix G. Several soil types yielded relatively high hydraulic conductivities; these types usually had a high sand content. Conversely, soil units comprising clay appeared to be impermeable when soil permeability tests were performed (no change in hydraulic head was recorded even after long time intervals of 30 to 40 minutes). In total, 110 permeability tests were performed, of which 19 provided null values.

Table 17 summarizes the results, divided according to a simplified classification of the Quaternary map for ease of further comparisons. Field permeability tests are useful for in situ measurements of hydraulic conductivity, but are subject to a variety of problems (vertical/horizontal heterogeneity, site representativeness, measurement errors, etc.). Indeed, a surprising number of negative values were found using this method, indicative of the soil heterogeneity. Also, results for the finer texture soils (the 'fine' category) seem to overestimate K. The first metre of soil could have experienced desiccation, thus providing a much higher K value than a clay or a silt below this shallow horizon. This could also be the result of incorrect locations of finer texture soils from the Quaternary map, which is at a scale of 1:100 000.

Pneumatic slug tests were conducted using four surficial piezometers, one located in the Thomas Brook subwatershed and the other three in the Green Acres area (Table 18). The resulting K values ranged from 1.3×10^{-5} to 2.1×10^{-4} m/s, in agreement with values from the 'coarse' unit. Indeed, site 1 is located at the bottom of the Thomas Brook subwatershed, where tills are quite sandy, and the Green Acres region is also covered with sandy material.

To measure the hydraulic conductivity of the brook bed sediments, a seepage meter was used. Field measurements of groundwater seepage through the sediments were taken at four sites along the length of Thomas Brook in July 2005. Despite the variability of the surficial deposit cover from the North Mountain down to the southern part of the subwatershed (overlying the Wolfville Formation), results are surprisingly homogeneous, ranging from 2×10^{-7} to 6.4×10^{-6} m/s, with a mean of 1.9×10^{-6} m/s. The driving point installed at each site confirmed that the brook was fed by groundwater (since the hydraulic head within the sediments was higher than the water level of the brook), with a vertical hydraulic gradient increasing from 0.01 upstream to 0.18 downstream. Infiltration rates ranged from 6×10^{-9} to 3×10^{-7} m^3/s. No measurement was taken in major rivers such as the Annapolis or Cornwallis since their width and flow were too large.

Table 17. Summary of Guelph permeameter results divided according to a simplified classification of the Quaternary map.

Unit type	Corresponding Quaternary unit	K_{sat} (m/s)
Fine	Silt, clay, and fine sands: glaciolacustrine and glaciomarine deposits (L and M units)	5.0×10^{-7}
Medium	Sand: subaerial proglacial-xcc fan sediments (Go)	1.0×10^{-5}
Coarse	Sand and Gravel: ice-contact sediments (Gx)	3.1×10^{-5}
Till	Thick continuous (Tb) and discontinuous till (Tv)	3.3×10^{-6}

Table 18. Results of slug tests in surficial deposits (UTMs in Nad 83, zone 20).

Well ID	X (UTM)	Y (UTM)	Borehole depth (m)	K (m/s)
05AVMG0001	362125	4991003	7.47	1.3×10^{-5}
05AVMG00012	349098	4984273	13.5	4.4×10^{-5}
05AVMG00013a	349124	4984376	4.5	2.1×10^{-4}
05AVMG00013b	349124	4984376	12	2.8×10^{-5}

Water and soil analysis

Water sampling

Geochemistry mainly focused on the Thomas Brook subwatershed, where two studies on groundwater/surface water interactions and groundwater nitrate contamination and vulnerability were being conducted. Figure 42 presents sampling-site locations for each activity performed. Samples were taken from residential bedrock wells, GSC piezometers, and the Thomas Brook. Results showed that the composition of water circulating within surficial deposits does not differ from water flowing in bedrock. Indeed, there is no major difference between the surficial deposit water signature and the bedrock water signature, the water showing mainly a typical calcium-bicarbonate signature. The Blomidon Formation is the only unit having a distinctive signature, with higher Cl, SO_4, Ca, and Na concentrations at some sites. These results are in complete agreement with those of Trescott (1968) (*see* 'Overview of groundwater quality' section).

Laboratory results from the summer 2004 sampling campaign have also shown that nitrates are found in much higher concentrations in the bedrock than in surficial deposits. Nitrates-N concentrations in all samples ranged from 0.01 (detection limit) to 17.8 mg/L with a median of 1.5 mg/L, i.e. higher than the assumed background level in the Annapolis Valley. However, if only bedrock wells are considered (17 samples), the median increases to 4 mg/L. The situation is thus of concern. More information about nitrates in the Annapolis Valley is presented in the 'Geochemistry' section, and detailed results and analysis for the Thomas Brook subwatershed can be found in Trépanier (2008).

Both total coliform and *E. coli* bacteria were also analyzed in the Thomas Brook subwatershed. Most of the contaminated samples were found in surficial deposits, i.e. where piezometers had been installed, and *E. coli* bacteria were much less frequently encountered than total coliform bacteria. Six samples taken in surface water and one in a piezometer showed total coliform levels above 200 colony-forming units (cfu)/100 mL. Seventeen samples exceeded the 0 cfu/100 mL guideline for total bacteria, of which seven were in bedrock. Five samples have shown the presence of *E. coli*, usually with low levels (except for two samples exceeding the 200 count, one in the brook and one in a piezometer).

For stable isotopes, three sampling campaigns were carried out for samples across the valley in 2004 and 2005 in residential wells. Fall-winter and winter-spring campaigns represent a subset of the summer campaign, to observe seasonal variations. Three additional sampling campaigns were conducted in 2005 and 2006 for the Thomas Brook

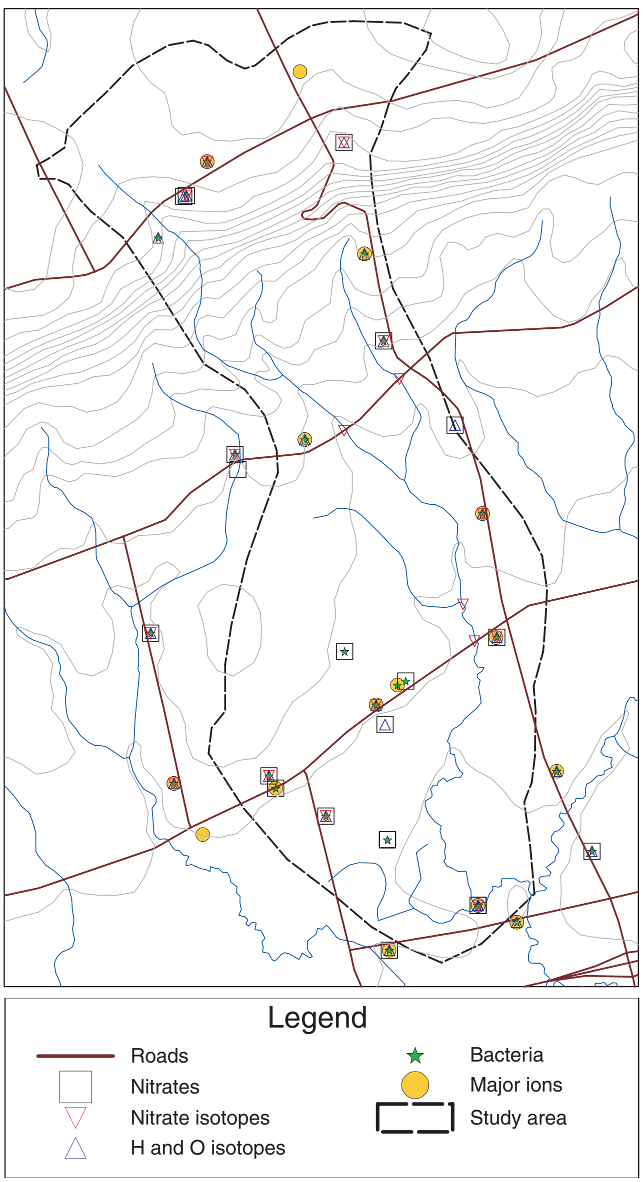


Figure 42. Sampling site locations within the Thomas Brook sub-watershed (taken from Trépanier, 2008).

subwatershed for the same periods. Results did not show any very old water (>10 000 years) and thus, measured ^{18}O and ^{2}H contents follow the local meteoric water line. Complete results are presented in the 'Geochemistry' section, along with the interpretation and a sampling-location map. Detailed results for the Thomas Brook subwatershed are available in Gauthier (2009).

Samples were taken for nitrate isotopes in 2005 and 2006 only in the Thomas Brook subwatershed. Groundwater was sampled in bedrock wells and in Thomas Brook. First, the results have indicated that natural denitrification cannot explain the occurrence of low values of nitrate concentrations at the bottom of the Thomas Brook subwatershed (*see* the 'Geochemistry' section). For the high nitrate-concentration zone, results of nitrate-isotope analysis did not provide a clear answer on their origin. The signature observed suggests a combined effect from plant residues, manure, and/or septic system leaching and application of ammonium fertilizers.

Water dating was performed in the summer 2006 in order to determine the age of the groundwater at various sites. Tritium (^{3}H) dating is generally used to determine if groundwater has mixed with surface water (including precipitation) or has been derived from surface water in the last 50 years. Tritium is a short-lived radioactive isotope of hydrogen with a half-life of 12.43 years. Tritium forms naturally in the atmosphere with natural tritium levels in precipitation being around 5 tritium units (TU). Atmospheric testing of nuclear weapons from 1952 to 1980 caused an increase in the tritium content of precipitation up to a maximum level of 2500 TU in 1963 (current levels are 10–30 TU). This recent spike in meteoric tritium levels can be used to determine if groundwater is 'old,' meaning that it has been cut off from the influx of surface waters since 1952, or if it is 'recent,' meaning that at least some of the water is younger than 50 years old. Old groundwaters will have tritium values significantly less than the naturally occurring value of 5 TU, given that tritium content continues to decrease once in the groundwater system. A tritium content of zero implies that the water is quite old and has been cut off from the surface environment for 100 years or more. Recent groundwaters will have tritium values greater than 5 TU. Although 'recent' implies that a portion of the groundwater is younger than 50 years old, there may also be a component of old groundwater, since old groundwater is tritium void and cannot be distinguished in a sample containing recent groundwater. Values slightly less than 5 TU can more definitively be said to be of a 'mix' composition, given that they are below natural levels (implying that they are old) and at the same time if they truly were old, tritium levels would have decreased to well below 5 because of the short half life of tritium.

Tritium results showed that water of all types (recent, mix, and old) can be found in the valley. Two out of seven samples were rated 'old' (i.e. <1952). These samples had been taken in a deep well (200 m) tapping the Meguma Group slates, and interestingly in a quite shallow (37 m) well completed in the Wolfville Formation, indicating that this water had likely circulated through the North Mountain and Blomidon formations (without much mixing with recent precipitation). For these two samples, ^{14}C analyses provided approximate ages of 9000 and 6000 years. The North Mountain and Blomidon formations appear to contain recent or mix water. This is not surprising for basalts since water infiltrates rapidly through vertical joints/fractures. The basalt well showing a mix age estimate is also tapping the Blomidon Formation in the last 5 m. The quite deep (100 m) well tapping the Blomidon Formation at the western end of the valley appears to have a component of recent water, likely due to the fact that this well contains mainly sandstones. A 'recent' or a 'mix' age estimate is more common in open (non-cased) wells, as waters from different horizons are combined in the well. Tritium results and some of the wells' characteristics are presented in the 'Geochemistry' section (*see* Table 33), along with additional results from NSE.

Soil sampling

Sampling of surficial sediments across the Annapolis Valley was carried out during fieldwork for Quaternary mapping. Samples were used for grain-size, microfaunal, and plant-remains analysis purposes. Grain-size analysis served to characterize the various surficial materials, in particular for groundwater modelling.

Of the first 34 samples collected for grain-size analyses throughout the valley, 17 were tills, nine came from glaciolacustrine units, five were from various sandy/gravelly units, and three were taken below organic material in a bog, presumably over fluvioglacial material. The location of these samples is presented in Figure 43. Important information can be derived from the grain size curves. For instance, four distinct classes of tills were recognized (Fig. 44) and the variability of glaciolacustrine sediment distribution is obvious (Fig. 45).

The tills with the finest matrix (2% sand, 55% silt, and 43% clay) were found in a stratigraphic section above the wall of an active slate quarry on South Mountain. The till (two samples, below a visually different till) is likely derived from the red beds of the Wolfville sandstones as well as from the local slates. This till probably represents the till sheet associated with the Escuminac-phase southeastward ice flow. Till stratigraphy was observed at one other location, on North Mountain, and might record this same lower unit, but the section was not sampled because the property owner did not authorize access. The majority of the tills belong to an intermediate group, subdivided into two subgroups. Those tills located on South Mountain have a silty-sand matrix (54% sand, 31% silt, and 15% clay), and those located on North Mountain have a sandy-clay matrix (38% sand, 27% silt, and 35% clay). These constitute two samples taken in the stratigraphic section described above, and are thought to represent Scotian-phase ice flow. The extreme end member of this till is found on North Mountain, and is represented by large South Mountain erratic boulders. The fourth class of till is found in the area of Middleton, and is characterized by a sandy matrix (84% sand, 12% silt, and 4% clay). It is believed that this till is associated with the final ice flow in the Valley, Chignecto phase, a late ice stream that likely reworked fluvioglacial deposits.

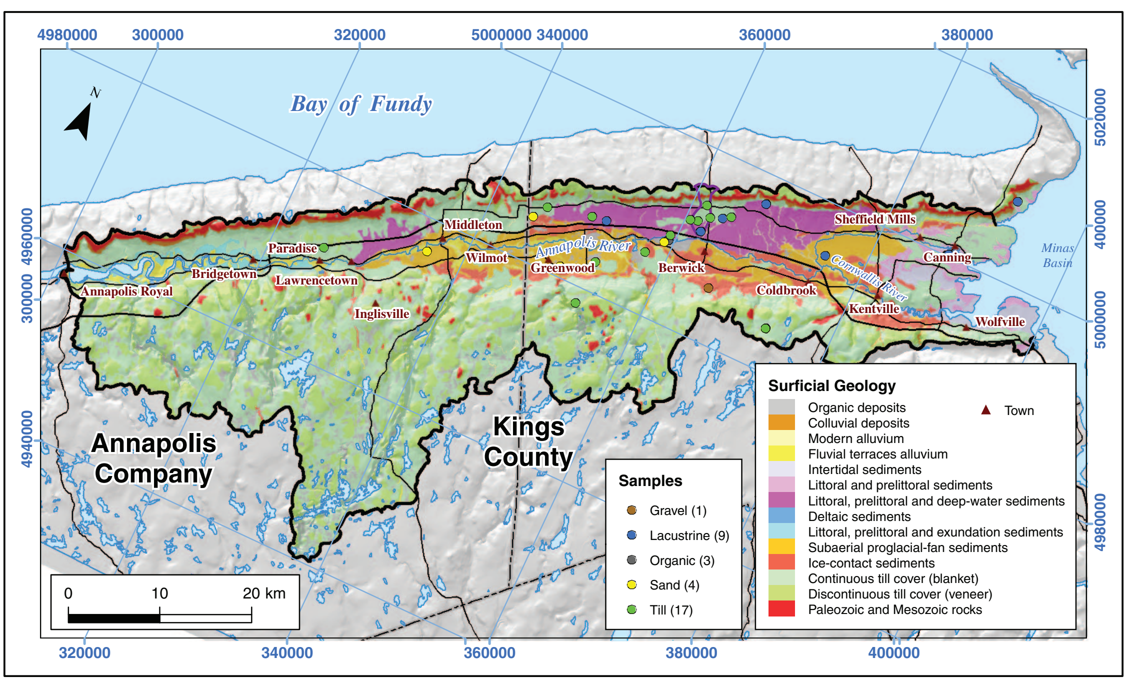


Figure 43. Location of those samples collected for grain size analysis.

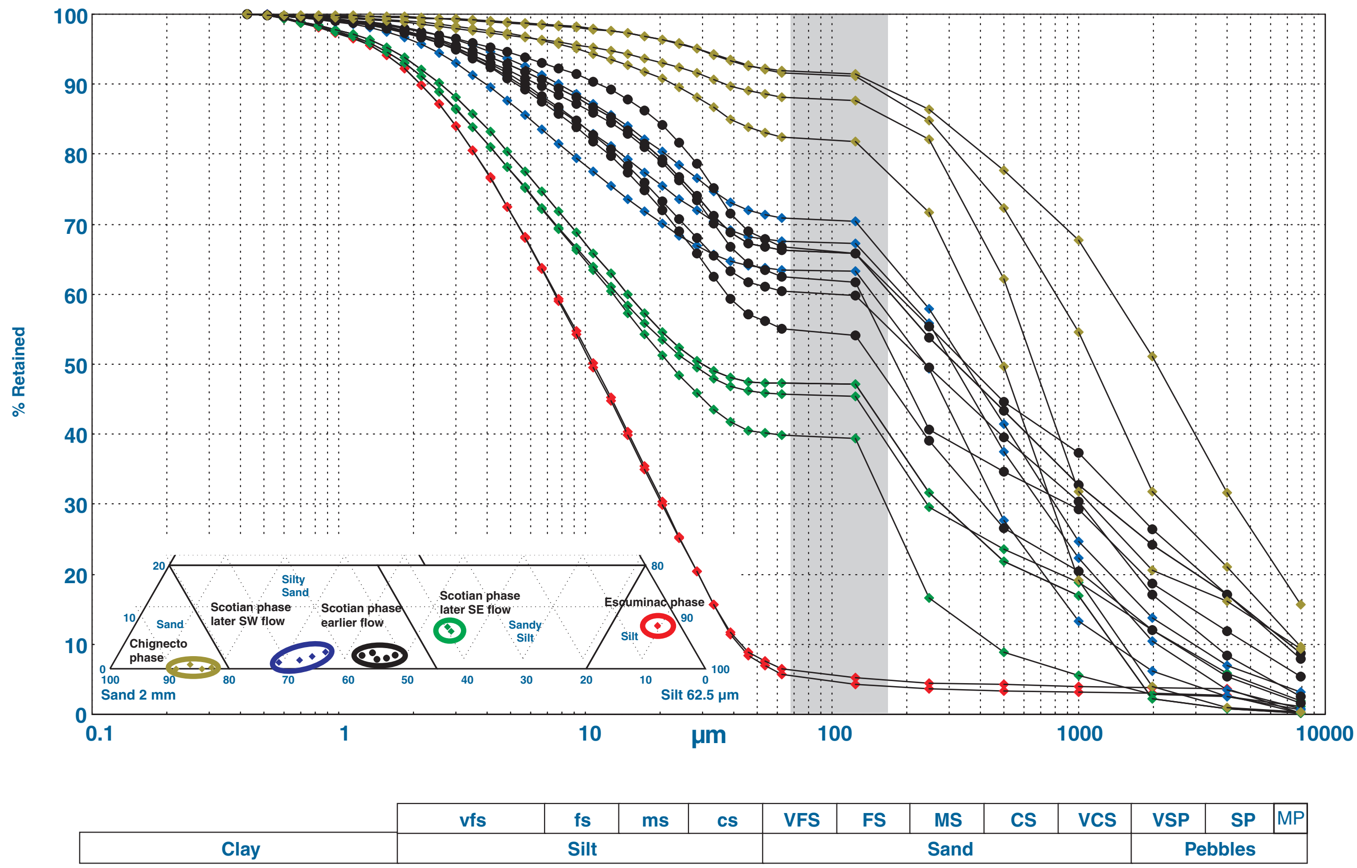


Figure 44. Grain-size curves of tills in the Annapolis Valley. Note the four distinct classes of tills (in green, black, blue, and brown), as well as the distinction that can be made in one group when plotting the data on a triangular diagram. The anomalous value at 125 µm is due to merging of data from two different analytical procedures.

Glaciolacustrine sediments can be grouped in three classes on the basis of grain-size distribution. The finest grained sample (4% sand, 68% silt, and 28% clay) comes from the base of a thick (>2 m) sequence and likely represents sedimentation in deeper waters. The three sandiest samples (78% sand, 14% silt, and 8% clay) come from sequences that were close to till knobs, and likely represent reworking of the underlying sediments.

As expected, the sandy-gravelly sediments plot (Fig. 46) in the 'sand' zone of the triangular diagram. The three samples from beneath the bogs, although thought to have been collected in fluvioglacial material, are clearly not sandy in nature. Although they have similar grain-size curves to the intermediate till class, they are more likely associated with glaciolacustrine sediments. They indicate that below the bogs, there exists a unit that is impermeable enough to impede proper drainage.

Microfaunal analyses were performed to establish whether those fine-grained sediments were in fact glaciolacustrine or glaciomarine. Only one sample yielded numerous sponge spicules and one foraminifer. These are likely contamination, and reprocessing of the sample has not allowed the identification of any marine fauna. All other samples were sterile, which either means that there was no fauna in them, or that all microfaunal tests were dissolved, a common phenomenon in noncarbonated sediments. Plant-remains analyses were performed to evaluate the paleo-environments at the time of deposition of the various units. With the exception of the Blomidon site, all others were very poor in plant remains, suggesting the sediments were laid out soon after deglaciation. At the Blomidon site, a known peat layer, which dates at 11.7 ka at the base and at 10.6 ka at the top (Mott and Stea, 1993), is evidence for an improved climate interval before the final glacial pulse of the Younger Dryas. The sediments above the peat, a glaciolacustrine sequence, are sterile. For details on this sequence, *see* the 'Quaternary' section.

In addition, a soil sampling was conducted for the specific area of the Thomas Brook subwatershed so as to get information on grain size, total porosity, apparent bulk density, natural-water content, and total organic matter. Grain-size analyses have allowed a better understanding of the local surficial sediment cover and, as a result, some corrections were brought to the Quaternary map. Four soil units with specific porosity, grain-size distribution, apparent bulk

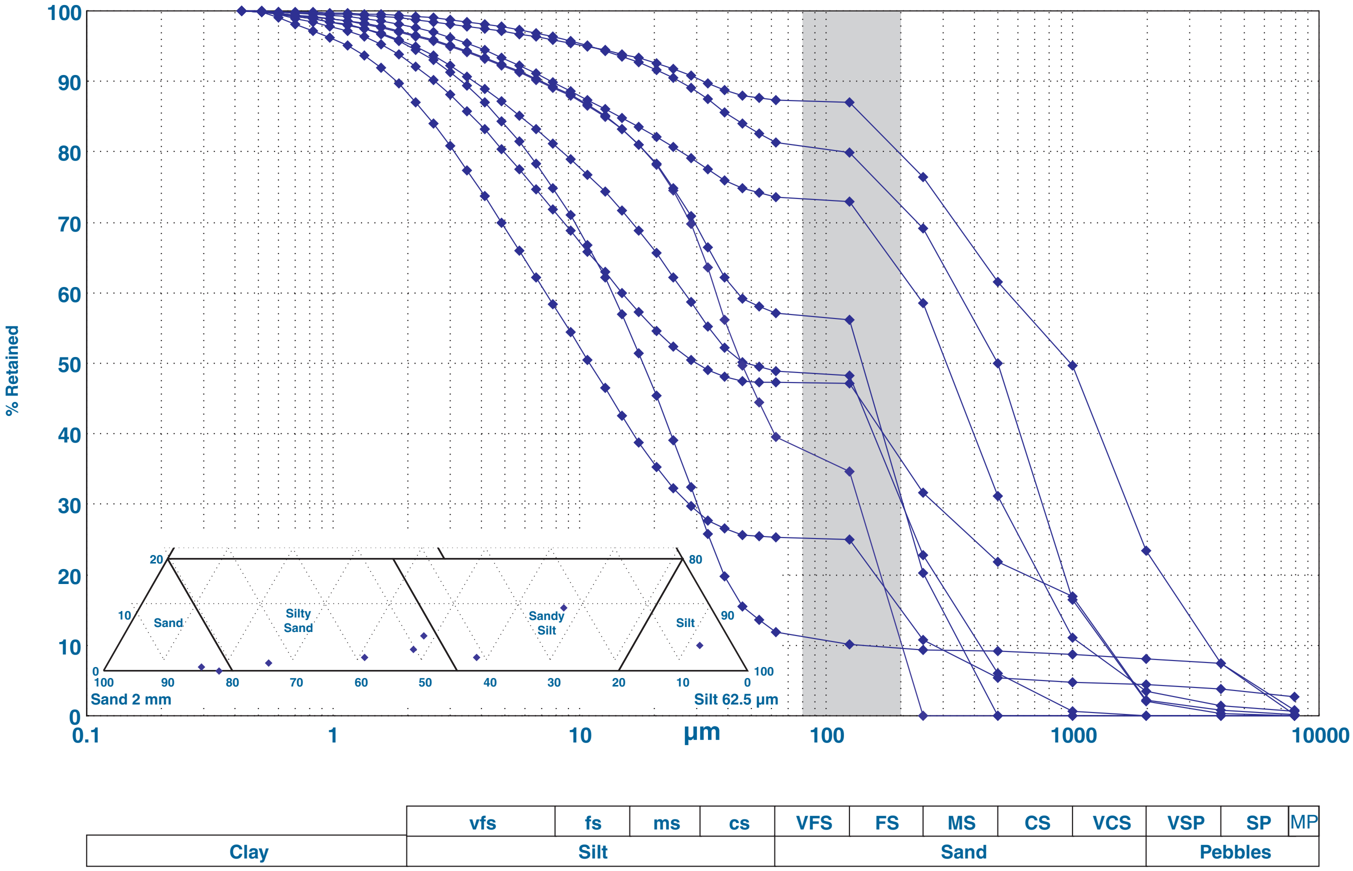


Figure 45. Grain-size curves of glaciolacustrine sediments. Note the heterogeneity of the curves. On the triangular diagram, some groupings are possible, and are coherent with the location of the samples, as explained in the text. The anomalous value at 125 µm is due to merging of data from two different analytical procedures.

density, and organic matter concentration were defined in preparation for the numerical simulations. These soil units were combined with six typical types of crop rotation of the study area. The combinations were used as input in the 1-D Agriflux (Banton et al., 1993) model to evaluate water flow and nitrate leaching out of the root zone. More information is provided in Trépanier (2008).

Remote sensing

The land cover map is only presented in the atlas (Rivard et al., 2007, Plate 1.5). It provides information on the spatial and structural characteristics of the land cover (land use and vegetation type) distribution in the Annapolis Valley area for the year 2002. A detailed classification scheme was employed, permitting the extraction of virtually all land-cover information that can be discerned from digitally enhanced Landsat images. Even for the atlas, the land use and vegetation classes had to be greatly simplified compared to the original map. Aggregation within each category was necessary in order to get an appropriate representation at the regional scale.

For the leaf area index (LAI) map, the forest, disturbed areas, and orchard plots were grouped in a single regression to an infrared vegetation index from coincident Landsat 5 imagery while the pasture plots were grouped in a second regression algorithm. Some improvement could be made by separating orchards from other cover types but there was sufficient uncertainty in the land cover map that it was decided to pool all treed vegetation together. The crop and vegetable LAI plots were used to verify published algorithms based on extensive crop specific data sets (Fernandes et al., 2002). The LAI map is presented in Figure 47.

The peak season LAI map was supplemented by a ten-day interval 1 km LAI product spanning the years 1985 to 2005 (Fernandes et al. 2002). Comparison of this product with LAI data over the Kejimkujik forest region (in the South Mountain, south from the study area) was performed (Abuelgasim, et al. 2006). The 1 km data overestimated LAI by 40% over this region primarily due to the incorrect use of boreal forest species (black spruce/jack pine) shoot parameterizations in the retrieval over the hemlock-dominated forests. This bias has been corrected in the data used in the study and in the publicly released Canada Centre for Remote Sensing (CCRS) LAI products (found at www.geogratis.ca).

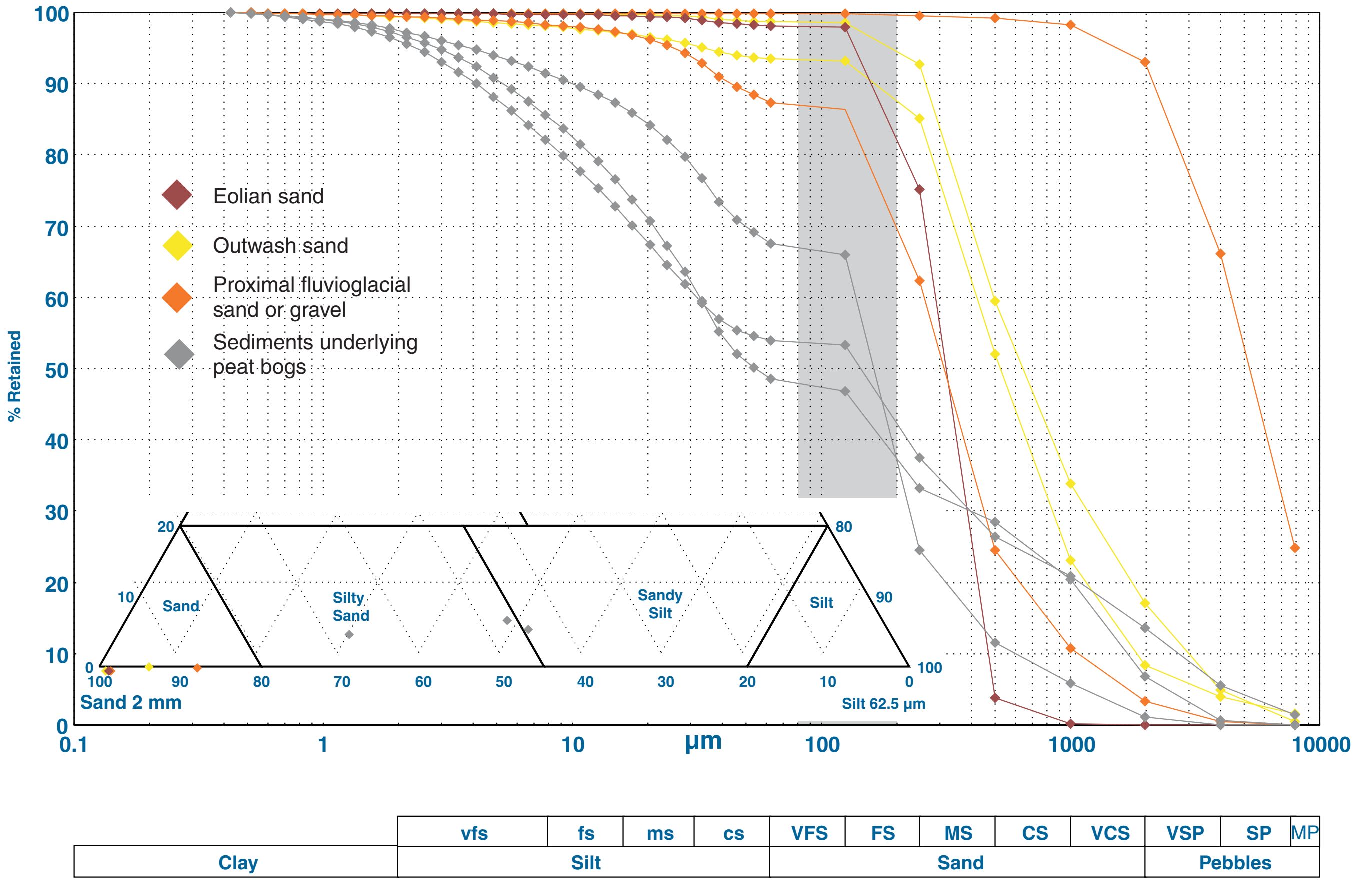


Figure 46. Grain-size distribution of sandy-gravelly sediments (orange and brown) and samples from beneath peatlands (grey). The curves and triangular diagram suggest that the sediments beneath the peatlands are more likely tills of the intermediate class, or glaciolacustrine in origin. The anomalous value at 125 µm is due to merging of data from two different analytical procedures.

Existing data or samples

Existing data were used to 1) calculate recharge rates, 2) verify previous results of hydraulic-conductivity values from pumping tests, 3) add approximate hydraulic conductivity values to increase the spatial coverage, 4) obtain more information on fracturing within each geological formation, and 5) estimate recharge and water-level trends of the last decades. Existing core samples were also analyzed to obtain total rock-porosity values.

Nova Scotia Environment (NSE) pumping tests

The reinterpretation of pump tests used common methods such as Theis or Cooper-Jacob for the available pumping tests in the Nova Scotia Environment (NSE) pump-test database. A few values were added to this database based on report sheets obtained at the beginning of the project from NSE. About one quarter of these had or now have raw data available in a digital format. Results were generally close to previously calculated values; however, in certain cases, the new interpretation sometimes led to a difference of plus or minus an order of magnitude or more. Maps showing the spatial distribution of the K values in bedrock and surficial sediments are presented in the 'Hydrogeological context' section (*see* Figure 52a and b). A few storage-coefficient values were also reinterpreted when possible; they were typically close to those reported in the database.

Most available data for bedrock wells showed a behaviour typical of equivalent porous media under confined conditions, i.e. following Theis-type curves. Few changes in slopes due to boundaries have been observed. S-shaped type curves, typical of double-porosity or unconfined aquifers, were sometimes seen in wells tapping sand and gravel aquifers (e.g. KIN-15, KIN-48, KIN-59, KIN-66) and in bedrock (ANN-32, in basalts of the North Mountain Formation and ANN-30A, in the Wolfville Formation). However, double-porosity media is improbable in this area. The primary porosity is too low in basalts and ANN-30A would be the only well from the Wolfville Formation (for which we

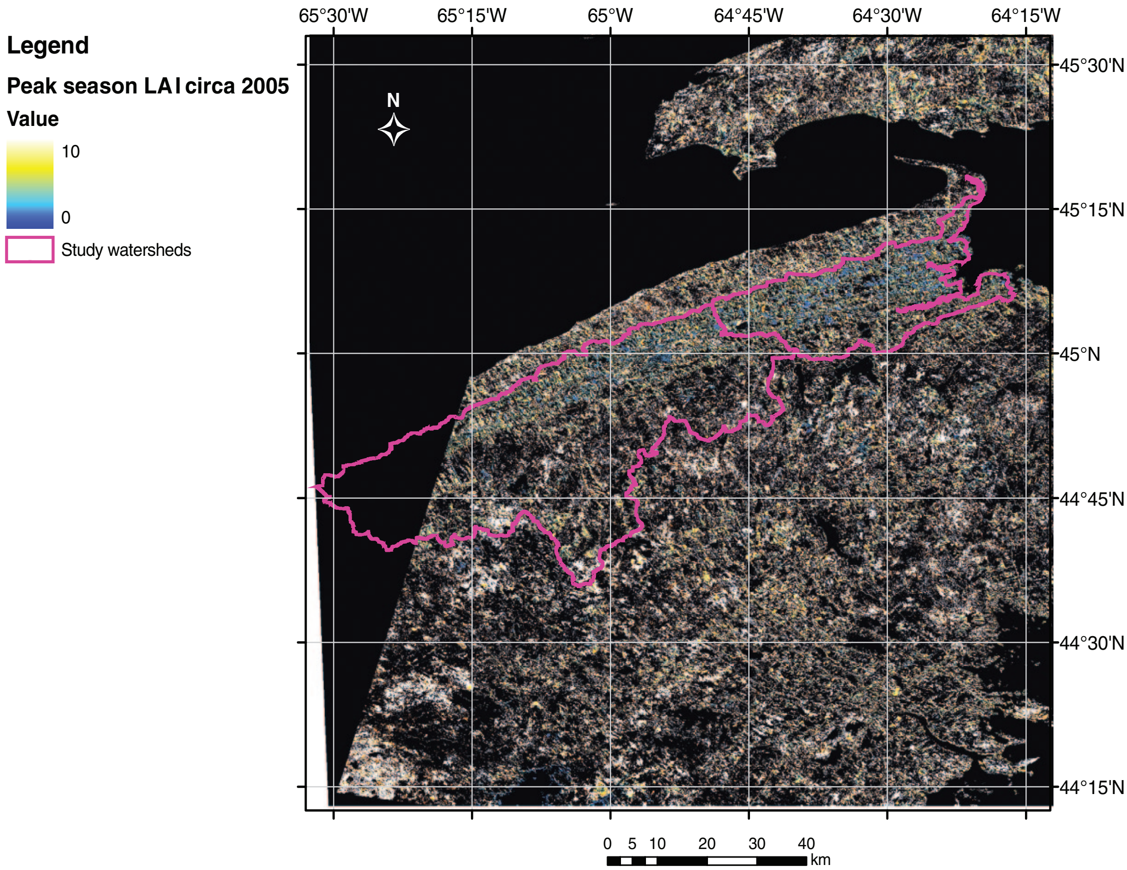


Figure 47. Peak season 30 m leaf area index (LAI) map ca. 2005 for Central Nova Scotia based on Landsat TM 5 imagery and in situ plots.

have data) that would have shown this type of behaviour. Consequently, they could more realistically be under local unconfined conditions.

Results from short-term pumping tests (usually in the development phase of the well, right after its construction) have also been added to Figure 52, but with a different colour, so that they can be distinguished from the longer-term pump test results. Indeed, those results represent a significant addition (55) to the long-term pump test results, but they do not have the same reliability and are often located very close to sites for which a pumping test result is available. They nevertheless provide an idea of K values in several additional locations. Also, these hydraulic conductivities seem to generally fit into the overall valley 'picture' and into the statistical distribution of individual formations. However, they did not significantly improve the definition of a variogram for the entire valley (*see* 'General hydraulic properties' section). Values are too variable for the number of data pairs to be sufficient and they depend heavily on the formation they belong to (and on the particular unit tapped), rather than on the geographical location. A well defined variogram could therefore not be obtained for the Wolfville Formation, where most data are available, because of its heterogeneity.

Groundwater recharge

Hydrograph separation method

An example of baseflow calculation using the Chapman (1991) method is presented in Figure 48 for daily flows calculated for the Annapolis River station at Lawrencetown (gauging station 01DC007) for 1996. The main contribution of the aquifer to the river can be observed after the snowmelt period (March–April) and, to a lesser extent, in the rainy season (November–December). During these specific periods, the contribution of the two components (surface and subsurface flow) can be almost equal, while during the rest of the year the surface flow is distinctly smaller than the baseflow or even negligible. For this particular example, annual recharge for this specific year was estimated to be 43% of the annual total precipitation.

The annual recharge rates estimated with the Chapman (1991) and Rutledge (1998) methods for the selected gauging stations are summarized in Table 19. The Annapolis and Cornwallis rivers have several hydraulic structures to regulate the flow, but these are not believed to have a major impact on the estimated values. As can be seen in Table 19, recharge is high and its variations for a given method are small. The watershed areas integrated into the calculations (depending on the location of the gauging station) vary from nearly 9 km^2 up to 1020 km^2. Stations are located close to the centre of the valley (except for 01DD004, which corresponds to the smallest watershed). It must be kept in mind that in this analysis, baseflow was assumed to represent recharge, which is not necessarily the case (*see* interpretation in the 'Hydrogeological context' section).

The Lawrencetown station (01DC007) integrates a large part of the Annapolis watershed (64%). However, only 6.5% of the area is covered by the two gauging stations in the Cornwallis watershed (01DD004; 01DD005). The mean groundwater recharge found, corresponding to the weighted average over the encompassed area, is 360 mm/a with the Chapman method. Higher values were found using the Rutledge graphical method. This could be due to the fact that runoff is still quite important in the segments used, but rain events in the valley are too frequent to be able to get the appropriate master recession curve (MRC) curve. Indeed, trials were carried out using periods extending from 2 to 6 days that were eliminated from the segments (at the beginning of the recession curve). Results showed that

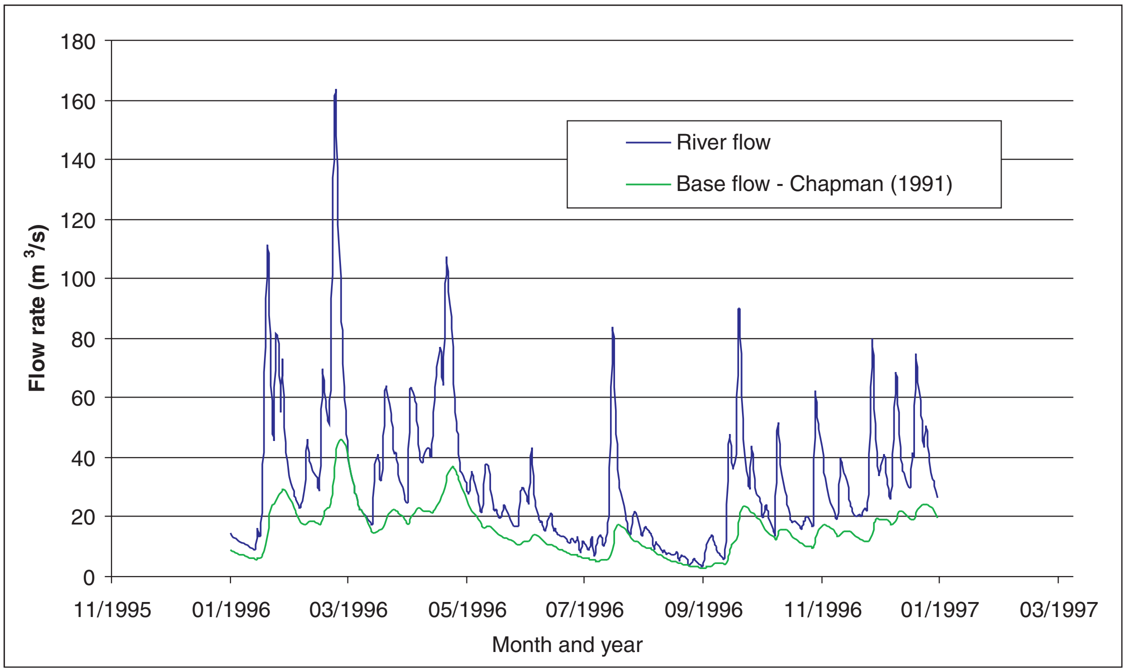


Figure 48. Example of base flow calculation for the Annapolis River at Lawrencetown (station 01DC007) for 1996.

Table 19. Annual recharge rates estimated using hydrograph separation.

Station ID	Location	X UTM	Y UTM	Watershed area (km^2)	Period covered	*number of years used	Recharge Chapman (mm/a)	Recharge Rutledge (mm/a)
01DC003	Paradise	327 276	4 967 871	107	1916–1949	30	392	-
01DC007	Lawrencetown	328 883	4 970 483	1020	1983–2007	22 / 16	364	558
01DC005	Wilmot	339 887	4 979 370	546	1963–2007	44 / 37	352	535
01DC006	Millville	356 254	4 984 754	119	1965–1979	14	395	-
01DD004	Lloyds	371 018	4 987 032	8.8	1966–1995	28 / 27	382	524
01DC001	Lequille	302 610	4 955 270	148	1915–1919	1	337	-
01DD005	Sheffield Mills	384 052	5 000 734	15.7	2000–2008	7	348	-
			Sum:	**1964.5**		**Mean:**	**360**	**539**

* This column provides the number of years used in the calculation for the Chapman (1991) and Rutledge (1998) methods. This number does not necessarily correspond to the period covered, since years were rejected if data were not recorded on a sufficient number of days (usually 300 days was taken as the threshold, except if the number of years were small, then 290 was accepted).

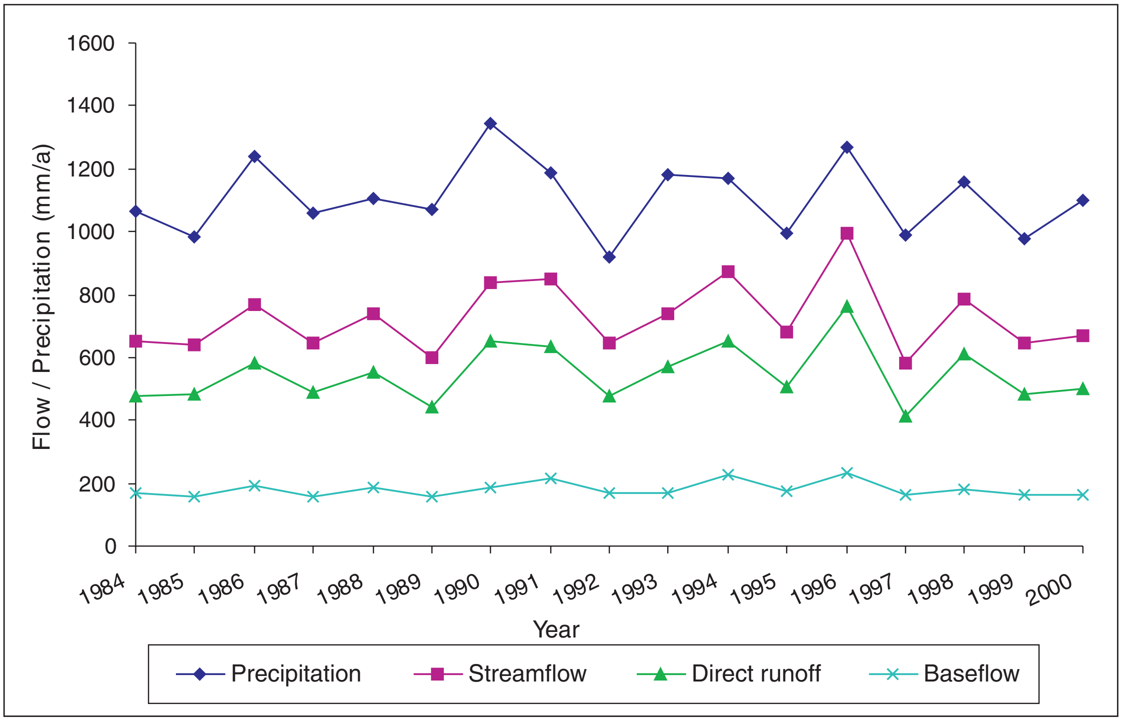


Figure 49. Mean annual precipitation, streamflow, direct runoff and baseflow based on the Greenwood climate station and gauging station 01DC007.

recharge was decreasing significantly as this delay was increased. Therefore, it was decided to reject these values for the potential range of recharge values.

The Chapman (1991) method also provided relatively high recharge rates for this hydrogeological context. It would be surprising if all this water could reach the bedrock aquifers, since a large portion of the study area is under confined conditions or underlain by low-K rocks. Therefore in the Annapolis Valley, high recharge values probably indicate that a significant percentage of the infiltrated water flows horizontally in the sediments toward streams and never reaches the bedrock. However, if months with snow, snowmelt, and important rain events (from November to May) were removed from the calculation, and the five-month estimate redistributed over 12 months, the annual value could become a more realistic estimate.

The Eckhardt (2005) two-parameter filter provided much lower values, with a mean of 180 mm/an for the 01DC007 station, using a maximum baseflow index of 0.25. Given that the surficial cover comprises mainly till, this value appears to be much more realistic. This recharge value would represent 16% of total precipitation and 25% of annual streamflow over the 1984 to 2000 period. Surface runoff was estimated to be on the order of 42%, giving an evaporative fraction of approximately 40% (Fernandes and Korolievich, unpub. rept. 2006; Figure 49).

Water-balance method

Annual recharge rates estimated with the water-balance method (*see* Equation 3, in the 'Water-balance method' subsection of the 'Groundwater recharge' section) are presented in Table 20 as a function of the simplified classification of the Quaternary map defined in the 'Geological context section'. Minimum and maximum recharge values are also provided in Table 20. They correspond to extreme values obtained for some of the cells in a given unit. Mean values, as well as mean plus or minus the standard error ($\mu \pm \sigma$) are also provided in this table, as recharge values calculated at each cell are approximately normally distributed within a given unit. The weighted average over the entire study area gives minimum, maximum, mean, and probable variation of recharge rates of, respectively, 73, 433, 249, and 162 and 336 mm/a, thus including values obtained with hydrograph-separation methods (Chapman, 1991; Eckhardt, 2005).

These estimated values are again rather high for this particular hydrogeological context and hence are probably not representative of the bedrock recharge. Indeed, it must be noted that values obtained with the water-balance method correspond to an estimate of the total amount of water leaving the root zone, and not water recharging the bedrock. Numerous small streams and lakes are present over the study area, suggesting that the soil is not well drained. A significant portion of the estimated infiltration is likely to reach streams before the bedrock. A good indication of this is the elevated values obtained for tills, even if they cover most of

Table 20. Annual recharge rates estimated using the water balance method.

Surficial units	Area covered (km^2)	% total area	Potential recharge (mm/a)				
			Min	Max	Mean**	$\mu - \sigma$ *	$\mu + \sigma$
Fine	234	12%	73	430	308	240	376
Medium	170	9%	73	430	275	184	366
Coarse	106	5%	73	430	264	168	361
Continuous till	925	47%	73	435	248	161	334
Discontinous till	547	28%	73	435	215	122	308
Weighted average:			**73**	**433**	**249**	**162**	**336**
Corrected weighted average (**-10%**):			**66**	**390**	**224**	**146**	**302**
Corrected weighted average (**-52%**):			**35**	**207**	**120**	**78**	**161**

* μ=mean **;** σ = standard deviation

** Recharge values provide illogical values due to use of a different map for the calcuation and the presention of the results (as the Quaternary map of Figure 15 was not availabl e at that time of the calculation).

South Mountain, representing nearly half of the study area. These high recharge values are the result of the difficulties to calibrate the runoff (SCS curves) with reliable streamflow gauging stations over the entire study area, especially for small streams in the North and South mountains. In addition, inconsistencies in the definition of the soil unit and rather qualitative definition of the soil drainage classes from the available pedologic maps result in a broad estimation of the soil type and drainage classes required to estimate runoff. In addition, pedologic maps were used for the estimation of recharge, while the classes used in Table 20 are based on the new surficial geology map, leading to inconsistencies in values obtained for each class. Therefore, the weighted average for the entire study area, rather than individual values, should be considered.

An attempt was made to estimate the percentage area where recharge is impossible (in other words, where the water cannot percolate from the root zone to the bedrock aquifers) due to upward gradient. Since few water-level measurements are available for the surficial deposits, a potentiometric map could not be obtained. Therefore, vertical fluxes (exchanges) between surficial deposits and bedrock are unknown for most of the study area and the Darcian approach cannot be used. Moreover, indications of artesian conditions could not be deduced from the interpolated bedrock potentiometric map (using areas where the potentiometric surface is higher than the topography), since water levels are generally too sparse for this result to be reliable at the regional scale. Instead, water-level measurements were used to estimate the percentage of areas where artesian conditions and springs are found. It was also decided to include wells for which the water depth was less than 1 m. Geological Survey of Canada (GSC) surveys indicated that only about 9% of visited wells falls within this category, and values from the NSE database provided a similar result of 11%. However, this might represent a small part of areas where recharge is impossible since bedrock aquifers are assumed to be often confined.

On the other hand, the comparison between water elevations in bedrock and streams using high precision GPS and LIDAR technology (*see* 'Data from fieldwork' section) showed that 52% of the wells had a difference in elevation of 2 m or more. Therefore, these two percentages (10% and 52%) were used as limits to estimate potential areas where recharge is not possible and thus, the bedrock-recharge range. As a result, minimum, mean, and maximum values that should be more representative of the groundwater recharge to the bedrock aquifers would be on the order of 35 to 66 mm/a, 120 to 224 mm/a, and 207 to 390 mm/a, respectively. Therefore, the mean groundwater-recharge range obtained with the corrected water-balance method (120–224 mm/a) is significantly smaller than the mean recharge obtained with the first hydrograph-separation method (360 mm/a with Chapman, 1991), which is likely less representative of what reaches the bedrock, but in agreement with the last method (180 mm/a, Eckhardt, 2005).

Groundwater fluctuations and specific yields

Values of $\Delta h/\Delta t$ estimated using four well hydrographs are summarized in Table 21. The number of years used for the calculation varies widely depending on the well. Recharge rates between 73 and 430 mm/a were chosen, since these values correspond to minimum and maximum values, and that selected wells for this estimation were all located in sand and gravel units. Specific yields (Sy) were found to range from 1 to 10%. These values are surprisingly low for granular aquifers (Todd, 1980 p.38 suggests Sy>20% for fine to coarse sand units). However, no well logs and no information on the well construction are available for these monitoring wells. In addition, other reasons could explain the finding of such low Sy values, such as additional water from field drainage (e.g. the Wilmot well is located at the limit of a cultivated field, next to the Annapolis River) or finer material located within (i.e. clogging) or above the aquifer that could create partly confined conditions (i.e. that the water table would not fluctuate freely).

It has to be kept in mind that this method is very local and strongly dependent upon the well-log knowledge. Since information for these wells is very limited, this method only

Table 21. Recharge rates obtained from well hydrographs.

Location	X UTM	Y UTM	Period covered	*Number of years used	$\Delta h/\Delta t$	S_y for W=73 – 430 mm/a
Coldbrook	375556	4991389	1965-1994	23	6624	1.1% - 6.5%
Greenwood	350674	4985513	1966-2002	20	4470	1.6% - 9.6%
Wilmot	339953	4979299	1966-1995	19	7800	0.9% - 5.5%
Wolfville 1	391899	4993763	1969-1990	22	6417	1.1% - 6.7%
* This column provides the number of years that was used for the calculation.						

provides an indication that these wells could possibly not be totally unconfined, or that more water than the average annual precipitation amount infiltrates.

Fracturing

Drillers' reports usually provide depths at which water-bearing fractures are encountered. However, the original database had room for only two records for water-bearing fractures. In some cases, these were the top two encountered, in others the top and bottom. The updated database has room for records for five water-bearing fractures. Wells from the original database (up to 1978) have likely not been corrected to include all fractures listed on the logs. Even so, only 1.33 of these features are reported on average for the Wolfville Formation (1557 wells available), and in 75% of the cases, at least one of these fractures was reported in the first 30 m. For wells tested with a larger pumping rate (≥3 L/s), the average number of effective fractures slightly increases to 1.5. Statistics are very similar for the Blomidon Formation, with 1.39 water bearing fractures on average for 257 available wells, and with 77% of the wells having at least one of these features within the first 30 m. For the North Mountain Formation (267 wells available), frequency of these fractures are a little more numerous (1.55 reported fractures on average), and fractures seem to be located deeper, as only 51% are encountered in the first 30 m. These statistics are not in agreement with what has been suggested using borehole geophysics (such as for the similar number of water-bearing fractures in the Wolfville and Blomidon formations), based on a very limited number of wells. However, drillers' reports have a high uncertainty attached to them (the report being filled sometimes several days after the well construction) and only report major water-bearing zones. In contrast, borehole logging also records intermediate water-bearing fractures. Nevertheless, these statistics on such a large number of available wells provide valuable information, such as the fact that usually fewer than two main water-bearing fractures are needed to supply a residence, and these fractures usually occur deeper in the North Mountain Formation than in the two other Triassic formations.

Total porosity analysis

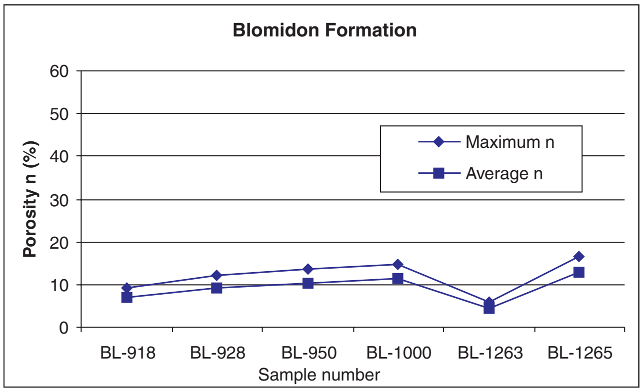
Sediments of the Wolfville Formation are, in general, coarse and moderately to well sorted and often display cubic packing, all characteristics that increase the potential for higher permeabilities. Therefore, the minimum and average 3-D porosity calculations are believed to be closest to the effective porosity. At the thin section scale, the Wolfville Formation sediments rarely displayed well developed anisotropy.

Lower porosities were encountered in the Blomidon Formation samples. Sediments of the Blomidon Formation are also both texturally and mineralogically immature to submature and are those prone to diagenesis that would inhibit permeability. Vugs (i.e. pores resulting from dissolution of less stable mineral grains) were commonly observed; this secondary 'vuggy' porosity is likely the strongest contributor to permeability. Blomidon Formation samples generally showed more anisotropy, a greater degree of syn- and postdepositional sediment deformation and greater concentrations of matrix, all of which inhibit permeability, regardless of porosity. Upon visual inspection, it was determined that the maximum porosity values were most representative of the effective porosity of the samples. When Blomidon sediments are well sorted, they have porosities that are similar to those in the Wolfville Formation.

Figure 50 shows sample porosities for both formations versus depth (in feet). Porosities seem to decrease with depth for the Wolfville Formation (typical of rocks dominated by primary porosity), whereas they seem to increase for the Blomidon Formation (typical of rocks dominated by 'vuggy' porosity), although disrupted by one sample, showing typical mudstones dominating this unit.

The average volume porosities for Blomidon Formation sediments are 7.9% with a highest measured volume porosity of 11.1%. These values assume rhombohedral packing and could thus be viewed as minima, but they appear to be consistent with observations of thin sections. Much of the porosity in the Blomidon Formation thin sections is secondary and is associated with dissolution of mineralogically immature grains (feldspars, exotics). The sediments have evidently been deformed by compaction and secondary cementation is evident, both of which have drastically reduced primary porosity in the samples. Porosity in these sections is strongly anisotropic. Associated permeability is therefore low to moderate and is associated primarily with dissolution cavities that have developed along relict bedding planes.

The average volume porosity for the Wolfville Formation is 28.1%. This value also assumes rhombohedral packing. It could be ±2% higher as some plucking of grains occurred in preparation of the thin sections. Porosity is largely primary



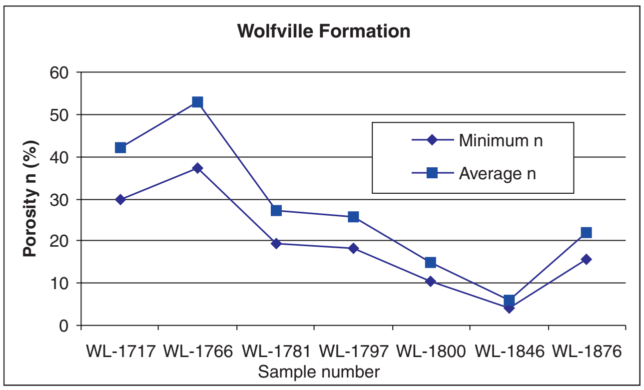


Figure 50. Porosities of rock samples from the Wolfville and Blomidon formations. Effective porosity is estimated to be closer to minimum values in the Wolfville Formation and closer to maximum values in the Blomidon Formation. The sample number represents the sampling depth in feet. Refer to Spooner (unpub. rept., 2006) for more details.

and is associated with intergranular voids developed during deposition. Siliceous cementation has reduced primary porosity somewhat, but its effect is minor (about 2%). However, permeability has been affected, as there is evidence of pore-throat cementation that may affect the interconnectivity of pores in the samples. These differences between the Wolfville and Blomidon formations, in depositional style and mineralogical maturity, in porosity values and styles, and in resulting permeabilities, are crucial in determining the differences in overall aquifer potential of these two units.

Depths of the samples used for these analyses are quite large (280 to 385 m for the Blomidon Formation, and 520 to 570 m for the Wolfville Formation), if compared to typical water supply wells (<200 m). However, similar results were obtained when samples of the Wolfville Formation taken near the surface were analyzed with the same method (I. Spooner, pers. comm., 2008). It is therefore expected that similar results would also be obtained for the Blomidon Formation.

Trescott (1968) had mentioned that the large ranges in grain size and sorting, as well as a matrix of quartz/mica and sparry calcite cement present in the Wolfville Formation, could reduce the overall intergranular porosity and permeability. Nevertheless, flow through primary pore space was suspected to be significant in sandstones of the Wolfville Formation at least in some areas, in particular where it is more friable (poorly consolidated and cemented), i.e. especially in the eastern part of the valley. However, wells in other regions, such as in the municipality of Lawrencetown, also had to be gravel packed or cased throughout the borehole length in order to avoid wall collapse, thereby suggesting a week cementation. Klein (1962) had reported that calcium carbonate cement ranged from 0 to 55%, and averaged 15% in the Wolfville Formation. Thomas (1974) had nevertheless noted that an active surficial groundwater flow zone was suspected near the surface because there was little or no carbonate cement between the grains, and that solution cavities from gypsum dissolution were common. However, with increasing depth, the amount of calcite cement increased and gypsum bands were common.

For surficial sediments, the only data available on porosity outside the Thomas Brook subwatershed comes from the work of Kempt (1996), who performed a geochemical study in the Kingston area. He obtained total porosity values between 35 and 48%, which are surprisingly high. Specific yields ranged from 10 to 29%, with sediments separated into five classes: floodplain sands, tills, kame sands, peat, and glaciolacustrine sediments (fine-grained sands). In the Thomas Brook subwatershed, total porosity was estimated at 15 sites. Values ranged from 15.5 to 30% for silty to sandy tills (Trépanier, 2008).

Nova Scotia Environment monitoring network

A groundwater-level monitoring network has been active in Nova Scotia since the 1960s, with four wells being still active in the Annapolis Valley. A total of 14 wells could be used from this monitoring program (10 have been abandoned), both in surficial and bedrock aquifers throughout the valley, but mainly in the centre, close to more-populated areas. Up until the 1990s, groundwater levels in each well were monitored using mechanical Stevens F Type chart recorders (similar to a seismograph), which recorded water level changes on a paper chart that was retrieved from the field on a monthly or quarterly basis (Nova Scotia Environment and Labour, 2007). Active monitoring wells are now equipped with a pressure transducer, temperature sensor, and electronic datalogger that record water levels and water temperature every hour. Table 22 presents a summary of all wells included in this provincial monitoring program, with their geographical co-ordinates, the formation or unit they tap, the monitoring period they covered and the average annual fluctuation. Geographical co-ordinates of abandoned wells were refined based on the knowledge of Terry Hennigar, a local hydrogeologist working in the valley since the 1960s.

Continuous water-level records in monitoring wells allow the description of typical water-level responses to natural seasonal fluctuations. The available hydrographs usually show

Table 22. Summary of the NSE monitoring wells (UTMs in Nad 83, zone 20)

Monitoring well	X UTM	Y UTM	Status	Formation	Period covered*	Average annual fluctuation (m)
Annapolis Royal	303028	4952587	Active	Granite	1990–1995; 2005–	1 – 1.5
Berwick	362777	4988495	Abandoned	Wolfville	1965–1974	1
Canning	388824	4999547	Abandoned	Wolfville	1961–1965	2 – 3
Coldbrook	375556	4991389	Abandoned	Sand & gravel	1965–2002	3
Greenwood	359530	4984959	Active	Sand & gravel	1980–	1
Kentville Industrial Park	385726	4987649	Active	Wolfville	1980–	0.7
Lower Canard	390454	4999078	Abandoned	Wolfville	1974–?	**
Sharpe Brook	370525	4986031	Abandoned	Halifax	1971–?	**
Sheffield Mills	383889	4998513	Abandoned	Wolfville	1967–1975	1 – 1.5
Wilmot	340012	4979363	Abandoned	Sand & gravel	1966–1995	2
Wittenberg Farm	384285	4997742	Abandoned	Wolfville	1975–1995	2.5
Wolfville 1	391899	4993763	Abandoned	(mostly) Sand & gravel	1969–1990	1.5 – 2
Wolfville 2	392093	4993838	Active	Wolfville	1969–	1.5 – 2
Wolfville 3	392923	4994170	Abandoned	Sand & gravel	1971–1995	1

* Within this period, several gaps are encountered, due to malfunctioning of the instruments.
** No available data.

a major spring recharge event, followed by a decline in the water table during the summer. A smaller but usually significant recharge event usually occur during the fall, followed by a decline during the winter. Mean annual water-level fluctuations generally range within 1 to 3 m, and are typically smaller than 2 m. Water levels (depths) of each monitoring well are presented in Appendix H. The log description is usually not known for the listed wells. As a rule of thumb, the type of condition can be assumed based on the mean annual fluctuations. Small (<1 m) fluctuations often suggest confined conditions, whereas large fluctuations are usually associated with unconfined conditions. However, most wells listed in Table 22 show fluctuations in the order of 2 m and thus conclusions based on this parameter only cannot be drawn in many cases. In addition, the Greenwood well and the Wolfville 3 well, both tapping unconfined sand and gravel aquifers, show small annual fluctuations (1 m). Based on geology, well depth, and/or groundwater fluctuations, the Annapolis Royal (in South Mountain granite), Sharpe Brook (in Meguma Group slates), Kentville Industrial park (Wolfville), and Sheffield Mills (Wolfville) wells are likely under confined conditions. The Wittenberg Farm well is reported to be very deep (100 m or more, but the precise depth is unknown), and therefore could also be confined since there is a good possibility that aquitard layers overlie the aquifer unit.

Statistical trends were estimated using these historical groundwater levels (depths), along with mean annual temperature and total precipitation. The commonly used non-parametric Mann-Kendall test was used on pre-processed data (using Sen's slope; *see* Yue et al. (2002) for more details). The Mann-Kendall test, also called "Kendall's tau," is a statistical test based on ranking, which allows the detection of a monotonous trend. The main advantages of a non-parametric test are that it is well adapted to the study of data that do not conform to a specific statistical distribution and to incomplete series, which is often the case with historical hydrological series. Only one well showed a decreasing trend when using annual values, and two wells showed this trend when considering only the month of August (i.e. at the end of the growing season, when groundwater levels are assumed to be lowest or close to minimum). More details and results are presented in the 'Monitoring wells and historical trends' section.

HYDROGEOLOGICAL CONTEXT

Groundwater can be exploited in relatively high quantities in the study area, especially on the valley floor (Wolfville Formation), where most of the population is located. It flows mainly within the bedrock but, in the eastern part of the valley, surficial aquifers can also be exploited (within sand and gravel glaciofluvial deposits).

This section presents the hydrogeological context of the Annapolis Valley, its major hydrostratigraphic units, and the hydraulic properties of these units. The potentiometric map of the bedrock obtained from water-level measurements is then presented, providing a general picture of the groundwater flow patterns. Finally, the hydrological budget, including estimates of groundwater use and storage in the bedrock aquifers, is provided.

General hydrogeological context

Bedrock aquifers

The bedrock geology of the Annapolis Valley is part of the Fundy Basin, and is composed of gently north-dipping Triassic sedimentary rocks of the Wolfville Formation (underlying most of the valley), which are overlain by the Blomidon and North Mountain formations constituting North Mountain. Cambrian to Devonian metamorphosed slates, wackes, and quartzites (Meguma and Annapolis Supergroups) and Late Devonian granites make up South Mountain. The main aquifer of the valley is the Wolfville Formation. The Blomidon Formation and, locally, the North Mountain basalts can also yield substantial quantities of water. The fractured, porous sedimentary rocks of the Wolfville Formation are crudely stratified and lenticular in nature, consisting of sequences of sandstone, conglomerate, shale, and siltstone. The overlying Blomidon Formation is composed of similar lithologies, but siltstone and shale are expected to be dominant, resulting in an aquifer with greater variability. These units were deposited in a subsiding basin in various tectonically controlled settings, including alluvial fans, fluvial floodplains to shallow lacustrine or aeolian dunes, and playa environments. As a result, the hydrogeological properties within each stratigraphic unit appear to be quite heterogeneous, due to extensive variations in lithologies, bed thickness, and fracturing. Although not exposed, northeast-trending faults may be present on both sides of the Annapolis Valley as indicated by magnetic anomalies and morphology of the Valley (Greenough, 1995).

Beds of the Wolfville Formation are arranged in fining-upward cycles ranging in thickness from 2 to 10 m and their individual lateral extent is highly variable (from 15 to 90 m according to Klein, 1962). Dominated by coarser grained lithologies, the Wolfville is the bedrock unit with the best and most consistent aquifer potential. In the Blomidon Formation, cycles seem to be slightly thicker (between 2 to 12 m), and individual beds are locally laterally continuous over larger distances, in some cases greater than 400 m (Brown and Grantham, 1992). However, the Blomidon may sometimes be dominated by finer grained lithologies. Because of the heterogeneous and discontinuous nature of the entire rock sequence, strata have variable hydraulic properties, acting either as aquifers or aquitards. Therefore, aquifers of the Wolfville and Blomidon formations are often under artesian conditions due to the interbedded siltstone and mudstone layers that act as local confining layers.

In all units, fracturing may be important, influencing groundwater flow and potential yields. Fractures have indeed been observed in all rock types; however, their pattern, strike, dip, and frequency vary widely in the various geological formations present in the study area. Field measurements indicate that movement of groundwater is predominantly controlled by fractures/bedding planes, although some aquifers (especially sandstones of the Wolfville and Blomidon formations) may have significant primary porosity. Because of the different sedimentation and stresses imposed on these formations, sandstone strata of the Wolfville Formation appear (based on a few investigated wells and only one pumped well) to have only a few permeable zones (water-bearing fractures), significantly less uniformly distributed than in the Blomidon sandstones, but with higher transmissivities. Nevertheless, the Blomidon Formation may contain more shale and siltstone and its porosity is lower; its hydraulic potential is thus considered to be variable.

Borehole geophysics revealed the spatially consistent pattern of fracture orientations, shallowly dipping toward the Bay of Fundy and striking northeast, parallel to the valley axis. This structural correlation among wells extending through the Wolfville and Blomidon formations is in agreement with the basin formation, as the basin was rifted (stretched) open by extensional stresses perpendicular to the valley axis (approximately north-south), creating compressional stresses in the perpendicular (east-west) direction. Borehole geophysics also confirmed that most planar features are shallow dipping (<15°). Sub-vertical fractures would represent only 20 to 30% of total fractures (not only including water bearing fractures) in these two aquifer units. Conversely, the well located in the North Mountain basalts (Baiani well) showed that water seems to be supplied by only a few high-angle fractures that preferentially strike parallel to the valley axis (*see* 'Data from fieldwork' section and Morin et al., 2006). Very few shallow dipping planes were observed in basalts.

Because of this preferential fracturing and lenticular arrangement of beds, fractured aquifers of the study area can certainly be locally anisotropic and very heterogeneous, resulting in significant groundwater flow channelling. However, no pump test could be conducted with observation wells in a nearby area (less than 200 m) to verify this assumption. Nevertheless, pumping tests from the database revealed that pumping wells generally behave similarly to porous media, with drawdown following a Theis-type curve.

As mentioned above, formations of the Fundy Group fine-upward individually, as well as collectively, and so the best aquifer potential could be in the lower portions of this group, which are preferentially present at shallow depths on the south side of the valley. Nonetheless, fracturing is a key feature in groundwater flow, and fracture aperture (and thus transmissivity) could tend to decrease with depth. Unfortunately, no information is available on the distribution of permeability below 100 m depth. It is possible that aquifer potential may decrease, as depth of the lower bedrock units increases, to the north. However, in the upper 100 m, both packer test and borehole geophysics results did not show any decrease in K with depth, as was reported in other parts of the Maritimes (for instance in the Maritimes Basin, see Rivard et al., 2008).

Surficial deposits

Tills present different facies due to changes in glacial dynamics during deposition, but the nature of the underlying bedrock lithology is usually the predominant controlling factor. Since sandstone of the Triassic Wolfville Formation is the most widespread bedrock over the valley floor, the overlying till is often sandy in this area. Most of the western, northern, and southern parts of the study area are overlain by a relatively thin layer of till. Over South Mountain, tills are mainly silty-sandy, and punctuated by numerous rock outcrops. North Mountain basalts are either overlain by sandy-clay tills, or are bare of till cover. In the middle and eastern parts of the valley, glaciofluvial sand and gravel sediments are present on each side of the Cornwallis and Annapolis rivers, and glaciolacustine sand and silt deposits are present on the northern side, up to the flanks of North Mountain. Their thickness increases from Kentville and further east, likely reaching up to 30 m.

The porosity and permeability of these deposits, especially for tills, can be highly variable because of internal heterogeneity. Nevertheless, surficial deposits contribute significantly to the aquifer recharge and may also locally constitute good aquifers. Fine-grained sediments such as glaciomarine and intertidal deposits can also play a role in the confinement of bedrock aquifers and thus in their protection from surface contamination (*see* the 'Groundwater vulnerability to potential contamination' section). The major limiting factor for aquifers is the limited saturated thickness. Sand and gravel units are exploited in the eastern and middle parts of the valley, where sediments are thicker and coarser. The towns of Kentville and Wolfville have some of their production wells in this sand and gravel unit. Some residential wells tap the till layer, but the water-level survey revealed that many of these wells have been abandoned as they have gone dry in the last ten years, especially those located on the flanks or top of both mountains.

Based on borehole-log descriptions found in databases, buried valleys, and thus high hydraulic potential units, were suspected initially in the eastern part of the valley. However, revision of these logs, combined with CPT/RPSS soundings and seismic surveys, suggest a maximum sediment thickness of 30 m, with no apparent buried valleys. The well-log and pump-test databases indicated several 'surficial' well depths that can exceed this depth (122 m has even been reported!). Indeed, 26 out of 110 wells (24%) for the well-log database and 17 out of 43 wells (40%) for the pump-test database are reported as more than 30 m deep. However, it is believed that drillers have not been able to distinguish between the semi-consolidated bedrock sandstone and the overlying compacted surficial sand units during conventional drilling.

In summary, aquifers of the Annapolis Valley are mainly fractured porous media from the Triassic Wolfville and Blomidon bedrock formations, having a total average porosity range of 8 to 28%. Good yields can also locally be found in the highly (vertically) fractured North Mountain basalts. These aquifers have usually shown a porous media Theis-type curve response when pump tests are conducted. Relatively few pumping tests (when raw data were available) showed the presence of boundary conditions, suggesting that the different rock types have fairly large spatial extents (likely multiple beds of similar hydraulic properties) in the Wolfville and Blomidon formations. However, very little information is available to characterize the anisotropy caused by fracturing, besides data obtained from borehole geophysics, as nearby observation wells at a similar depth were rarely present. It is suspected that anisotropy has a significant impact on the flow system behaviour at both local and regional scales, as fractures mainly strike northeast, parallel to the valley axis. However, at the regional scale, fractures should be sufficiently connected to provide an equivalent porous media. The following subsections describe the major geological formations encountered within the study area, along with their characteristics and properties.

Hydrostratigraphic units of most interest and their hydraulic properties

The main bedrock aquifers occur in the Wolfville and Blomidon formations and, to a lesser extent, in the North Mountain basalts. Other geological formations such as those included in South Mountain can provide good yields only on rare occasions, depending on their fracturing and jointing, but are not considered good or even variable aquifers. Locally, surficial sand and gravel deposits constitute very good aquifers in the eastern part of the valley. However, tills cannot provide significant yields. Even if they have a key role in this hydrogeological system, as they allow recharge to aquifers, they are not considered in this section. Also, the Horton Group is not included in the following subsections, as it constitutes only a very small part of the study area, and the only wells in the pump-test database identified as tapping this formation, were also producing from the overlying Wolfville Formation, and are thus probably not representative of the Horton Group alone.

Hydrostratigraphic units of most interest for water supply

<u>Wolfville Formation</u>

In the Wolfville Formation, good water-bearing sandstones and/or conglomerates may be penetrated almost anywhere within the boundaries of the formation (Trescott, 1968). Nevertheless, the heterogeneity of this formation, resulting from the layering and the lateral discontinuity of the dominantly fluvial subunits, control the circulation of groundwater through these Triassic rocks. In addition, permeability and movement of the water are often limited by the poorly sorted sediments and cementation of the grains by secondary minerals (Trescott, 1968). Variations in porosity (from 5–40%) were indeed confirmed by thin-section analysis (*see* the 'Fracturing' subsection of the 'Groundwater recharge' section). Therefore, variable aquifer conditions and water quality are encountered even in this generally permeable formation.

Trescott (1968) thought that water was primarily circulating through intergranular pore spaces and only secondarily through joints. However, borehole-geophysics investigations suggest that water is mainly circulating through fractures, though it is believed that the primary porosity has a significant influence on groundwater flow. Indeed, packer tests seemed to indicate that even when water-bearing fractures are not present, the aquifer still can produce a substantial amount of water.

Investigations with borehole geophysics suggested that water-bearing fractures (and thus effective transmissivity) in the Wolfville sandstones would be concentrated within a few areas only, mainly corresponding to highly permeable subhorizontal bedding planes. Sandstones of the Wolfville Formation are friable and have thus been subjected to matrix deformation, while few brittles fractures (both subvertical and subhorizontal) have been created. If these highly permeable zones only appear every few tens of metres of depth, as in the MN5-Kentville well, then wells may have to be drilled fairly deep (~ 100 m) in order to intercept one or two zones. Nevertheless, if large yields are not required, wells do not need to be drilled deep as primary porosity and secondary (smaller) fractures or fractured zones can often provide sufficient supplies. This hydrological structure also implies that anisotropy must be quite significant in these rocks ($T_{horiz} >> T_{vert}$). However, it has to be stressed that the flowmeter/pumping test method could be used only in one well (the MN-5 Kentville well) due to malfunctioning of the flowmeter during the summer of 2004. Statistics on well depths for multi-user wells (those for which a pump test was conducted), indicate that wells have a median depth of 74 m and a median long-term yield[2] (Q_{20}) of 5.7 L/s.

Most municipalities of the Annapolis Valley (including Wolfville, Kentville, New Minas, Lawrencetown, Canning, and Port Williams) have wells tapping the Wolfville Formation. The pumping-test database reports values for hydraulic conductivities varying from 10^{-9} to 10^{-3} m/s, with a median value of 6.6×10^{-6} m/s (86 available values). Long-term yields were estimated to range between 0.2 and 34 L/s (with an 'outlier' at 258 L/s), with a median of 5.7 L/s (79 values). A slightly lower value for rates used during long-term pumping tests is reported (4.7 L/s, 92 values). These high-capacity wells have a mean depth of 74 m (with minimum and maximum values of 9 and 198 m). Hydraulic-conductivity results from pumping tests and median values for well depths, Q_{20}, and pumping test rates are summarized at the end of this section in Tables 23 and 24. Table 25 presents equivalent values to Table 24 obtained from the well-log database for comparison. The well-log database contains many more values, but they usually relate to residential wells, and therefore values for well depths and yields are lower.

Table 23. Summary of pumping tests results (K in m/s).

Formation or group	Lithology	K_{mean} (m/s)	K_{min} (m/s)	K_{max} (m/s)	Number of values
North Mountain	Basalts	5.2×10^{-7}	2.6×10^{-7}	3.0×10^{-5}	7
Blomidon	Shale, siltstone, and sandstone	2.8×10^{-6}	9.1×10^{-7}	2.9×10^{-5}	7
Wolfville	Sandstone, conglomerate, shale, and siltstone	6.2×10^{-6}	3.8×10^{-9}	7.3×10^{-3}	90
Horton	Shale, sandstone, dolomite and sandstones	2.7×10^{-6}	1.8×10^{-6}	3.9×10^{-6}	4
South Mountain batholith	Granite	1.6×10^{-6}	1.9×10^{-8}	1.9×10^{-5}	5
Meguma	Slates	6.8×10^{-7}	5.8×10^{-9}	8.4×10^{-6}	12
Surficial sediments	Sand and gravel	1.3×10^{-3}	4.8×10^{-6}	1.6×10^{-2}	41

Table 24. Summary of median well depths and yields for each formation using the pump test database.

Formation or group	Depth (m)	Number of values	Q_{20} (L/s)	Number of values	Test pumping rate (L/s)	Number of values
North Mountain	88.7	8	0.77	6	0.86	8
Blomidon	58.2	8	3.79	7	3.79	7
Wolfville	74.1	91	5.68	79	4.65	92
Horton	120.4	4	-	0	-	0
South Mountain batholith	59.8	5	0.30	5	1.14	5
Meguma	71.7	12	0.50	12	1.04	12
Sand and gravel	23.9	43	8.86	32	9.47	46

[2] The "safe rate" or "safe yield" is estimated to be 70% of the 20 year yield calculated for the pumping well based on Farvolden's work, who assumed that the long-term drawdown would follow the line predicted by the Cooper-Jacob semi-logarithmic plot (over 8 cycles). Therefore:

$$Q_{20} = \frac{4\pi T(H_A/8) \cdot S_f}{2.3} = 0.683.TH_A \cdot S_f$$

where T is the transmissivity, H_A is the maximum available drawdown and S_f is a safety factor (usually taken as 0.7 or 70%). For more insights and relevant comments on the Q_{20} method, see van der Kamp and Maathuis (2005).

Table 25. Summary of median well depths and yields for each formation using the well-log database.

Formation or group	Depth (m)	Number of values	Q_{20} (L/s)	Number of values	Test pump rate (L/s)	Number of values
North Mountain	53.35	1165	0.61	951	0.61	1168
Blomidon	36.58	648	1.14	477	0.91	651
Wolfville	35.05	6160	0.76	4555	0.76	6174
Horton	42.68	457	0.45	347	0.45	460
South Mountain batholith	48.77	589	0.30	427	0.30	589
Meguma slates	48.78	1212	0.23	861	0.30	1212

Blomidon Formation

The Blomidon Formation, composed predominantly of interbedded strata of shale, siltstone and sandstone, is an inconsistent aquifer that can usually yield small to moderate amounts of water, primarily through bedding planes and joints. Occasionally, coarser sandstones and/or more frequent fractures are encountered, which will yield more water to drilled wells. Trescott (1968) suggested that this formation could act, regionally, as a thick sealing aquitard for aquifers of the Wolfville Formation close to the North Mountain. It is considered here as a 'variable' aquifer, as its hydraulic potential varies widely from one area to another (varying from good to moderate or even poor), mainly depending on the fracturing, porosity, and sandstone content.

Borehole-geophysics logging in two wells indicated that transmissivity in the Blomidon sandstones seems to be much more scattered and dispersed than in the Wolfville Formation because of the presence of subvertical joints that intersect the bedding planes and form a more pervasive network of fracture planes within this rock unit. As a result, transmissivity anisotropy in these sandstones should be less pronounced ($T_{horiz} > T_{vert}$). Permeable intervals appear with greater frequency and, in general, wells should not have to be as deep in order to intercept several of them, if sandstone is encountered. However, when normalized to depth, the overall transmissivity of sandstones from both the Wolfville and Blomidon formations was roughly the same in the investigated wells

Few high-capacity wells tapping the Blomidon Formation are reported in the pump-test database (as compared to the Wolfville Formation), probably in part because this formation may contain more fine-grained strata than coarse-grained layers, but also largely because most municipalities are located on the valley floor. The database contains only seven values with quite similar K values ranging from 5×10^{-7} to 3×10^{-5} m/s, with a median of 3×10^{-6} m/s. Values for mean yield and well depth are similar to those of the Wolfville Formation. The estimated median long-term yield for these wells is 3.8 L/s, with minimum and maximum values varying between 0.4 and 22.4 L/s. Pumping rates range from 0.2 to 8.7 L/s, indicating a quite large variation, also reflected in the well depths (31 to 122 m, with a median of 70 m). Wells supplying the municipality of Annapolis Royal/Granville Ferry are located in this formation, on Department of National Defence property. Their three production wells are used in rotation (with only two pumped at the same time) and the total withdrawal can reach up to 15.2 L/s.

North Mountain Formation

Groundwater flow in this unit is primarily through joints, fractures, and along weathered zones (Thomas, 1974). Indeed, during magma crystallization, polygons formed in the lower flow unit (LFU). These polygons are sensitive to freeze/thaw cycles and thus water can easily vertically infiltrate these rocks. Furthermore, borehole-geophysics investigations in a well drilled in this formation and down to the Blomidon Formation (Baiani well), combined with modelling incorporating stress conditions, suggested that hydrogeological properties of the basalts may be directly influenced and enhanced by lack of buttressing that produces extensional stresses perpendicular to the cuesta (Morin et al., 2006). Indeed, results indicated that stresses associated with the valley shape, configuration, and composition may combine to directly influence the hydrological properties of the basalts and potentially affect groundwater availability among local users. The basalt cap would be subjected to a gravitational horizontal stress acting perpendicular to the cuesta slope face. Indeed, the contemporary regional stress field in western Nova Scotia likely retains the components of extensional basin development, and these compressional stresses parallel to the ridge and tensional stresses perpendicular to it make stress conditions even more favourable for permeability enhancement of preferentially oriented fractures (Morin et al., 2006). As a consequence, steeply dipping fracture planes near or within the cuesta parallel to the valley axis would be more open, and thus would receive more infiltration than elsewhere in the basalts. This work also allowed the identification of two conjugate sets of fractures that share the same strike direction (N 75° E), but dip steeply to the south-southeast (54°) and to the north-northwest (58°). However, observed water-bearing fractures in the Baiani well all fell into the southward-dipping fracture set.

Therefore, this abundant fracturing and opening of some of the planes due to crustal stresses in the North Mountain basalts could potentially provide significant transmissivity. However, (sub-)horizontal fracture connectivity is a problem in most areas, often resulting in poor aquifer potential. Within the context of this study, basalts of the North Mountain Formation seem to have intermediate hydraulic conductivities that are adequate to meet minimal water requirements. The only investigated well (Baiani) using borehole geophysics was located in the abrupt cliff of the North Mountain (facing the valley). This well was highly fractured and its observed permeability could be artificially enhanced by gravitational stresses due to its location. Therefore, its estimated hydraulic conductivity (10^{-6} m/s) may not be typical of this geological formation as a whole and it could in fact be more representative of K_z than of K_x as the flowmeter/pumping test estimates the horizontal component of (sub-)vertical fractures in this case. This K magnitude may not extend to other areas of North Mountain (especially further north), where the stress influence may have diminished considerably. This formation is therefore also classified as a 'variable' aquifer unit.

The seven values reported for wells drilled in the North Mountain Formation in the pump-test database have a median of $5x10^{-7}$ m/s, and range between 3×10^{-7} and 3×10^{-5} m/s. Three of these wells are located on the northern flank, facing the Bay of Fundy. Mean values for estimated long-term yield, test pumping rate and well depths are 0.77 L/s (0.02 to 3.3 L/s), 0.86 L/s (0.2 to 1.2 L/s), and 88.7 m (35 to 132 m), respectively. Both wells supplying the municipality of Margaretsville tap this formation. The combined yield of these wells is close to 2 L/s, and is available during the driest months (summer), when the village doubles its population due to tourism. Trescott (1968) stressed that wells in this formation could seldom be counted on to meet more than domestic needs.

Paleozoic rocks of South Mountain

The metamorphosed Paleozoic rocks of South Mountain are mainly composed of Devonian granodiorites and Cambro-Ordovician slates (mainly the Halifax Formation of the Meguma Group). These rocks contain a large number of fractures and their strike is aligned with the valley axis, inferring a correlation with tectonic forces and basin deformation. Borehole geophysics indicated that fractures in the granodiorite well (Jack well) dipped steeply to the south, while fractures in the slate well (Walsh well) dipped steeply to the north. However, these planes showed no evidence of providing pathways for groundwater flow, and water supply was negligible in both wells. These rock types likely exhibit very low hydraulic conductivities, except in a few areas. They are thus considered poor aquifers.

The five available values of hydraulic conductivities for wells in South Mountain granites have values ranging between 2×10^{-8} m/s and 2×10^{-5} m/s, with a median of 1.5×10^{-6} m/s. Granite wells can be surprisingly transmissive in a few areas of the Annapolis Valley. However, it is believed that three out of these five values are not representative of the majority of the formation (but are rather an indication that a good local fracture interconnectivity is possible in different areas in these granites; *see* the 'Stratigraphy and fracturing' section). The highest value corresponds to the municipal well of Lawrencetown. The borehole flowmeter pumping test found a K value close to the lower reported K (10^{-8} m/s). Estimated long-term pumping rates vary from 0.06 to 2.5 L/s, with a median of 0.3 L/s. Mean well depth is 59.8 m (± 30 m).

Eight wells out of twelve reported in the database for the Meguma Group belong to the Kejimkujik National Park that is located outside the study area. The data from these wells was nonetheless retained as they are believed to provide representative values for this group. The 12 values have a median K value of 7×10^{-7} m/s, with minimum and maximum values of 6×10^{-9} and 8×10^{-6} m/s, respectively. Borehole geophysics was unable to provide a K value since the flow rate was too low. It is therefore assumed that the Walsh well K value was on the order of 10^{-9} m/s. Mean values of estimated long-term yield, test pumping rate, and well depths are 0.5 L/s (0.04 to 4.6 L/s), 1.0 L/s (0.1 to 4.6 L/s), and 71.7 m (43 to 121 m), respectively.

Sand and gravel deposits

Glaciofluvial deposits of the valley appear to be generally composed of sand and gravel, but they tend to have a wide range of particle sizes due to highly variable meltwater-flow conditions associated with glaciers. Proglacial-fan sediments are usually better sorted than ice-contact deposits.

Quite a few high-capacity wells (45), all located in the middle and eastern part of the valley and mainly along the Cornwallis and Annapolis rivers, tap sand and gravel aquifers. Examples are some of the municipal wells for Kentville, Wolfville, Nictaux, Greenwood, and Tremont. These wells sometimes yield exceptionally high rates within only a few metres, especially in the eastern part of the valley. Available hydraulic conductivities for 41 wells provide elevated values, ranging from 5×10^{-6} to 1.6×10^{-2} m/s, with a median of 1.3×10^{-3} m/s. Estimated long-term yields and pumping rates vary between 0.03 to 38 L/s and 0.04 to 49 L/s, respectively, with a median around 9 L/s in both cases. The median well depth is 23.9 m (varying between 2.4 to 123 m). There is no significant tendency for wells to yield more water (both higher yields and transmissivities) as depth increases. This unit has by far the best aquifer potential of the valley, but is restricted to limited areas. No data could be obtained for Table 25, as it was impossible to distinguish wells in sand and gravel units in the well-log database.

General hydraulic properties

To construct a portrait of the hydraulic properties of the valley, 167 transmissivity values (122 for bedrock and 45 for surficial aquifers) and 21 storage coefficient values are currently available. However, 157 values of hydraulic conductivity (116 for bedrock and 41 for surficial aquifers) are available since some well depths or screen lengths are unknown (all in the Wolfville Formation). Hydraulic conductivities were calculated with K = T/b, where T is the transmissivity and b the saturated thickness of the aquifer. It has to be noted that when no screen length was available for a surficial well, the mean screen thickness from available values was assigned to this well. For open bedrock wells, the saturated thickness was approximated using either the static water level (SWL) or the casing length, depending on which value was larger (e.g. if the casing length >SWL: well depth minus casing length). Wells of the pumping-test database are often located using the grid system of the province for the gas or mining industry, with a precision of approximately 1 km^2. Several wells have therefore identical geographical co-ordinates.

Pump tests in the provincial database were re-interpreted when possible (i.e. when raw data were available as numbers or graphs). Nine new hydraulic-conductivity data have also been added to the database based on the GSC fieldwork (four from pump tests and five from slug tests). Figure 51 presents the minimum, maximum, and median K values, as well as 25^{th} and 75^{th} percentiles obtained for the various hydrostratigraphic units. Hydraulic properties exhibit large variations, as is to be expected in fractured rocks. This figure shows that K values generally range between 10^{-8} and 10^{-4} m/s, with median values between 5×10^{-7} and 10^{-5} m/s (except for sand and gravel), indicating that a relatively good hydraulic capacity is available throughout the valley. The mean sand and gravel unit K value is by far the highest.

However, it has to be kept in mind that these reported values are not necessarily representative of each geological formation, especially for the less permeable ones for which very few values are available. For instance, medians from the South Mountain (including granites of the batholith, and the Meguma and Horton groups) appear to be quite elevated for these types of rocks, likely not representative of these formations if a more comprehensive sample set were available. Indeed, the Blomidon Formation is not, on average, as transmissive as the Wolfville Formation, and slates of the Meguma Group and granites of the South Mountain batholith are certainly less permeable than the North Mountain Formation, at least on a regional basis, unlike what is suggested in Figure 51 based on the pump-test database. It is most likely that many more wells were drilled in these less permeable formations and then abandoned: only 'promising' wells with good yields are being tested by drillers, and therefore values contained in the pump test-database are biased. This is obvious for almost all bedrock formations, except for the Wolfville Formation, where sufficient data are available (90) and good yields can be found almost everywhere. Nevertheless, Figure 51 and values from the pump-test database demonstrate that good transmissivities and yields can, surprisingly, be found in all formations, mainly due to local fracturing. Good examples would be the Lawrencetown municipal well tapping granite and one of the Kejimkujik National Park wells exploiting slates, with values on the order of $T = 10^{-4}$ m^2/s and $Q = 4$ L/s. Therefore, most bedrock formations, especially the less permeable ones, probably have lower K values than the medians presented in Figure 51, on an average basis for the entire formation. Statistical distributions of available K and S for the bedrock and surficial aquifers, as well as K distributions for specific hydrostratigraphic units, are presented in Appendix I.

The total porosity analysis has also shown that in the Wolfville sandstones, porosity is largely associated with intergranular voids developed during deposition, while porosity in the Blomidon sandstones is associated with dissolution of mineralogically immature grains. Therefore, even if the fracture networks are well developed, the significant

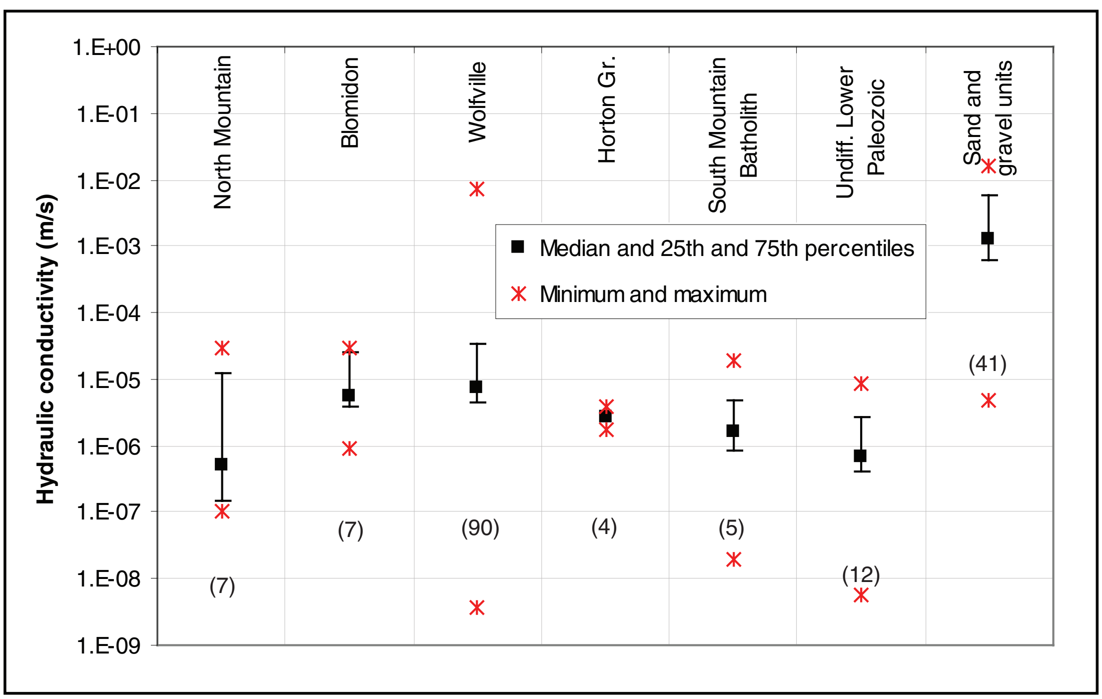


Figure 51. Graph summarizing hydraulic conductivity values of the various hydrostratigraphic units.

primary porosity increases the permeability (and storage capacity) of the Wolfville Formation even more, whereas this is not the case for the Blomidon Formation.

Reported storage coefficients (S) usually range between 10^{-5} and 10^{-2} in the bedrock with a median value of 2×10^{-4} (33 data, mainly from values obtained in the Wolfville Formation), suggesting common confined conditions (Todd, 1980 suggests the range $5 \times 10^{-5} < S < 5 \times 10^{-3}$ for confined conditions). The median S value is 2.6×10^{-3} (17 data) in sand and gravel aquifers. However, these data have to be viewed with caution since the storage-coefficient parameter is not easy to interpret, and tests have not always been performed over sufficiently long periods of time to obtain a reliable value. However, especially for bedrock aquifers (that are suspected to be mostly confined), these values likely provide a good indication of the distribution of S. Storage-coefficient data were too sparse to allow the building of a variogram and the creation of a spatial-distribution map.

Figure 52 illustrates the spatial distribution of hydraulic conductivities (K) using three classes, according to their value. Two maps are presented, one for bedrock aquifers (blue circles) and one for surficial aquifers (green circles). From this figure, it can be seen that relatively high capacity wells ($K > 10^{-5}$ m/s) can be found in many areas of the Annapolis Valley, especially along main rivers, as they are located either in the Wolfville Formation or in thick sand and gravel deposits. Some low K values can undoubtedly be found in all bedrock formations (including the Wolfville Formation), but, as mentioned earlier, no pumping tests are usually performed on the less productive wells. Since long-term pump tests are required only for industrial, municipal, and institutional supplies, it limits the information to populated areas. For this reason, values found based on specific capacities were added to this figure using red circles. These values allow the integration of 'soft' data, often providing additional information in areas where very little data are available. However, the specific capacity data had to be discriminated from the pump test results as they are less reliable.

Groundwater levels and flow

Groundwater levels in the Annapolis Valley often appear to be significantly different for wells at different depths, even if they are very close to one another (or even within the same well, at different stages of drilling), as shown by the work of Trescott (1968) and well hydrographs from the work of Thomas (1974) in all three Triassic formations. Indeed, groundwater levels, especially in the North Mountain Formation, were reported to vary widely, showing a strong downward gradient. Thomas (1974) believed that vertical gradients were less strong in the Wolfville Formation than in the other Triassic formations. The comparison between water levels in streams, in surficial deposits, in the upper few metres of the bedrock, and in the deeper bedrock aquifers using the GSC water-level surveys also show that they are not usually at the same elevation, despite their proximity. Even piezometers installed in sand deposits of the Green Acres area at different depths show noticeable differences in water levels. However, piezometers installed by Thomas (1974) in the sand and gravel deposits (in the Canning area) indicated little or no vertical gradient.

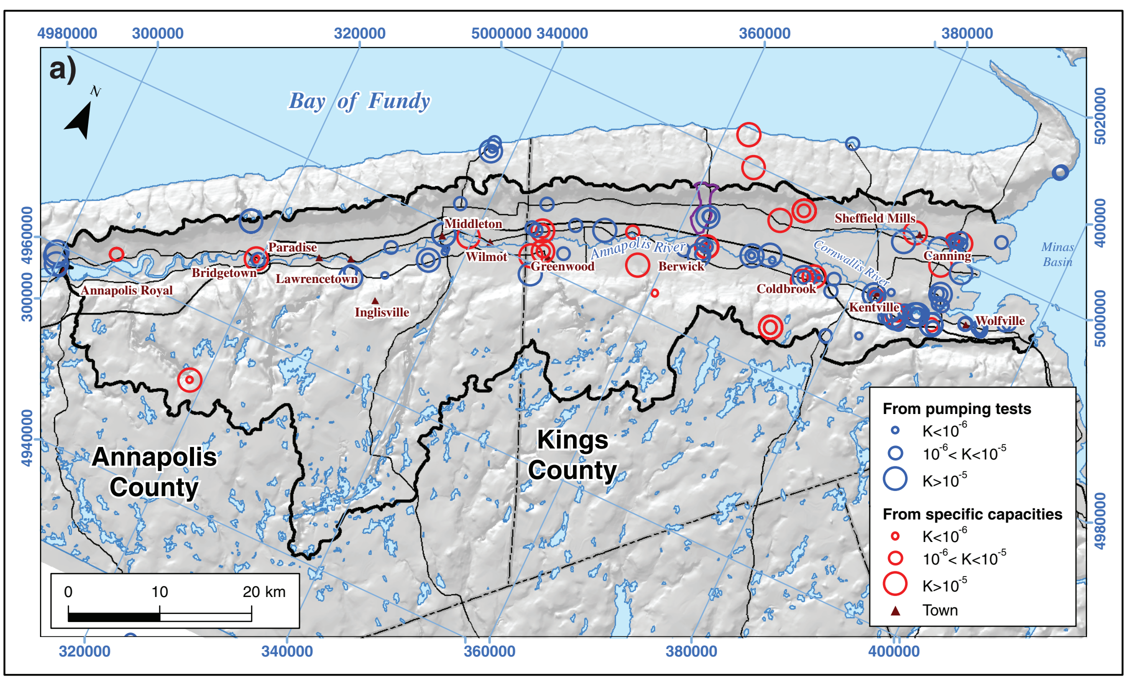


Figure 52. Spatial distribution of hydraulic conductivities (m/s) obtained from existing and acquired pumping test data. Red circles represent estimates obtained with specific capacities, **a)** bedrock aquifers, **b)** surficial aquifers.

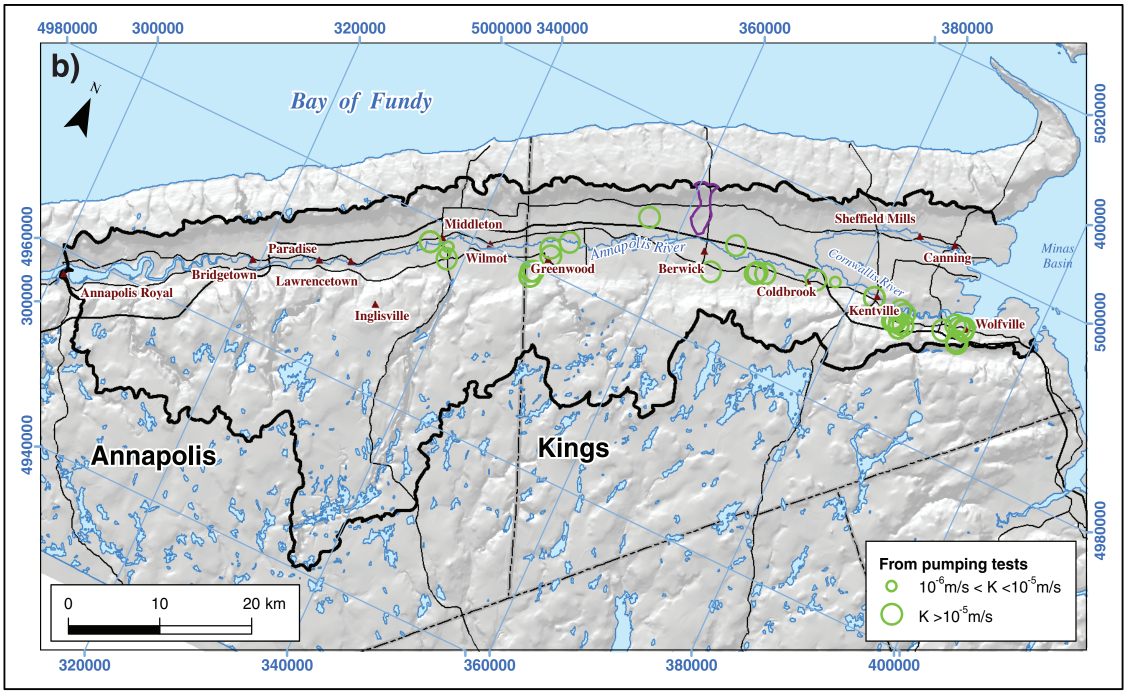


Figure 52. (cont.)

Water levels from various sources were collected to construct the bedrock potentiometric map (*see* "Groundwater-level survey' section). Table 26 summarizes static water levels (i.e. groundwater depths below the ground or the casing) from the different hydrostratigraphic units, for all sources and for the pumping test database only. Values are indeed often significantly different between high-capacity wells and all wells combined (mainly including residential wells from the well-log database). For instance, the median static water level for the pump-test database is about two times larger (i.e. much deeper, *see* Figure 23 for an illustration of SWL) than for the well-log database for the North Mountain Formation, but is significantly smaller (closer to the surface) for granites of the South Mountain. Wells from the pumping-test database (corresponding to multi-user wells) are generally deeper than those of the well-log database (mainly corresponding to residential wells) as shown in Tables 24 and 25. Therefore, when the median static water level (SWL) in the pumping-test database is larger (i.e. deeper water level), this suggests a downward hydraulic gradient (e.g. North Mountain and Wolfville formations, and Meguma Group), whereas a smaller SWL value would be indicative of an upward gradient (e.g. Horton Group and South Mountain granite). However, upward gradients in the Wolfville and Blomidon formations must be frequent (the investigated TW3-Granville Ferry and MN5-Kentville wells are two examples) since confined conditions are quite common.

Bedrock aquifers of the valley are indeed often under local artesian conditions. Various pumping tests have shown very limited interaction between groundwater circulating in surficial deposits and the upper part of the bedrock, and lower (confined or semi-confined) bedrock strata. For instance, the pumping test conducted at Sheffield Farm in a bedrock well showed that no, or very little, response (on the order of a few centimetres) was recorded in the nearby observation well and piezometers installed in surficial deposits. In addition, tests performed for the Towns of Kentville and Wolfville in both surficial and bedrock wells have shown almost no reaction in the other aquifer unit. However, groundwater circulating within the bedrock and surficial units are assumed to be hydraulically connected at the regional scale, due to the lenticular nature of rock strata. Nitrate contamination of groundwater circulating into the bedrock (as will be seen in the 'Geochemistry' section) is one of the indicators of this connection.

Fieldwork performed in the Thomas Brook subwatershed suggested that the water percolating within surficial deposits often reaches the upper few metres of the bedrock (and the water table), then flows horizontally over a fine-grained layer or a non-fractured strata toward a stream. Therefore, a significant portion of the infiltrated water does not reach bedrock aquifers and feeds tributaries of the Annapolis and Cornwallis rivers, mainly due to the stratification of the geological formations. Indeed, groundwater circulating into surficial deposits or in the first few metres of bedrock needs a 'window' (unconfined condition area, i.e. absence of a confining layer), a (sub-) vertical joint or fracture, or a downward gradient to allow groundwater migration to the lower fractured aquifer. From comparisons of groundwater elevations with surface water and from groundwater flow modelling (*see* the 'Conceptual and numerical models' section) across the valley, it has been estimated that up to half of this water may never reach deeper parts of the bedrock aquifers.

Table 26. Summary of static water levels (SWL) for each formation or group.

Formation or group	From all sources		From the pumping-test database	
	SWL* (m)	Number of values	SWL* (m)	Number of values
North Mountain	15.55	807	31.12	8
Blomidon	7.47	432	7.55	8
Wolfville	6.10	4687	7.32	90
Horton Gr.	6.10	305	3.35	4
South Mountain granite	6.10	424	1.80	5
Meguma Gr.	4.88	859	5.80	12
Sand and gravel	8.86	45	5.68	45

* Static water levels (SWL) correspond to groundwater depths below the ground (or the casing).

Because bedrock and Quaternary deposits have contrasting groundwater-flow patterns, water levels in bedrock aquifers should be mapped independently from those in the Quaternary surficial deposits (or first few metres of bedrock). However, not enough static water levels for wells tapping surficial deposits were available in the database, and thus a representative potentiometric map could not be drawn. Therefore, only the potentiometric map of the bedrock is presented in this document (Fig. 53). A large majority of the available bedrock wells are open holes in bedrock. Hence, water level measurements represent a composite of encountered horizons and may be considered illustrative of the upper 100 m of bedrock. This regional bedrock potentiometric map reflects confined and sometimes unconfined conditions. Even if conditions are changing within this flow system, connected permeable zones and fractures ensure the hydraulic continuity throughout the valley. Hydraulic heads were evaluated based on water-level measurements, by subtracting water levels (depths) from ground-surface elevations (and, when available, the length of the casing above the ground was included in the estimation). Details of the map generation are given in the 'Groundwater-level survey' section.

In the bedrock aquifers (likely in the first few 200 m or so), groundwater flows toward the main rivers of the watershed, generally following the topography. Indeed, groundwater flows from the topographic highs of the South and North mountains to the main rivers located in the centre (lower part) of the valley floor. According to Thomas (1974), groundwater at depth (likely on the order of a few hundreds of metres) would flow from South Mountain toward the Bay of Fundy, in accordance with geological formation dips (not shown). In the surficial deposits (and sometimes first few metres of the bedrock), groundwater commonly flows toward tributaries, often perpendicular to the main rivers.

Water flowing in the southern flanks of North Mountain likely has distinct pathways. It is well known that some of the water in these basalts, infiltrated through (sub-)vertical fractures (the quantity or percentage is however unknown), discharges as springs in this area, either in the Blomidon Formation when groundwater encounters a low permeability layer or in basalts through a horizontal fracture. Therefore, a seepage face is present along almost all the southern flanks of North Mountain and many residents take advantage of these springs for their water supply. Trescott (1968) reported that the geochemistry of these springs resembled the recent water circulating in tills more than deeper water in the Blomidon Formation. Thomas (1974) reported a 5 to 6 day delay response to rain events in the Blomidon Formation in a 69 m test hole, as compared to a more shallow hole (21 m). Although both test holes had a marked response to that rain event, the response was considerably smoothed in the deeper one.

Hydrological budget

Groundwater is the primary source of drinking water for municipal and rural residents in the Valley. Indeed, 99% of Kings County residents obtain their drinking water from groundwater (Kings Community Economic Development Agency, 2000), and the percentage for the entire valley should be similar, since only one small municipality in the valley (Bridgetown) is still using surface water. The move to reliance on groundwater is a relatively recent phenomenon, with several towns and villages switching from surface water to groundwater sources within the last decade.

The Annapolis Valley is Nova Scotia's most important agricultural region, and agriculture represents by far the largest water-use sector during the growing season. However at present, the majority of irrigation demands are supplied by surface water. It was estimated that 80% of stream water is taken every summer for irrigation in Kings County (Kings Community Economic Development Agency, 2000). Since the demand for irrigation peaks during the months with the lowest streamflows, this use has a significant impact on water resources. Year round management of water allocation thus poses challenges for both municipal and provincial authorities. According to AGRA Earth and Environment Limited (unpub. rept., 2000), demand exceeds supply in the Canard River watershed, and 25%, 40%, and 95% of the supply is used in the Annapolis, Cornwallis, and Pereaux watersheds, respectively. According to a survey conducted by Kings Community Economic Development Agency (2000), residents are experiencing dry wells in many areas. During GSC surveys, several cases of dry wells were reported by residents, the majority of them being dug wells in surficial deposits on both sides of the valley.

The available information on well yields provides an approximate picture of groundwater usage within the valley. Only the high-capacity wells (generally for industrial, municipal, or institutional supplies) are likely to provide an accurate yield (thus representing the 'true' hydraulic capacity) since a long-term pumping test was normally performed

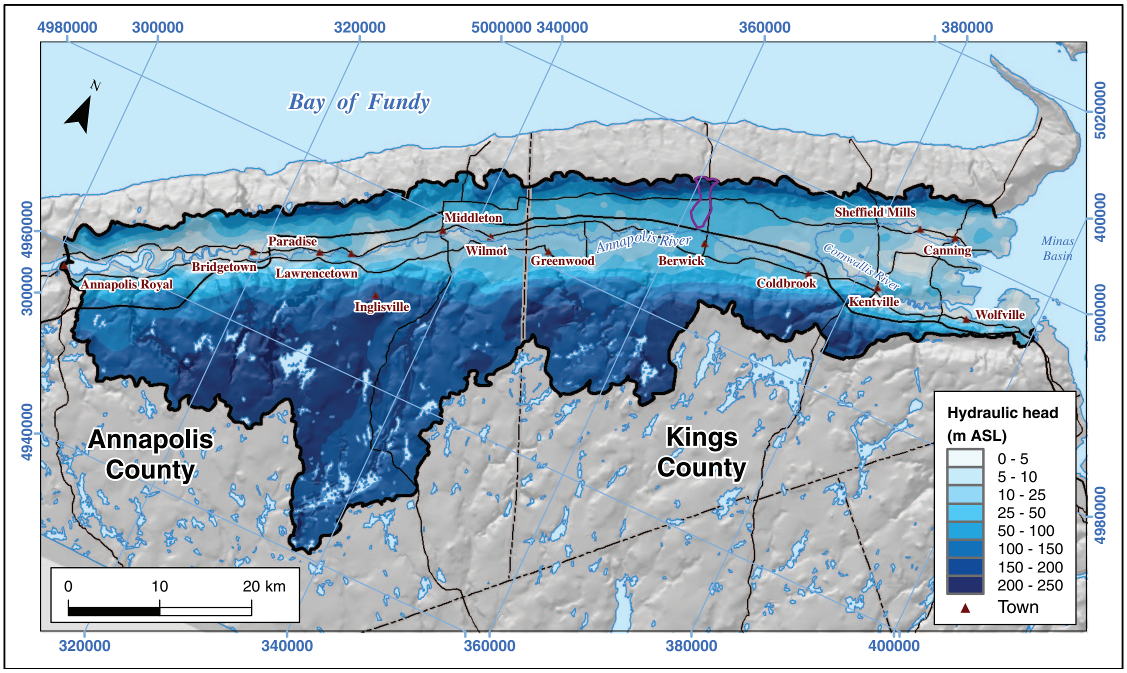


Figure 53. Potentiometric map of the bedrock obtained using water-level measurements.

on these wells. As a result, the map of Figure 54 simply provides an indication of the water use (or needs), rather than the hydraulic capacity, in various areas of the valley. No values from irrigation approval permits could be used for this figure, as all data included in this NSE database were related to surface water usage. The yields used for Figure 54 usually correspond to the value estimated by the driller based on a one-hour air-lift test. However, some Q_{20} 'safe continuous pumping rate' calculated based on the transmissivity or on specific capacity in the case of short pumping tests (i.e. during well development) and maximum available drawdown (*see* the 'Wolfville Formation' section) were available in the pump-test database. These yields were classified into three categories, according to their values.

The spatial distribution of yields shows that most productive wells are found in the eastern, more populated, part of the valley, as expected. This area is also the region where the Wolfville Formation outcrop/subcrop belt has the greatest width and is the least consolidated, and also where surficial aquifers can be exploited. The average yield reported in the provincial database (median for 11 828 wells) is 0.6 L/s, whereas 5.5 L/s is the median value from the pumping-test database. Most wells (70%) have a yield smaller than 1.1 L/s (mostly residential wells); only 3.6% have a yield larger than 3 L/s, and 0.4% above 10 L/s. For the pumping-test database, these percentages become 61% for Q_{20} >3 L/s and 26% for Q_{20} >10 L/s. It must be noted that the Q_{20} values are typically less than the well yields estimated by the drillers because they consider how much pumping the well can sustain over a twenty-year period, whereas the one-hour test rate might not be sustainable over the long term.

An indication of the hydraulic capacity can also be obtained using cumulative frequency graphs of the specific capacity (C_s) values (Q/s, where Q is the pumping rate and s is the total drawdown). The median specific capacity was found to be 0.07 L/s/m for wells reported in the well-log database (913 data), with 5% of the wells having a value larger than 5 L/s/m, and 0.45 L/s/m for wells of the pump test database (158 data), with 14% of the wells with C_s >5 L/s/m. Figure 55 illustrates the C_s curve frequency for the well-log database and the pumping-test database.

A 'theoretical' water-use survey of the valley (MacPherson, unpub. rept., 2004), using available data from four recent reports (2000–2003), indicated that the total groundwater demand for the study area was between 31 000 and 404 000 m^3/d. The wide range is attributable to the method of calculation and assumptions used in the different reports. These numbers are based on the fact that most groundwater demands come from domestic, institutional, municipal, industrial, and commercial sectors. They therefore exclude irrigation demands. As a comparison, the estimated total groundwater demand evaluated based only on an approximate daily consumption of 350 L (the Canadian average) would provide 35 000 m^3/d. Table 27 and the pie charts of Figure 56 present the maximum groundwater-use distribution as a function of watersheds, in terms of rate (in m^3/d) and pressure on the resource (i.e. rate divided by the watershed area, in mm/a). It can be observed that the largest watershed (Annapolis) is the least exploited with 43 mm/a, whereas two of the smallest watersheds (Canard and Habitant, totalling 5% of the study area) are the most exploited with more than 220 mm/a. As a comparison, the minimum and maximum total withdrawals (31 000 and 404 000 m^3/d), when

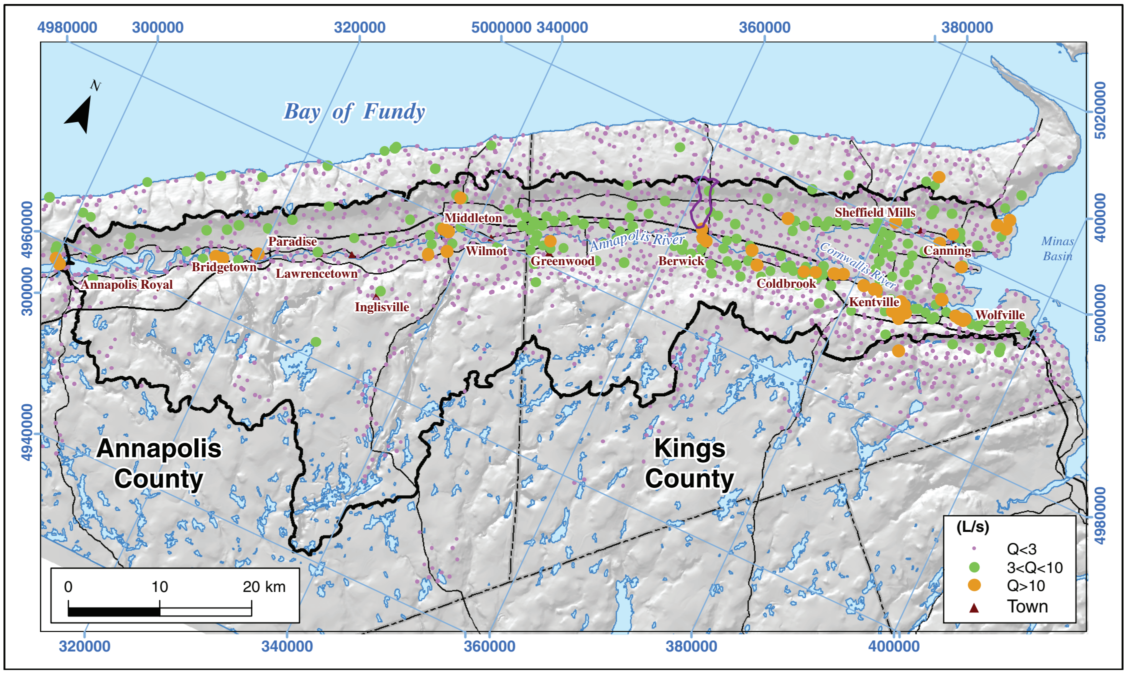


Figure 54. Spatial distribution of groundwater yields.

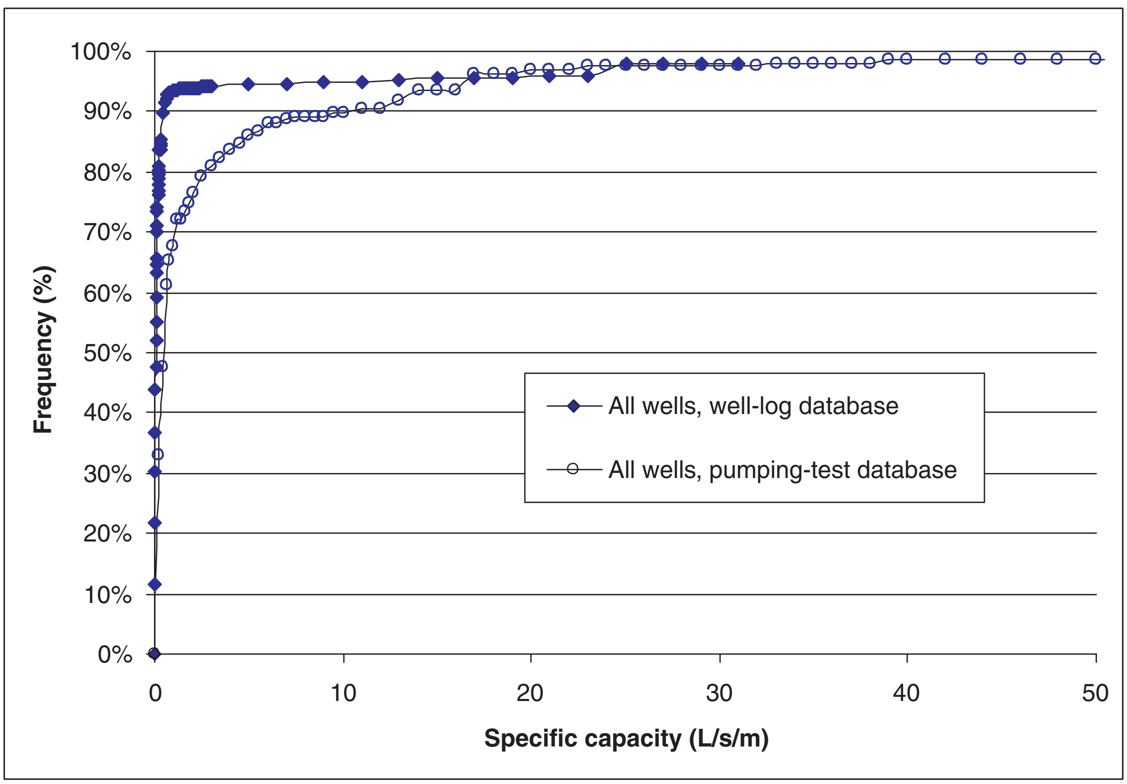


Figure 55. Specific capacities for both databases.

Table 27. Maximum groundwater demand for each watershed.

Watershed	Area (km^2)	Max GW demand (m^3/d)	Equivalence in mm/a
Annapolis	1581.1	185 873	42.9
Canard	53.0	31 792	219.1
Cornwallis	361.0	151 974	153.7
Habitant	51.5	31 268	221.4
Pereau	8.4	2 643	114.6
Total:	**2055.0**	**403 550**	**71.7**

applied over the entire study area, correspond to approximately 5 and 70 mm/a. Using arithmetic means of the ranges estimated, the groundwater use would therefore represent 3.4% of the precipitation (37 mm/a / 1100 mm/a) and 21.5% of the mean bedrock recharge (37 mm/a / 172 mm/a). On a more local scale (e.g. small watershed scale), more problematic conditions could occur, but watersheds which are the most exploited (Canard and Habitant) also correspond to areas where recharge should be higher (likely in the range of 200–250 mm/a). Nevertheless, groundwater extraction may represent a very large proportion of the groundwater recharge, likely on the order of 50%, which is of some concern.

Estimated values of infiltration range from 73 to 430 mm/a, with a probable bedrock recharge average over the valley of 120 to 224 mm/a, obtained with the corrected water-balance method. Recharge to bedrock aquifers would then represent approximately 11 to 20% (with a mean of 15.5%) of the precipitation, whereas recharge to the sand and gravel aquifers (probably close to the upper limit, i.e. 350–400 mm/a), would represent one third of the total precipitation. Mean values for the hydrological budget are presented in Figure 57.

The percentage of groundwater demand as a fraction of recharge can only be estimated using several assumptions and should thus only be considered as a rough estimate, with a high uncertainty attached to it, due to inherent difficulties in determining recharge rates and especially groundwater demands. Moreover, some of the groundwater demands are supplied by sand and gravel aquifers, and the differentiation between surficial and bedrock demands was not made in the groundwater usage study. The use of maximum values of groundwater withdrawals (404 000 m^3/d or 70 mm/a) for the groundwater demand estimate results in such a large portion of the bedrock recharge, that we believe this value to be considerably overestimated. Indeed, historic water levels in different areas of the valley have not shown any significant decrease in the last decades (*see* the 'Monitoring wells and historical trends' section, below).

It is widely accepted that only a certain percentage of the recharge should be used in order for the groundwater resource to be sustainable. There is no consensus in various authorities or in the scientific community as to what

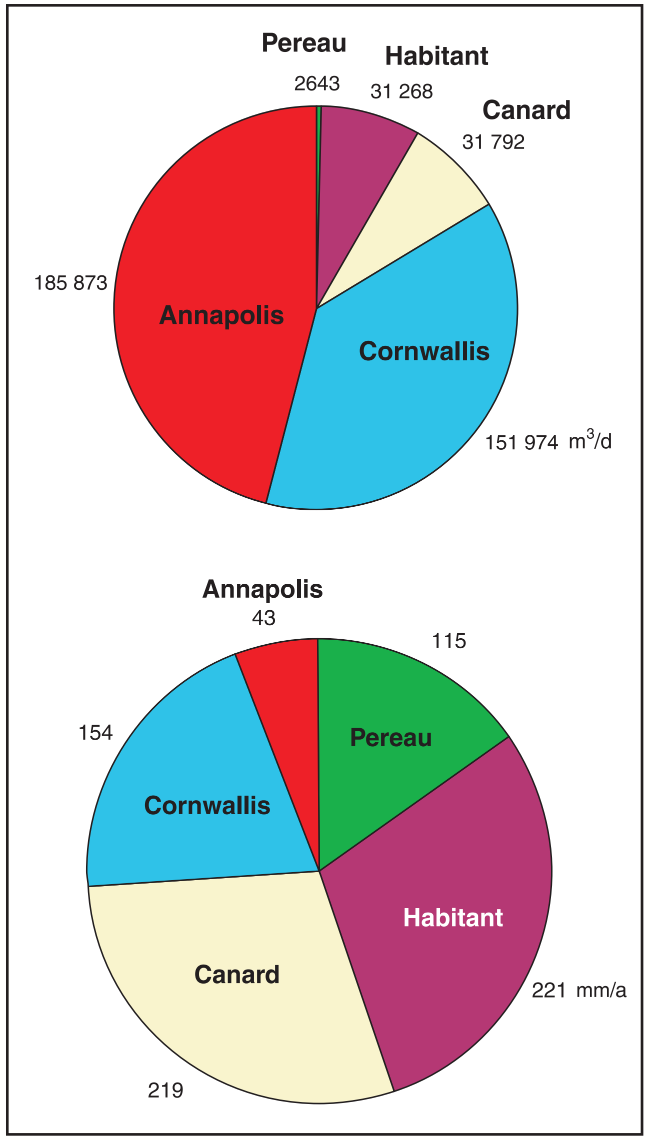


Figure 56. Pie chart of maximum groundwater use for each watershed (in m^3/d and mm/a).

this 'certain percentage' should be, with regard to fauna and flora. The province of Nova Scotia is actually using a threshold of 50%. Therefore, the upper limit (50% or more for small watersheds) could be considered of concern. In comparison to other regions of eastern Canada where similar regional studies were conducted, 4% of the recharge was found for the Maritimes project (14 000 km^2 for the study area, which included parts of three provinces, Rivard et al., 2008). For two projects in Quebec, it was estimated that 12% was used for anthropogenic activities in the Châteauguay area (2500 km^2, Lavigne et al., 2006) and 18% in the Mirabel region (1500 km^2, Nastev et al., 2004).

Precipitation infiltrates preferentially through thick sandy tills, exposed fractured bedrock, and sandy and gravelly units on the valley floor, where slope angles are the smallest.

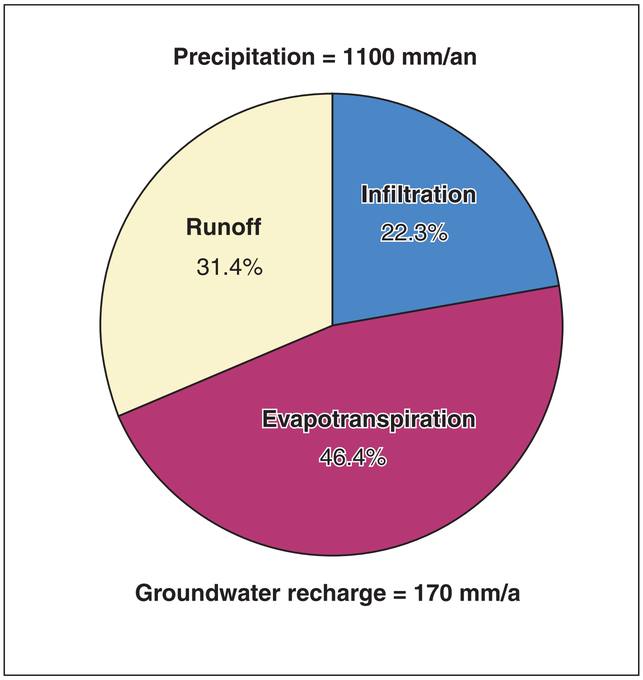


Figure 57. Hydrologic budget. Pumping uses the equivalent of 38 mm/a of the total bedrock recharge (170 mm/a), so the effective recharge is 132 mm/a.

North Mountain seems to contribute significantly to the aquifer recharge in the study area, as reported in earlier studies (e.g. Thomas, 1974; Trescott, 1968; Kempt, 1996). Some of the water infiltrated into North Mountain discharges as springs at the foot of the mountain, and a large percentage is probably unable to re-enter the bedrock once on the valley floor. Indeed, water is probably drained in colluvial deposits to streams.

Groundwater recharge was also quantified independently over the Thomas Brook subwatershed. Recharge was estimated using the 1-D model Agriflux, taking into account the various crops and types of soils. The weighted average found over this 8 km^2 subwatershed was 347 mm/a. This value represents the amount of water reaching the water table, but without taking into account the layering of the bedrock media, and thus possible confined conditions. This value is thus higher than those found for the entire study area (120–224 mm/ with the corrected water balance). However, the surficial deposits in the Thomas Brook subwatershed are quite sandy (mostly sandy tills), and infiltration on the North Mountain basalts is relatively easy, due to the thin (or even non-existent) till cover and highly (vertically) fractured rocks. In addition, the entire study area includes, for a large part, the South Mountain batholith that does not favour infiltration. Therefore, bedrock recharge for the Thomas Brook subwatershed should likely be higher than for the entire study area. For details, *see* Gauthier (2009) and Trépanier (2008).

To estimate the groundwater storage (i.e. water available for pumping) within the valley, mean total porosities were used for the Blomidon and Wolfville formations, while the percentage of fracturing was used for rocks of both mountains. Effective porosity was estimated as 25% of the total porosity (therefore multiplying 8% for the Blomidon and 28% for the Wolfville sandstones), and 1% (often used in rock types where fractures are not well connected) was used to represent the percentage of connected fractures in both mountains. Hypothetical percentages of sandstone were estimated to range from 60 to 100% for the Wolfville Formation and from 40 to 80% for the Blomidon Formation. Over a depth of 100 m, these estimates provided a mean value of 4.7 km^3 (or 2300 mm when divided by the area) of groundwater storage.

Monitoring wells and historical trends

Statistical trends were investigated for mean annual temperature, total annual precipitation, baseflows, and groundwater levels in an effort to study potential impacts of climate change and anthropogenic activities on groundwater resources of the valley. Mean temperatures correspond to arithmetic means of daily mean temperature (data being approximately normally distributed), whereas total precipitation and baseflows were calculated by adding daily values. The use of annual values avoided dealing with seasonal (monthly) variations.

Table 28 summarizes the results for six weather stations (within or nearby the study area). Only four could be used for temperature, due to incomplete series (i.e. missing data). It has been assumed that below a confidence level of 90%, there was no significant statistical trend. Half of the weather stations showed significant increasing trends over the last decades, for both variables. Increases of 8.9 and 22.5% have been obtained for temperature and from 16.8 to 21% for precipitation.

These results are in agreement with other studies conducted in eastern Canada (Rivard et al., 2003; Mehlman, 2003) and Zhang et al. (2000) for a study across Canada. Mehlman (2003) investigated the Kentville and Greenwood station data for statistical trends in temperature and precipitation, and also looked at minimum and maximum temperatures. This study found that both minimum and maximum annual temperatures (T°) for Kentville, while only minimum T° for Greenwood, showed an increasing trend at the 95% significance level. For the Kentville station, summers indicated a significant increase in minimum T°, while spring and winter had a significant increase in maximum T°. For the Greenwood station, spring, summer, and fall showed significant increases for minimum T°, while annual values did not indicate any trend. However, the 1914 to 1945 period showed a significant increase in annual total precipitation. At both stations, the number of days with high

Table 28. Mean annual temperature and total annual precipitation statistical trends.

Time series	First year	Last year	n	Mann-Kendall trend		Confidence level	Variation (%)*
				Test S	Test Z		
Mean annual temperature							
Annapolis	1919	1997	58		-0.58	<75%	-3.6
Digby	1919	1996	64		1.42	90%	8.9
Greenwood	1944	2002	59		-0.09	<50%	-0.4
Kentville	1915	2001	84		5.12	99.9%	22.5
Total annual precipitation							
Annapolis	1917	2001	68		2.81	99%	16.8
Digby	1919	1996	64		4.15	99.9%	21.1
Bear River	1954	2002	45		0.54	<50%	2.9
Greenwood	1944	2002	59		0.90	60%	4.4
Middleton	1916	1946	25	54		70%	6.8
Kentville	1915	2001	83		3.19	99%	19.1

* Variation (%) = (m x n)/E(X_t) x 100. It serves to quantify the parameter increase or decrease over a given period, where m is Sen's slope, n is the series length, and E(X_t) is the mathematical expectation of the data series.
Grey shaded areas show >90% confidence levels.

Table 29. Annual baseflow and water level statistical trends.

Time series	First year	Last Year	n*	Mann-Kendall trend (Test S)	Confidence level	Variation (%)**
Annual baseflows						
Annapolis	1965	2002	38	-109	90%	-16.7%
Sharpe Br.	1968	1994	27	-41	<70%	-7.6%
Bear River	1918	1950	33	48	<70%	16.7%
Paradise	1920	1948	29	42	<70%	8.6%
Annual groundwater levels (depths)						
Wittenberg	1976	1994	16	52	95%	17.3%
Coldbrook	1965	1990	22	-5	<50%	-
Greenwood	1967	2001	21	-44	70%	-
Kentville	1983	2000	15	3	<50%	-
Wilmot	1967	1992	23	33	60%	-
Wolfville 2	1973	1993	18	45	90%	0
Wolfville 3	1973	1993	17	-10	<50%	-
Wolfville 1	1969	1990	20	38	70%	-
August groundwater levels						
Kentville	1986	2000	8	2	<50%	0.6%
Wittenberg	1976	1994	16	48	95%	14.3%
Wolfville1	1970	1988	15	45	95%	4.8%
Coldbrook	1965	1990	22	-11	<50%	-
Greenwood	1966	2001	21	-56	90%	0
Wilmot	1966	1995	23	-17	<50%	-
Wolfville 2	1970	1995	20	52	90%	0
Wolfville 3	1971	1993	19	-5	<50%	-

* n: number of 'usable' years.
** For water levels, a positive sign indicates a decreasing trend.
Grey shaded areas show >90% confidence levels.

precipitation (>2.5 mm) suggested no significant trend over the entire period, and years 1976 to 2000 appeared to be drier, especially during summer months.

Table 29 presents statistical-trend results for annual baseflows and groundwater levels. Groundwater levels were studied both annually and for the month of August, as this month was considered the most critical for water supply and exploitation for this rural area. Wells used for this study are those of the provincial monitoring program. Groundwater depths were recorded on Stevens F-type chart, using a similar method to that for seismographs. Due to technical problems, historical series contain many gaps.

Only one gauging station (Annapolis) and one well (Wittenberg) showed a significant trend for annual values, and both were decreasing, with a Sens' slope of approximately 16 to 17%. However, the Annapolis gauging station is the only station for which data are available in the 2000s and, similarly, most monitoring wells were abandoned in the 1990s. For the month of August only, groundwater levels in one additional well (Wolfville 1) indicated a statistically significant decreasing trend (4.8%). It is noteworthy that a study conducted in three Maritime provinces (Rivard et al., 2003) had shown, in general, a slight decrease in baseflows over the last 30 years. Baseflows had been used as an index for aquifer recharge due to the availability of long and continuous streamflow series. More analyses should be performed in the future, when additional years will be available. Indeed, a short record length (below 30 years) results in a reduced power of the Mann-Kendall test and, therefore, a trend will not necessarily be detected, even if it is present. In addition, each month of the year or each season should be studied, to develop a better picture of the situation.

The findings of this study should help to reinforce the importance of, and interest in, monitoring programs, including gauging stations and wells, in order to detect decreases in aquifer recharge, especially since groundwater now constitutes the main water supply in the valley. Also, withdrawals are likely to increase in future years, mainly for irrigation purposes. Shallow wells, as well as small rivers, brooks, and wetlands, are probably more at risk for water level declines and should probably be targeted or looked at closely by environmental authorities.

GROUNDWATER VULNERABILITY TO POTENTIAL CONTAMINATION

Introduction

Aquifer vulnerability applies the concept that strata containing water can be influenced by impacts occurring above, below, or laterally adjacent to them. Researchers have also recognized that overlying strata can provide the groundwater source some degree of protection from potential contamination occurring at the ground surface (Foster, 1998; Fredrick et al., 2004), and that the concept of vulnerability can be used for delineating land areas that are more vulnerable than others to potential contamination (Gogu and Dassargues, 2000). Mapping the vulnerability of aquifers as a function of hydrogeological conditions, using diverse methodologies, has been used since the 1960s to display spatially the potential vulnerability of groundwater resources to contamination and to assess the degree of aquifer protection needed.

An aquifer vulnerability study of the entire Annapolis Valley, for both bedrock and surficial deposits, was conducted within the framework of the ACVAS project as a M.Sc. thesis (Blackmore, 2006). This study aimed at presenting a regional evaluation of the relative vulnerability of the groundwater to potential and current contamination problems. The DRASTIC methodology (Aller et al., 1987) was used in combination with an overlay system in a geographic information system (GIS) to generate maps of both bedrock aquifer and surficial aquifer vulnerability to surface contamination. This methodology was selected because DRASTIC is widely recognized as a standard for vulnerability assessment in the literature, and includes several significant hydrogeological parameters that could be easily modelled. It must be noted that groundwater-vulnerability prediction results are relative, not absolute; therefore, this work should be viewed as a tool providing guidance for future water management decisions. The work of Blackmore (2006) is summarized in this section.

Previous groundwater vulnerability modelling in the study area

Within the Annapolis Valley, previous groundwater-vulnerability assessments include those conducted by the Nova Scotia farm-well water-quality assurance study (Dramowicz, unpub. data, 1993) and by Atari (unpub. internal rept., 2005). The study of Dramowicz (unpub. data, 1993), in relation with the study of Briggins and Moerman (1995), utilized GIS capabilities to analyze and model the relationships between the contaminants found, the susceptibility of the groundwater to contamination, and the use of agrochemicals such as fertilizers and pesticides. For this purpose, an adapted version of the DRASTIC methodology was developed, which included four parameters: depth to water, aquifer media, soil media, and topography. The proximity to contamination sources (manure production, usage of pesticides and fertilizers, and home septic systems) was modelled in the study. Other land uses were also incorporated into the modelling to determine susceptibility to contamination. The goal of this assessment was to assist in developing agricultural management practices and policies for Kings County.

Atari (unpub. internal rept., 2005) studied the potential risk of groundwater exposure to nitrates, and focused on an area of Kings County as a case study. He attempted to calibrate the DRASTIC methodology to study, specifically and statistically, the risk of nitrate contamination in the groundwater. The high well yields were found to be correlated with high groundwater-nitrate concentrations, with shallow wells tending to have higher nitrate contaminations than deeper wells. Atari (unpub. internal rept., 2005) suggested that the results showed a need to improve management practices for healthier groundwater quality.

DRASTIC methodology

Description of the DRASTIC model

The DRASTIC methodology was developed by the U.S. Environmental Protection Agency (EPA) in the 1980s. It can be described as a qualitative parametric method (as opposed to a quantitative method that determines travel time to the groundwater table). It uses a selection of parameters considered to have the greatest impact on the aquifer vulnerability. DRASTIC is an acronym for the seven hydrological conditions selected by Aller et al. (1987): Depth to groundwater, net Recharge by rainfall, Aquifer media, Soil media, Topography, Impact of the vadose zone, and hydraulic Conductivity of the aquifer. Each DRASTIC parameter is classified into ranges (for continuous variables) or significant media types (for thematic data), according to the assessed impact on pollution potential, where the ratings range for each parameter is from 1 (low vulnerability) to 10 (high vulnerability). Each parameter is assigned a weighting factor according to its relative importance to the equation (Equation 6), as determined by Aller et al. (1987). The product of the weighted and rated values are then added together for a final score to determine relative vulnerability (the higher the score, the greater the vulnerability of that area).

$$D_R D_W + R_R R_W + A_R A_W + S_R S_W + \qquad (6)$$

$$T_R T_W + I_R I_W + C_R C_W = \text{Pollution potential}$$

where the subscript R is rating and w represents weight. More details and a figure showing where these parameters take a part in a hydrogeological system are given in Blackmore (2006). DRASTIC index ratings and weights for the seven parameters are provided in Table J-1 of Appendix J. From this table, it can be seen that higher weights were given to ‘Depth to groundwater’, ‘net Recharge ’ and ‘Impact of the vadose zone’ (5, 4, and 5, respectively). The ‘Depth to groundwater’, ‘net Recharge’, ‘Topography’, and ‘hydraulic Conductivity’ parameters have been assigned vulnerability values within specific ranges of the quantitative input data. ‘Aquifer media’, ‘Soil media’, and ‘Impact of the vadose zone’ correspond to more qualitative or ‘subjective’ parameters and the user must use his professional judgement in assigning appropriate ratings according to the study area, given a set of criteria.

Although the reasoning for the development of the parameter selection was not outlined by Aller et al. (1987), the influences of various processes such as sorption, dispersion, reactivity, and travel time were accounted for in the development of the parameter ranges and ratings. The resulting DRASTIC index can somewhat be regarded as an aggregation of implicit factors including travel time, sorption, and dilution (Rosen, 1994).

All parameter data were processed to a raster grid format for an index/overlay decision system using the DRASTIC methodology, implemented using ArcObject modelling for the programming scheme. Final vulnerability maps for both bedrock and surficial aquifers were generated using equation 6, for each of the determined scenarios. Finally, the DRASTIC index results can be classified into relative vulnerability categories.

Seven scenarios were generated for each of the bedrock and surficial aquifers in the M.Sc. thesis of Blackmore (2006). In this section, a baseline (or moderate) scenario is adapted from this thesis and presented for both bedrock and surficial aquifer vulnerability, as they were thought best suited to represent relative vulnerability in the Annapolis Valley. The range of vulnerability categories obtained from the other vulnerability scenarios are discussed to show potential ranges in vulnerability.

Description of the seven parameters of DRASTIC

Depth to groundwater

The depth to the groundwater is a significant factor in controlling the ability of pollutants to reach the aquifer. The shallower the aquifer, the faster water can transport contaminants through the vadose zone, the less contact time there is between contaminants and chemical attenuating materials, and the more potentially vulnerable to contamination the aquifer (Aller et al., 1987; Zhang et al., 1996). All the water-level point data were separated into the bedrock (approximately 95% of the data) and surficial aquifers (approximately 5% of the data) by an interpolated bedrock-depth surface. In situations where the aquifer was known to be confined, the depth to groundwater was taken to be the depth to the top of the confined aquifer, or the base of the confining layer (Aller et al., 1987). Water-level data were available from the GSC database. Most values were rated relatively high, especially in the surficial aquifer, since water levels are generally shallow (median is at 6.1 m).

Net Recharge

Net recharge represents the annual average amount of water that infiltrates the vadose zone and reaches the water table. Recharge represents the primary contaminant transport mechanism into the aquifer. In the DRASTIC method, the greater the amount of recharge, the greater is the potential for groundwater pollution (Aller et al., 1987). The net-recharge values used in this study were values generated by the water balance method (*see* the ‘Water- balance method’ sections). The ratings for this parameter ranged from 1 (lowest) to 10 (highest), with areas of higher vulnerability being mainly located throughout the valley floor proper. The correction factor was not applied, so as to be on the conservative side.

Therefore, the net recharge was likely overestimated (as much as 50%) and a bias is introduced toward higher vulnerability in areas where the geological units impede water infiltration. The data resolution of the 500 × 500 m^2 grid cells have also affected the final results for some parameters, since only the dominant properties could be taken into account. For instance, the 'net Recharge' parameter showed a 'blocky' appearance in both the bedrock and surficial aquifer results.

Aquifer media

The groundwater circulation is very strongly influenced by the permeability, composition, and type (fractured versus porous) of the media. The travel-path length affects the time available for attenuation processes (reactivity, dispersion, and sorption). The larger the grain size of the aquifer media (or the more the fractured the aquifer), the higher the permeability; therefore, the greater the potential vulnerability of the groundwater. The DRASTIC methodology uses designated descriptive names for the types of aquifer media and provides users with rating value ranges when evaluating the aquifer media for potential vulnerability (Aller et al., 1987). The bedrock- and surficial-geology data used for the potential aquifers were originally digitized from geological maps (Keppie, 2000 and Paradis et al., 2006), and integrated into coherent data layers consisting of vector polygons.

The Wolfville Formation, composed mainly of sandstone beds that have both primary and secondary porosity, was considered the most vulnerable bedrock formation to contamination. However, basalts of the North Mountain Formation, which are highly vertically fractured, were also considered quite vulnerable, even if groundwater cannot easily circulate due to poor fracture interconnectivity. For surficial deposits, sand and gravel of the valley floor were assigned the highest ratings.

Soil media

Numerous soil characteristics, including hydraulic conductivity, texture, structure, and thickness, control the recharge and migration (residence time and chemical processes) of contaminants percolating to the water table. Finer-textured material such as silts and clays tend to reduce soil permeability and restrict contaminant migration, and thus are considered less vulnerable. The DRASTIC methodology provides an index scheme for contaminant potential based on soil types. These rating values take into account the dominant soil type affecting infiltration, as well as the soil depth or thickness.

The soil data digitized from the 1960s soil reports of both Annapolis County (MacDougall et al., 1969) and Kings County (Cann et al., 1965) were used for the 'Soil media' parameter. The soils rated as the most vulnerable are those defined as rocky land, or areas of thin cover or absent soil cover. The next highest ratings are associated with sandy deposits, which tend to occur on sandy and gravelly surficial deposits. Most soils overlying till deposits are composed mainly of sandy loam and were given moderate vulnerability ratings.

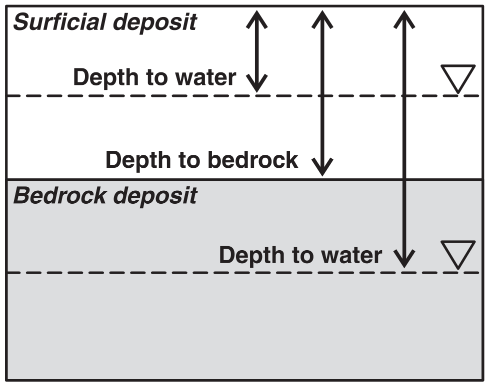
Topography

Topography in the DRASTIC methodology refers to the slope or slope variability of the ground surface, and thus has some control on potential runoff versus infiltration of a contaminant. The possibility of infiltration decreases with increase of the angle of the slope, as it is less likely that the contaminant will have the opportunity to infiltrate the surface (Aller et al., 1987). Topography also influences soil development as well as the gradient and direction of groundwater flow. In DRASTIC, the topography parameter utilizes the percent slope, and is rated according to the ranges of these values. The percent-slope data were directly calculated from DEM data (20 m resolution), provided by the Nova Scotia Geomatics Centre (NSGC), and the value ranges rated according to the DRASTIC requirements. The ratings for this parameter ranged from 1 (lowest) to 10 (highest), but most data (approximately 90%) were rated as 5 or higher (including the valley floor and the peneplain of South Mountain).

Impact of vadose zone media

The vadose zone, the unsaturated zone above the water table and below the soil horizon, controls the attenuation, path length, and route of water and potential contaminants. Greater thickness would imply a longer distance and therefore longer time of travel through the vadose zone, although sediment stratification can confine or limit direct vertical flow, and cause infiltrating water to spread more laterally than vertically (Heath, 1987). In addition, for unsaturated media, the hydraulic conductivity is strongly dependent on the degree of saturation. These factors are not directly accounted for in the DRASTIC model. The DRASTIC parameter 'Impact of the vadose zone' is intrinsically linked with the 'Depth to groundwater' parameter, which usually provides only a generalized (interpolated) thickness of the vadose zone (Bekesi and McConchie, 2000). However, this parameter is considered one of the most important parameters for the DRASTIC method, as it is given the highest weighting of 5. Modelling this parameter can become very complicated if the strata of the geological units are considered separately, for both bedrock and surficial aquifer considerations, as observed in the study by Ross et al. (2004).

Determining the overall impact of the vadose ratings values involved using diverse criteria, including the DRASTIC-rated geological units for this parameter, the depth to the water table, and the depth to bedrock. Therefore, several parameters came from the same data sets as the 'Aquifer media' parameter. In the case of fractured aquifers, the overlying surficial-deposit layer was also taken



If the depth to the bedrock is 10 m and the depth to the water in the bedrock unit is 15 m (from the ground surface), then the final Impact of the vadose zone is calculated by:

$10/15 \times I_{surficial} + (5/15) \times I_{bedrock}$

where:
$I_{surficial}$ = Impact of vadose zone rating in surficial deposit
$I_{bedrock}$ = Impact of vadose zone rating in bedrock deposit

Figure 58. This illustration shows a simplified case of how the final 'Impact of the vadose zone' values for the bedrock aquifer were calculated. In the case above, if the surficial deposit is sand and gravel (rating of 8), and the bedrock deposit is the Wolfville Formation sandstone (rating of 4), the final impact of the vadose zone for the bedrock aquifer value is calculated at about 6.7.

into account, as explained and illustrated in Figure 58. The bedrock depth surface provided a general estimate of the thickness of the surficial deposits and interpolated piezometric maps provided estimates for the depth to water in bedrock and surficial units. As the relative thickness of the surficial deposits increases, the surficial value for the impact of the vadose zone becomes more influential on the final result.

The impact of the vadose zone media ratings in DRASTIC methodology were designated by descriptive names and associated characteristics, which were applied to both the bedrock and surficial media. The bedrock- and surficial-geology data used for the impact of the vadose zone units were originally digitized from bedrock and Quaternary maps, and integrated into coherent data layers consisting of vector polygons. The 'Impact of vadose zone' vulnerability ratings ranged between 3 and 7. The North Mountain foot was rated the lowest for this parameter, likely more due to the protective influence of the siltstone and shale strata of the Blomidon Formation, than to the overlying, thin, discontinuous till deposit. The areas of the highest vulnerability for this parameter are mostly within the valley floor, due to the vulnerable Wolfville sandstone and conglomerate, as well as in regions where the overlying sand and gravel deposits are present. The North Mountain basalts and most of the South Mountain granites, both overlain by till deposits, are rated as moderately vulnerable. The impact of the vadose zone results show a more direct relation to the overlying surficial deposits in the sense that the higher vulnerability of overlying surficial deposits seem to cause an overall increase in vulnerability for the bedrock aquifer. If surficial deposits are not taken into account for the bedrock aquifer impact of the vadose zone results, the overall results are less vulnerable.

Hydraulic Conductivity of the aquifer media

Hydraulic conductivity controls the rate of groundwater flow under a given hydraulic gradient. It is dependent on the size and connectivity of the pores and/or the fractures. The greater the hydraulic conductivity, the farther the contaminants can travel, which can allow greater volumes of groundwater to be contaminated. The hydraulic conductivity of the aquifer-media ratings in DRASTIC methodology were designated by ranges of hydraulic-conductivity values. Hydraulic conductivity values were obtained from the GSC hydrogeological database, personal communications with hydrogeologists familiar with the area, and estimates based on knowledge of the rocks or deposit materials (Aller et al. 1987; Heath, 1987).

In the hydraulic-conductivity results for the bedrock aquifer, about half of the study area is rated at 1, as the slopes and peneplain of the South Mountain are rated the lowest for this parameter. The region of highest vulnerability due to hydraulic conductivity is the Wolfville sandstone and conglomerate, for which K values are the largest. The fracturing system within the North Mountain basalt allows limited horizontal movement, which limits the ability to transport contaminants throughout the aquifer.

In the surficial aquifers, large areas of the study area were rated as low to vey low, due to the less permeable till deposits underlying substantial sections of the North Mountain, valley floor, and South Mountain. The highest vulnerability ratings correspond to sand and gravel units. Between these two extremes are areas of somewhat low to moderately high vulnerability, due to the relatively fine-grained sediment, such as silt and glaciolacustrine materials, and the deposits containing organic material.

DRASTIC results

Baseline scenarios

The final DRASTIC vulnerability index results can range between 0 and 230, where the higher the value, the greater the potential vulnerability. These values were later divided into standard relative-vulnerability categories from 1 to 8, where again the larger the number of the category, the

Table 30. DRASTIC results ratings and descriptions of relative vulnerability (*after* Aller et al., 1987).

Model index value result	Vulnerability category	Description of relative vulnerability
1 to 79	1	Extremely low
80 to 99	2	Very low
100 to 119	3	Low
120 to 139	4	Moderate
140 to 159	5	Moderately high
160 to 179	6	High
180 to 199	7	Very high
200 to 230	8	Extremely high

greater the relative vulnerability. Each vulnerability category was assigned a description, presented in Table 30, using the index ranges used by Aller et al. (1987). The description for each vulnerability category was assigned based on the general relative vulnerability for each range.

The bedrock baseline vulnerability scenario is presented in Figure 59. It confirmed that the valley floor region is the most vulnerable region of the bedrock aquifer, which was categorized as having low to moderately high vulnerability (category 3 to 5). This suggested that the bedrock aquifers of highest vulnerability included mainly those within the Wolfville Formation (approximately 30% of the study area). The remaining area was categorized as mainly very low to low in terms of vulnerability (category 1 to 2), with sections of extremely low vulnerability (category 3).

The surficial baseline-vulnerability scenario results provided a much more vulnerable picture of the study area (Figure 60). The sand and gravel deposits within the valley floor are the most vulnerable regions, with high to extremely high vulnerability (category 6 to 9). The areas of lowest vulnerability occur in patches of low vulnerability (category 3) within the till deposits. The remaining sections of the study area, including those within the till, glaciolacustrine, marine, modern fluvial and marine, and organic deposits, were mostly rated within the moderate to moderately high vulnerability range (category 4 to 5).

For comparison purposes, the percentage of the study area correspond to each vulnerability category (from 1 to 8) is provided in Figures 61 and 62. In the bedrock aquifers, most units appear to have a relative vulnerability index comprised between very low and moderately high (2–5), whereas surficial units appear to range from moderate to extremely high (4–8)..

As expected, the aquifer units with the greatest production potential also correspond to higher potential to vulnerability, due to elevated values of hydraulic conductivity and recharge and a flat topography (in the case of the valley floor). These areas also correspond to the more populated regions and thus are areas where risk of surface contamination is highest.

Categorized vulnerability ratings

The final vulnerability results were also categorized according to relative vulnerability for both bedrock and surficial aquifer hydrostratigraphic units, using the classification scheme selected by Aller et al. (1987). Where the vulnerability category range was so wide that it encompassed most of the possible range, it was most useful to compare the median values for comparison between hydrostratigraphic units.

Bedrock hydrostratigraphic units

The range of vulnerability category spanned from 1 (extremely low) to 6 (high) in both the Wolfville and Blomidon formations, with a median average category of 4 (moderate) and 3 (low), respectively (Fig. 63). The range within the Horton Group unit (covering 0.6% of the study area) is between 2 (very low) to 4 (moderate), with a median of 3 (low). The remaining units ranged between 1 (extremely low) and 5 (moderately high) for Meguma slates and North Mountain basalts or 1 (extremely low) and 4 (moderate) for the South Mountain Batholith.

The highest median vulnerability occurred in the areas underlain by the Wolfville Formation, due to the predominance of coarse-grained lithofacies (sandstone and conglomerate) and the overlying coarse-grained surficial sediments derived from that bedrock. The Blomidon Formation is slightly less vulnerable, due to its numerous laterally extensive shale and siltstone beds, which provide some protection from potential contamination. The high vulnerability variability within both the Wolfville and Blomidon formations is due to their compositional heterogeneity, and varied overlying geological units.

Surficial hydrostratigraphic units

As can be observed on Figure 64, the surficial aquifer vulnerability ranged from 3 (low) to 8 (extremely high) for the glaciofluvial, glaciolacustrine, and modern fluvial and marine deposits units. The highest median of 7 (very high) occurred in the glaciofluvial deposits (esker ice-contact sediments and subaerial proglacial-fan sediment), whereas a slightly lower median of 6 (high) occurred within the glaciolacustrine (littoral, prelittoral, and deep-water sediments) and within modern fluvial and marine (modern alluvium and fluvial terraces alluvium) deposits units. The remaining units ranged from 3 (low) to 7 (very high) for the bedrock outcrops (or residuum) and colluvium hydrostratigraphic units, 2 (very low) to 8 (very high) for the continuous and discontinuous till units, and 3 (low) to 8 (extremely high) for the marine and organic deposits.

The sand and gravel composition of these surficial hydrostratigraphic units tends to have a large impact on their vulnerability results, which can range from very low to extremely high potential vulnerability. Contributing factors to the high vulnerability results included the shallow depth

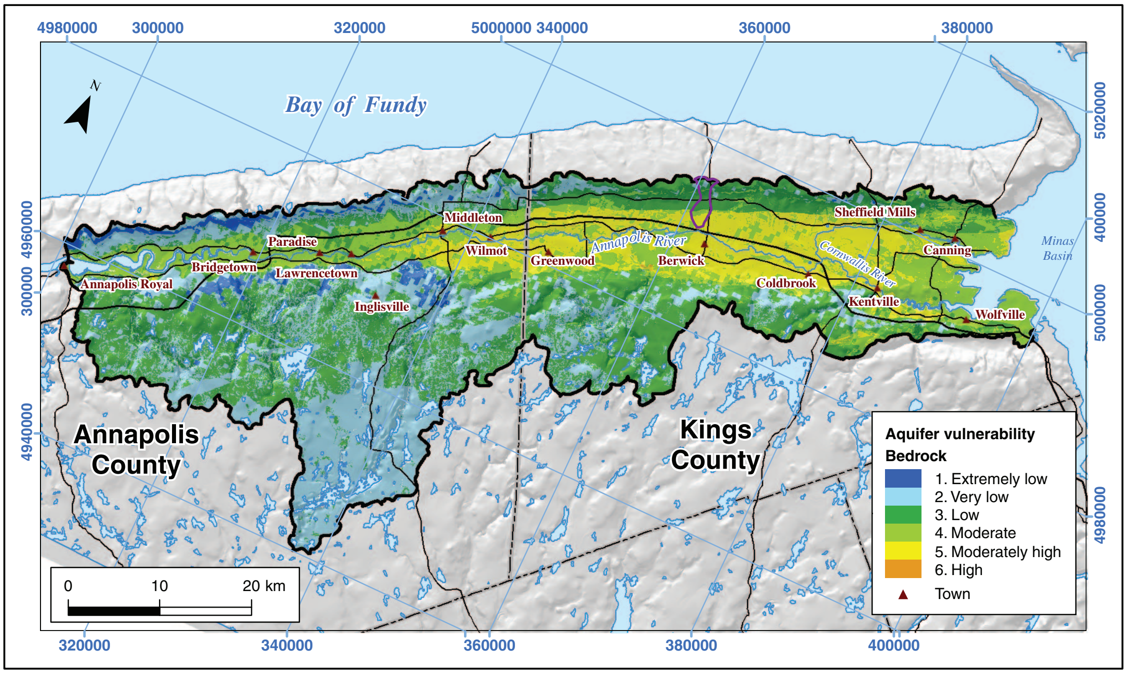


Figure 59. Bedrock aquifer results - vulnerability to potential contamination.

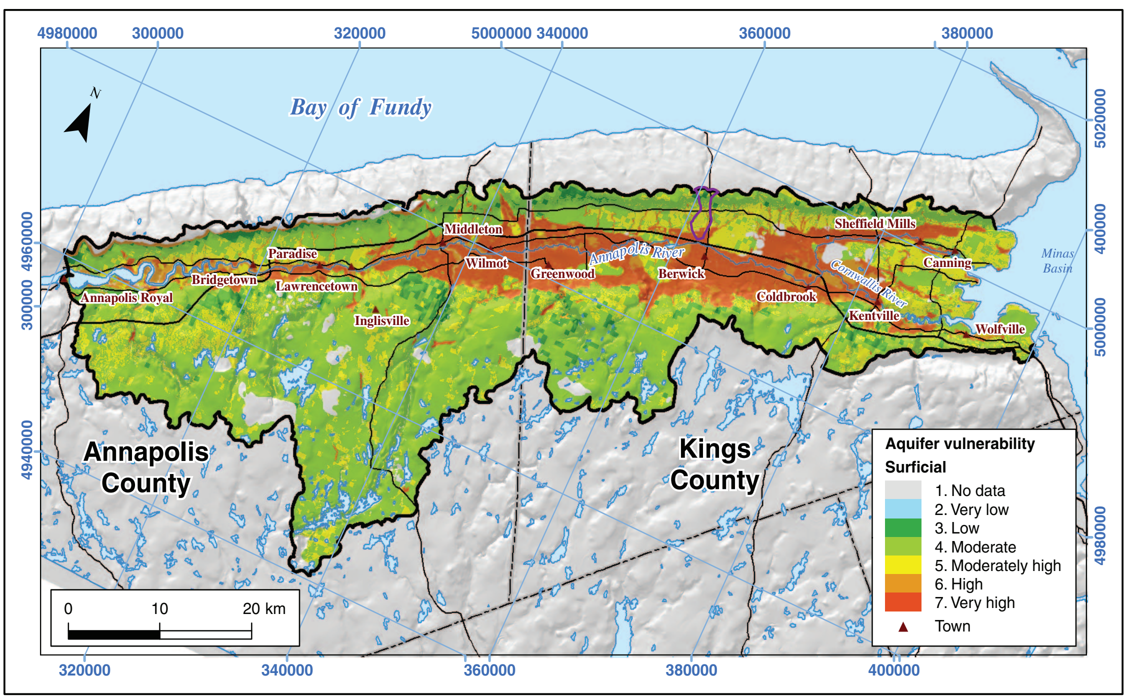


Figure 60. Surficial aquifer results - vulnerability to potential contamination.

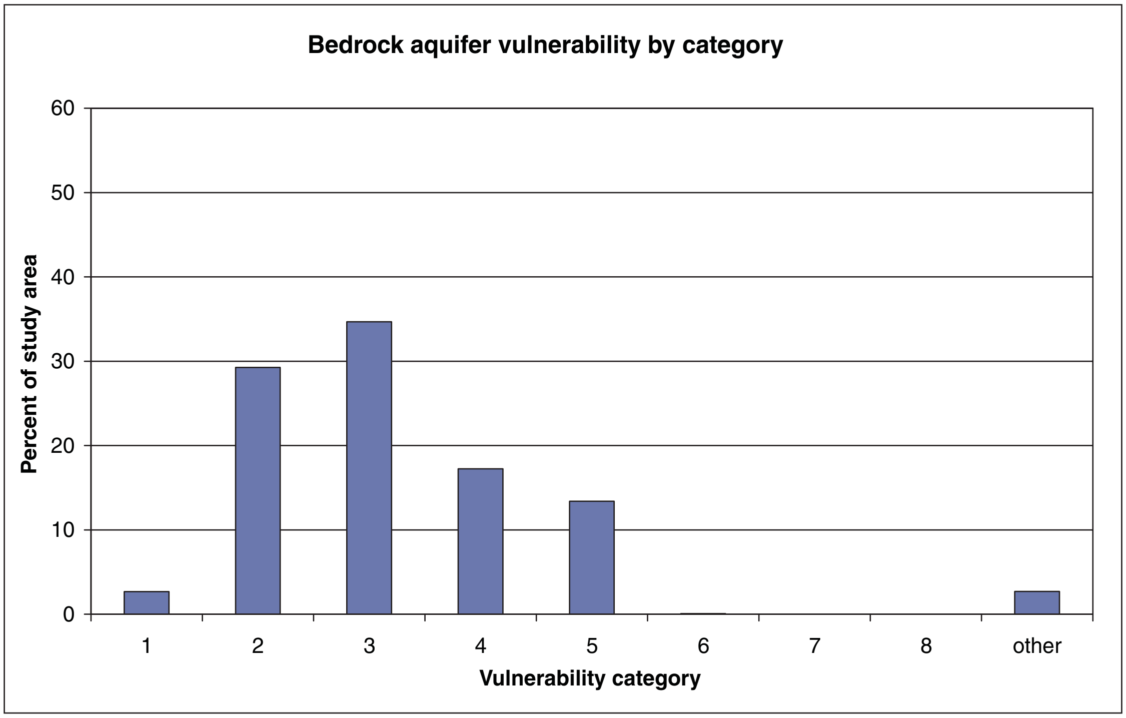


Figure 61. Percent of the study area within each vulnerability category for the bedrock aquifer.

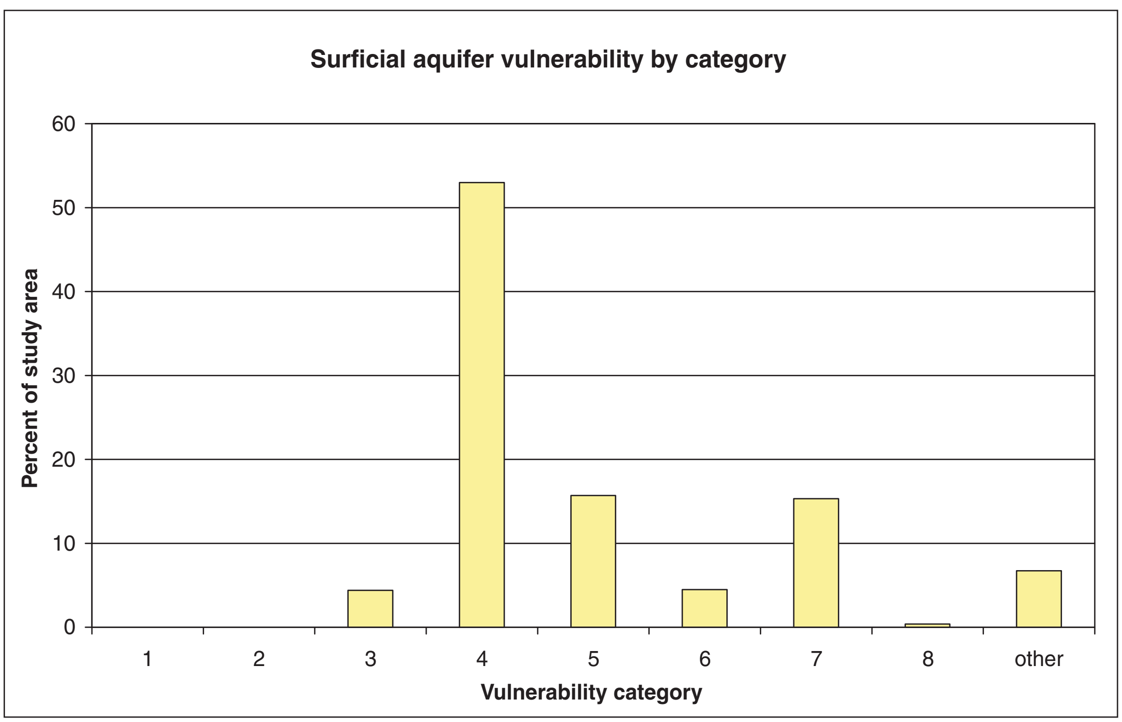


Figure 62. Percent of the study area within each vulnerability category for the surficial aquifer.

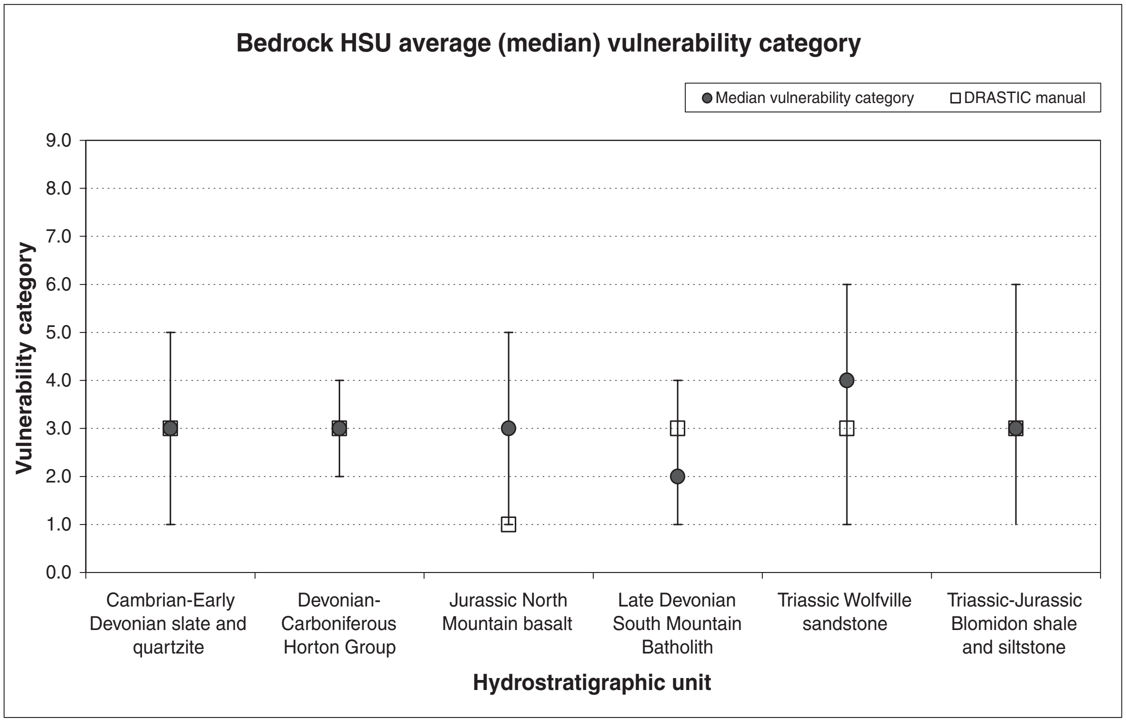


Figure 63. Bedrock hydrostratigraphic unit ranges in aquifer vulnerability. Both the median category (black square) obtained for the Annapolis Valley and the corresponding unit category found in the DRASTIC manual (Aller et al., 1987) (open square) are graphed for comparison. Note that the North Mountain basalts were considered much more vulnerable than the theoretical value assigned for basalts due to their significant fracturing.

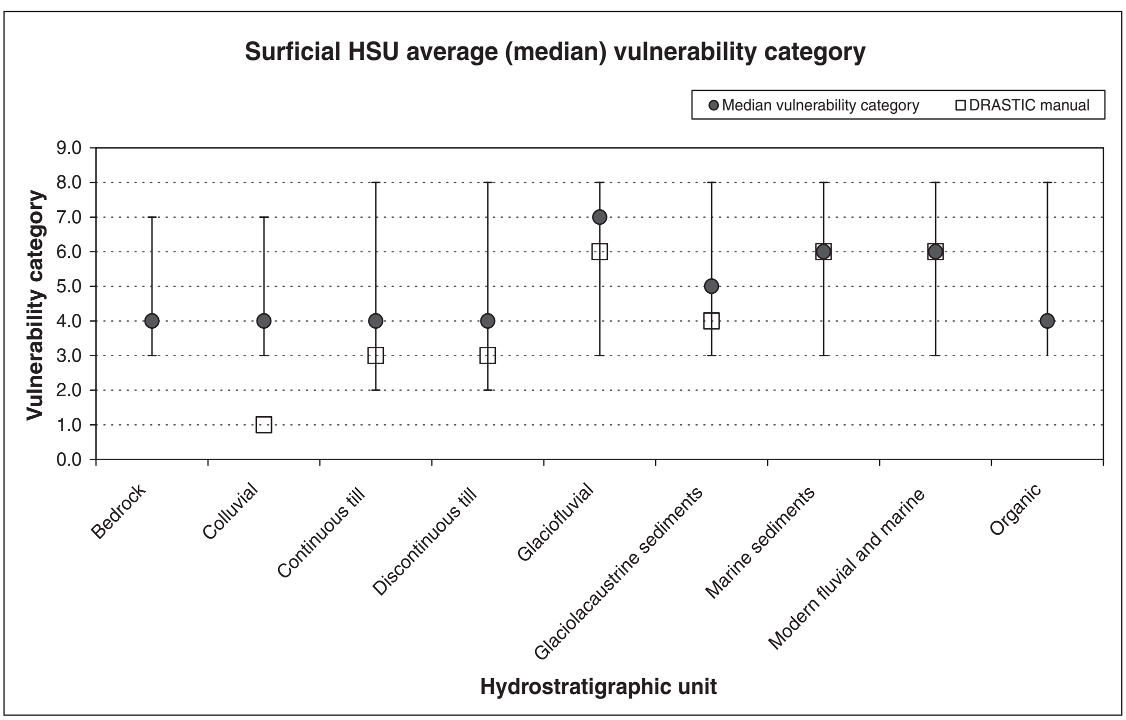


Figure 64. Surficial hydrostratigraphic unit ranges in aquifer vulnerability.

to water levels, great amounts of net recharge in the valley floor where these sediments were deposited, the intrinsic characteristics of the deposit (high hydraulic conductivity), the properties of the soil cover (coarse loamy and sandy), and the very flat slopes of the valley floor.

Interpretation and discussion

The results of the vulnerability study indicated that the bedrock aquifers tend to be significantly less vulnerable than the surficial aquifers. This was generally expected, due to the shallow water depths, common confined conditions of bedrock aquifers, and in places high permeability of the unconsolidated sediment of the surficial aquifers. However, the DRASTIC method has been known to underestimate the vulnerability of bedrock (or fractured) aquifers, because of the way the aquifer media and hydraulic conductivity of the aquifer were rated (Rosen, 1994). The 'Aquifer media' and 'hydraulic Conductivity of the aquifer' parameters tend to have relatively low ratings, although the aquifer media ratings in this study range from 2 to 6 for the baseline scenario and the hydraulic-conductivity values range from 1 to 4. Indeed, the only hydraulic-conductivity rating value above 2 in the baseline-vulnerability scenario for bedrock was that of the Wolfville Formation, at a rating of 4.

The applicability of the DRASTIC model is often discussed in terms of the precision and accuracy of the (numerous) input data, the suitability of the DRASTIC parameter selection and ratings, and the weighting scheme as they apply to the study area. The results are indeed limited by the quality of the input data (i.e. by their availability, uncertainty, and variability) and the qualitative nature of its approach. The DRASTIC method has also been criticized for incorporating highly correlated parameters, as well as for the lack of background information regarding the weighting scheme (Foster, 1998; Rosen, 1994; Zhang et al., 1996). In this case, the main concern was consideration of topography (assigned a low weighting of 1), as the study area included the region from the North to South mountains. However, the topography parameter did have an indirect additional impact on the 'Soil media' parameter as well, as topography influences soil development, and on the 'net Recharge' parameter, as runoff and infiltration are greatly influenced by the slope of the terrain. Therefore, a weighting of 1 may be sufficient to account for the 'Topography' parameter.

Data accuracy and precision are critical to an adequate assessment, as a change affecting only one parameter or a modification in data source can possibly have a great impact on the final results, especially for those parameters to which a large weight is assigned (such as 'Depth to groundwater', 'net Recharge', and 'Impact of the vadose zone'). In this heterogeneous regional hydrogeological system, several factors (such as various sources of data, spatial (point density) and temporal distribution of data and their accuracy, imprecise geographical locations, intrinsic variability of each parameter, the use of a 500 × 500 m^2 grid cell resolution, and interpolation, had a major impact on the evaluation of the ratings and the generation of the seven different DRASTIC parameter maps (or layers). In this case, the parameter having the least accurate data would seem to be the 'net Recharge' data, as the values for this 500 m resolution data were highly uncertain (10 to 50% variability, depending on the underlying bedrock). Also, the interpolated water depth (potentiometric) maps (based on a DEM precise to ±5 m), developed with a non-uniform distribution of data (of variable uncertainty), had a large influence on the 'Depth to groundwater' and 'Impact of the vadose zone' parameters. The resolution and accuracy of the input data must then be recognized and associated with the final results.

In order to address concerns about parameter uncertainty, several scenarios were developed to obtain an overall range in the aquifer vulnerability and to estimate a possible range of error (Blackmore, 2006). Previous aquifer vulnerability assessments have in some cases used comparisons of different models or methods (Gogu et al., 2003; Ibe et al., 2001) to assess the variability of potential aquifer vulnerability. Others have adjusted or modified the DRASTIC method according to data availability and applicability (Denny et al., 2007; Fritch et al., 2000; Zhang et al., 1996). The flexibility of the GIS platform is ideal for examining how plausible variances in specific or suites of parameters might affect model results.

In this study, 'optimistic' and 'pessimistic' ratings were assigned to each parameter, based on available ranges of values and assumed or known uncertainty. In addition, the aquifer anisotropy and heterogeneity, which can significantly affect the final vulnerability results, were qualitatively taken into account in most DRASTIC parameters in the multiple scenario process, where the limiting characteristics were known. For instance, the Blomidon Formation was in some cases (optimistic scenarios) assigned low vulnerability values, due to the common occurrence of fine-grained strata (siltstone and claystone), which would provide some protection to the more coarse strata (sandstone). Blackmore (2006) found that most of the results decreased by one vulnerability category when taking the optimistic (lower) ratings into account, and increased by one category, when taking the pessimistic (higher) ratings into account. In general, evaluating the results per hydrostratigraphic unit widened the overall potential vulnerability category range for this unit by at least one if not two categories. In addition, modelling multiple scenarios revealed that changing just one parameter, such as depth to water (or any other parameter with a high weighting), appeared to significantly alter the final relative vulnerability results. Changing the delineations of units (soil or geology) changed groundwater vulnerability on a local scale. The sensitivity analysis results are fully described in Blackmore (2006).

Areas where point data are lacking are generally expected to be less accurate as well as less precise, such as throughout the South Mountain area. More data were available, in general, in the eastern part of the valley floor and the area immediately adjacent to it. Results are therefore expected to be more accurate in the Kings County section of the study area than in the Annapolis County section, or more accurate within the valley floor than on North and South mountains. Nevertheless, results of this vulnerability study should only be taken as indicative. Because the purpose of this vulnerability modelling was to generate regional vulnerability trends within the Annapolis Valley watersheds, the input data are likely of sufficient resolution for the final mapping in the most populated (and thus more subject to contamination) areas. Areas mapped as highly vulnerable suggest future targets for further local, more detailed assessments.

GEOCHEMISTRY

In the Annapolis Valley, water pollution is of great concern, especially with respect to nitrates, bacteria, and pesticides, as a large part of the land is devoted to agriculture. Besides farming related activities, concerns are mostly related to: poorly constructed or maintained septic systems, removal of riparian vegetation by agricultural and forestry operations, and a lack or malfunction of municipal sewage treatment plants (Timmer, 2003). Levels of nitrogen and fecal coliform in rivers that exceed limits for drinking, irrigation, and even recreational activities, are commonly reported throughout the valley (Timmer, 2003).

Some groundwater-quality problems (mostly nitrates) have been documented in earlier studies, especially in Kings County, and could likely increase in future years due to intensive agricultural activities. The natural occurrence of some parameters (such as iron and manganese) may also be a problem in some areas, but they do not pose a threat to health. Groundwater flowing in bedrock usually has a higher mineral content, alkalinity, and hardness than the water from surficial deposits. However, surficial aquifers of the valley are more vulnerable to contamination than bedrock aquifers (*see* the 'Groundwater vulnerability to potential contamination' section).

In addition to collecting and mapping geochemical data of the entire Annapolis Valley, a local-scale study on migration of nitrates was included within the framework of this regional project during the second year. The local study focuses on the Thomas Brook subwatershed located just north of Berwick in the western part of the Cornwallis watershed. Some results are provided in this section, but interested readers should refer to Trépanier (2008) for the complete results and report.

Overview of groundwater quality

Groundwater chemistry is controlled by the composition of the rocks or sediments it circulates through, and by contact time with these units. Thus, water which has travelled only a short distance in a shallow groundwater-flow system may have a considerably different chemistry from water found deep within a regional groundwater-flow system (Trescott, 1968). Trescott (1968) and Thomas (1974) both found that, in general, water from the North and South mountains had a similar composition, with lower hardness and total dissolved solids (TDS), than rocks in the Wolfville or Blomidon formations. According to Trescott (1968), this could stem in part from the fact that water is younger in both mountains, while a portion of the water circulating in the lowland units has been travelling for a longer time. In addition, dissolution is easier in sedimentary rocks (e.g. calcium and carbonate are quite soluble, whereas components of basaltic and granitic rocks are not).

Natural groundwater from the Wolfville Formation has, on average, a moderate hardness of about 84 mg/L, TDS of 144 mg/L, and an electrical conductivity less than 300 µS/cm. These values are in agreement with those of Trescott (1968). The most important dissolved ions are calcium and bicarbonate. This water is thus mainly of the calcium bicarbonate type and its median pH is close to neutral (7.4). Contrary to what was noted by Trescott (1968), high (>8.5) and low (<6.5) pH values seem to be scattered throughout the valley. High pH values could be due to the dissolution of calcium carbonate cement, or result from membrane filtration or the natural softening effect in shales. Trescott (1968) also noted a few deep wells near estuaries that were predominantly sodium chloride in composition. Chloride and sodium could also come from halite, which is thought to occur in the calcareous cement of this formation (Kempt, 1996).

Table 31. Median parameter values according to the geological formation or group.

Formation or group	No of wells	Alkalinity (mg/L $CaCO_3$)	Hardness (mg/L)	pH	TDS (mg/L)	Electrical conductivity (µS/cm)
North Mountain	53	50	57.1	7.0	96.7	220
Blomidon	44	76	174.8	7.5	202	375
Wolfville	176	74	83.8	7.4	144	290
Horton	23	116.5	87.2	7.7	195.8	351
Undiff. Lower Paleozoic	42	34	44.6	6.5	70.7	172
South Mountain granites	12	46	54.4	7.4	103.5	163
Highest values are highlighted in grey.						

Values of alkalinity, hardness, pH, TDS and conductivity are provided in Table 31. Wells have been located based on the Keppie (2000) map and have thus all been assumed to be tapping bedrock aquifers (since no information was available on the well type).

Water from the Blomidon Formation is much harder and higher in total dissolved solids and conductivity than any other units considered in this study. Trescott (1968) reported that the water chemistry of this formation is controlled primarily by calcium sulphate dissolved from gypsum lenses which accounts for Ca^{2+} and SO_4^{2-} concentrations. Calcium bicarbonate is also an important dissolved constituent (likely coming from the cementing materials), increasing the value of alkalinity, hardness, and total dissolved solids (Trescott, 1968). Trescott (1968) also noted that water from springs along the North Mountain scarp contained lower TDS than water from drilled wells (often confirmed by residents during our water level survey) and often approximated the composition of the till overlying the Blomidon Formation. Water from the Horton Group, despite fewer samples, seems to also have high TDS and conductivity, and the highest alkalinity. Water circulating in the North Mountain basalts is low in total dissolved solids and is very soft as a result of the low mineral dissolution of the basalts and the rapid infiltration through the subvertical fractures. It is also of the calcium bicarbonate type. Water from the South Mountain granites and undifferentiated Lower Paleozoic rocks (mainly slates) is similar in composition.

Thomas (1974) found that the water chemistry from the sand and gravel deposits in the Canning area was similar to water of the Blomidon Formation, suggesting that water in these surficial units comes from the latter, thus controlling their geochemistry. Trescott (1968) found that water in tills overlying the North and South mountains had a similar composition to water flowing in the underlying bedrock formation. However, water from tills overlying the Blomidon Formation was of better quality than that of the underlying bedrock. Water in tills overlying the Wolfville Formation showed no marked difference to water from the bedrock. However, all the above conclusions were based on a limited number of samples.

Figure 65 presents a Piper diagram illustrating data from all geological formations of the Valley, since there was relatively little difference between individual formations. The generally neutral pH value (7.25) observed using the geochemical database for all geological formations is in agreement with values found by Trescott (1968).

Few pollution cases are known in the Annapolis Valley, and they can be considered very local. Trescott (1968) reported tank leaks in Greenwood and Nictaux Falls, probably from the 1960s, and an organic-waste contamination produced by an apple-processing plant in Coldbrook, also in the 1960s. Also, 15 private wells in the Greenwood area have shown levels of PCE (perchloroethylene, an organic contaminant) above the Health Canada drinking-water guidelines (30 ppb), while another 12 wells had detectable amounts. Concentrations in affected wells ranged from 1 to 1400 ppb, and the average was 170 ppb. In 2005, these wells were distributed over an area of 0.2 km^2. The extent of this contamination, or plume, as well as the inferred groundwater-flow direction, tend to point toward a dry-cleaning business that was destroyed by a fire in 1994. The PCE would likely have been released to the ground during the fire and regular operations. The NSE has commissioned a private consultant firm to conduct a study so as to confirm the source of the contamination. More details can be found in Pinchin Leblanc Environmental Limited (2005).

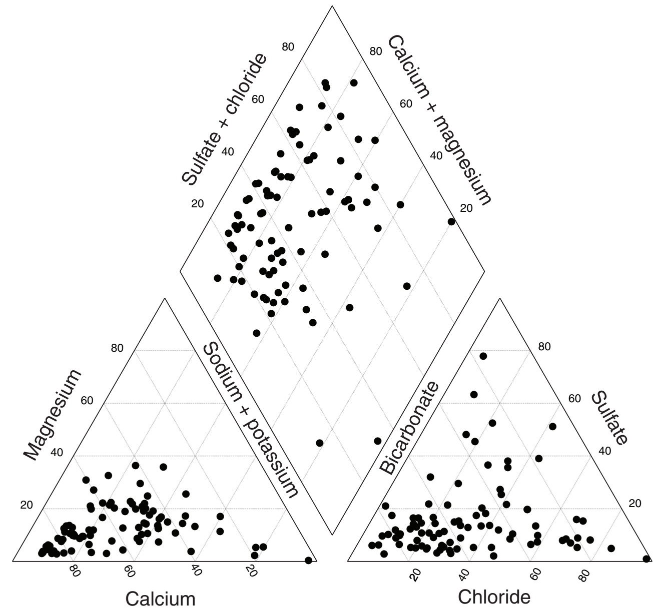


Figure 65. Piper plot for all wells with available data in the valley.

Radionuclides have also been found in a few wells throughout Nova Scotia, and in some places in the Annapolis Valley. Naturally-occurring uranium was first identified in groundwater in 1978. In 2002, ^{210}Pb (a daughter product of the ^{238}U decay series) was identified in the water of a school near Halifax. As a result, a province-wide radionuclide-testing program was initiated. The initial results indicated that ^{210}Pb and uranium could exceed drinking-water guidelines in drilled wells in granite and upper Carboniferous sandstone and shale. However, subsequent investigations revealed that ^{210}Pb-testing methods did not provide a realistic indication of ^{210}Pb levels because radon gas in the water samples was rapidly decaying to ^{210}Pb. The ^{210}Pb sampling protocol was then modified in Nova Scotia to eliminate radon effects. The majority of water supplies that had originally exceeded the ^{210}Pb guideline were below guidelines when they were re-tested using the modified sampling protocol. For more details, *see* Drage et al. (2005a and b).

Regional picture of various chemical ions and parameters

Several parameters have been analyzed in different types of wells in Nova Scotia, including residential, industrial, and institutional, as an indication of groundwater quality. Above a certain concentration threshold, these elements may have negative effects on human health and well being. Three kinds of limits were used in this study, based on Health Canada limits and guidelines for drinking water (Health Canada, 2008): 1) maximum acceptable concentration (MAC), which is defined as the concentration above which domestic use during life-span could give rise to health problems, 2) interim maximum acceptable concentration (IMAC), when the harmful dose is unknown, and 3) aesthetic objectives (AO), when the limit is not related to health problems but to unpleasantness (e.g. taste, odour, staining) or to technical nuisance (e.g. pipe clogging).

Data for groundwater quality was gathered from five different sources: the provincial geochemical database (252 sites), the provincial pumping-test database (47 sites) the Kings County nitrate database (28 sites), Envirodat (from Environment Canada, nine sites), Clean Annapolis River Project (CARP), and the GSC field campaign (39 sites, excluding those for isotope analysis). Data span more than 30 years (1974 to 2006), but most of the 2004 to 2006 data came from CARP and the GSC. The last three sources include mainly residential wells. Provincial databases contain results from schools, hospitals, town offices, institutions, and municipal wells. The overall database comprises only a limited number of data, since geochemical analysis results from private wells are not necessarily sent to the provincial department of Environment (NSE), like in some other provinces. Except for the GSC field-campaign results, it was not possible to know if the sampled well was tapping bedrock or surficial units.

The geochemical database includes major and minor ions, some trace metals, a few organic components, and other parameters such as hardness, total dissolved solids (TDS), and pH. The Kings County nitrate database only contains, as the name indicates, $N\text{-}NO_3$ results, mainly from the Briggins and Moerman (1995) and Blair (2001) reports. The CARP data provided four nitrate concentrations related to the GSC water-level survey, and finally the GSC results include major ions, and sulphate and nitrate concentrations for the Thomas Brook subwatershed. When more than one result was available for the same site (well), all values were included in the statistic or figures to avoid a biased picture (the use of a single value, e.g. median, maximum, or more recent value, would have, of course, provided a subjective picture). However, for the evaluation of the number of wells exceeding the Canadian drinking-water guidelines, the median has been used, so as to provide a conservative geochemical portrayal of the study area. In the database, several wells have the same (x, y) co-ordinates (due again to the 1 km^2 precision of their localization), and thus cannot be distinguished from one another on the figures of the atlas (plates 6.1.1 to 6.5, Rivard et al., 2007). Very little documentation and no information on the method of laboratory analysis are available for the provincial geochemical database. The database created for this project includes a 10 km buffer around the study area.

Spatial distributions of available parameters were drawn, and maps of the most interest are presented in the atlas (mostly for problematic parameters and where the number of analyses was sufficient to be considered representative). On each map, a small black dot was used to indicate samples below the given criteria, and an increasing symbol size with a different colour was assigned as the concentration increased. Frequency graphs, along with mean, median, and maximum observed concentrations, type of limit defined for the parameter, and percentage of samples above this limit were calculated and added to those maps to provide a better representation of the groundwater quality. Specific parameters that were chosen include chloride (Cl), iron (Fe), manganese (Mn), sodium (Na), sulphate (SO_4), nitrate ($N\text{-}NO_3$), arsenic (As), lead (Pb), hardness, pH, and total dissolved solids (TDS). All results are presented without discrimination of the tapped unit (bedrock or surficial deposits), since this information was unknown most of the time.

Major and minor ions

Six ions are of particular interest, based on their potential occurrence in the study area (as in the case of sulphates and nitrates due to agricultural activities, and sodium and chloride, since some of the study area is close to salt water) or a widespread presence in relatively high concentration (e.g. iron and manganese). There is no evidence of adverse health effects specifically attributed to calcium, magnesium, phosphorus, or potassium in drinking water. Guidelines for these elements have therefore not been defined and, as such, they are not discussed here. Table 32 summarizes percentages of wells exceeding the different ion and other parameter limits.

Chlorides

High concentrations of chlorides occur only to a limited degree from natural sources (e.g. evaporitic rock dissolution, sea water intrusion). Important sources of chloride are mainly from sewage, effluents from chemical industries, deicing salts, and induced seawater intrusion (from pumping). The aesthetic objective is <250 mg/L. In the valley, only 1.1% of the wells exceeded this limit. The map in the atlas (Plate 6.1.1 Rivard et al., 2007) shows that the only three wells exceeding this limit are located at both ends of the valley, close to the Annapolis and Minas basins as might be expected.

Iron

Iron is one of the major elements of the earth's crust and especially of sandstones (as oxides, carbonates, and sulfides or iron clay minerals). Elevated values of iron are commonly observed in reducing environments such as peat, bogs, and coal deposits. There are no indications that iron is a health threat in the concentration range that is normally found in groundwater. However, in concentrations larger than 0.3 mg/L, iron may stain laundry and give a red-brown colour to water and a bad taste. Moreover, iron can stimulate the growth of (iron) bacteria in piping, creating a viscous thin layer. The aesthetic objective is thus to maintain concentrations below 0.3 mg/L. This element can be present in relatively high concentration almost anywhere in the valley. Of the 261 tested wells, 14.9% exceeded this objective. Elevated concentrations do not seem to be associated with a specific formation or group. Very few wells were tested on South Mountain.

According to Kempt (1996), who conducted a study in the eastern part of the study area, high iron concentrations could be due to the high iron content of the till, which formed by glacial erosion of the Blomidon and Wolfville formations, and of the kame sands, where it occurs as an iron coating on quartz grains. This parameter is more likely to be elevated during the spring, due to greater surface runoff and infiltration of snowmelt.

Table 32. Summary of groundwater sampling results.

Ions	Type of limit*	Limit (mg/L)	Number of wells sampled	% of wells exceeding the limit
Arsenic	MAC	0.010	150	6.0%
Barium	MAC	1	57	1.8%
Chloride	AC	250	265	1.1%
Iron	AC	0.3	261	14.9%
Fluoride	MAC	1.5	89	3.4%
Lead	MAC	0.01	123	11.4%
Manganese	AC	0.05	225	24.0%
Nitrate (N-NO_3)	MAC	10	290	14.8%
Selenium	MAC	0.01	55	14.5%
Sodium	AC	200	253	0.8%
Sulphate	AC	500	264	0%
Other parameters				
Hardness		500	243	0%
pH		6.5 to 8.5	252	15.5%
TDS		500	225	3.1%

* MAC: Maximum acceptable concentration
IMAC: Interim maximum acceptable concentration
AC: Aesthetic objective

Manganese

Manganese can be found in more than a hundred minerals, often in combination with iron. Reducing conditions in aquifers favour the dissolution of manganese, which explains why it is significantly more abundant in groundwater than in surface water. As in the case of iron, manganese can stain laundry and favour micro-organism growth. At concentrations as low as 0.02 mg/L, black precipitates may form in the piping. It is technically difficult to reduce concentrations below 0.05 mg/L; thus this value corresponds to the aesthetic objective. Of the 225 wells, 24.0% exceeded this objective. Again, elevated manganese concentrations can be found almost everywhere in the study area and they do not seem to be associated to a specific formation or group.

Sodium

Sodium is not toxic at concentrations generally found in the environment. However, a threshold of 20 mg/L in drinking water is recommended for people with heart disease and hypertension. The taste of water is affected by this parameter and is usually considered unpleasant at a concentration of 175 to 185 mg/L. The aesthetic objective is <200 mg/L. In all, only 0.8% (three wells) of the 253 wells exceeded the limit. Two of the three wells also had high concentrations of chlorides (NaCl); they are located in the Annapolis Royal area. The last well is located close to the Minas Basin.

Sulphate

Sulphate ions can be found in a natural state in numerous minerals and are not very toxic. Sulphates can be an indicator of gypsum dissolution in natural groundwater, but also come from acid mine drainage and oxidation of barnyard and domestic effluents (H_2S or HS into SO_4^{2-}). At concentrations higher than 1000 mg/L in drinking water, they can have a laxative effect among adults (600 mg/L for children). The taste of various sulphate salts can be detected at around 500 mg/L and thus the threshold for aesthetic criteria has been fixed at this level. High sulphate values may be related to high nitrate concentrations as many commercial fertilizers contain sulphate salts, but this does not seem to be the case in the valley. Indeed, no wells were found to exceed the 500 mg/L threshold.

Nitrates

Nitrates and nitrites are often encountered in natural environments. Both are products of the oxidation of nitrogen, mainly by micro-organisms in plants, soil, and water. Nitrates are easily leached because they are highly soluble and correspond to a stable phase within the nitrogen cycle in many groundwater environments. Nitrites are usually found in very low concentrations under typical aquifer conditions, and therefore only nitrates are of general interest in this project. Nitrogen in groundwater systems can be derived from a variety of natural sources, such as air, plants, organic matter, and precipitation. Anthropogenic nitrogen sources include: effluent from sceptic tanks, deforestation, changes in soil organic regime due to crop rotation, inorganic fertilizers and manure. In the case of the Annapolis Valley, the major source of pollution for groundwater appears to be related to agricultural activities, but effluents from septic tanks have been the cause of some local contamination (reported by residents during the water-level survey). Nitrate isotopes have been analyzed in the Thomas Brook subwatershed so as to determine nitrate sources (*see* the 'Nitrate isotopes in the Thomas Brook subwatershed' section).

The Canadian Drinking Water Quality guideline for nitrates expressed in mg/L of nitrogen ($N\text{-}NO_3$) is 10 mg/L. Nitrate results indicate that 14.8% of the 290 wells exceeded the criteria for drinking water. The atlas map (plate 6.2 Rivard et al., 2007) shows that the most elevated values are located in Kings County (the most intensively farmed region of the province). Fewer data (19% of the wells) are available for Annapolis County. The median value for all wells is 2.0 mg/L. More details about nitrate concentrations are provided in the 'Previous studies on nitrates conducted in the Annapolis Valley' and 'Nitrate issues in the valley' sections.

Trace metals

Metals such as arsenic and lead, which could lead to serious health problems, were included in this study because some samples showed elevated concentrations.

Arsenic

Arsenic is a metalloid that can reach groundwater in two ways: through mineral and ore dissolution, and industrial dumping. In addition, arsenic concentration in groundwater could also result from past agricultural practices, since arsenic was used as a component of pesticides prior to the 1960s. The level for this metal in a region without natural sources is on the order of 5 µg/L. The maximum acceptable concentration (MAC) for drinking water was established to 10 µg/L in May 2006. In the Annapolis Valley, 6% of wells (out of 150 tested wells), apparently located in a dozen of sites, exceeded this limit. These sites seem to be located in various geological formations, but always on the southern side of the study area.

Lead

The presence of lead in potable water may originate from the dissolution of lead from natural sources, but it's more likely in this case that concentrations result from the combination of old household plumbing containing lead and corrosive (low ph) groundwater. The MAC is set at 10 µg/L. Samples have exceeded the limit in 11.4% of 123 wells. High concentrations of lead are mainly located in South Mountain. Lead mining represents an important mining industry in Nova Scotia.

pH, hardness, and total dissolved solids

pH

Generally, a pH value between 6.5 and 8.5 is the objective for drinking water. Below a pH of 6.5, corrosion may become significant, while above 8.5, the frequency of incrustation and scaling problems, as well as inefficiency of chlorine disinfection, can worsen (Health Canada, 2008). In the study area, out of 252 wells, 13.9% showed a pH value lower than 6.5 and 1.6% indicated higher values than 8.5. The median pH value is 7.25, very close to the neutral level. Wells showing alkaline and (slightly) acidic waters are surprisingly often very close.

Hardness

Hardness results from the presence of divalent metallic cations, of which calcium and magnesium are the most abundant in groundwater (Todd, 1980). Because of their reaction with soap, hard waters are unsatisfactory for most domestic purposes. Generally, hardness levels between 80 and 100 mg/L (as $CaCO_3$) are considered acceptable; levels greater than 200 mg/L are considered poor but can be tolerated; those in excess of 500 mg/L are normally considered unacceptable (Health Canada, 2008). Water from 6.6% of the wells have a $CaCO_3$ concentration above 200 mg/L, but no wells exceeded the unacceptable threshold. Again, values are well distributed across the various geological formations.

Total dissolved solids

Total dissolved solids (TDS) are comprised of inorganic salts and small amounts of organic matter that are dissolved in water. The principal constituents are usually the cations calcium, magnesium, sodium, and potassium, and the anions carbonate, bicarbonate, chloride, sulphate and, especially in groundwater, nitrate (Health Canada, 2008). The presence of dissolved solids in water can affect its taste; more than 500 mg/L is considered undesirable for drinking water. Only 3.1% of the wells exceeded the aesthetic criteria of 500 mg/L. The median for all wells is 125 mg/L. Because of elevated concentrations of certain ions (such as sodium and chlorides), wells showing other problems of elevated ions also consequently appear having high TDS concentrations.

Table 32 summarizes results of some of the ions and parameters contained in the geochemical database, the type of limit (criteria) and its value, the number of samples and the proportion of samples exceeding the guideline for drinking water. Some trace metals have also been added to the table (arsenic, barium, lead, and selenium) due to their relatively high percentages (>10%) of occurrence above the guideline or their importance for health. This table shows that major and minor ions, trace metals, and other parameters are usually well within the guidelines for Canadian Drinking Water Quality (Health Canada, 2008) in groundwater of the Annapolis Valley. However, lead, selenium, and nitrates exceeded the limits in more than 10% of the cases, as well as iron and manganese (15 and 24%), but the latter ions do not present any health risk. Low pH values are also found in different areas.

Previous studies on nitrates conducted in the Annapolis Valley

Problems resulting from agricultural land uses have arisen in the last couple of decades in the Annapolis Valley, especially in Kings County. In particular, elevated nitrate concentrations have been found in surface water and groundwater. Several studies have been devoted to this topic: Thomas (1974), McLeod and Fulton (unpub. rept., 1985), Briggins and Moerman (1995), Kempt (1996), and Blair (2001). As early as 1972, nitrate contamination was detected in several domestic wells, during random testing of 50 wells in the eastern part of the Annapolis Valley (Thomas, 1974). In response to this finding, Thomas undertook a study in 1973, and found that 25% of the wells in the Canning area (covering about 11.7 km^2) exceeded the nitrate-N drinking water guideline of 10 mg/L, and that 56% had concentrations above 5 mg/L. For this study, 359 wells were tested for nitrate and other major ions, and 20 wells were regularly tested in 1973 for nitrates (NO_3) and other major ions. Thomas (1974) also estimated that 60–70% of the study area was cultivated farmland, that 212 700 kg/year of inorganic nitrogen were applied (essentially in the form of chemical fertilizers), and that an additional 259 000 kg of NO_3/year were applied directly from livestock waste. Background nitrate concentrations were found to be less than 0.2 mg/L in the Blomidon and North Mountain formations, and less than 1 mg/L for the Wolfville Formation. Therefore, Thomas (1974) concluded that background NO_3 concentration was likely ≤ 1 mg/L. Depth of water table, thickness of surficial material, and well construction were identified as the main factors influencing nitrate contamination. In addition, the regular monitoring of nitrates at five stations showed concentrations slightly higher and more variable during the growing season, but not markedly higher than during the rest of the year, likely due to the fact that rain events and infiltration can occur all year long in the Annapolis Valley.

In a summary of historic nitrate data for Nova Scotia, McLeod and Fulton (unpub. rept., 1985) reported that 7% of wells province-wide and 29% of wells in the intensive agricultural regions in Kings County exceeded the 10 mg/L guideline (in Briggins and Moerman, 1995). However, those wells were selected based on reported problems, and are therefore not representative of the entire valley. Agricultural sources of nitrates and poor well construction were thought to have an impact on the groundwater quality (Blair, 2001).

Kempt (1996) conducted another geochemical study in the Kingston area (just north of the CFB Greenwood military base), which contains a mixed urban-rural land use. A sampling campaign including surface water (9 samples) and groundwater (from 33 domestic wells) was carried out during spring and fall 1995, with all sites being visited twice. Samples were tested for nitrate, phosphate, chloride, sodium, potassium, calcium, magnesium, and iron. Surface-water samples were tested for coliform bacteria. In addition, temperature, pH, conductivity and dissolved oxygen were analyzed on site. In this sandy area, most residences are supplied by wells located in surficial aquifers. The main conclusions of this B.Sc. thesis were that water quality of wells sometimes had a high degree of variability (even in wells in close proximity), and that surficial geology and land use practices play a major role in the water quality of the region. Agricultural practices, road salting, and lawn care all adversely affected water quality of this area. Anomalous and potentially unsafe low pH values occurred in a few places, but the cause was unknown (acid rain? decomposition of organic matter?). Ion concentrations were all below Canadian drinking water standards, except for iron. Nitrate concentrations were on average below 2 mg/L-N (being higher in the fall), but had an equal standard deviation (2 ± 2 mg/L-N). The highest values were found during the fall, after the harvest season, with 9 mg/L being the highest recorded.

In 1989, a four-year study (Briggins and Moerman, 1995) was initiated to test pesticides, but also nitrates, bacteria, and other common ions and parameters in Kings County. Indeed, almost no information was available on the presence or absence of pesticide contamination in groundwater in Nova Scotia. Trescott (1968) had reported that no pesticides had been found in the samples taken in two orchards near Berwick and one potato crop field west of Berwick, two sites considered vulnerable due to their shallow water table and sandy soils. In this study by Briggins and Moerman (1995), water samples were collected between June and September 1989 from 102 farm wells for pesticides, nitrates-N, and bacteria analyses, and in 135 wells for nitrates-N only. All wells were selected based on a ranking associated with a modified DRASTIC approach. In all, 69% of visited wells tapped the bedrock while 16% tapped surficial deposits (no data was available for the remainder). Results of the study indicated that none of the 102 visited wells contained pesticides above maximum acceptable concentrations (MACs). Nevertheless, pesticides were detected in 41% of the wells and atrazine (usually associated with corn crops) was the most frequently detected pesticide. Nitrate-N concentrations above the 10 mg/L guideline were encountered in 13% of the wells, and 19% had concentrations higher than 5 mg/L. However for the Canning area (an intensive farming community considered as highly vulnerable in this study), the percentage of wells exceeding the N-NO_3 limit was similar to that of Thomas (1974) (29% versus 25%), suggesting that there had been no significant changes in this region in the last 15 years. Bacteria were found above the limit of that time (10 per 100 mL, the limit now being 0) in 9% of the wells, but were detected in 25% of the wells. In general, wells with pesticides also had elevated nitrates-N concentrations. Indeed, 71% of the wells with pesticides had N-NO_3 concentrations greater than 5 mg/L. Well type and depth were correlated with nitrate concentrations. Indeed, Briggins and Moerman (1995) concluded, based on statistical analysis, that their results suggested a higher susceptibility of shallow, poorly constructed wells (despite large variations in point source contamination by nitrates and bacteria) and underlined the fact that high percentages of elevated concentrations were found due to the biased weighted sampling approach implemented (using DRASTIC indexes).

Blair (2001) used the same study area as Briggins and Moerman (1995) and a subset of their domestic well sites for his sampling. The purposes of Blair's study was mainly to 1) compare results with the Briggins and Moerman (1995) study, 2) understand better the extent and persistence of nitrates in domestic wells of Kings County, and 3) examine seasonal variations and patterns in nitrate concentrations. Samples were collected monthly from 114 wells between July 1999 and October 2000 to cover an entire seasonal cycle and to compare two crop harvest seasons. The median N-NO_3 concentration found for the entire study period was 3.9 mg/L. In all, 16% of the 114 wells and 17% of all 1693 samples collected exceeded the 10 mg/L guideline. Blair (2001) observed considerable variability in N-NO_3 levels both spatially (large differences even for wells not too far apart), and temporally, as compared to the 1989 sampling campaign. Indeed, 35% of wells showed an increase of 1 mg/L and more, and 25% showed a decrease of 1 mg/L and more. The remaining 40% showed changes in concentrations less than 1 mg/L, corresponding to no significant change. In addition, variability was also noted between years, as the median concentration was higher in 1999 than in 1989 or 2000. Results of Blair's statistical analyses led to the conclusions that

1) There was no seasonal or monthly variation trend in the data analyzed, suggesting that more effort should be put on sampling each year, rather than repeatedly over the same year.
2) There was little difference between median nitrate concentrations of drilled and dug wells, but nitrate concentrations seemed to diminish with depth.
3) Areas close to Canning, Port Williams, and Centreville (in the eastern part of the study area) were found to have the highest nitrate levels.
4) When using multivariate analysis, surficial and bedrock geology surprisingly appeared to be more strongly correlated with nitrate concentrations than land use.

Also, NSE has been publishing annual reports on this issue since 2008, which can be found at: http://www.gov.ns.ca/nse/groundwater/nitrate.asp. These reports present NSE monitoring program objectives, methods, sites, and results. The Clean Annapolis River Project (CARP) recently completed an inventory of pesticide usage in the Annapolis watershed. The objectives of the study were twofold: to document for the first time all pesticide usage within the watershed, and to develop a methodology for this type of inventory at a watershed scale. The full report is available at http://www.annapolisriver.ca/downloads/ARW_Pesticide_Risk_Ranking_2006.pdf

Nitrate issues in the valley

Groundwater in Kings County has shown elevated nitrate concentrations in different wells and in surface water for at least 30 years. It has the highest nitrate concentration in Nova Scotia (Blair, 2001), reflecting the intensive agricultural activity of this region. Of the total land area of Kings County, about 25% is used for agriculture, and of this percentage, 42% consists of land for crops (fruits, nuts, vegetables, etc.) that requires large amounts of fertilizers and pesticides.

The most significant environmental effect of agriculture on groundwater is probably increased concentrations of nitrates. Adding a surplus of nitrogen to a crop results in residual nitrogen that can easily travel towards groundwater and surface water since nitrate is highly soluble. Blair (2001) reported that literature suggests that applications of nitrogen to agricultural systems frequently exceed crop requirements. The main concerns for human effects include methaemoglobinaemia (blue baby syndrome) and cancer, and, potentially, reproductive problems and diabetes. Nova Scotia has had a nutrient management plan since 1999 to help farmers incorporate environmental considerations into their decisions. In addition, several pilot projects related to farm management, including the one being conducted in the Thomas Brook subwatershed, have been initiated by the provincial and federal governments and academic institutions in an effort to protect water resources. However, changes in agricultural practices and tangible improvements to groundwater quality take time.

Even if mixing of contaminated and natural groundwater seldom occurs in the valley, as noted by Thomas (1974), some problems have also been solved only by deepening wells and/or casings. For instance, the Somerset school well, which taps the Wolfville Formation, was affected by nitrate contamination in 1990. The original well was 18 m deep, and it was deepened to 35 m (below a less permeable layer) and the casing extended. In this case, the contamination problem was resolved due to the aquifer/aquitard layering present in this formation. Indeed, the less permeable strata favours horizontal groundwater circulation over the other (confined) aquifer, hence protecting it against contamination.

Reported geochemical values show that elevated nitrate concentrations can be found in different areas of the valley, but are mostly concentrated in the eastern, more populated, portion of the valley. Intensive agricultural regions have started to be severely affected. For wells randomly sampled throughout the valley (i.e. using the overall database), 14.8% of the wells exceeded the 10 mg/L Canadian drinking water guideline. This percentage is not much different for Kings County alone, since few wells are available in Annapolis County. However, the percentage of tested wells exceeding the 1 mg/L background concentration probably provides a better picture of the groundwater degradation, as it indicates wells already affected by anthropogenic activities (and thus a possible increase in the following years if corrective measures are not taken). Indeed, Thomas (1974) had found evidence of a ≤1 mg/L background concentration and the M.S. thesis on modelling of nitrates in the representative Thomas Brook subwatershed seems to corroborate this result (see Trépanier, 2008). Of the 290 wells available, 64.5% exceed this 1 mg/L background threshold.

On the other hand, wells in the Kings County database show that of 148 wells more or less regularly tested, 18 to 25% of wells exceeded the 10 mg/L guideline, and between 75 and 83% of wells exceeded the 1 mg/L background level. Despite the fact that the Kings County database is biased as it includes more wells in vulnerable areas, the situation is cause for concern. Figure 66 illustrates the spatial distribution of N-NO_3 for all data included in the database. Even if several areas have sparse data, this figure shows that almost all of Kings County is affected by agricultural activities (i.e. N-NO_3 concentrations above 1 mg/L). Very few data are available in the western part of the study area, especially on North and South mountains.

Of the seven wells having multiple values (and dates) dating back to the 1970s in the provincial database, four show an evident increase in nitrate concentration. Three are located at the extreme eastern end of the valley, in the extensively farmed area (in Wolfville, Canning, and Port Williams), while the last one is located at the extreme western end, near Annapolis Royal. Only two of the wells have values of concern, on the order of 1 to 5 mg/L for the Canning well and 2 to 14 mg/L for the well in Port Williams.

As per 2008, only surface water is being tested on a weekly basis during the growing season by environmental associations, and nitrate analyses were only begun in 2004. The fact that groundwater in the bedrock is also being affected by nitrates confirms the frequent hydraulic connection between surface water and groundwater circulating within surficial deposits (likely corresponding to the largest part of the river and brook flows during the summer) and the bedrock at the regional scale.

Nitrate levels obtained for the Thomas Brook subwatershed corroborate previously found values for intensive agricultural areas (*see* the 'Previous studies on nitrates conducted in the Annapolis Valley' section). Indeed, N-NO_3 concentrations in bedrock wells (17 samples) range from 0.01 (detection limit) to 17.8 mg/L with a median of 4 mg/L. When including all samples (from surface water, bedrock, and piezometers), 5 of 33 samples (15%) showed N-NO_3 concentrations exceeding the 10 mg/L guideline, while 22 samples (67%) exceeded the 1 mg/L background concentration, thus showing that water resources are being affected by anthropogenic activities. For bedrock wells only, these numbers increase to 24% and 77% respectively. Elevated nitrate concentrations were found in wells mainly located in the middle part of the subwatershed, tapping the Blomidon Formation. The concentrations decrease rapidly to the north and the south of this zone. The spatial distribution of nitrate concentrations is presented in Plate 7.6 (Rivard et al., 2007). As mentioned in the 'Groundwater-level monitoring' section, the high values of nitrate concentrations in the middle of the subwatershed are likely due to the existence of a downward hydraulic gradient. Lower values tend to be located in the southern part of the subwatershed, probably attributable to the thicker silty sand glaciolacustrine unit present at the surface that favours horizontal flow to the brook

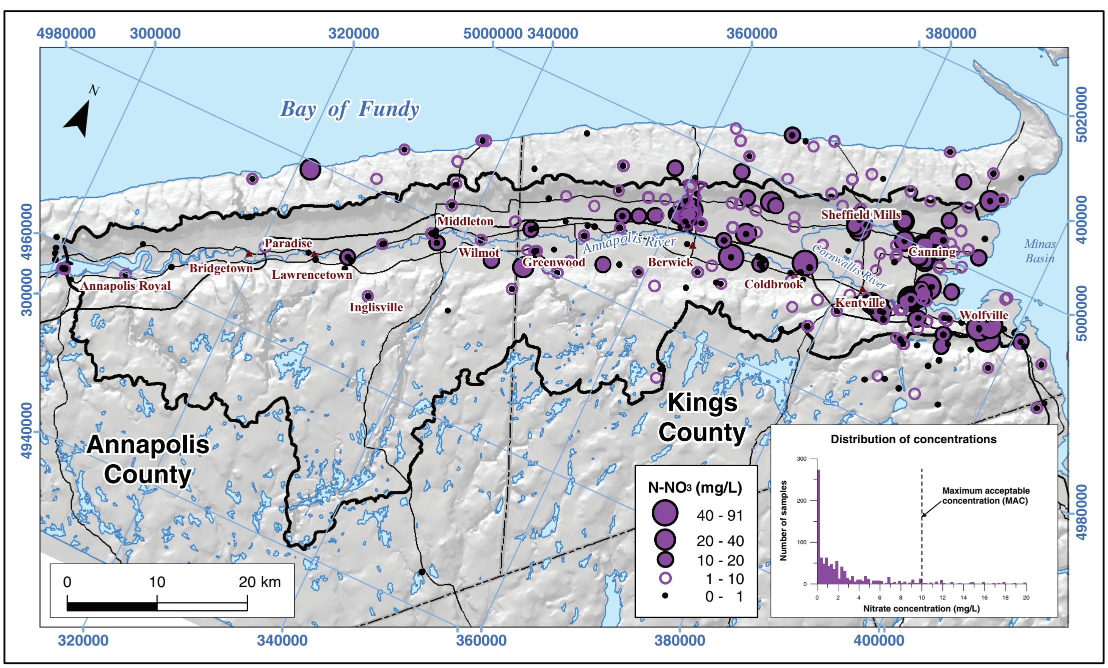


Figure 66. Spatial distribution of nitrate concentrations.

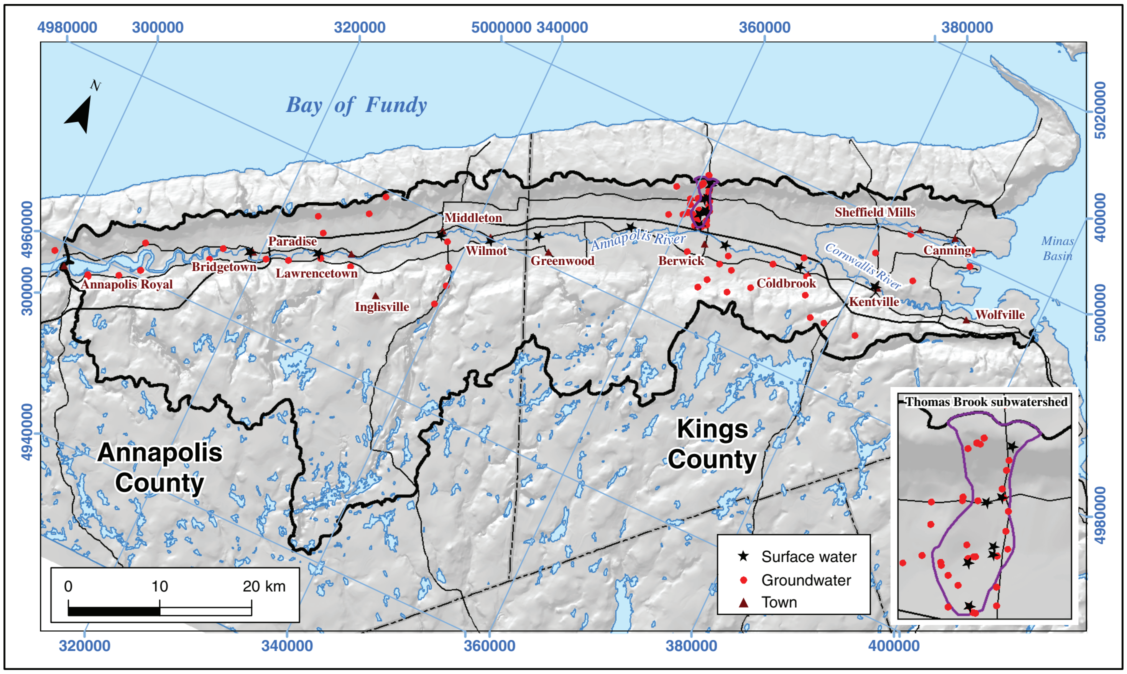


Figure 67. Location of the 92 sampling sites (22 are located in the Thomas Brook subwatershed). Stars represent surface water (15 sites, of which six are located in the Thomas Brook subwatershed), and circles groundwater sampling sites (77 sites, of which 16 are located in the Thomas Brook subwatershed).

(in its saturated part). The heterogeneous pattern of the spatial distribution is thus a consequence of the bedrock and surficial unit composition. For additional information and analysis see Trépanier (2008).

Random sampling obtained from Nova Scotia Agricultural College for nitrate concentrations (among other elements) in Thomas Brook from 2001 to 2003 show that surface water is also affected by agricultural practices. For the years 2001 to 2006, median nitrate levels for the two downstream stations range from 1.8 to 2.5 mg/L, a similar, though slightly lower value than what has been found on average in bedrock. The similarity is not too surprising since a large part of the brook flow comes from baseflow. However, several peaks between 3.5 and 4.5 mg/L were observed for each year. There is a high possibility that even higher values could have been observed, had the sampling been carried out on a daily basis. Indeed, daily values of nitrate-N loading (in kg) show for each year, but especially for 2002 and 2003 at stations 4 and 5 downstream, daily loading of 6 to 23 times higher than the yearly average value, likely from rain events following recent spreading. More details are available in Trépanier (2008).

Stable hydrogen and oxygen isotopes

Precipitation, surface water, and groundwater were sampled during 2004 and 2005. The sampling locations for surface water and groundwater are presented in Figure 67. Rain and snow samples were collected in Greenwood.

Isotopic principles and previous isotopic work in the study area

The applications of environmental tracers for hydrogeological studies have rapidly expanded since their first use in the 1960s. They are commonly used in groundwater dating and to analyze aquifer recharge, groundwater contributions to streams, and surface water/groundwater interactions. Isotopic tracers, and especially stable isotopes (δ^2H and $\delta^{18}O$), have rapidly gained in popularity, as they are natural constituents of water and therefore well adapted to groundwater-flow studies. Condensation and evaporation processes, which are dependent on the vapour pressure of water, are the primary causes of oxygen fractionation in the hydrosphere. In this study, oxygen and hydrogen isotopes have been used to provide additional support for the interpretation of the system hydrodynamics, providing a first portrayal of the approximate age of waters and information on the contribution of groundwater to streams (baseflow) by comparing isotope signatures of precipitation and stream waters.

Thomas (1974) randomly sampled 88 wells across the valley for oxygen isotopes from indoor taps. Samples taken from shallow dug wells showed significant seasonal variations (from −11.4 to −10.3% from winter to spring, Thomas (1974) p. 39), reflecting seasonal fluctuations of $\delta^{18}O$ in precipitation and thus, indicating a very short residence time. Based on stable isotope results, Thomas (1974) divided aquifer recharge into three classes: 1) water infiltrating North Mountain and feeding the underlying Blomidon Formation, and discharging as springs located on the flanks and some on the valley floor; 2) water circulating into surficial aquifers and shallow bedrock wells (<30 m) likely coming from local valley-floor recharge; and 3) water encountered in deep (>30 m) wells tapping the Triassic formations. The last class suggested that there was no recent recharge to these depths; hence she concluded that either the water was very old or had been recharged elsewhere.

Precipitation

Figure 68 shows the results of all samples taken in 2004 and 2005 for the hydrogen and oxygen isotopes, as well as the nearest meteoric water line (MWL). Several of the rain samples and most of the groundwater and surface water data lie well above the Truro MWL ($\delta^2H = 7.3\ \delta^{18}O + 3.59$; Fritz et al., 1987). This indicates that the Truro MWL does not suitably describe precipitation in the Annapolis Valley, despite its geographical proximity. This is not surprising given the unique microclimate in the Annapolis Valley that makes the area well known for abundant fruit production.

A local meteoric water line (LMWL) for the Annapolis Valley was constructed from monthly composite precipitation samples collected in the Valley in 2004 (Fig. 68). This LMWL ($\delta^2H = 7.5\ \delta^{18}O + 9.74$) is based on linear regression of 12 monthly rain samples from a single precipitation gauge located in the middle of the valley (Greenwood). Despite the fact that the data points comprising this LMWL exhibit a fair degree of scatter, the LMWL formed by these points is positioned right through the groundwater data and appears to be a better fit than the Truro MWL. Hence the LWML provided the basis for interpreting groundwater and surface water data, and could provide some insight into climatic variability in Nova Scotia.

Groundwater

Groundwater data from six seasons of domestic-well sampling in the Annapolis Valley has $\delta^{18}O$ values ranging from –11.4 to –8.4‰ (avg. –10.2‰), and δ^2H values ranging from –78 to –53‰ (avg. –66‰). Groundwater data points generally fall near the LMWL (with the exception of a small group of data points that have δ^2H values that lie above –60‰) confirming that groundwater in the region is derived from 'modern' (from a geological time-scale point of view) or 'Holocene' precipitation (<10 000 y). It must be noted that for groundwater to exhibit a really distinct isotopic signature characteristic of older waters, the groundwater would have to be several thousand years old. It is interesting to note that groundwater data falls near the middle of the LMWL, approximately equidistant from the isotopically enriched end of the LMWL and the most isotopically depleted end of the LMWL. This implies that summer precipitation and winter precipitation have contributed about equally to the groundwater system, assuming

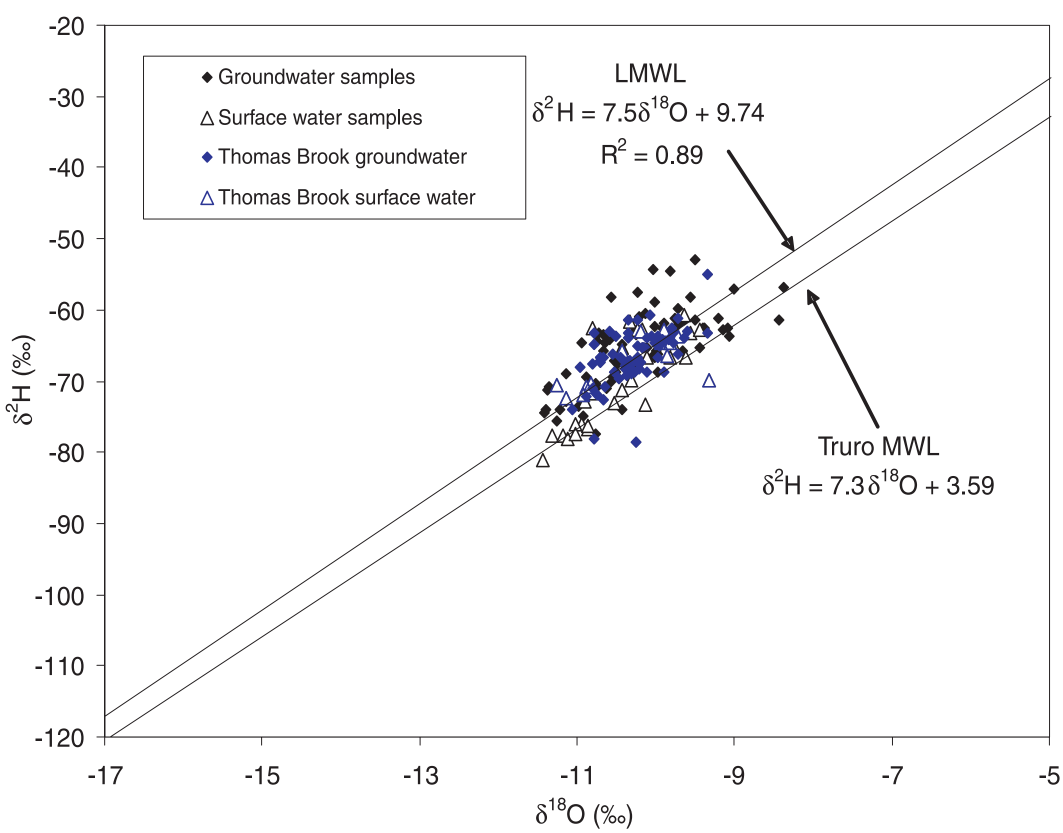


Figure 68. $\delta^{18}O$ versus δ^2H plot showing all groundwater and surface water data from 6 seasons, with the Thomas Brook sub-watershed data highlighted in blue.

that the groundwater composition is fairly constant throughout the year. Indeed, fall precipitation accounts for a large part of the recharge and snowmelt can infiltrate gradually during winter, due to the valley microclimate. This is a quite different situation than in other areas of Canada, where the spring snowmelt can represent a disproportionate contribution to the annual groundwater budget (Simpson, 2001). The groundwater data points that lie above –60‰ δ^2H are from the winter 2004/2005 and spring 2005 sampling expeditions.

Average oxygen-isotope values for Nova Scotia groundwater have been published as falling between −9 and −10‰ (Fritz et al., 1987). The results of this study show a slightly more depleted oxygen isotope composition (avg. −10.2‰), more typical of groundwater in eastern New Brunswick. Since the groundwater composition is a direct reflection of local precipitation, the implication is that precipitation in the Annapolis Valley is not typical of the rest of Nova Scotia, and would thus be closer to a maritime climate such as the one occurring in eastern New Brunswick. Indeed, the 'continental effect,' in which an air mass travels inland (from the ocean), results in the removal of isotopically heavier precipitation, leaving the air mass and subsequent precipitation progressively enriched in the lighter isotopes. Therefore, precipitation falling further from the ocean will have progressively lighter values (depleted in the heavy isotopes, or more negative). The Thomas study (1974) had found the average δ^{18}O value of 81 groundwater samples to be –9.8‰. This is very similar to values obtained in the present study.

Surface water

Surface water data from the Annapolis Valley has δ^{18}O values ranging from –11.4 to –9.3‰ (avg. –10.4‰) and δ^2H values ranging from –81 to –61‰ (avg. –69‰). These values are slightly more depleted in heavy isotopes than groundwater values. In Figure 68, the surface-water data cluster is near the groundwater data cluster, but is shifted slightly along the LMWL toward the more isotopically depleted end of the diagram. The fact that the surface water samples lie pretty much on the LMWL (with the exception of these more isotopically depleted samples) and are close to the groundwater compositions implies that surface water in the Annapolis Valley is derived from 'modern' groundwater discharge and/or precipitation and has not been subject to significant evaporation. If surface water was derived entirely from precipitation with no input from groundwater (baseflow), then summer surface-water samples would have a much more isotopically enriched composition than that observed here. In addition, evaporation is an isotopically fractionating process that would cause the surface water to plot below the LMWL on a line with a smaller slope. However, for flowing surface waters like those sampled in the Annapolis Valley, the residence times are likely on the order of days or weeks (rather than several months, which may be observed in lakes); hence, it can probably be assumed that these surface waters are not strongly evaporative, even in the summer time.

The surface-water samples plotting at the depleted end of the surface water data cluster are all spring samples (spring 2005 and 2006). In fact, all the spring surface water data are isotopically depleted in the heavy isotopes of oxygen and hydrogen. Given that snow is the isotopically depleted end member in this system, this implies that spring snowmelt is the dominant source of water to the surface waters in spring, completely flushing out the previous year's isotopic signature. There is slightly less scatter in the δ^{18}O values of the surface waters (–2.1‰) than for the groundwater δ^{18}O values (3.0‰). For δ^2H there is also less scatter in surface water values (–20‰) than in groundwater values (25‰). This could be due to the larger number of groundwater samples, and hence opportunity for sampling and analytical error, relative to surface water samples, or be related to water sources or seasonal variations.

Seasonal variations

Groundwater that is influenced by recharge from precipitation and/or surface waters will often show variations throughout the seasons. Constant values would be expected for Annapolis Valley groundwater samples given the confined nature of most of the bedrock aquifers. For the Annapolis Valley, seasonal groundwater averages for summer 2004, winter 2004/2005, spring 2005, summer 2005, winter 2005, and spring 2006 are −10.5‰, −10.3‰, −9.6‰, −10.3‰, –10.4‰ and –10.1‰, respectively, for δ^{18}O, and –67‰, –64‰, –63‰, –67‰, –65‰, and –66‰, respectively, for δ^2H and the seasonal plots show some variation (Fig. 69). These variations are slightly greater than the normal conservative analytical error expected for δ^{18}O (±0.2‰) and δ^2H (±2‰) values. However, the stable isotopic variations in the groundwater do not exhibit the systematic seasonal changes expected when precipitation or seasonally recharged surface waters enter a groundwater system, in which summer groundwater values would be more enriched in the heavy isotopes relative to winter values. However, this seasonal change depends on the lag time between precipitation and infiltration to the groundwater system.

Given the absence of any systematic variation in groundwater stable isotope compositions, the cause of the exhibited variations is not readily apparent. Influx from the annual spring snowmelt would show up as an isotopically depleted signature immediately following this event. The fact that this feature cannot be observed could mean that there is no input from surface water sources, or it could be that infiltration of surface water/precipitation to the water table is longer than several months. This would result in significant mixing of recharge and in situ water obscuring any seasonal signature. Sampling in open wells (as opposed to sampling at discrete intervals) can create additional mixing during the sampling process. Since nitrate concentrations in groundwater are above natural background levels (1 mg/L) in some wells, especially in those located in Kings County (*see* Figure 66), there seems to be a mix of groundwater recharge from post-agricultural (i.e. any time after the onset of agricultural activity in the region) surface water/precipitation with

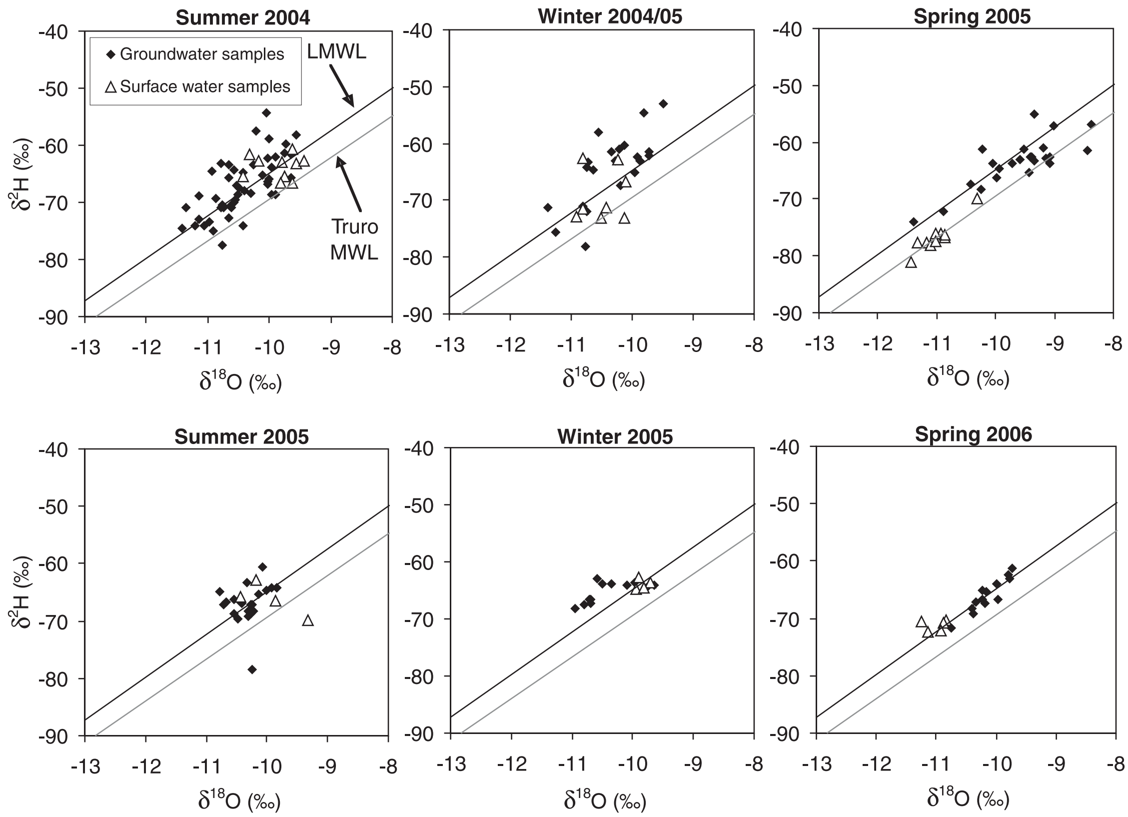


Figure 69. $\delta^{18}O$ versus $\delta^{2}H$ plot showing seasonal data for groundwater and surface water (◆ groundwater samples, Δ surface-water samples).

flowing groundwater. The variations may also be explained partially by the fact that in some cases samples from different sites were collected on different sampling trips, while some sampling sites were discontinued. Also, it is interesting to note that winter groundwater values show more scatter than spring groundwater values, suggesting that there may be something unique to the winter sampling trips that caused the greater degree of scattering (perhaps differences between indoor and outdoor taps?).

Surface waters in the Annapolis Valley exhibit seasonal variations expected in fast-flowing surface water bodies (Fig. 69). Seasonal surface-water averages for summer 2004, winter 2004/2005, spring 2005, summer 2005, winter 2005, and spring 2006 are –9.9‰, –10.5‰, –11.0‰, –9.9‰, –9.8‰ and –11.0‰, respectively, for $\delta^{18}O$, and –64‰, –69‰, –77‰, –66‰, –64‰, and –71‰, respectively, for $\delta^{2}H$. Summer and winter values are similar, as if large volumes of precipitation were not able to penetrate the ice/snow cover on surface waters during the winter months. It is important to note that surface-water values are not clustered directly above groundwater values. This likely implies that surface waters are derived from both groundwater and precipitation. The proportion of each type of water could not be estimated, since several months of mixed precipitation looked similar to groundwater composition at this site. The surface water is probably mostly derived from groundwater with an obvious contribution from the spring snowmelt (the most negative values). Indeed, spring surface water values are typical of those derived from snowmelt.

Thomas Brook subwatershed

Figure 68, illustrating the Thomas Brook groundwater and surface water $\delta^{2}H$ and $\delta^{18}O$ values in blue, shows that the groundwater oxygen and hydrogen stable isotopic compositions for the Thomas Brook subwatershed are very similar to those of the entire Annapolis Valley. Average $\delta^{18}O$ and $\delta^{2}H$ compositions for the Thomas Brook subwatershed (–10.3, –66‰) are nearly identical to those of the Annapolis Valley (–10.2, –66‰). There appears to be slightly less variability in the oxygen and hydrogen stable isotopic compositions of the Thomas Brook subwatershed. This is explained by the small size of the Thomas Brook subwatershed (8 km^2) compared with the entire study area (2100 km^2). The fact that the Thomas Brook subwatershed results are so similar to the Annapolis Valley results implies that the groundwater composition is not affected by localized, site-specific factors, such as variations in land usage, or by surface factors such as precipitation and runoff/infiltration. This is another confirmation that the Thomas Brook subwatershed is representative of the study area.

Groundwater oxygen and hydrogen stable isotopic compositions for the seasonal sampling trips to the Thomas Brook subwatershed appear to be very similar to those for the entire Annapolis Valley. For six sampling seasons of Thomas Brook groundwater, average $\delta^{18}O$ compositions (−10.5, −10.4, −9.9, −10.3, −10.4, −10.0‰ for summer 2004, winter 2004/2005, spring 2005, summer 2005, winter 2005, and spring 2006, respectively) and $\delta^{2}H$ compositions (−69, −69, −63, −67, −65, −64‰ for summer 2004, winter 2004/2005, spring 2005, summer 2005, winter 2005, and spring 2006, respectively) are nearly identical to those of the entire study area with the exception of winter 2004/2005 and spring 2005 sampling trips. For these two sampling trips, $\delta^{18}O$ values differ by up to 0.3‰, while $\delta^{2}H$ values vary by up to 5‰. These differences are slightly greater than those expected from analytical error. Seasonal plots for the year 2004–2005 are presented in Gauthier (2009). Graphs for the year 2005–2006 correspond to the seasonal graphs presented in Figure 69 (since samples in 2005–2006 were collected in the Thomas Brook subwatershed only).

Nitrate isotopes in the Thomas Brook subwatershed

The nitrate $\delta^{18}O$ values in the groundwater of the Thomas Brook subwatershed range from 1.0 to 9.3‰ and the $\delta^{15}N$ values range from 0.6 to 12.8‰, not including results for the surficial piezometers. A graph of N-NO_3 concentration versus $\delta^{15}N$ may be used to interpret whether or not microbial denitrification has occurred in the samples. This is important information required prior to the interpretation of the nitrogen sources, as denitrification can obscure the isotopic source signatures. If denitrification had occurred, then the data points of Figure 70 would have followed a curve in which exponentially higher $\delta^{15}N$ values occur at low N-NO_3 concentrations. Despite the high degree of data scatter in this N-NO_3 concentration versus $\delta^{15}N$ plot, and the small number of data points that limits the level of interpretation, it is evident that the data for the Thomas Brook subwatershed do not follow a denitrification curve. Therefore, denitrification does not seem to be a controlling factor for $\delta^{15}N$ values.

In Figure 71, these $\delta^{18}O$ and $\delta^{15}N$ isotopic compositions are compared with the isotopic domains of various known nitrate sources (Kendall and McDonnell, 1998). This figure presents typical ranges of various sources worldwide (thereby resulting in an overlap of values). These results show that nitrates likely derive from a mix of sources, mainly including naturally occurring soil zone plant residues (organic matter), NH_4 (ammonium) fertilizers, and manure and/or septic systems. Ammonium fertilizers would likely be the main source of nitrates in the surface water (Thomas Brook) samples. To refine the different boxes and avoid overlapping of sources, commonly used fertilizers and probable manures should be analyzed.

Water dating

Tritium and ^{14}C dating was performed on seven samples within the framework of the ACVAS project. Water was sampled in the North Mountain, Blomidon and Wolfville formations, as well as in the Meguma Group. Results generally confirmed the groundwater-flow pattern shown on the piezometric map. Water seems to be young in the North Mountain

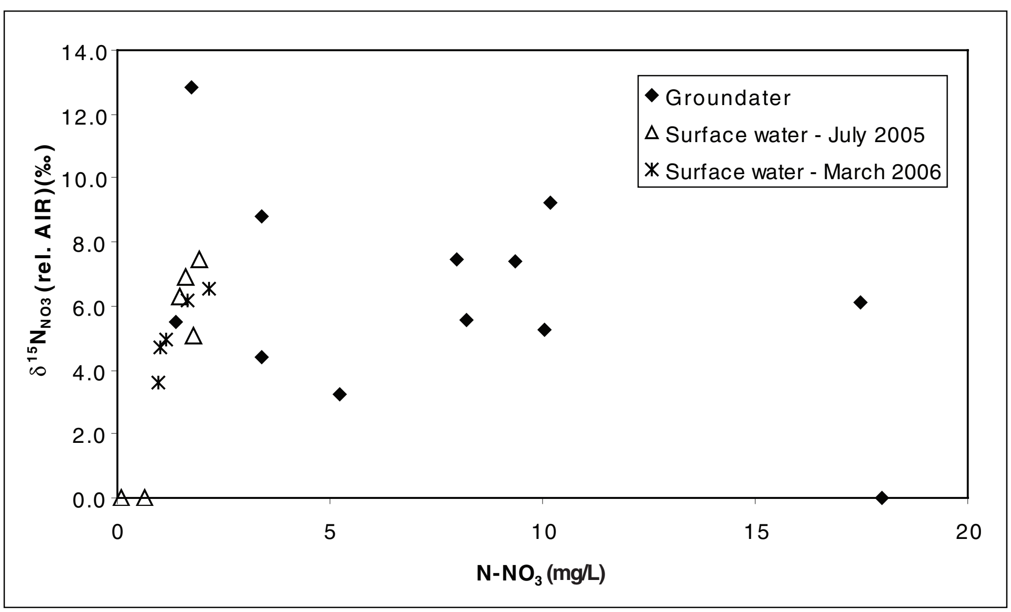


Figure 70. N-NO_3 concentration versus δ15N plot for groundwater (July 2005) and surface water (July 2005 and March 2006) samples.

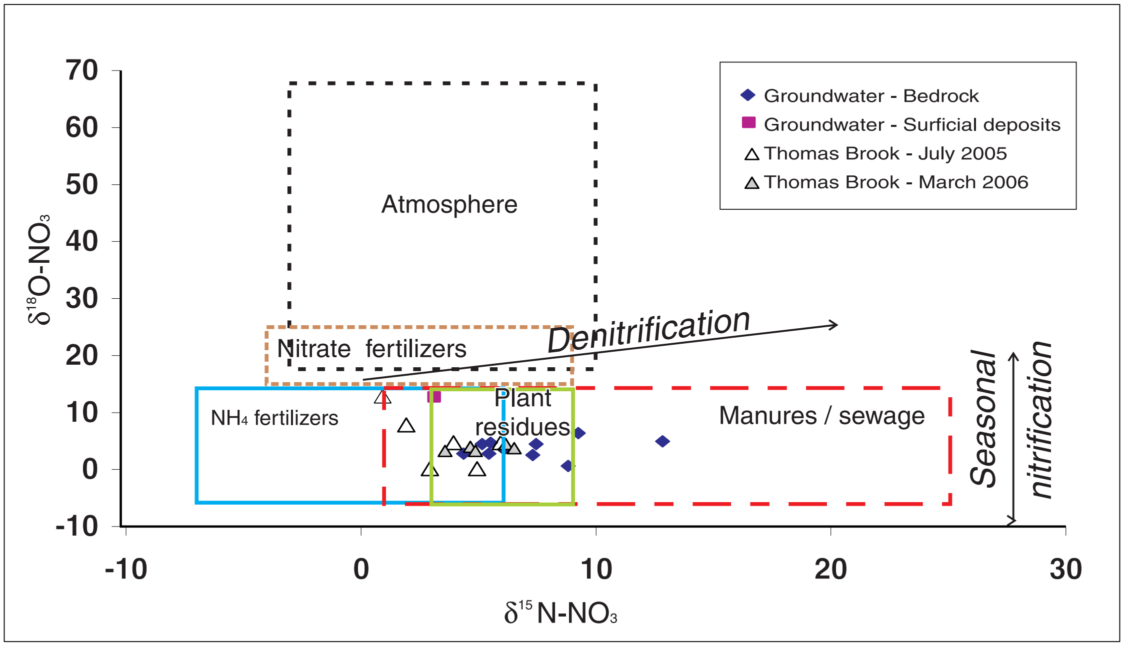


Figure 71. Nitrogen isotope results (*modified from* Kendall and McDonnell, 1998).

Table 33. Tritium values for different geological formations.

Well ID	X UTM	Y UTM	Formation	Well depth (m)	Tritium level (tritium units)	Age estimate
TB-Callow	360 551	4 995 327	North Mountain	48.8	5.8 ± 0.6	Recent*
Baiani	360 415	4 995 125	North Mountain	66.2	2.6 ± 0.5	Mix
Spring on road 360	361 418	4 995 072	North Mountain	-	6.2 ± 0.6	Recent
TB-Malcom	361 705	4 992 308	Blomidon	35.4	3.6 ± 0.5	Mix
Town of Granville Ferry	299 523	4 958 797	Blomidon	104	4.6 ± 0.6	Recent
TB-Parker Condon	362 295	4 990 883	Wolfville	36.6	<0.8 ± 0.4	Old (9000 a)
Walsh	365 379	4 985 964	Meguma Gr.	200.6	<0.8 ± 0.4	Old (6000 a)
MW-Wolfville 2**	392 093	4 993 838	Wolfville	17.7	4.7 ± 0.4	Recent
MW-Kentville**	385 726	4 987 649	Wolfville	17.1	3.8 ± 0.3	Mix
MW-Annapolis Royal**	303 028	4 952 587	Granites	56.7	0.27 ± 0.17	Old
MW-Greenwood**	359 530	4 984 959	Sand & gravel	7.6	5.76 ± 0.47	Recent

* Recent is >1952.
** MW: monitoring well

basalts, 'mixed' in the Blomidon and old (pre-1952) in the Wolfville Formation (Table 33), suggesting that groundwater typically flows from the North Mountains down to the main rivers in the centre of the valley over the long-term. Four additional values obtained from NSE for provincial monitoring wells show that shallow wells in the Wolfville Formation could contain recent or mix water. Deep wells (>50 m) in the granites or Meguma Group slates contained old waters. Nevertheless, shallow wells could probably contain more recent water. The sand and gravel well in Greenwood shows, of course, a recent water. Carbon 14 analyses provided approximate ages for the TB-Parker Condon well (Wolfville Formation) and the Walsh well (Meguma slates) of 9000 and 6000 years, respectively.

CONCEPTUAL AND NUMERICAL MODELS

Conceptual model

A three-scale conceptual model including regional, local, and point scales can be used to schematically describe aquifers of the Annapolis Valley, similar to the one developed for the Maritimes Basin (Rivard et al., 2008). This three-scale model is illustrated in Figure 72 and summarized in Table 34. The two most important aquifer formations of the valley (i.e. the Wolfville and Blomidon formations), comprise layers of sandstone, conglomerate, siltstone,

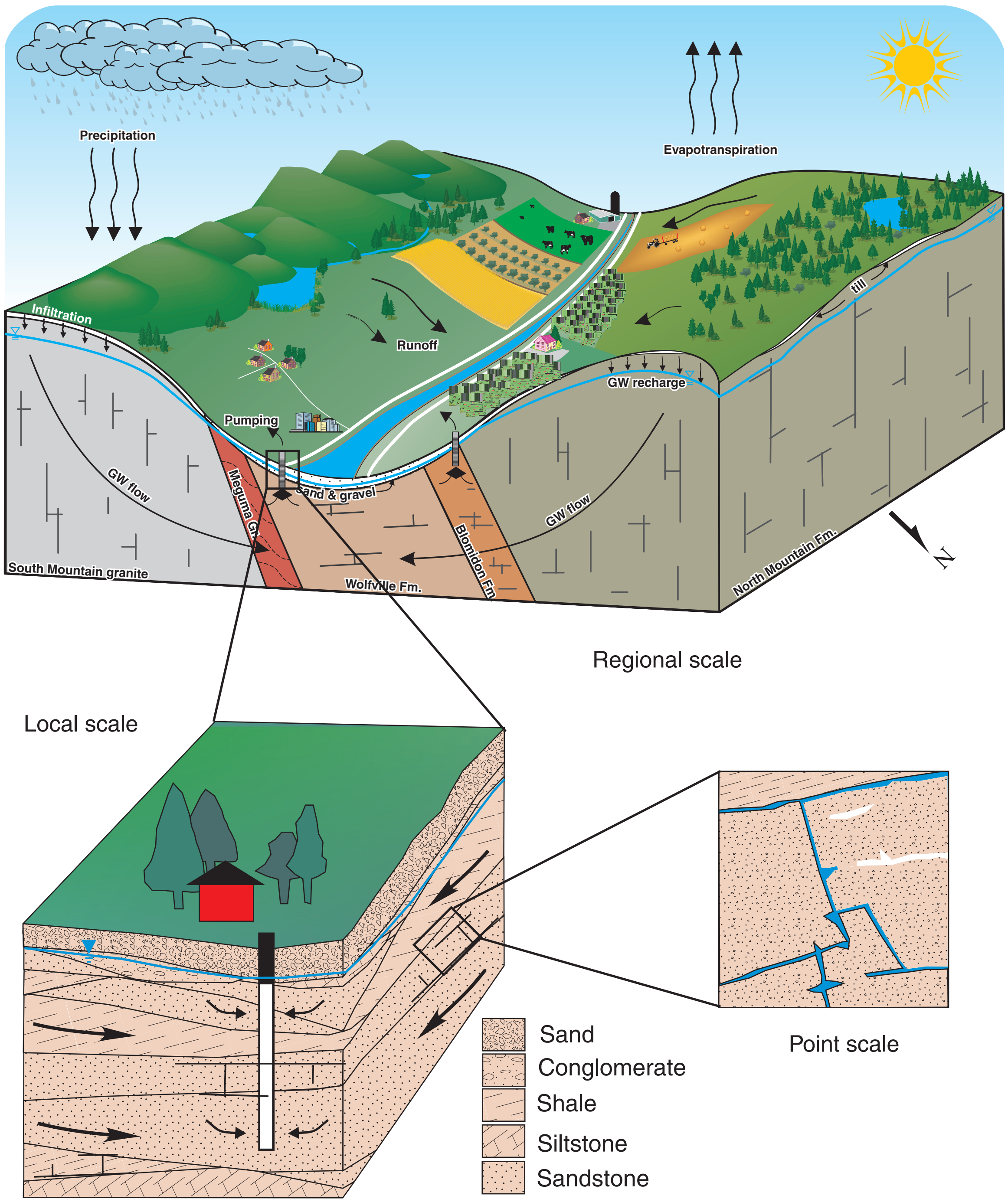


Figure 72. Conceptual model for the sedimentary aquifers of the valley: regional (2100 km²), local (≈1 km²), and point (≈1 m²) scales.

and shale in different proportions that form a discontinuous and layered aquifer/aquitard sequence. At the regional scale, these lenticular bodies of rocks cannot be taken into account individually, although more detailed sedimentological data could, in future, allow a more refined model. Thus, each formation is considered as only one hydrostratigraphic unit with uniform properties, as shown on Figure 72. The surficial-deposit layer contains various units, but these are 'homogeneously' defined over the entire sediment-layer depth, due to a lack of accurate information on the internal stratigraphy and sedimentology. Folds and faults are not represented in this model as they are currently poorly known. Sediment thickness varies on average from 0 to 30 m, but thicker deposits (>15 m) can only be found in the eastern part of the valley floor. Preferential groundwater-recharge occurs in flat areas through sandy units and where the bedrock is permeable or highly fractured. Bedrock aquifers are often confined, mainly depending on the bedrock composition, layering, and fracturing.

The local scale illustrated on Figure 72 corresponds to the area being influenced by a pumping test, and is on the order of a few km^2. At the local scale, the layering and fracturing of the heterogeneous bedrock aquifers can strongly influence the hydraulic behaviour. The sketch in Figure 72 depicts a hypothetical cyclic sequence of the common sedimentary rock types encountered in the region, representative of the near-surface stratigraphy in the Wolfville Formation. The mean percentage of each rock unit and layer thickness

Table 34. Summary of characteristics for each conceptual model scale.

Regional scale (characterization of the entire study area, 2100 km^2)
• Sediment thickness varies on average from 0 to 30 m, but thicker deposits (>15 m) can only be found in the eastern part of the valley floor. • Preferential groundwater (GW) recharge occurs over the Wolfville Formation, where the topography is flat and especially where sandy surficial units are encountered, and over the North Mountain basalts, where vertical fracturing is well developed. • Bedrock aquifers are often confined, mainly depending on the bedrock composition, layering, and fracturing. • GW recharge rates vary from 73 to 435 mm/a with a weighted average of 120–224 mm/a over the study area when using a correction factor of 10 to 52% for artesian/confined conditions. • Lenticular beds are not considered individually in this version of the model. Therefore, each hydrostratigraphic unit is considered homogeneous over the model depth using mean pump test-values. • Formations are generally gently dipping towards the Bay of Fundy (~.4-12°). • GW depth is on average 6.1 m, but varies from 0 to more than 30 m. • Bedrock groundwater flow (of the upper 200 m) generally follows the topography (water flowing from the mountains towards the center of the valley). • At depths of 1 km or more, groundwater likely flows parallel to the formation dips towards the Bay of Fundy.
Local scale (hydraulic behaviour as observed during pumping tests, ≈ 1 km^2)
• Based on pumping tests, all units seem to behave as equivalent porous media, likely because fractures are well interconnected (at least in the area of the tested well). • Aquifer condition often depends on the presence or absence of overlying fine-grained bedrock strata or fracturing. • Layered media (Wolfville and Blomidon Fms) lead to an aquifer/aquitard sequence. • Formations can locally be very heterogeneous and anisotropic due to the lenticular beds and/or fracturing. • Each hydrostratigraphic unit has its own characteristic structural and hydrogeological properties. • Groundwater circulates mainly through fractures.
Point scale (scale of borehole, ≈ 1 m^2)
• Fractured porous media for Wolfville and Blomidon formations; • Mean total-matrix porosities of 28% and 8% for the Wolfville and Blomidon formations respectively. • Fractured media for North Mountain Fm, South Mountain granites, and Meguma Group (slates). • For Wolfville and Blomidon formations: fractures and bedding planes are mainly sub-horizontal with a gentle dip towards the Bay of Fundy, in agreement with formations' dips. • In the North and South mountains: fractures are mainly subvertical and are generally poorly interconnected horizontally, except for some areas (with higher yields). • Fractures usually have a northeastern strike (aligned with the valley axis). • Groundwater flow through fractures is erratic.

varies between the Wolfville and Blomidon, and is also variable within each formation. The other formations or groups of the study area (North Mountain Formation, South Mountain granites, and Meguma Group slates) do not have this type of layering. Hence, heterogeneity mainly comes from fracturing. All units can therefore be locally very heterogeneous and anisotropic due to these discontinuities and the fracturing, but seem to behave as equivalent porous media, according to the interpretation of pumping test data, likely because fractures are well interconnected (at least in the area of the tested wells).

Finally, the point scale of Figure 72 presents the aquifer-material heterogeneity with plausible fracture patterns and matrix characteristics of the Wolfville Formation. The Wolfville and Blomidon Formations are porous fractured media, with total matrix porosities ranging between 0 and 40%, with means of 28% and 8%, respectively. Their fractures and bedding planes are generally subhorizontal, shallowly dipping toward the Bay of Fundy, in agreement with formation dips. In contrast, numerous vertical (steeply dipping) fractures were observed in wells drilled into the North Mountain basalts, South Mountain granites, and Meguma Group slates of North and South Mountains, and very few subhorizontal fractures were observed, limiting the fracture interconnectivity and thus the flow circulation. These units belong to fractured media, their primary porosity being insignificant. In all formations or Groups, fractures usually strike parallel to the valley axis.

Numerical model

General characteristics

The regional numerical model was constructed with the finite-element software FEFLOW (Diersch, 1998), based on the geological 3-D model. The latter was developed using the topographic map and constrained using borehole data and outcrops from the most reliable data available (*see* the 'Three-dimensional geological model' section). Similar to the regional-scale conceptual model, lenticular bodies of rocks cannot be taken into account individually at this scale. Each geological formation or group has been assigned homogeneous, though sometimes anisotropic, properties (*see* below). Surficial sediments have been grouped into five categories (units) based on the Quaternary map classification: coarse, medium, fine, continuous till cover (Tb) and discontinuous till cover including bare rock (Tv). Each unit has been considered homogeneous over the entire sediment thickness layer. This model was run in steady state using saturated conditions. The model thus represents a simplified representation of the bedrock and surficial deposits of the Annapolis Valley hydrogeological system.

The model contains eight layers, corresponding to the six formations and groups shown in the geological model (Fig. 22), a Quaternary sediment layer on top, and a base at 1200 m. FEFLOW requires that each layer be continuous throughout the model. Therefore, where the layer is inexistent (for example, the North Mountain and Blomidon formations over the Wolfville formation), the layer is assigned a minimum thickness of 10 cm, and hydraulic property values of the 'real' geological unit are assigned (in this example: values of the Wolfville formation). Figure 73 illustrates schematically the model construction. The model base was assigned relatively deep, following results of another project in the Maritimes that studied similar rocks (Rivard et al., 2008). The latter project showed that even if most of the water circulates in the upper 200 m, neglecting the lower part (600–800 m) had a significant impact on hydraulic heads. Each layer has approximately 10 000 nodes. The mesh was refined in the northern part of the model, including the North Mountain basalts, in the narrow Blomidon Formation band (flanks), and on the valley floor (Wolfville Formation) where major rivers flow.

Boundary conditions

No flow-boundary conditions (Q = 0) were imposed at all faces of the 3-D model. These limits correspond to water divides delineating the external side of the five watersheds (i.e. the study area, *see* Figure 1). Indeed, the potentiometric map drawn using measured water levels indicated that the study area delineation could correspond to a subsurface watershed. Major rivers (five, one in each watershed) and tributaries (17 in the Annapolis watershed, of which only two extend beyond the Wolfville Formation, and one in the Cornwallis watershed) within these watersheds were also

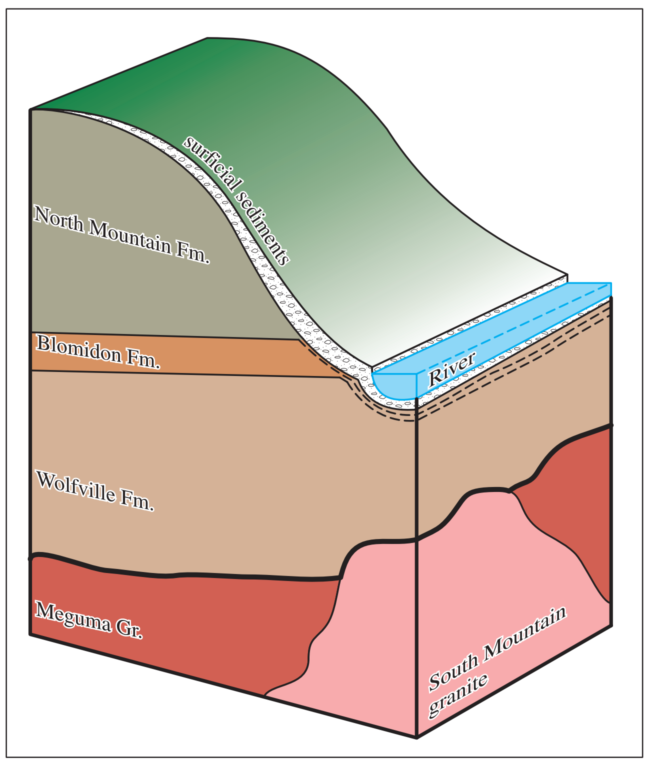


Figure 73. Sketch of the model construction.

Table 35. Comparison between modelled and measured hydraulic conductivities.

Unit, formation or group		$K_{measured}$* (m/s)	$K_{x\ modeled}$ (m/s)	Modeled anisotropy
Sediments	Fine	[1]5.0×10^{-7} - [2]5.6×10^{-7}	10^{-7}	-
	Medium	[2]2.8×10^{-6} - [1]1.0×10^{-5}	10^{-5}	-
	Coarse	[1]3.1×10^{-5} – [3]1.3×10^{-3}	10^{-4}	-
	Tb	[2]2.8×10^{-6} - [1]3.3×10^{-6}	10^{-6}	-
	Tv	[2]2.8×10^{-6} - [1]3.3×10^{-6}	5×10^{-6}	-
1. North Mountain Formation (basalts)		5.2×10^{-7}	10^{-7}	$K_z = K_x$ *100
2. Blomidon Formation		2.8×10^{-6}	10^{-6}	$K_z = K_x$ /1000
3. Wolfville Formation		6.2×10^{-6}	10^{-5}	$K_z = K_x$ /100
4. Horton Group		-	5×10^{-7}	$K_z = K_x$
5. South Mountain granites		1.6×10^{-6}	5×10^{-7}	$K_z = K_x$
6. Meguma Group (mainly slates)		6.8×10^{-7}	2×10^{-7}	$K_z = K_x$

*Obtained from permeameter testing[1], grain-size analysis from Soil Landscapes of Canada (2005)[2], and pumping tests[3]
Tb: till
Tv: discontinuous till

imposed using Dirichlet (constant head) conditions. Indeed, the stream network is very well developed in the study area (see for instance plates of the atlas).

A drain was imposed at the foot of North Mountain to mimic the seepage face, as the steep slope of the cuesta is known for its numerous springs all along the valley. To accomplish this, a constant head boundary with a constraint condition of maximum flux set at 0 (to avoid discharge of the drain into the aquifer) was imposed in the Blomidon formation.

Hydraulic properties and recharge rates

Assignment of hydraulic conductivities for the five surficial sediment units of the first layer was based on permeameter test results, data from the Nova Scotia Department of Agriculture (including grain-size analyses), results of the pumping test data available for the sand and gravel units and professional judgment (Table 35). Values are relatively high, since most units contain sand, and even fine sediments seem to allow water to infiltrate, due to the fact that they are usually thin and likely contain cracks, from which preferential channels develop.

Hydraulic conductivity (K) values for the bedrock were assigned based on pumping, packers, and slug-test results, as well as professional judgment. Hydraulic tests are biased since only 'promising' wells are tested. In addition, very few well results are available for formations other than the Wolfville in the provincial database. Therefore, slightly lower values than those derived from the pumping test results were assigned to the North Mountain and Blomidon formations. Conversely, a value higher than the mean value of pump tests was assigned to the Wolfville Formation, based on packer and slug tests, borehole geophysics, and pumping-test results performed in screened wells. Because of their small importance, formations of the Annapolis Supergroup (Torbrook, White Rock, New Canaan, and Kentville) were included in the Meguma Group, based on their composition and low permeability. Due to the layer continuity constraint, the K value of the appropriate formation was assigned where a geological formation was absent (for instance, where the North Mountain Formation is absent, K values of the Blomidon, Wolfville, granite, etc. were assigned).

Only rock formations of the Fundy Group (North Mountain, Blomidon and Wolfville) were assigned anisotropic values (*see* Table 35). For the North Mountain Formation, $K_z = K_x$ *100 ratio was assigned since vertical fractures are abundant, while horizontal-fracture connectivity is poorly developed. Conversely, for the Wolfville and Blomidon formations, lower K_z values were assigned. In the Blomidon Formation, a ratio of $K_z = K_x$ /1000 was used, as numerous, laterally extensive and sometimes thick impermeable strata are present. For the Wolfville Formation, the assigned ratio was $K_z = K_x$ /100 since fine-grained layers are less frequent and usually less thick. It is believed that anisotropic factors estimated using packer tests for the Blomidon and Wolfville formations (7 to 39, *see* the 'Packer tests (multi-level slug tests)' section) are not really representative of these formations, as mainly sandstones were found in these wells.

For recharge rates (W), values based on previous estimates had first been assigned. However, mean estimated values led to overestimated hydraulic heads. Other runs were thus performed using smaller values of W for the fine and Tb units. Values of recharge assigned to the finer units (i.e. fine and Tb) appear to be in the lower part of the defined range based on the corrected water balance method, while for the coarse unit, the assigned value is closer to the maximum limit. A higher value was assigned to the discontinuous (thin) till cover over the North Mountain basalts, since infiltration is facilitated through the numerous vertical fractures (as compared to the South Mountain batholith) and the till is usually quite thin or nonexistent.

Table 36 presents the comparison between recharge values obtained using the corrected water-balance method and values assigned in the model as a function of the simplified Quaternary map classification. Of note are the anomalous values for the fine- and coarse-grained units that should be lower and higher than the medium values, respectively. This is not too surprising, considering drawbacks and limitations of each method. Indeed, values obtained using the water-balance method were estimated using a different classification, based on the Nova Scotia Department of Agriculture map. Moreover, the water-balance method does not take into account the underlying bedrock properties. For instance, recharge in the sandy tills overlying South Mountain granites was estimated to be high. As discussed in the 'Groundwater recharge' section, weighted averages for the entire study area

Table 36. Comparison between modelled and estimated recharge rate values.

Sediment unit	$W_{calculated}$ * (mm/a) min / mean / max	Mean $W_{modeled}$ (mm/a)
Fine	35 / 148–277 / 387	30
Medium	35 / 132–247 / 387	250
Coarse	35 / 127–237 / 387	350
Tb (till)	35 / 119–223 / 392	75
Tv (discontinous till)	35 / 103–194 / 392	100 / 200**

* Recharge rates calculated using the corrected water-balance method (using plausible percentages of artesian/confined conditions). Min and max values correspond to different cells in the area, corrected for the 'worst' scenario.

** Recharge rate over the North Mountain basalts

should be considered, rather than individual unit values in this case. These values were added to this table for comparison purposes only.

In addition, the thinness of surficial sediments covering most of the study area combined with the poor coverage of thickness data often resulted in almost no till cover at all when interpolated in FEFLOW. This is especially evident on the South Mountain, which represents nearly half of the area. This first layer was thus unable to allow infiltration that could either permit subsequent recharge to bedrock or subsurface runoff (hypodermic flow). Therefore, recharge rates assigned in the model over these less permeable units and hence, the weighted average over the entire study area, would likely be more representative of minimum recharge to bedrock.

Results

Hydraulic conductivity and recharge values assigned in the final model (summarized in Tables 35 and 36) were calibrated using the potentiometric map obtained from water-level measurements. The K values are usually quite close to the average values obtained from average pumping test results. As mentioned above, slightly lower or higher values than the mean pumping test results were sometimes assigned, but values were always within the range of values obtained from pump test results (*see* Figure 51 and Table 23, 'Hydrogeological context' section).

All recharge rates imposed over the study area also lie within the range of values previously estimated. The weighted averages over the entire modelled domain correspond to 120 to 224 mm/a for the corrected water-balance method (using 48 and 90% of areas where recharge is possible) and 115 mm/a with the model (Table 37). Over the valley floor (Wolfville Formation), the corrected water-balance method provides a range of 64 to 225 mm/a on average, whereas 160 mm/a was obtained with the calibrated model. The fact that the simulated recharge (115 mm/a) lies in the lower range of the water-balance values, or is notably smaller than what was obtained using the hydrograph separation method, likely suggests that infiltrated water circulates quite well in surficial sediments (or first few metres of bedrock) and that only about 50% of this amount in certain areas reaches the bedrock. This result would thus corroborate the percentage of confined wells estimated using high-precision technology tools (*see* 'Data from fieldwork' section) and is in agreement with the well developed stream network that can be observed across the entire study area (although that cannot be represented in the regional model).

Table 37. Recharge rate summary for the entire study area.

Method	Mean recharge rates (mm/a)
Stream hydrograph separation	360
Water balance	249
Corrected water balance	120–224
Modelling	115

The need to use significantly lower values of recharge in the numerical model could also indicate that the previously used methods tend to overestimate recharge rates. For instance, the water balance method could have underestimated runoff (using the SCS method), thereby overestimating infiltration. This bias is however difficult to evaluate.

The simulated potentiometric map is presented in Figure 74. It clearly shows that major features such as maximum hydraulic heads on the North and South mountains and lower values on the valley floor are well represented, but that local features cannot be represented at this scale. For instance, the drain at the foot of North Mountain seems to have an overpowering impact on the hydraulic heads of the North Mountain flanks. Indeed, springs are discontinuous features that could not be represented otherwise. In addition, very few measurement points were available on South Mountain and thus the validation cannot really be made in these areas. Velocity fields (including both horizontal and vertical components) provided by FEFLOW show that values in surficial units generally vary from 5×10^{-9} to 10^{-7} m/s over both mountains and between 10^{-7} and 5×10^{-6} m/s over the valley floor.

First, two hundred and thirty four (234) points were randomly selected for the comparison between the modelled potentiometric map (corresponding to approximately 1 out of every 40 node points available from the model) and the map obtained with the interpolation of water level measurements (*see* Fig. 52). Figure 75 demonstrates that the linear-regression line is very close to the 45° line, with a good coefficient of determination ($R^2 = 0.87$) despite the point scatter. The mean error was found to be 1.9 m. This means that there is no tendency for the model to systematically over- or underestimate the potentiometric surface over the study area.

The points further from the 45° line in Figure 75 often correspond to points located on both sides of the valley floor, i.e. on the mountain flanks, where the slopes are largest (large differences in hydraulic heads within a few hundred

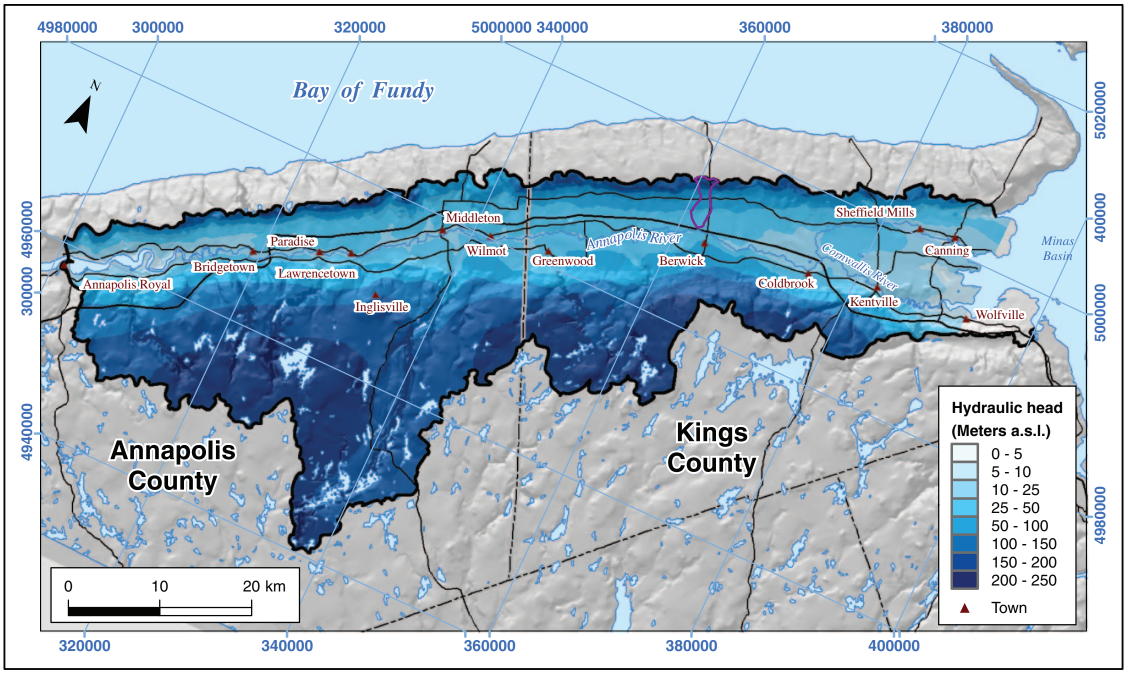


Figure 74. Modelled potentiometric map.

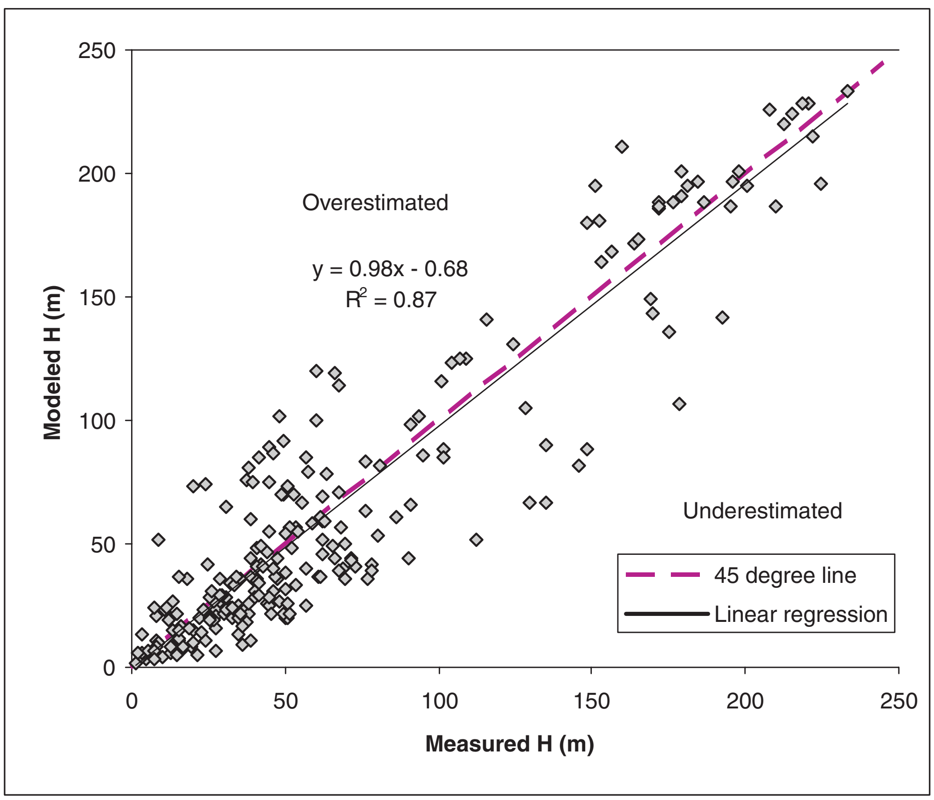


Figure 75. Observed versus simulated heads. The dashed line is the theoretical perfect fit presented for reference. The full line is the linear regression whose equation and R^2 are indicated on the graph. Labels indicate if simulated heads 'overestimate' or 'underestimate' observations.

metres) and in the North and South mountains. Indeed, there are very few water-level measurements available over North and especially South mountains, and therefore the interpolation in these regions is not very reliable. The mean absolute error on these 234 points is 16.9 m (the median value being 12.2 m) and the root mean square error (RMSE) is 23 m, within the model calibration target that was set at 25 m (about 10% of the range in hydraulic heads in the study area). In addition, the model was validated using 245 point measurements randomly selected (approximately 1 out of 6) for the comparison between the model results and the measurements. Again, a good coefficient of determination ($R^2 = 0.87$) was obtained (not shown), although the mean error between measured and simulated values is –6.1 m, slightly above the DEM accuracy (≈5 m). The RMSE is similar (22 m). However, this model is only a simplified representation of the regional hydrogeological system (2100 km^2) and was intended to confirm ranges of recharge and hydraulic conductivity previously found. Thus, no additional calibration of heads was carried out.

In addition, a validation was performed using gauging station 01DC005 (comprising a subwatershed of 546 km^2) located on the Annapolis River near Wilmot (close to Middleton), in the Annapolis watershed. An approximate polygon was drawn in FEFLOW to represent the subwatershed for which the gauging station provided river flows. Based on the Chapman filter, this station provides a mean annual baseflow (groundwater contribution) value of 4.5 m^3/s over five years. The FEFLOW model provided a value of 2.2 m^3/s at the exit of the defined polygon. This is quite reasonable, since about half the infiltration amount estimated using hydrograph separation was assigned to the model. Indeed, even if surficial deposits are represented in the model, the ramified (dense) network of streams present all over the study area could not be incorporated in this regional model. As a result, the assigned values were closer to an actual bedrock-aquifer recharge than to the infiltration amount as mentioned above.

It would be interesting in a further study to revisit the 'no-flow' northern boundary of the study area in light of the north-dipping orientation of the three main geological formations. This could conceivably lead to flow patterns toward the Bay of Fundy, i.e. in a direction opposite to that determined by the topographic gradients at depths (500 m? 1 km?), but also across the North Mountain basalts away from the cuesta. Indeed, the effect of extensional stresses dissipates away from the cliff (*see* Morin et al., 2006), and one could expect either or both sets of conjugate fractures of this formation to be permeable (but to a lesser degree than those near the edge of the cliff, *see* the 'Borehole geophysics' section). Acquisition of any data supporting (or contradicting) such a hypothesis would also need to be undertaken.

DISCUSSION AND CONCLUSIONS

The Annapolis Valley lies within the Mesozoic Fundy Basin and is predominantly underlain by Triassic sedimentary rocks of the Blomidon and Wolfville formations. The valley is bounded on the northern side by the scarp of North Mountain, essentially composed of Triassic basalts, and on the southern side by the interior Paleozoic highlands of South Mountain, which are composed mainly of granitic rocks. The Annapolis Valley has been eroded through friable Triassic sandstones, conglomerates, shales, and siltstones of variable proportions.

With the rapid economic development of the Annapolis Valley, water allocation and water-quality maintenance are posing challenges to municipal and provincial authorities. Since surface-water supplies within the valley are becoming insufficient, groundwater has become the major source of water supply. The objective of the ACVAS project was therefore to improve the understanding of the hydrostratigraphy and the groundwater dynamics of the Annapolis Valley. Existing data were structured into databases and analyzed, and fieldwork was performed, in an effort to provide data to support the protection and management of the groundwater resources of the Annapolis Valley.

The most important aquifers are found within the Triassic bedrock, especially the Wolfville Formation, which covers almost all the valley floor. Based on previous literature, the Wolfville was expected to contribute significantly to the aquifer potential of the valley, and this implication was confirmed by data collected in this study. It comprises a thick succession of mainly thick-bedded medium- to coarse-grained sandstone, with subordinate conglomerate, and minor siltstone and shale. Unexpectedly good aquifer potential can also be found in the Blomidon Formation, which forms the flank of North Mountain and underlies the basalts. It comprises similar lithologies to the Wolfville Formation, though more common and laterally extensive fine-grained strata have been reported. However, this study has shown that the Blomidon Formation present in the Annapolis Valley is likely coarser grained and has therefore probably a better aquifer potential than literature implied. This may be explained by the fact that the Blomidon strata of the study area lay closer to their sediment source and represent the southern tip of the Fundy sedimentary wedge, which is overall fining up-section and laterally basin-ward (towards the north). On the other hand, the well-log database could be biased for this formation since probably only wells with coarser-grained strata (possibly more productive) are reported by drillers. Regional-scale groundwater circulation through these Triassic sedimentary formations is likely non-uniform due to regional dip, fracturing, lateral discontinuity of subunits, and aquifer/aquitard layering. Therefore their aquifer potential can vary over short distances, both stratigraphically and geographically. The interbedded siltstone and mudstone strata may commonly act as local confining layers. Although these complex bedrock units constitute the most important aquifer systems in the valley, their groundwater potential is still poorly known from a stratigraphic/sedimentological point of view, especially for the Blomidon Formation. Good yields can also be developed in other geological units, for instance in the North Mountain basalts and South Mountain granites, but on a local basis only, mostly depending on fracture interconnectivity.

Quaternary sediments do not usually correspond to good aquifers, except in the eastern part of the Annapolis Valley. They are composed mainly of glacial till, whose composition reflects the underlying bedrock, and are quite thin. Thicker sandier deposits have been, or are currently being, used by some municipalities in the eastern half of the valley. Nevertheless, all surficial deposits play a major role in the aquifer recharge throughout the valley, because they influence both the quantity and quality of the bedrock groundwater. Therefore, the need for a new surficial geology map of the valley was addressed within the framework of this project, leading to the development of a 1:100 000-scale map (Paradis et al., 2006).

Preferential recharge occurs through vertical fractures within the highland basalts of North Mountain and through sandy tills and sand and gravel units, predominantly overlying the permeable Wolfville Formation, over the flat valley-bottom areas. The potential recharge (infiltration) estimated using hydrograph separation and the water-balance method often seems to largely overestimate the recharge to bedrock, especially over low-permeability rocks and in slopes where subsurface runoff is large. Once corrected using reasonable percentages of confined areas (indicating percentage of areas where recharge is impossible), the weighted average obtained with the water-balance method ranged from 120 to 224 mm/a. The well developed hydrographic (drainage) network, modelling, and comparisons of water elevations between groundwater and nearby streams all suggest that a large portion (up to 50%) of the infiltrated water would not reach bedrock aquifers. It would rather circulate as hypodermic flow into sediments (and sometimes into the first few metres of bedrock). The 3-D numerical model developed using steady-state conditions indicated that overall recharge to bedrock would be on the order of 115 mm/a for the study area, close to the lower value of the range previously found.

The bedrock potentiometric map obtained using water-level measurements confirmed that the regional groundwater flow is mostly controlled by the topography, flowing from the North and South mountains toward the major rivers in the centre of the valley. Comparison with the potentiometric map obtained from modelling was quite satisfactory, since major characteristics were well reproduced. The modelling exercise was also useful since it validated the regional conceptual understanding of the hydrogeological system, and confirmed the importance of the seepage face along the foot of North Mountain. A potentiometric map of the surficial deposits could not be drawn since not enough data were available. Nevertheless, nitrate concentrations reported in several bedrock wells and in streams provided evidence of a hydraulic connection (between groundwater flowing within surficial deposits and bedrock, and surface-water resources) in many areas. Groundwater/surface water (GW/SW) interactions in the Thomas Brook sub-watershed were investigated in a M.Sc. thesis (Gauthier, 2009).

Groundwater within the Annapolis Valley is generally abundant and of good quality. Good hydraulic conductivities (K) on the order of 10^{-7}-$5x10^{-5}$ m/s can be found in many areas, and geochemistry data showed that over 85% of wells typically show concentrations of major and minor ions (except for manganese), nitrates, metals, and other parameters below the Health Canada guidelines for drinking water. Manganese is not considered a health issue since the recommended limit is based on aesthetic criteria. Nitrate levels are of more concern, since the 10 mg/L drinking water guideline is exceeded in almost 15% of the randomly tested wells, and that the 1 mg/L background concentration (above which anthropogenic activities are believed to affect the resource) appears to be exceeded in 65% of the cases. Geochemical analyses carried out within the representative Thomas Brook subwatershed during the ACVAS project confirmed these percentages (Trépanier, 2008). Saline intrusion does not seem to be a problem in this region, despite the valley being bordered by saltwater basins.

Bedrock aquifers of the Annapolis Valley were found to react similarly to an equivalent porous medium when pumped, likely due to the presence of a well developed fracture network. Indeed, pump tests usually showed a behaviour similar to Theis-type curves. Borehole geophysics confirmed that the predominant fracture set within the Blomidon and Wolfville formations is composed mainly of subhorizontal fractures and that bedding planes have a gentle dip of 4 to 12° toward the Bay of Fundy. Conversely, the numerous fractures of the North Mountain basalts are mostly sub-vertical and define two conjugate fracture sets that are not very well connected horizontally. Some of the water infiltrated through these basalts discharges as springs along the foot of North Mountain. All fractures appear to have a main strike northeast, aligned with the valley axis. No evidence of a significant decrease in hydraulic conductivity with depth was found in the valley, unlike what was reported in other parts of the Maritimes having similar rock types (Rivard et al., 2008).

Aquifers of the valley are vulnerable to over-exploitation and to surface pollution from agricultural activities (especially nitrates). Within the framework of this study, the commonly used DRASTIC method was utilized to map trends of relative vulnerability for both bedrock and surficial aquifers (Blackmore, 2006). DRASTIC is widely recognized as a relative vulnerability evaluation tool that generates qualitative results from generic input parameters. Groundwater-vulnerability results varied according to, and within, each hydrostratigraphic unit, although overall surficial hydrostratigraphic units appeared to be more vulnerable than bedrock units. As expected, the Wolfville Formation for the bedrock and glaciofluvial deposits (i.e. sand and gravel units) for surficial units, both being potentially productive aquifers, were also found to be the units having the highest vulnerability to potential contamination. Elevated values of permeability and recharge, a flat topography, and higher point-data density resulted in an increase of the vulnerability. These areas also correspond to the more populated regions and thus are areas where risk of surface contamination is highest. Because considerable variation in results was obtained depending on the parameter values used, the level of confidence of these results was studied using multiple scenario sensitivity analysis. Given the resolution of the data acquired for the model, the results for relative vulnerability are considered acceptable on a regional scale.

Historical water levels did not indicate any significant statistical trends in seven out of eight monitoring wells when using annual values, but six of the wells had been abandoned in the 1990s. However, two wells showed a decreasing trend when the single month of August (representing the worst low-water level conditions, with little rain and at the end of the harvest season) was used for the analysis. The only gauging station still active in the 2000s (and for which more than 20 years of data were available) showed a significant decreasing trend when using annual baseflow values. The monitoring of groundwater levels is thus crucial in future years, since aquifer recharge ensures supply to the majority of the population and will likely play an increasing role in irrigation supplies in the near future.

Aquifers of the Annapolis Valley do not appear to be overexploited on a regional basis. However, local conflicts are likely to occur, especially in the more populated and intensely farmed areas (such as in the Canard and Habitant watersheds). The uncertainty related to the estimation of recharge rates, and especially of groundwater usage, has allowed us to obtain only a wide range for the water budget. Based on several assumptions, the groundwater use would represent 5.7% of the precipitation and 11% of the bedrock recharge on average, but could certainly reach 50% of the bedrock recharge in some areas. Since an accurate estimate of groundwater use in the valley represents key information for management programs, the Provincial Government and the Nova Scotia Federation of Agriculture collaborated to carry out a groundwater-use survey in 2008–2009. The survey was completed by a consultant (CBCL Limited, 2009) and was funded by the Canada–Nova Scotia Water Supply Expansion Program, with matching support from the Provincial Government.

The results of this regional hydrogeological study are expected to be valuable to the agricultural industry and to all residents of the valley by providing baseline information to develop, manage, and protect long-term water supplies. This study has resulted in the development of hydrogeological and geochemical databases, and has increased the understanding of aquifers of the Annapolis Valley by providing information on stratigraphy and thickness of surficial deposits, characteristics of fractures and hydraulic properties for each geological formation, a mean annual hydrological budget with recharge rates, a potentiometric map, conceptual and numerical models for this region, and a new Quaternary map explaining the surficial-sediment deposition history. In addition, a highly colourful and graphical atlas (Rivard et al., 2007) presenting the main results and available data was developed to provide a quick picture of hydrological, geological, and hydrogeological conditions in the valley. Three M.Sc. theses were also carried out within the framework of the ACVAS project in order to address different issues: aquifer vulnerability, groundwater / surface water interactions, and nitrate contamination.

In order to build on the accomplished work, the next phase of this project could include 1) an M.Sc. thesis focusing on the improvement of the numerical model, including pumping based on the results of the groundwater use survey, and 2) another M.Sc. thesis devoted to the understanding of the detailed internal stratigraphy and sedimentology of the Wolfville and Blomidon formations because they represent the most important aquifer units. Both outcrop and subsurface studies of these two geological formations will provide the best avenue to better understand the regional aquifer potential in the valley. Finally, this report strongly recommends that:

1) a better knowledge of actual monitoring wells' stratigraphy and construction be acquired,
2) continued support for monitoring programs be provided for groundwater levels and for annual testing of nitrates in wells that have shown elevated values or are in areas considered most at risk, for the expansion of the existing networks, and for regular reporting.
3) a high priority should be placed on collecting groundwater-use information, including installation of flow meters and reporting requirements for all large groundwater users;
4) a well tagging system be implemented, which would allow more accurate groundwater information to be collected. This would ensure that well location, chemistry result and pumping test information is properly tracked with greater confidence.

Main findings of this characterization study could be summarized as follows:

- Major aquifers of the Annapolis Valley are found within bedrock, mainly in the Wolfville formation, composed predominantly of sandstone.
- The layering of fine-grained (shale and siltstone) and coarse-grained (sandstone and conglomerate) strata of the Wolfville and Blomidon formations lead to an aquifer/aquitard sequence.
- The Blomidon Formation in the Annapolis Valley would likely contain much more sandstone than what has been reported in many publications (at least within the upper 100–200 m). Its aquifer potential should thus probably be revised upwards.

- The North Mountain Formation is composed of basalts and contains mostly subvertical fractures; therefore, its aquifer potential is reduced. Nevertheless, good yields can be found on a local basis and particularly near the cliff face, where gravity-induced stresses lead to an enhanced opening of fractures.
- Bedrock aquifers are often under confined conditions.
- Good sand and gravel aquifers can be found in the eastern part of the valley.
- Mean hydraulic conductivities from 10^{-7} to 5×10^{-5} m/s for bedrock and 10^{-3} m/s for sand and gravel aquifers were estimated based on pumping-test results.
- Surficial sediments are generally thin (0–30 m), and mainly composed of tills.
- Preferential recharge occurs mainly through vertical fractures of the North Mountain basalts and over the valley floor (Wolfville Formation).
- Groundwater recharge varies from 73 to 435 mm/a with a weighted average of 120 to 224 mm/a over the entire study area when a correction factor of 10 to 52% for discharge zones or artesian/confined conditions is applied. Groundwater depth is on average 6.1 m, but varies from artesian to more than 30 m.
- Groundwater flow generally follows the topography. It flows from the mountains toward the centre of the valley. Old (6000 – 9000 years) water was found in the Wolfville sandstones and the Meguma slates, mixed water in the Blomidon formation, and young water (>1952) in the North Mountain basalts. Young water can also be found in the Wolfville formation, when sufficient precipitation can penetrate the aquifer.
- Based on pumping tests, all units seem to behave as equivalent porous media.
- Formations can, however, locally be very heterogeneous and anisotropic due to the fracturing and the lenticular nature of the beds.
- Fractures are mainly oriented in a N45°E direction, aligned with the valley axis.
- Aquifers are vulnerable in some places (especially surficial aquifers where glaciofluvial deposits are present), but seem relatively well protected, mainly due to the till layer covering a large part of the study area and common confined conditions for bedrock aquifers.
- Mean groundwater use seems sustainable at the regional scale, being in the order of 38 mm/a, hence accounting for 22% of the mean groundwater recharge.
- Groundwater storage was estimated to be 2300 mm for the upper 100 m.

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Appendix A

CPT/RPSS sounding results

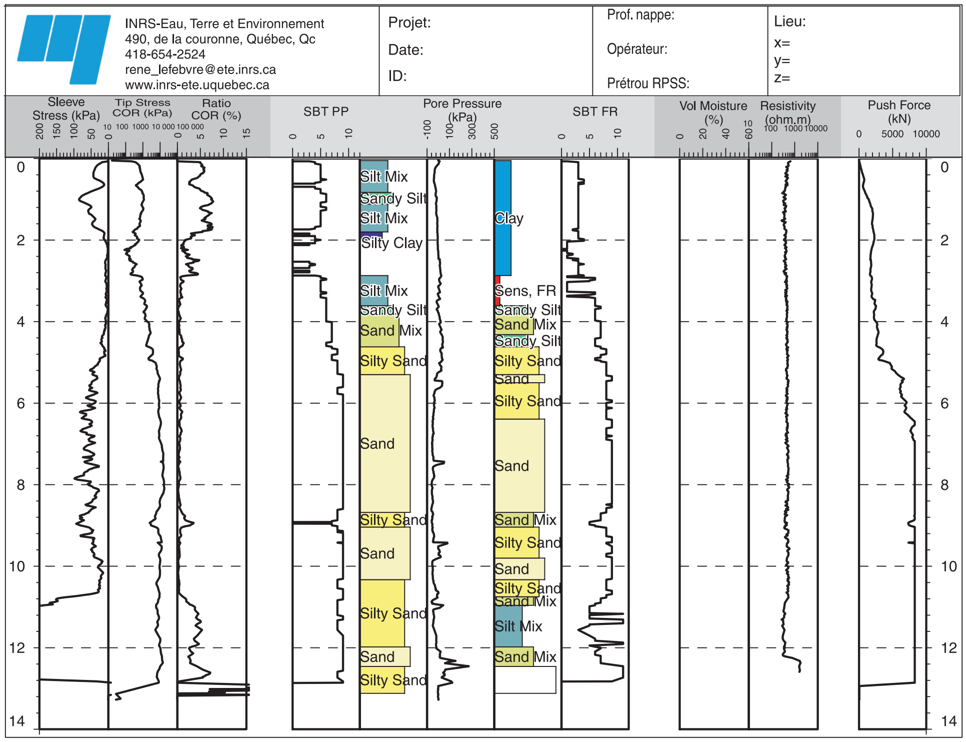
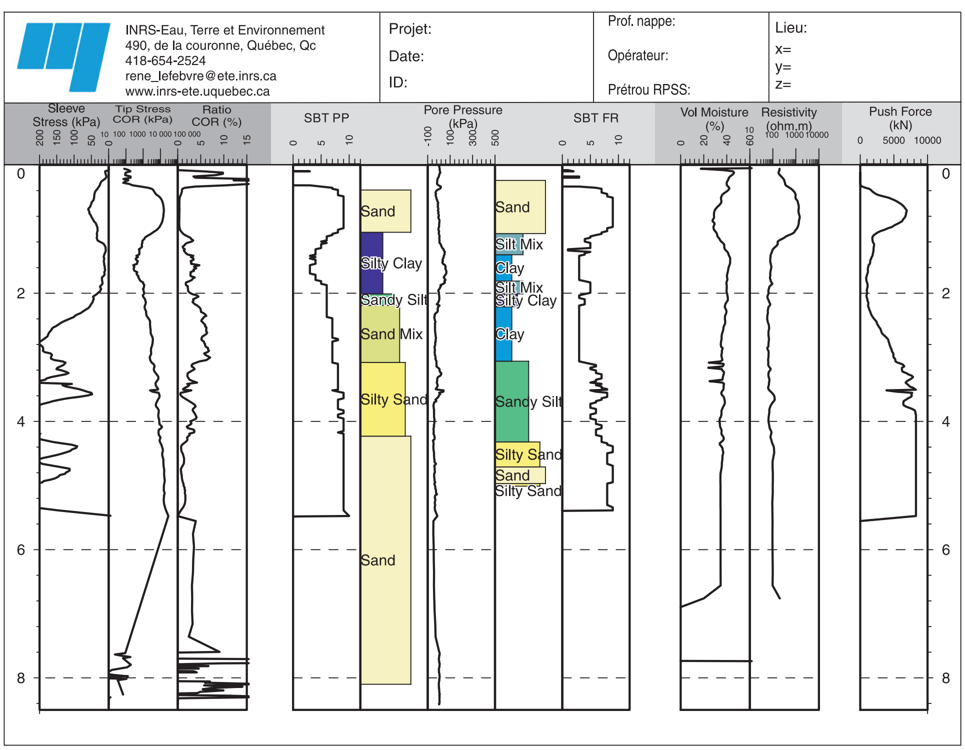


Figure A1. Site 05AVMG0001.



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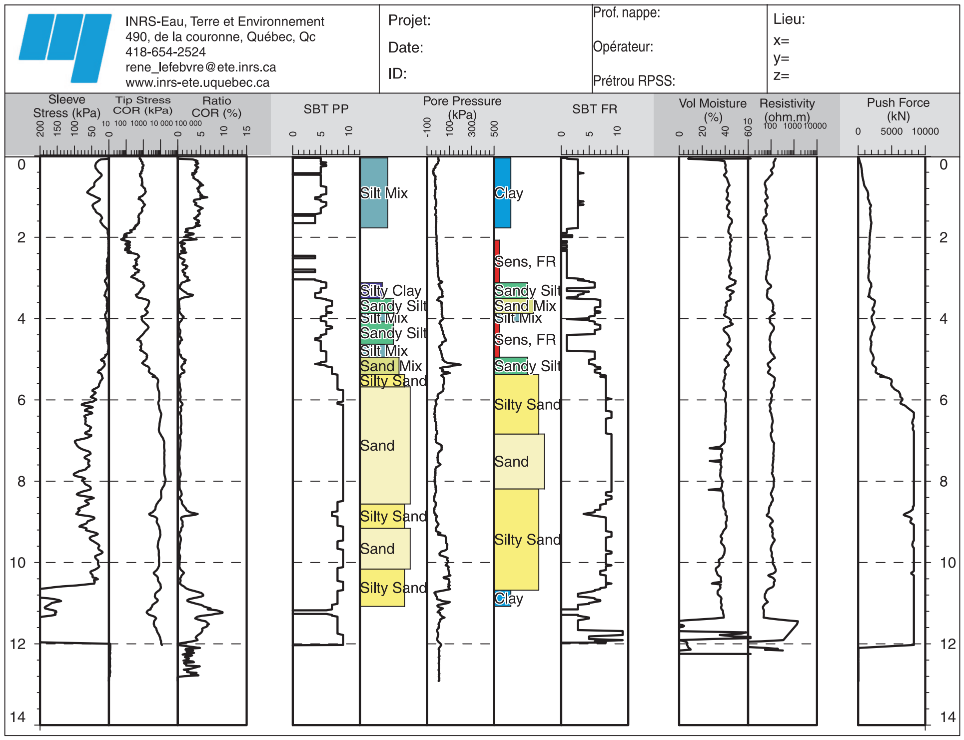

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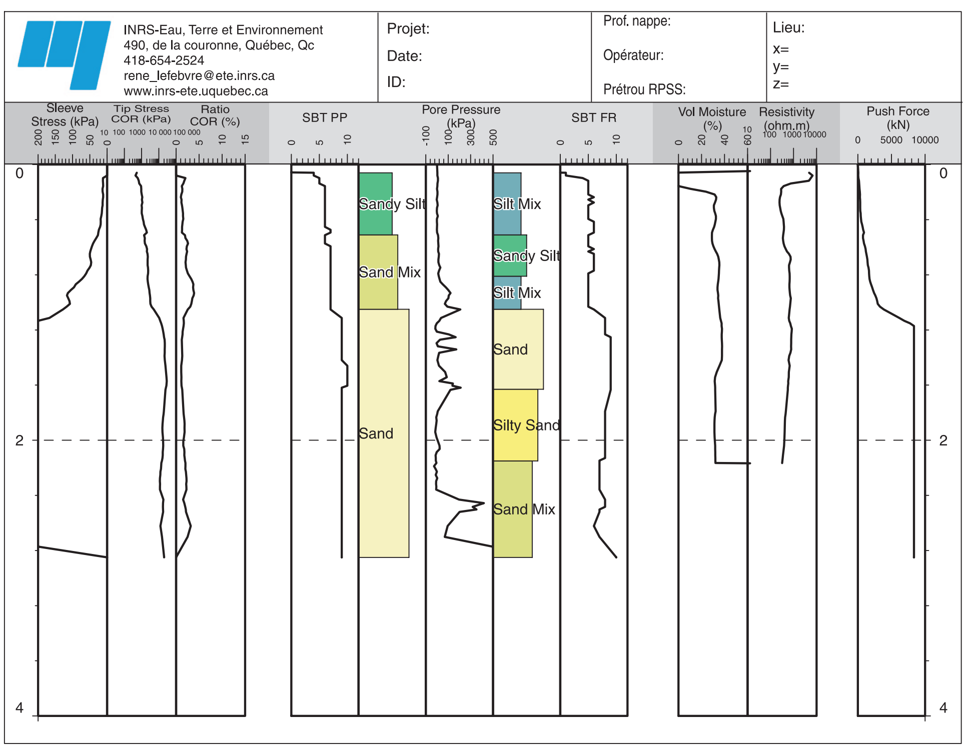

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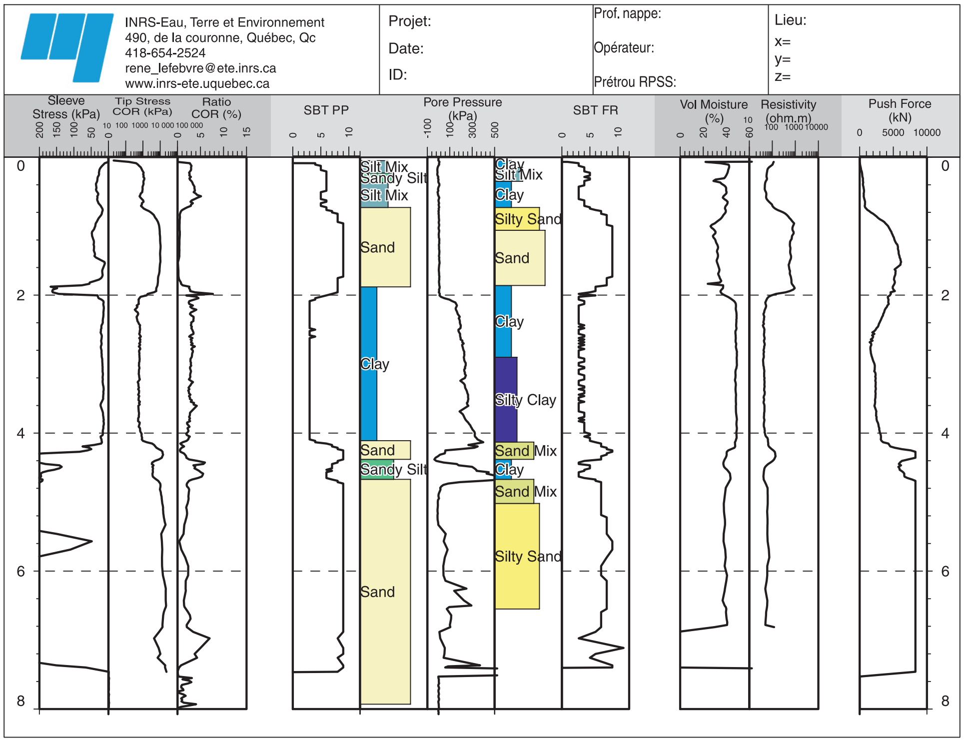


Figure A5. Site 05AVMG0010.

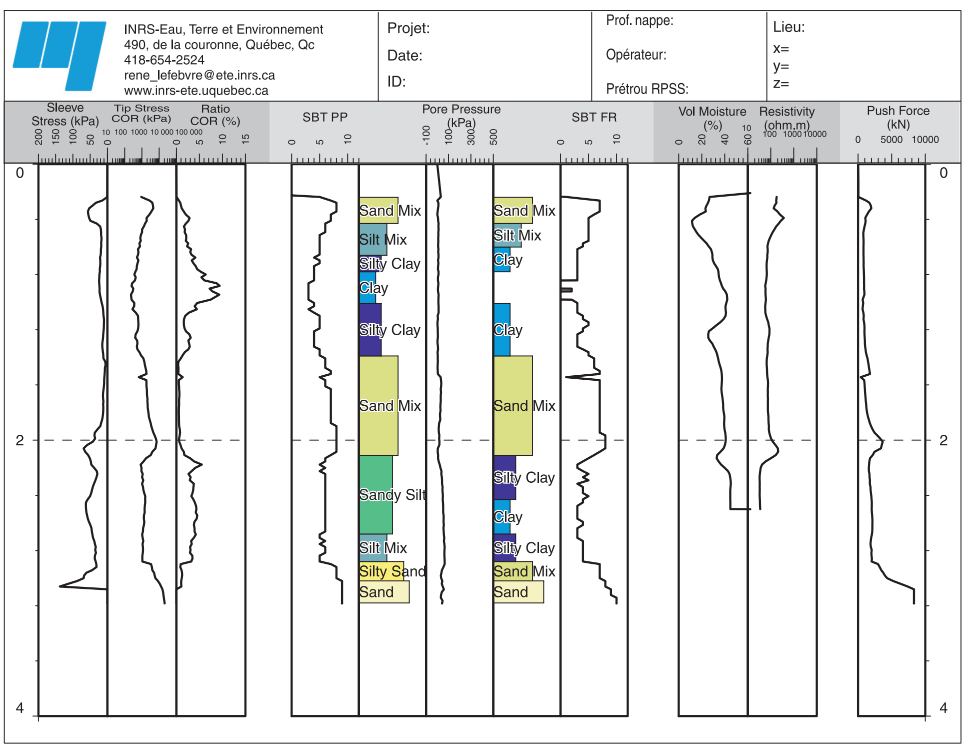


Figure A6. Site 05AVMG0011.

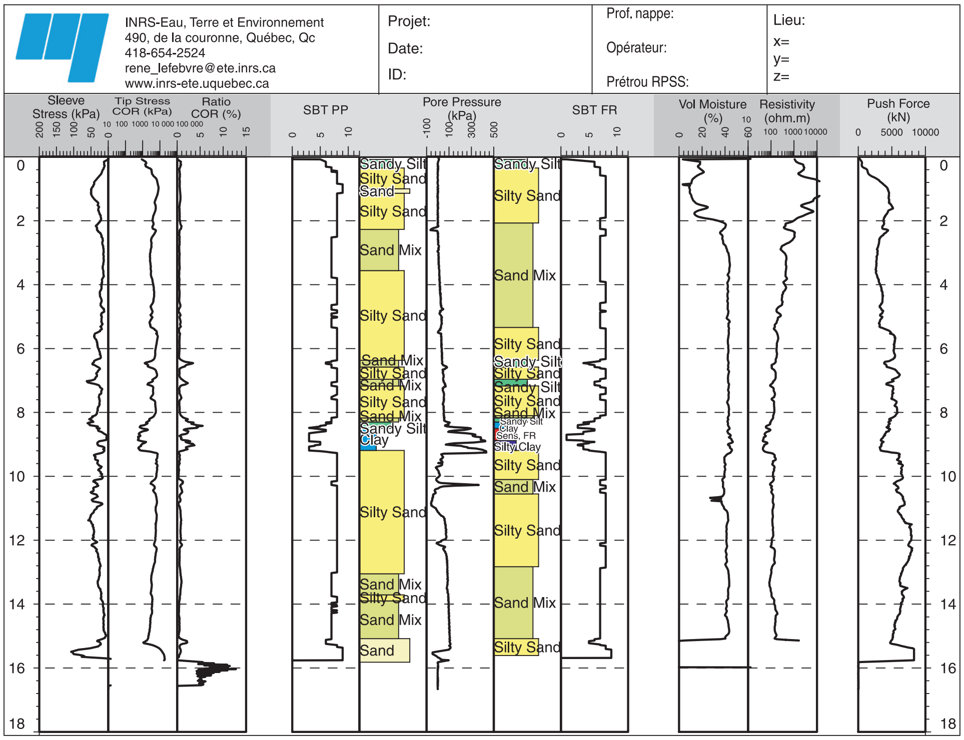


Figure A7. Site 05AVMG0012.

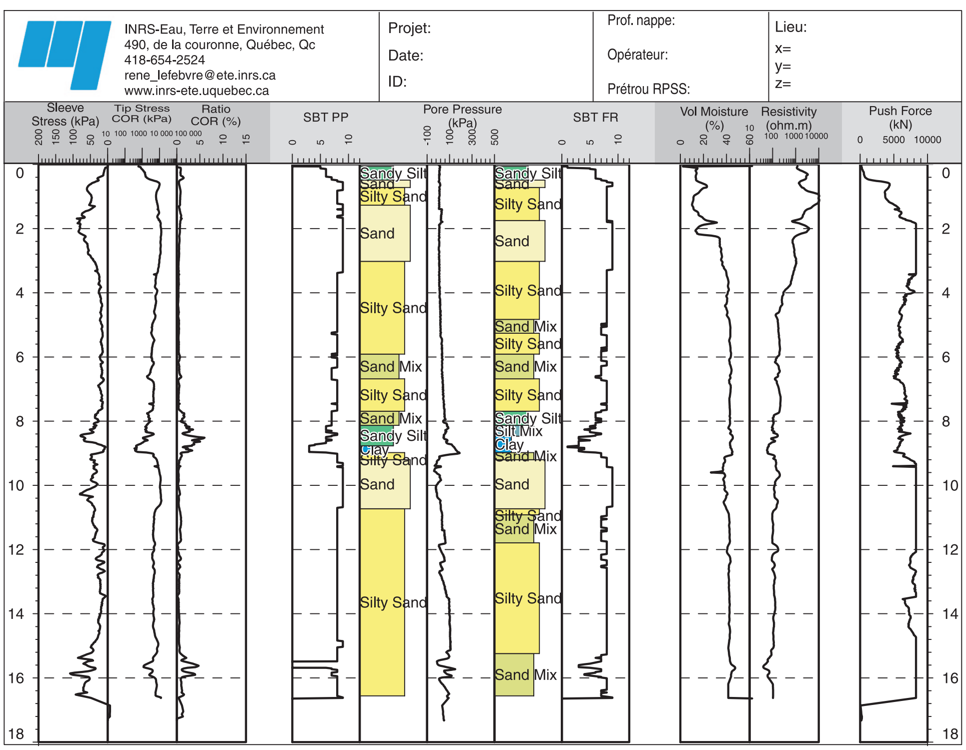


Figure A8. Site 05AVMG0013.

Appendix B

Example of a slug-test interpretation

UNCONFINED AQUIFERS

Bouwer and Rice, 1976

Project:	**Annapolis Valley**	File:	**MNno5.xls**
Test well:	**Monitoring Well no. 5**	Test no :	**1**

BOREHOLE DESCRIPTION

Radius of tubing (**Rc)** :	**0.0762**	m	d/Rw =	371.65
Radius of borehole (**Rw)** :	**0.0762**	m	b/Rw =	408.27
Length of well screen or open section of well (**d**) :	**28.32**	m		

Length from water table to base of screen (open section) (**b)** :	**31.11**	m	**A, B & C coefficients**	4 < d/Rw < 100	100 < d/Rw < 500
Aquifer thickness (**D)** :	**100**	m	**A =**	9.96	7.57
Filter sand pack porosity :	**0**		**B =**	2.65	1.80
Equivalent radius (**Rc')** :	0.0762	m	**C =**	-24.72	9.62

if Lw < H (partially penetrating well)

A = 7.57

B = 1.80

ln (Re/Rw) = 4.23

if Lw = H (fully penetrating well)

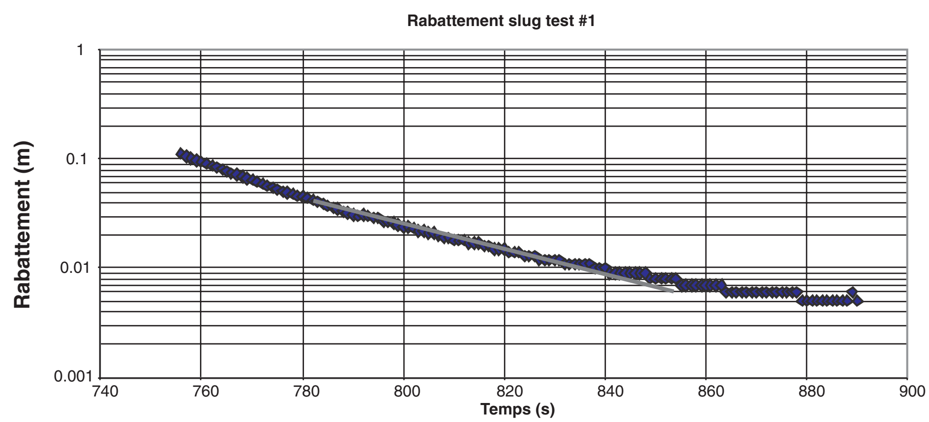
C = 9.62

ln (Re/Rw) = 4.79

Note: Re is theoretic radius at which no difference head is measured

INTERPRETATION

Date:	**20-févr-06**	Test done by :	**M-J Gauthier**	
Test type:	bailer	Initial calculated drawdown :	**0.112**	m



HYDRAULIC CONDUCTIVITY

$$K = \frac{Rc^2 \cdot \ln(Re/Rw)}{2 \cdot d \cdot t} \ln(Ho/Ht)$$

courbe bleue	Ho =	**0.04**	m	ln(Re/Rw)=	4.23	
	Ht =	**0.013**	m	Rc =	0.0762	m
	t =	**41**	sec	Rc'=	0.0762	m
				d =	28.32	m

Hydraulic conductivity

if Rc K = **1.16E-05** m/sec if Rc' K = 1.16E-05 m/sec

Appendix C

Description of the water-balance method

Methodology for the evaluation of the aquifer recharge with the water balance method

General formulation of the hydrological budget:

GW = (P – R) – ETR – Δ RAS

where:

P: Precipitation

T: Temperature

R: Runoff

I: Infiltration (P – R)

ETR: Actual evapotranspiration

ETP: Potential evapotranspiration

RAS: Available water in soils for the plants

Δ RAS: Variation of the available water in soils for the plants

GW: Aquifer recharge

CR: Field capacity of the soils (water content at soil tension of 10 kPa)

WP: Plant wilting point (water content at soil tension of 1500 kPa)

d: Thickness of the plant effective root zone

The studied period extends over 20 years (1983–2002). The hydrological budget is based on a monthly basis. Only the runoff was estimated on a daily basis (due to the method used), before being used on a monthly basis.

The spatial resolution is 500m x 500m. A numerical code in C++ was developed to automate the process.

Precipitation and temperature

The period for this hydrological budget was selected according to the availability of the daily measurements for precipitation and temperature parameters. Two weather stations were selected at first: (1) 8202000 at the centre of the Annapolis Valley, and (2) 8205200 on the South Mountain (outside the study area). However, the first runs confirmed that the second station was not representative enough of the valley conditions and was thus rejected. Several other stations were available but their historic series were much shorter and the missing daily measurements were too numerous for the 'filling' (using statistical regression) to be realistic. Comparison between incomplete temporal series and the selected station (station 8202000) showed that the latter was representative of all other stations in the study area.

Runoff

Presentation of the Soil Conservation Service method

Runoff was evaluated using the Soil Conservation Service (SCS) method (USDA, 1972) modified by Monfet (1979). Indeed, modifications implemented by Monfet allows a more reliable estimation of the runoff in watersheds that have a short concentration time (for instance with abrupt slopes or small subwatersheds). Its application requires a daily basis. The SCS method allows the prediction of the volume of water flowing as runoff down to a stream, following a major rain event. The SCS method was originally developed to get an evaluation of this parameter throughout the United States. Therefore, watersheds used were quite large, and certainly not representative of the eastern Canada conditions. Monfet used Quebec conditions to improve the SCS method. It was hypothesized that the Quebec conditions were fairly close to the Maritimes ones. Validation of the curves confirmed that these modifications significantly improved the estimates compare to the original SCS method results. Indeed, a run performed using a small subwatershed within the valley provided very similar values of runoff than those obtained using the hydrograph separation approach, while the original SCS method provided very different results (much too small).

The SCS method needs the following information:

1. Soil characteristics (infiltration capacity based on the soil texture)

Soil classes (in descending order of infiltration capacity)

A- Gravel and coarse sand

B- Medium to coarse sand

C- Poorly drained fine sand, silty soils, and thin permeable soils

D- Clay, poorly structured and poorly drained, and very thin soils covering bedrock

2. Land use

A- Intensive agriculture intensive (corn, cereals, horticulture)

B- Extensive agriculture (hay, pasture, uncultivated lands with herbaceous)

C- Wooded and uncultivated lands with brushwood

D- Residential and commercial, dense and poorly dense

3. Hydrological conditions (quality of the vegetation by respect to the runoff potential)

4. Prior conditions of the soil humidity

5. Slope

A- slope <3%

B- slope 3–8%

C- slope >8%

Table C-1 presents the SCS numbers for the various soil combinations, soil covers, hydrological conditions and slopes (from Monfet, 1979).

Application of the SCS method

Classes of soils were selected according to their drainage quality reported on the soil maps developed by the Nova Scotia Department of Agriculture (soil.shp). Because of the difficulty to make correspondences between the drainage quality from the soil maps and the soil classes of the SCS method, an adjustment by trial and error had to be performed to find the classes. This adjustment was made to take into account:

- the runoff/precipitation ratio estimated using river hydrograph separation on some limited segments of rivers.
- the limited thickness of Quaternary deposits in many areas (0–5 m)
- Classes for the soil cover were determined using:

  1) alip_all.shp (polygons showing the various types of cultures);

  2) vegetation.shp (polygons showing forested zones);

  3) zones that correspond to uncultivated or deforested lands and that do not correspond to lakes were converted into pixels of the 'poorly dense residential and commercial zones' type.

(*see* Table C1).

A 'poor' hydrological condition was used in order to favour runoff (since the first runs had shown that the runoff was unrealistically low). For the same reason, prior conditions for the soil humidity were not used.

Classes for the slope were determined using the Digital Elevation Model (DEM) from Geomatics Canada.

Once the classes were determined, a SCS number was attributed to each pixel. Based on precipitation and the SCS curve number, runoff is evaluated using the rain-runoff relations of Monfet presented below. These equations correspond to the curves presented in the table on page 30 of the Monfet report (1979).

No. SCS 80–100 R = 0.50P-1.04

No. SCS 70–80 R = 0.47P-1.40

No. SCS 60–70 R = 0.43P-1.64

No. SCS 60–50 R = 0.41P-2.43

No. SCS 50–40 R = 0.35P-2.51

No. SCS 40–20 R = 0.31P-2.60

Snow precipitation is considered instantaneously available, since snow does not stay for a long time on the ground before it melts in most of the study area.

Evapotranspiration

$ETR = Min(ETP; I + RAS_{prior})$

ETP was estimated with the Thornthwaite method, using simply monthly averages for the air temperature, and the latitude of the weather station.

RAS

$RAS_{max} = d*(CR-WP)$

$\Delta RAS = Min(I-ETR; RAS_{max} - RAS_{prior})$

$RAS = RAS_{prior} + \Delta RAS$

CR and WP are determined from soil maps. They correspond to the soil water content at 10 kPa and 1500 kPa respectively. The parameter d is evaluated according to the type of vegetation (*see* land use) and corresponds to the depth of the root zone. As a simplification, it is considered constant throughout the year. When crops are seasonal, this simplification implies that the aquifer recharge is underestimated.

Because Δ RAS is a function of the prior RAS value, water balance runs have to be initialised for the first value (January 1983 in this case). The RAS_{max} value was used as the initial value, as at this period (January), water contents are usually at their maximum.

Soil map: soil.shp (fields: 10kp; 1500kp)

Thickness of the root zone (see http://web.ask.com): effective root zone depth

Soil cover map:

- alip_all.shp (polygons of the various types of crops)
- vegetation.shp (polygons of the forested zones)
- zones that correspond to uncultivated or unforested lands and that do not correspond to lakes were converted into pixels of the 'poorly dense residential and commercial zones' type (*see* the classification in Monfet, 1979).

Table C-1. SCS numbers for the various soil combinations, soil covers, hydrologic conditions and slopes (from Monfet, 1979).

			Hydrological conditions	
Soil group	**Cover type or land use**	**Slope (%)**	**Good**	**Poor**
A	Intensive agriculture	3	60	63
A	Intensive agriculture	3-8	63	65
A	Intensive agriculture	8	67	72
A	Extensive agriculture	3	25	39
A	Extensive agriculture	3-8	39	49
A	Extensive agriculture	8	49	68
A	Forest	3	22	25
A	Forest	3-8	25	41
A	Forest	8	41	47
A	High-density residential, Commercial	3	73	73
A	High-density residential, Commercial	3-8	73	73
A	High-density residential, Commercial	8	73	73
A	High-density residential, Commercial	3	59	59
A	High-density residential, Commercial	3-8	59	59
A	High-density residential, Commercial	8	59	59
B	Intensive agriculture	3	70	74
B	Intensive agriculture	3-8	75	76
B	Intensive agriculture	8	78	81
B	Extensive agriculture	3	40	61
B	Extensive agriculture	3-8	61	69
B	Extensive agriculture	8	69	79
B	Forest	3	53	55
B	Forest	3-8	55	63
B	Forest	8	63	68
B	High-density residential, Commercial	3	83	83
B	High-density residential, Commercial	3-8	83	83
B	High-density residential, Commercial	8	83	83
B	High-density residential, Commercial	3	74	74
B	High-density residential, Commercial	3-8	74	74
B	High-density residential, Commercial	8	74	74
C	Intensive agriculture	3	78	80
C	Intensive agriculture	3-8	83	84
C	Intensive agriculture	8	85	88
C	Extensive agriculture	3	70	74
C	Extensive agriculture	3-8	74	79
C	Extensive agriculture	8	79	86
C	Forest	3	65	70
C	Forest	3-8	70	75
C	Forest	8	75	80
C	High-density residential, Commercial	3	88	88
C	High-density residential, Commercial	3-8	88	88
C	High-density residential, Commercial	8	88	88
C	High-density residential, Commercial	3	82	82
C	High-density residential, Commercial	3-8	82	82
C	High-density residential, Commercial	8	82	82
D	Intensive agriculture	3	81	82
D	Intensive agriculture	3-8	87	88
D	Intensive agriculture	8	89	91
D	Extensive agriculture	3	78	80
D	Extensive agriculture	3-8	80	84
D	Extensive agriculture	8	84	89
D	Forest	3	74	77
D	Forest	3-8	77	81
D	Forest	8	81	84
D	High-density residential, Commercial	3	90	90
D	High-density residential, Commercial	3-8	90	90
D	High-density residential, Commercial	8	90	90
D	High-density residential, Commercial	3	86	86
D	High-density residential, Commercial	3-8	86	86
D	High-density residential, Commercial	8	86	86

A- Coarse sand and gravel
B- Medium to fine sand
C- Poorly drained fine sand; loamy soil; soil usually high in clay
D- Soils that swell significantly when wet; heavy plastic clay; thin soil cover

Appendix D

Seismic survey report

Objectives and methodology

Shallow seismic-reflection/refraction test surveys were conducted in the summer of 2004 in different areas of the Annapolis Valley to determine whether seismic techniques could be used to delineate the bedrock surface and overlying stratigraphy. The seismic-reflection method is best suited for determining the depth to bedrock in areas where the surficial deposits are tens of metres thick, so the prime targets of these surveys were areas where borehole information suggested a substantial overburden thickness. Figure D1 shows the locations (centroids) of the twenty-six seismic test sites. The sites in the eastern portion of the Annapolis Valley were aimed at testing areas where overburden thickness was estimated (based on existing data) to be >30 m.

The initial objectives of this work were 1) to obtain an idea of the stratigraphy, 2) to evaluate the depth of surficial deposits and spatial extent of the suspected buried valleys in the eastern part of the study area, and 3) to delineate the clay or fine-grained strata in the western portion of the valley. It was hoped that shallow seismic-reflection surveys would be able to provide

- detailed subsurface structural information (~10–>60 m depth);
- potential vertical and horizontal resolution on sub-metre to metre scale;
- depth to bedrock and stratigraphy of overlying sediments;
- 2-D structural information and means of evaluating lateral continuity of subsurface units, complementing available borehole information.

The success of any reflection survey depends on two critical factors: 1) the existence of acoustic impedance (product of seismic velocity and material density) contrasts across the target interface, and 2) the ability to produce and detect energy that is of sufficiently high frequency to allow imaging of the target reflector. Surface conditions are critical to the final data quality, where generally the highest resolution data are associated with fine-grained surface materials and a very shallow water table. A testing phase is required to define the data quality, the reflection character and the target depth across the survey area. When successful, the testing phase also provides data that are useful in determining the recording parameters and optimum locations for a follow-up phase to record continuous seismic-reflection profiles. It is these profiles which provide the information needed to delineate the stratigraphy and 2-D structural information of the bedrock and overlying sediments.

Figure D2 is a schematic diagram of the source and receiver setup used to acquire data at the 26 test sites. At each site, a 24-channel array of 50-Hz vertical geophones at 3 m spacing was laid out in the ditch alongside the road. Seismic records were obtained for shots in the centre of the spread, and at

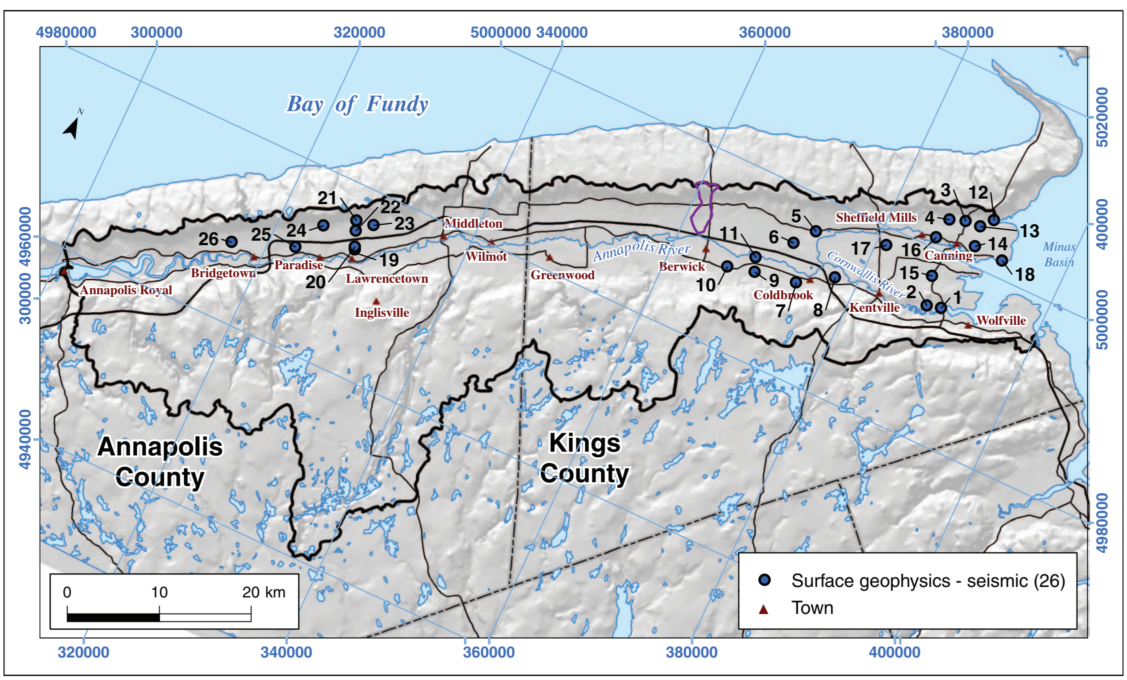


Figure D1. Locations of the 26 seismic test sites.

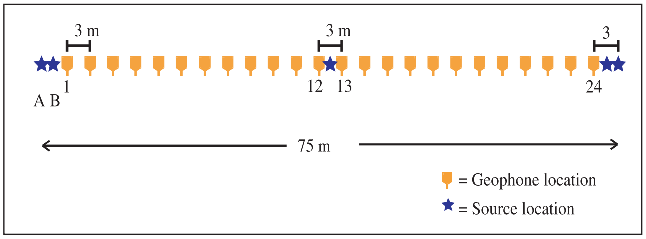


Figure D2. Layout of source and receivers at seismic test sites.

3 and 4.5 m off each end. In some cases, data were also recorded with shots 30 m off each end of the geophone array or at intermediate locations within the array. The compressional wave seismic source was a 12-gauge in-hole shotgun source or 'Buffalo gun', which detonates a 180-grain blank, black-powder load at ~1 m depth in a shallow 4-cm diameter shothole. The seismic data were recorded with a Geometrics Strataview ™ engineering seismograph. Figure D3 presents a photo of investigated site 12, showing the test site setup alongside a road. The geophones and sources were planted in the bottom of roadside ditches. The data were processed and displayed using WinSeis™ seismic processing software produced by the Kansas Geological Survey.

The data acquired in the test site program did not provide the information needed to reach the objectives of the geophysical work as outlined above. In many cases, it was difficult or not possible to determine the depth to bedrock, and little information could be obtained on the stratigraphy of the overlying surficial deposits. Therefore, no follow-up seismic profiling was carried out as part of this project.

Results

The near-surface geophysics survey included 18 sites in the eastern part of the Annapolis Valley, where the main objective of the survey was to confirm the presence of suspected buried valleys; and 8 sites in the Lawrencetown area, to delineate the extent of fine-grained layers (Fig. D-1). At each test site a suite of 5 or more seismic records were acquired using the source-receiver geometry shown in Figure D-3. [REMOVED SEQ FIELD]Several issues were identified during the ACVAS project, including low velocity of the upper bedrock unit, similarity between the velocity of till and that of the bedrock, and dry, sandy surface conditions, as well as shallow bedrock. For these reasons, data from only a few of the 26 investigated sites could be interpreted. Sites 1, 2, 4, 7, 18 and 22 serve as examples to illustrate the type of results obtained.

Site1 (refraction case – no reflection energy observed)

An example of the suite of raw field files obtained at Site 1 is shown in Figure D-4. This site was close to the south bank of the Cornwallis River at Port Williams, where the surficial sediments are fine-grained marine deposits (silt). These data are good quality in that there is clear first arrival energy on all traces across the spread. However, there is no indication of high-frequency reflection (hyperbolic) events from depth, either on these raw records or after low-cut or bandpass filtering was applied to the data. Thus, these data have been interpreted as a three-layer refraction case (Fig. D-4) by picking the first arrival times of the seismic energy on each trace.

The three-layer velocity-depth interpretation of the refraction interpretation for Site 1 is shown in Figure D5. The low-velocity surface layer (v = 500m/s) represents the unsaturated near-surface sediments. Fully water-saturated sediments are found at a depth of 1–2 m as indicated by the increase in velocity to ~1400 m/s. This velocity is consistent with an interpretation of fine-grained, water-saturated sediments, but it cannot uniquely identify the lithology of these subsurface sediments. At a depth of ~10–12 m below ground surface, velocity is observed to increase to ~2100 m/s. Though such a velocity is considered low for competent bedrock, this in interpreted as the bedrock surface, as there is no indication in the data of deeper reflectors. The borehole

Figure D3. Installation of the sources and receivers into ditches alongside roads. **a)** photo of Site 12; right side; **b)** photo of inhole seismic source in ditch.

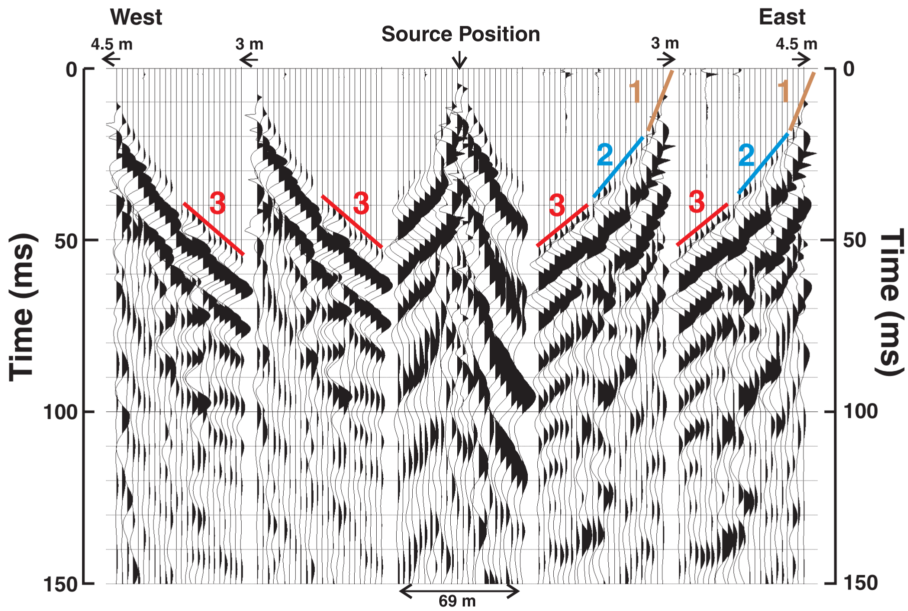


Figure D4. Suite of the five raw field files obtained at Site 1 (Port Williams) using the source-receiver geometry shown in Figure D3. The arrows above each record indicate the source locations; the numbered lines represent the first arrival refraction arrivals for an interpreted three-layer case (Fig. D5).

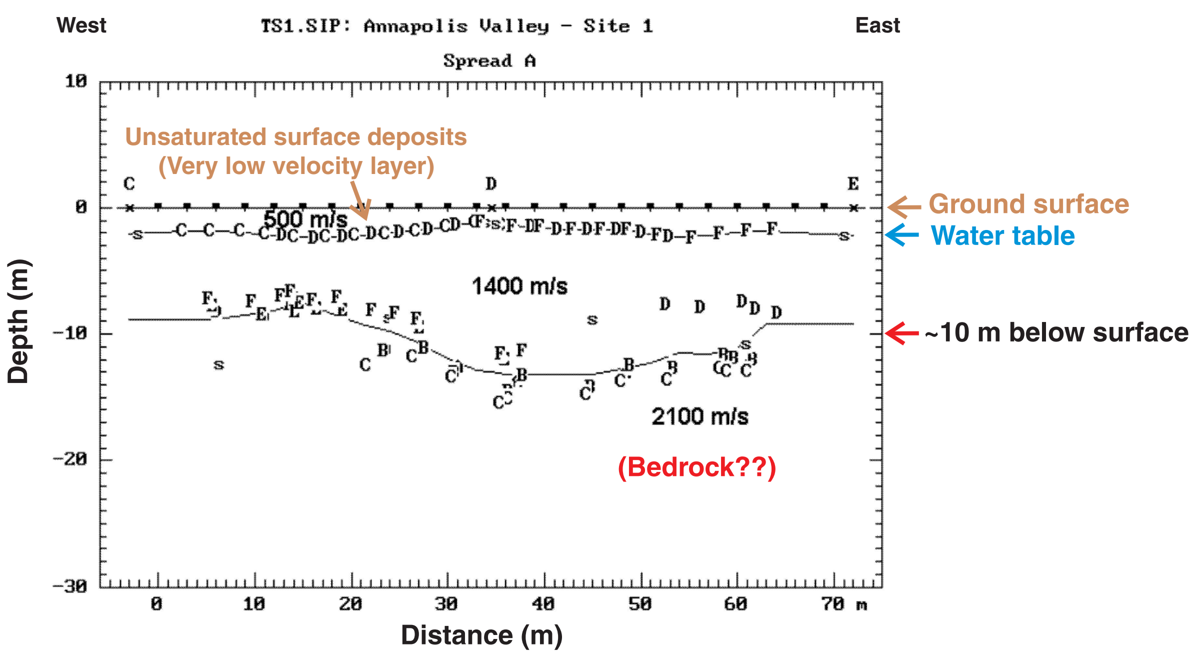


Figure D5. Depth model from three-layer refraction interpretation of the first arrival data from Site 1. The letters indicate the subsurface refracting locations from the data acquired with the shot locations indicated above the ground surface.

database does indicate that a few holes within ~500 m of Site 1 encountered bedrock (usually sandstone) within 15 m of ground surface, thus corroborating this interpretation. It is also known that the upper part (at least 50 m and maybe more) of the Wolfville sandstone is semi-consolidated, and indeed, many wells in the area have to be cased or gravel packed in order to avoid collapsing of the borehole walls.

Site 18 (measurement of bedrock velocity)

The velocity contrast at the bedrock surface is a critical factor in the effective use of seismic techniques for mapping this interface. Site 18 was chosen specifically to obtain a velocity estimate of the bedrock surface. This site is within 100 m of the coast at Kingsport, where the Wolfville sandstone outcrops in the beach cliffs. An interpretation of the first arrival data from this site, suggests that the velocity at the bedrock contact is only ~2000 m/s (Fig. D6). This low velocity may indicate a thick weathered zone at the bedrock surface. However, if the bedrock surface is not characterized by a significant velocity contrast with respect to the overlying surficial sediments, it is a difficult target to observe using seismic techniques.

Site 2 (very shallow reflection case)

An example of the suite of filtered field files obtained at Site 2 is shown in Figure D7. This site is 1.5 km west of Site 1 north of the Cornwallis River, where the surficial sediments are mapped as silty till (sediments in the ditches were quite rocky). These data are good quality and there are significantly higher frequency components to the signal than observed at Site 1. At this site, the near-surface velocity (below the ~1 m unsaturated zone) is 1900 m/s, as determined from the first arrivals. This suggests that the surficial sediments are coarse grained and/or compacted. A weak shallow reflection (hyperbolic event) is just visible on the filtered records, and there are possible indications of deeper events on one or two records (*see* Fig. D7). The shallow reflection has been interpreted as the bedrock surface at a depth of ~13 m.

Site 4 (good reflection case)

Site 4 was the only example of good reflection records obtained during the survey, and the filtered field files from this site are shown in Figure D8. This site is on the north side of the Annapolis Valley northeast of the Village of Canning. At this site a strong reflection is visible on most of the field records. However, variations in surface conditions still strongly affect the data quality. When the shots are at the south end of the geophone spread, the data quality is excellent with a strong high-frequency seismic signal. In contrast, the data recorded from shots located within the geophone spread, or at the north end of the spread, show much lower signal strength (as indicated by the higher noise level on these trace-normalized displays) and considerable low-frequency components. Though the ground surface was essentially flat at this site, the south end of the geophone spread was close to a small stream, and it is assumed that the higher data quality is related to improve coupling between the seismic source and the ground when the surficial sediments were more damp.

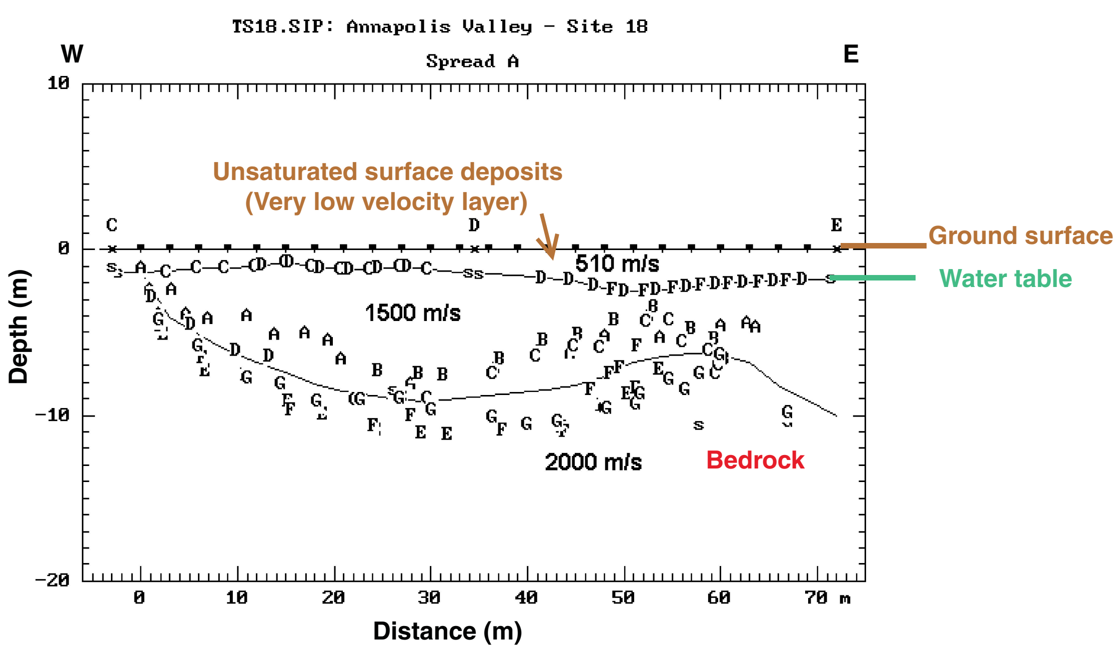


Figure D6. Depth model from three-layer refraction interpretation of the first arrival data from Site 18 where bedrock outcrops in the beach cliffs within 100 m of the geophone spread. These data confirm that the bedrock surface in this area is characterized by velocities of only ~2000 m/s.

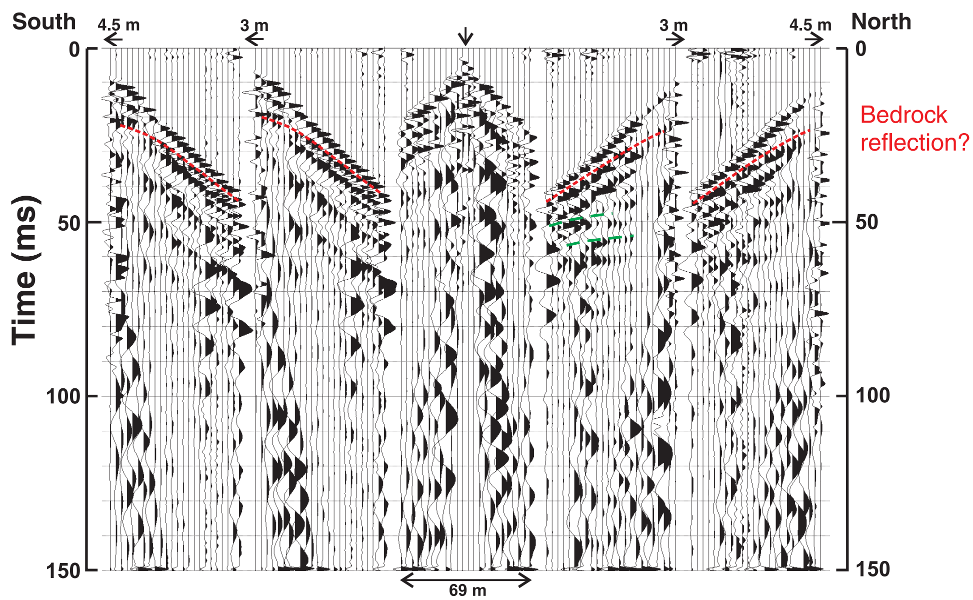


Figure D7. Suite of the five filtered (150–800 Hz bandpass) field files obtained at Site 2. A weak shallow reflection (indicated in red) is interpreted as the reflection from the bedrock surface at an estimated depth of 13 m. Possible deeper reflection events (green) may be related to bedrock stratigraphy.

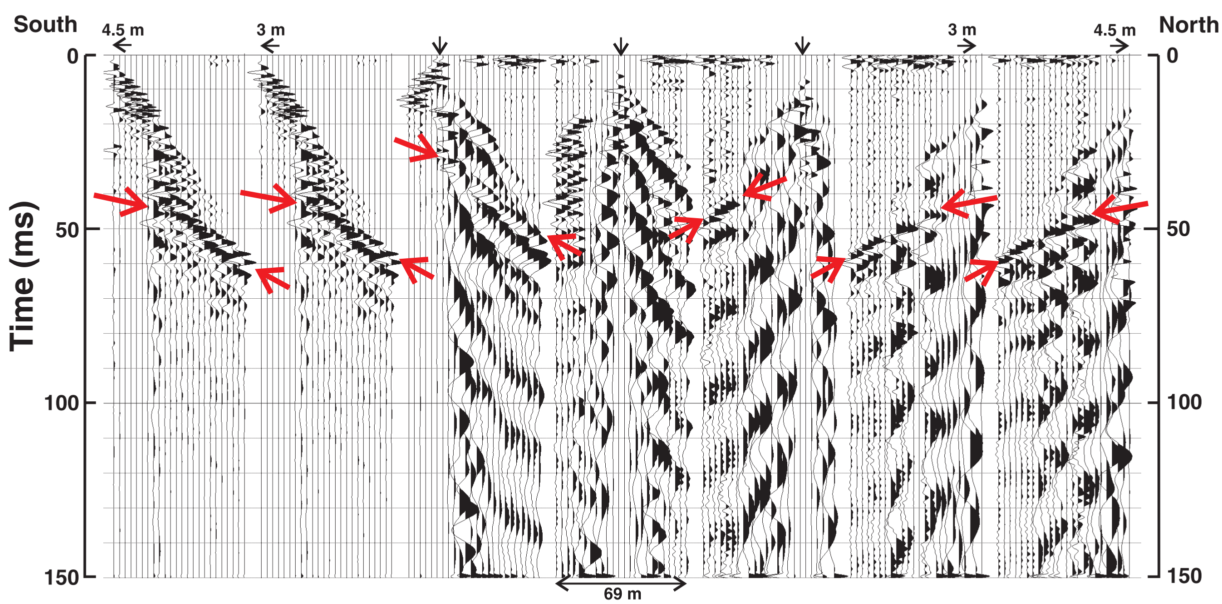


Figure D8. Suite of the filtered (150–800 Hz bandpass) field files obtained at Site 4. A clear reflection event can be seen as indicated by the red arrows. Note that the data quality (frequency content and signal to noise ratio) is much higher when the shots were located at the south end of the geophone spread, close to a small stream.

The entire suite of records obtained at the site can be processed to produce a low-fold seismic section, which is a two-way travel time image of the subsurface structure (Fig. D9). The profile provides two-way travel time determined for the reflection from the interpreted bedrock surface. Using the velocity estimates determined during the processing sequence, the travel time can be interpreted as depth.

Site 7 (Effect of surface conditions)

In some areas of the valley, surface materials consist of dry sand with the water table several metres below ground surface (thick low-velocity near-surface layer). These conditions make it difficult to effectively transmit high-frequency seismic energy into the ground and often result in poor

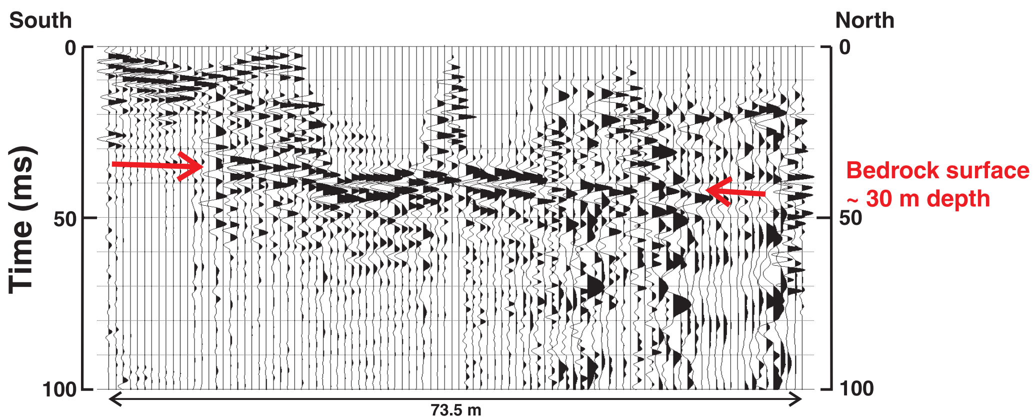


Figure D9. Low-fold seismic section for Site 4 produced from the records shown in Figure D-8. The high-amplitude reflection at 35 to 40 ms two-way travel time is interpreted to be the bedrock surface at a depth of ~30 m.

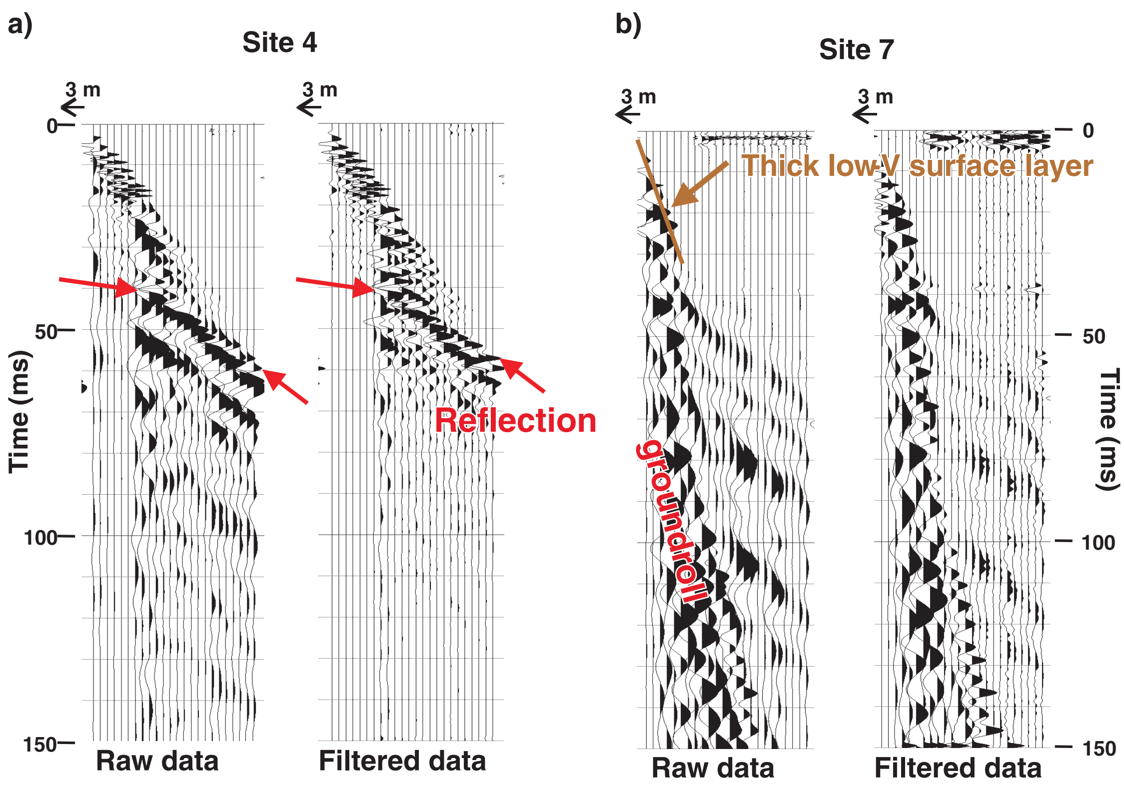


Figure D-10. Effect of surface conditions **a)** raw and filtered field record from Site 4 where the water table was close to the ground surface, showing good reflection data, high-frequency signal with little interference from ground roll; **b)** equivalent data from Site 7 where the water table was several metres below surface, showing poor reflection data with no high-frequency signal and strong ground-roll interference.

Table D-1. Summary of information acquired at each seismic test site (UTMs WGS84, Zone 20).

Site ID	Site location	Easting UTM	Northing UTM	Seismic characteristics	Estimated bedrock depth (m)
1	Port Williams	389417	4994439	Bedrock refraction (2100 m/s)	10
2	Port Williams	387876	4994007	Weak shallow reflection interpreted as bedrock surface	13
3	N of Canning	387853	5004117	No clear reflection or breakover	?
4	N of Canning	386179	5003557	Good reflection	30
5	N of Coldbrook	373549	4996227	Shallow reflection???	<15
6	Centre of valley - NW of Coldbrook	371874	4994072	Refraction (2500 m/s) - statics	12
7	W side of Coldbrook	373929	4990279	Thick low-velocity near-surface layer - poor signal	?
8	Between Coldbrook and Kentville	377523	4992550	Weak reflection (bedrock?)	40-45?
9	SE of Waterville	369372	4989414	Thick low-velocity near-surface layer – suggestion of deeper reflection ?	>30?
10	W of Waterville	366418	4988680	Bedrock refraction? (2000 m/s)	15
11	NE of Waterville	368760	4990910	Thick low-velocity near-surface layer – suggestion of deeper reflection ?	>30?
12	Upper Pereaux watershed	390600	5005525	Thick low-velocity near-surface layer - severe statics	?
13	North of Pereaux watershed	389540	5004271	Bedrock refraction? (2100 m/s)	~10
14	E of Canning	389903	5002066	Very poor data	?
15	Cannard R. flats - N of Port Williams	387033	4997172	Thick low-velocity near-surface layer - very poor data	?
16	West of Canning	385664	5001161	Relatively high near-surface velocity (2100–2200 m/s)	<10?
17	SW of Centreville	381098	4998106	Thick low-velocity near-surface layer - poor signal	?
18	Kingsport	393243	5001918	Low-velocity bedrock refraction (2000 m/s)	5-10
19	N of Lawrencetown	328869	4973223	Velocities ~2000 m/s from surface	?
20	N of Lawrencetown	328763	4973511	Velocities ~2000 m/s from surface	?
21	Lawrencetown - close to Highway 101	327679	4976164	Velocities ~2000 m/s from surface	?
22	Lawrencetown - N of Highway101	328109	4975104	Velocities ~2000 m/s from surface	?
23	at North Mt - 2 km E of Lawrencetown Rd	329596	4976465	Velocities ~2000 m/s from surface	?
24	North Mt - 3 km E of Lawrencetown Rd	324670	4974138	Velocities ~2000 m/s from surface	?
25	Between Paradise and Bridgetown	322887	4970748	Velocities ~2000 m/s from surface	?
26	W of Bridgetown	316367	4968312	Poor data	?

quality seismic data. An example of the effect of surface conditions is shown in Figure D10, which compares with data acquired at Sites 4 and 7.

Site 22 (central Annapolis Valley)

Eight sites were occupied in the central Annapolis Valley (Lawrencetown area) to determine whether seismic techniques could be used to determine the thickness of the fine-grained till observed at the surface. Information from the borehole database suggests that in most areas, bedrock (usually sandstone or shale) is within 10 to 15 m of the ground surface. At seven of the eight sites, very good data (in terms of signal strength) were obtained. However, in all cases the near-surface velocity was ~2000 m/s and there was no breakover to higher velocities that could be associated with the bedrock surface. Thus it appears that the till and the shallow bedrock are characterized by very similar velocities, making the interface between these two units essentially impossible to image using seismic techniques.

DISCUSSION AND CONCLUSION

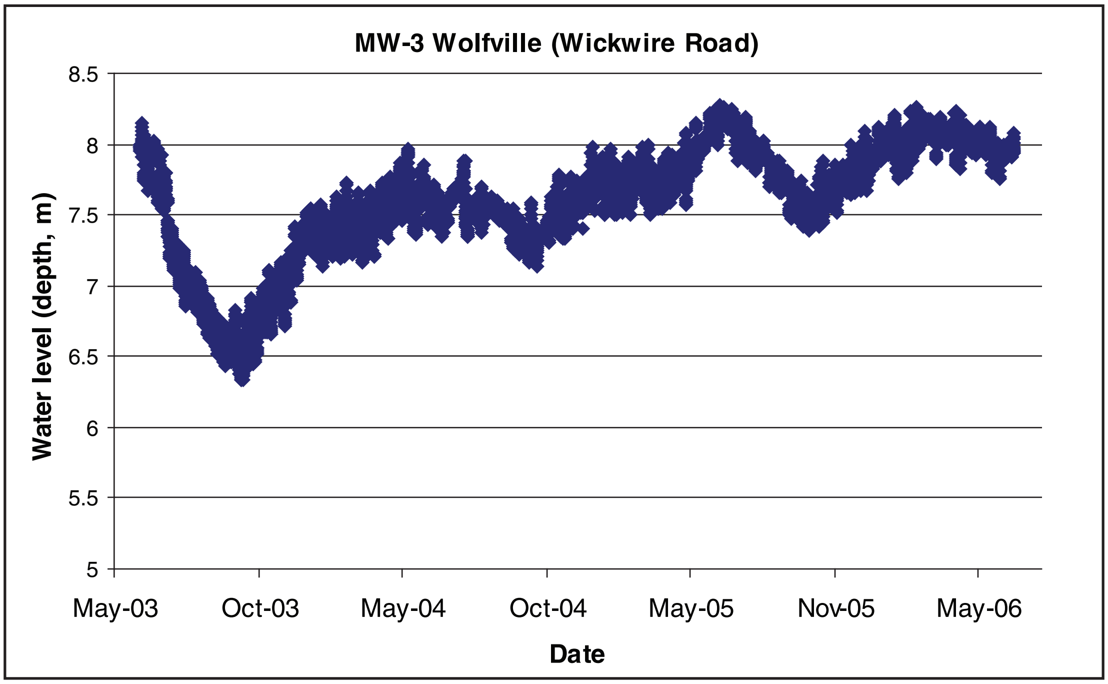
Unfortunately the seismic results were not able to meet the main goal of the survey, which was to provide 2-D structural information on the bedrock surface and the overlying sediments. In light of the data collected, the problems can be attributed to a number of factors, including:

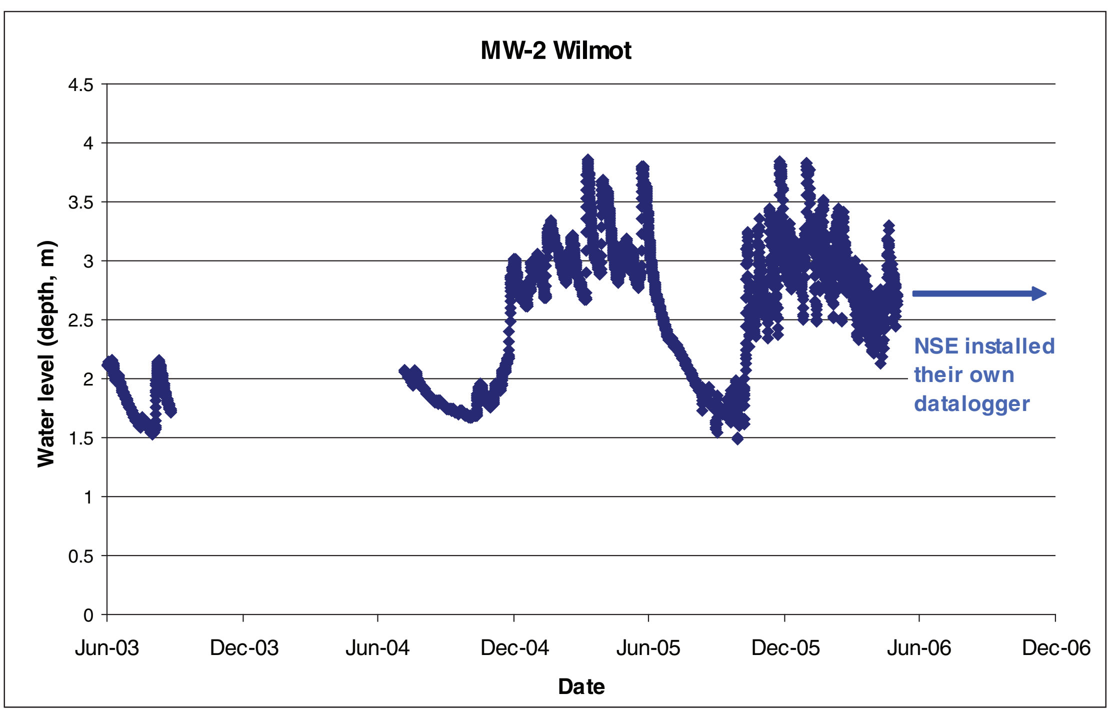
- low velocity of the upper bedrock unit (2000–2400 m/s) in many areas. As a result, the bedrock surface is characterized by a low acoustic impedance contrast (where acoustic impedance is the product of seismic velocity and material density), and makes a poor seismic target for both reflection and refraction methods;
- similar seismic velocities for some surficial sediment units (e.g. silty till, 1900–2200 m/s) and bedrock, making the differentiation of till and bedrock difficult;
- poor coupling of seismic energy into the ground. In many areas, dry, sandy surface conditions (thick low-velocity near-surface layer) resulted in poor data quality and low resolution (low signal-to-noise ratio and poor or non-existent high-frequency signal components). However, ground coupling was often a problem even in areas where surface conditions appeared favourable (e.g. Figure D8);
- shallow bedrock. One of the main objectives of the survey was to evaluate the depth and spatial extent of suspected buried valleys in the eastern part of the study area. Bedrock depths to 60 m were anticipated, but they are estimated to be >20 m at only 4 of the sites surveyed. In most cases, bedrock is within 10 to 20 m of the ground surface, and seismic-reflection methods are of little use.

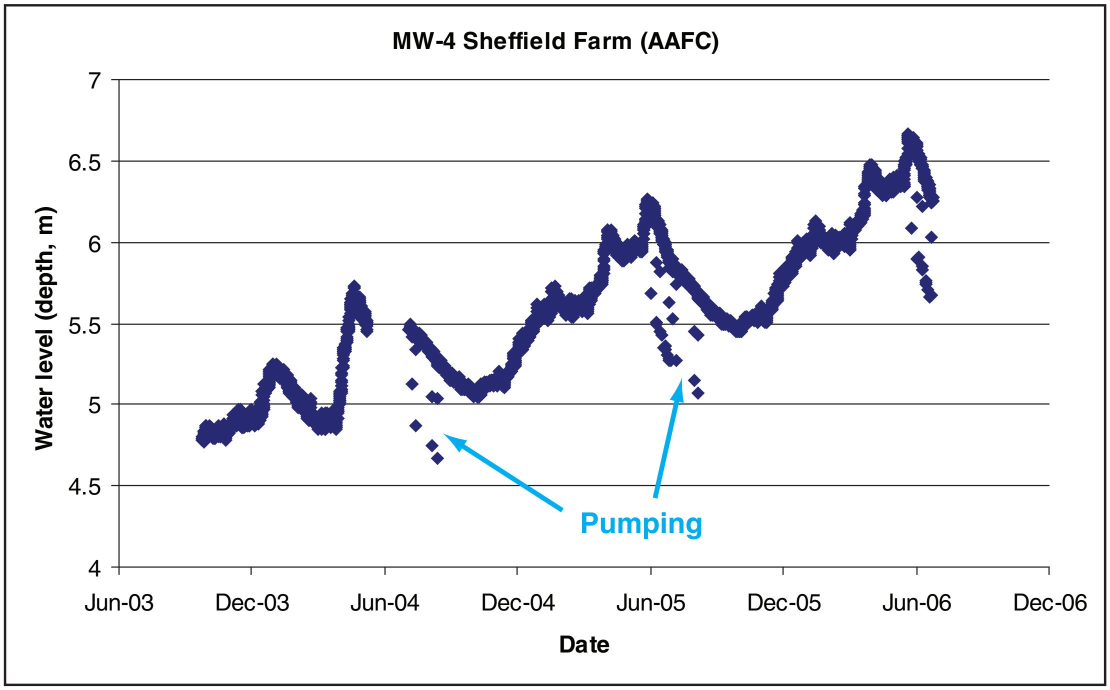
For the above reasons, the seismic surveys were unable to provide any information other than some velocity estimates on the overburden stratigraphy, and only limited depth to bedrock information (Table D1). Bedrock depth estimates that could be made are generally on the order of 10 to 30 m, in agreement with CPT/RPSS soundings and ground penetrating radar carried out as part of this project. No data acquired during this survey was able to confirm the buried-valley hypothesis, as occurrences of thick overburden (>50 m) suggested by some borehole data were not found. However, these thick surficial deposit occurrences could be quite limited in extent, and not precisely located, as borehole locations are often only specified to within a 1 km^2 grid. As well, the main suspected buried valley occurs in a highly urbanized corridor (Kentville/Port Williams/Wolfville), where it was difficult to find locations to conduct the seismic surveys.

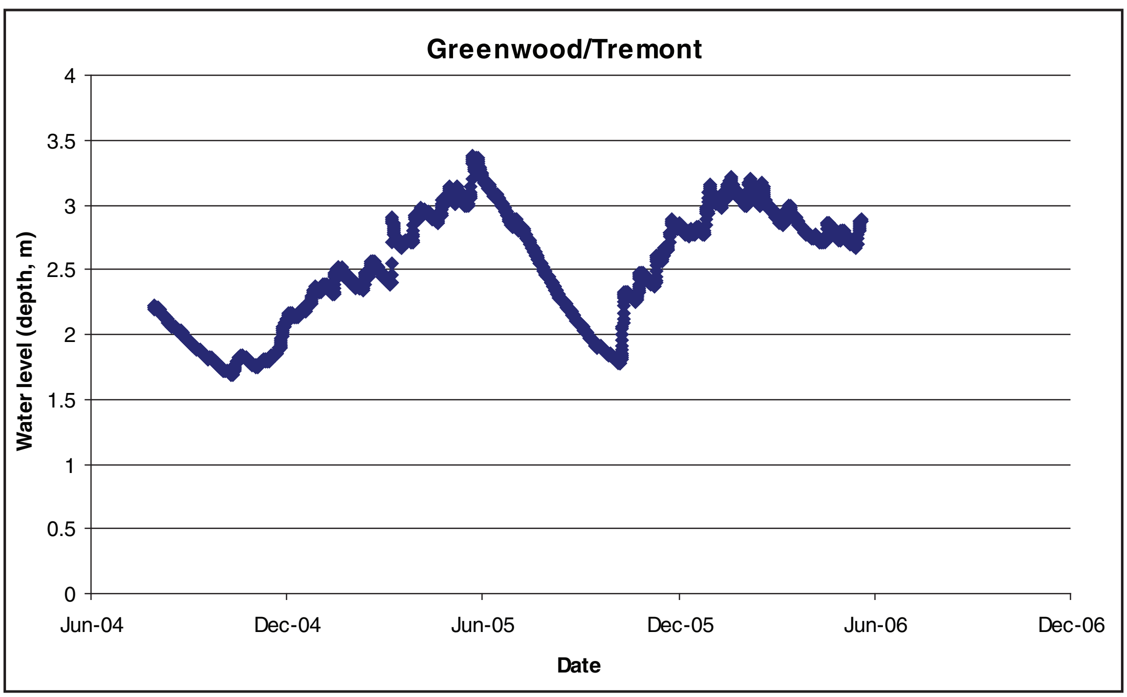
Appendix E

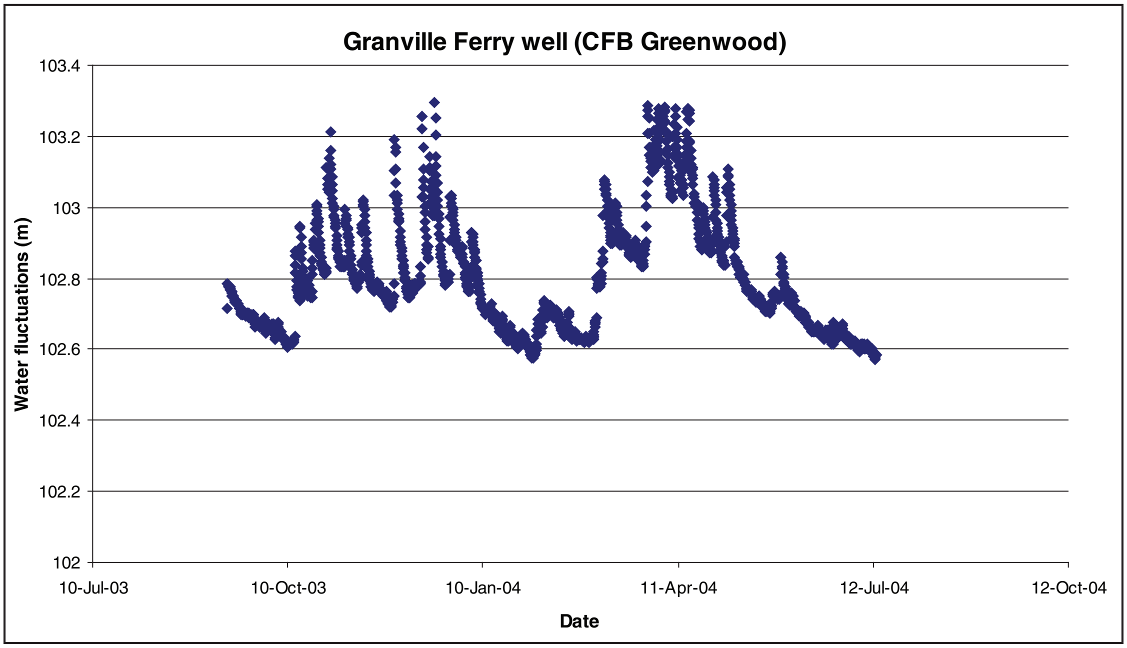
GSC monitoring-well hydrographs

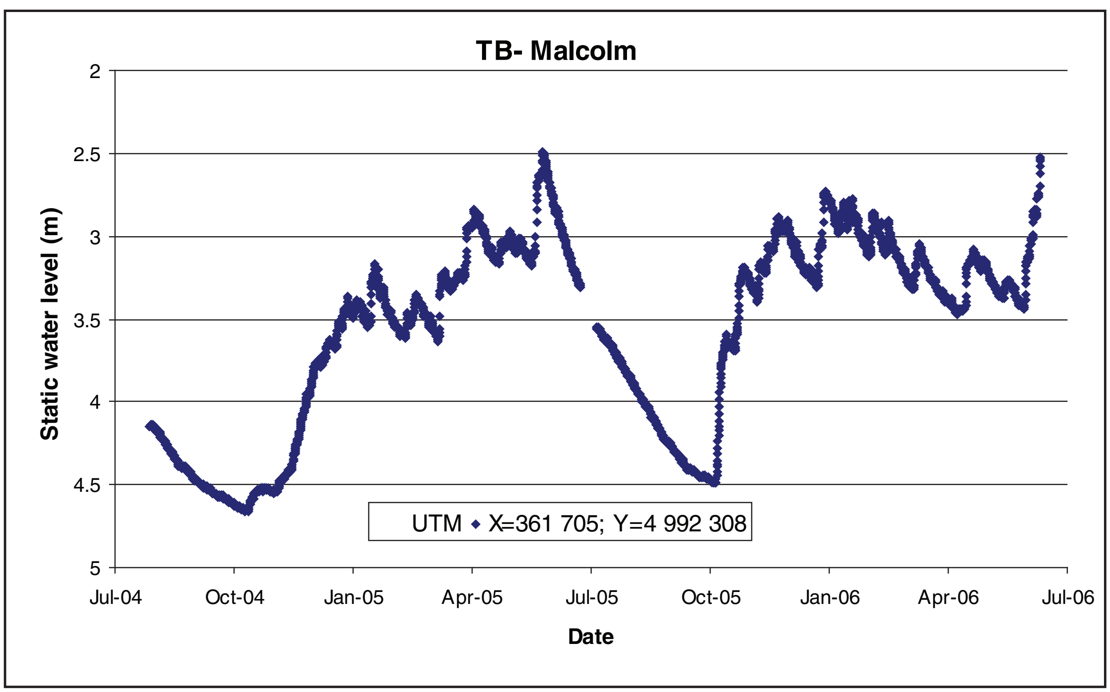


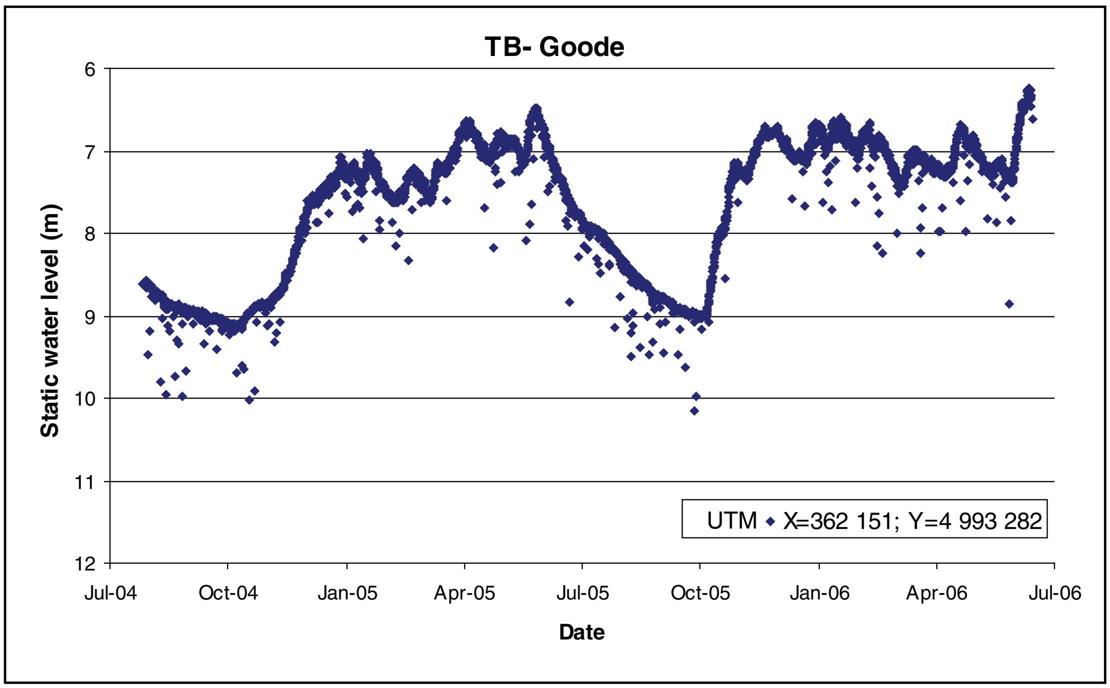



MW-4 Sheffield Farm (AAFC)
Water level (depth, m)
7
6.5
6
5.5
5
4.5
4
Jun-03
Dec-03
Jun-04
Dec-04
Jun-05
Dec-05
Jun-06
Dec-06
Date
Pumping


Greenwood/Tremont
Water level (depth, m)
4
3.5
3
2.5
2
1.5
1
0.5
0
Jun-04
Dec-04
Jun-05
Dec-05
Jun-06
Dec-06
Date


Granville Ferry well (CFB Greenwood)
Water fluctuations (m)
103.4
103.2
103
102.8
102.6
102.4
102.2
102
10-Jul-03
10-Oct-03
10-Jan-04
11-Apr-04
12-Jul-04
12-Oct-04
Date

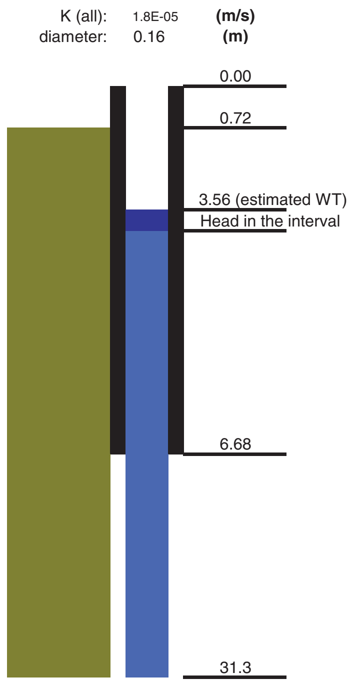

TB- Malcolm
Static water level (m)
2
2.5
3
3.5
4
4.5
5
UTM X=361 705; Y=4 992 308
Jul-04
Oct-04
Jan-05
Apr-05
Jul-05
Oct-05
Jan-06
Apr-06
Jul-06
Date



TB- Goode
Static water level (m)
6
7
8
9
10
11
12
Jul-04
Oct-04
Jan-05
Apr-05
Jul-05
Oct-05
Jan-06
Apr-06
Jul-06
Date
UTM X=362 151; Y=4 993 282

Appendix F

Results from packer tests



Interval length: 3.70

Datum: 100

Interval	From	To	Depth (m) Center	WT	Head	Elev. (m) Head	Packer (psi)	b	K (m/s)
1		10.20	8.4	3.56	3.56	96.44	100	6.64	1.34E-05
2	10.10	13.80	12.0	3.58	3.57	96.43	110	10.24	3.12E-05
3	13.70	17.40	15.6	3.56	3.31	96.69	120	13.84	8.62E-06
4	17.30	21.00	19.2	3.61	3.68	96.32	125	17.44	1.36E-05
5	20.90	24.60	22.8	3.66	3.7	96.30	125	21.04	2.72E-05
6	24.50	28.20	26.4	3.66	3.48	96.52	130	24.64	2.96E-06

Kh = Σ **Ki*bi/** Σ **bi** = 1.6E-05

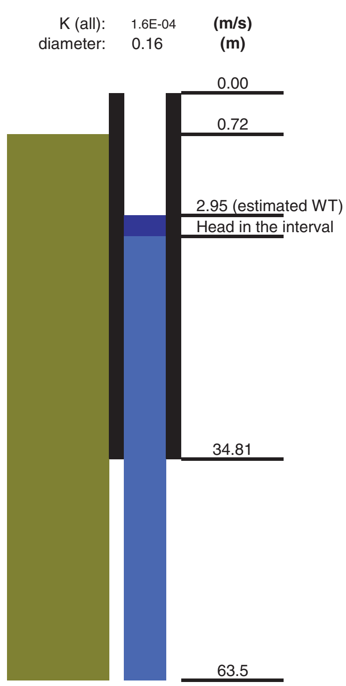
Kv = Σ **bi** / Σ **(bi/Ki)** = 8.9E-06

Kh / Kv = 2

Note

WT: Water table (from the top of the casing)
Head: Water level in the piezometer once isolated
b: saturated section

Figure F1. Packer-test results for the Malcolm well (Blomidon Formation, Thomas Brook subcatchment).



Packer increment: 3.5
Interval length: 3.70

Datum: 100

Interval	From	To	Depth (m) Center	WT	Head	Elev. (m) Head	Packer (psi)	b	K (m/s)
1	34.50	38.20	36.4	2.95	3.07	96.93	160	35.25	1.27E-03
2	38.00	41.70	39.9	3.09	-2.13	102.13	165	38.75	*3.74E-07*
3	41.50	45.20	43.4	3.09	-1.49	101.49	170	42.25	1.75E-06
4	45.00	48.70	46.9	3.09	-1.04	101.04	185	45.75	1.80E-06
5	48.50	52.20	50.4	3.09	-0.08	100.08	190	49.25	1.66E-06
6	52.00	55.70	53.9	3.09	-0.07	100.07	195	52.75	1.04E-06
7	55.50	59.20	57.4	3.09	-0.18	100.18	200	56.25	4.90E-06
8	59.00	62.70	60.9	3.09	-4.46	104.46	205	59.75	4.63E-06
9	62.50	66.20	64.4	3.07	-3.87	103.87	210	63.25	1.13E-05
10	66.00	69.70	67.9	3.04	-1.32	101.32	215	66.75	5.32E-05
11	69.50	73.20	71.4	3.03	-1.82	101.82	220	70.25	*n.d.*
12	73.00	76.70	74.9	3.04	-1.87	101.87	225	73.75	2.63E-06
13	76.50	80.20	78.4	3.03	-0.09	100.09	230	77.25	2.32E-06
14	80.00	83.70	81.9	3.02	-3.31	103.31	235	80.75	1.74E-06
15	83.50	87.20	85.4	3.02	-2.99	102.99	240	84.25	3.90E-06
16	87.00	90.70	88.9	3.01	-1	101.00	245	87.75	3.13E-06
17	90.50	94.20	92.4	3.01	-1.8	101.80	250	91.25	2.36E-06

Kh = Σ **Ki*bi/** Σ **bi** = 8.5E-05

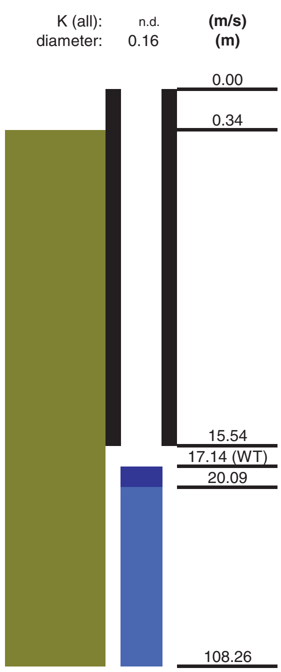
Kv = Σ **bi** / Σ **(bi/Ki)** = 1.9E-06

Kh / Kv = 44

Note

WT: Water table (from the top of the casing)
Head: Water level in the piezometer once isolated
b: saturated section

Figure F2. Packer-test results for the MN5-Kentville well.



Interval length: 3.70 Datum: 100

	Depth (m)					Elev. (m)	Packer		
Interval	From	To	Center	WT	Head	Head	(psi)	b	K (m/s)
1	17.14	24.50	20.8	17.14	17.14	82.86	115	7.36	n.d.
2	23.25	26.95	25.1	17.16	16.95	83.05	120	9.81	3.13E-07
3	26.80	30.50	28.7	16.81	18.12	81.88	125	13.36	9.68E-07
4	30.00	33.70	31.9	n.d.	n.d	n.d	130	16.56	7.42E-07
5	33.50	37.20	35.4	15.29	17.31	82.69	135	20.06	1.62E-05
6	37.00	40.70	38.9	17.46	20.37	79.63	140	23.56	4.01E-05
7	40.50	44.20	42.4	18.25	20	80.00	145	27.06	7.48E-06
8	44.00	47.70	45.9	17.99	20.08	79.92	150	30.56	7.77E-06
9	47.50	51.20	49.4	18.35	19.62	80.38	155	34.06	2.45E-05
10	51.30	55.00	53.2	18.42	20.28	79.72	160	37.86	1.23E-05
11	54.50	58.20	56.4	19.05	20.2	79.80	165	41.06	3.09E-04
12	58.25	61.95	60.1	19.19	20.57	79.43	170	44.81	2.50E-06
13	61.50	65.20	63.4	19.78	20.28	79.72	175	48.06	2.21E-06
14	65.00	68.70	66.9	19.78	20.41	79.59	180	51.56	2.97E-06
15	68.50	72.20	70.4	19.79	20.62	79.38	185	55.06	1.07E-05
16	72.00	75.70	73.9	19.79	20.63	79.37	190	58.56	9.85E-06
17	75.50	79.20	77.4	19.8	20.67	79.33	195	62.06	5.67E-06
18	79.00	82.70	80.9	19.79	20.88	79.12	200	65.56	6.54E-06
19	82.50	86.20	84.4	19.79	20.85	79.15	205	69.06	3.05E-05
20	86.00	89.70	87.9	19.94	20.51	79.49	210	72.56	1.98E-06
21	89.00	92.70	90.9	19.93	20.63	79.37	210	75.56	9.44E-06
22	92.50	96.20	94.4	19.95	20.47	79.53	215	79.06	9.59E-06
								$K_h = \Sigma K_i*b_i / \Sigma b_i =$	2.4E-05
								$K_v = \Sigma b_i / \Sigma (b_i/K_i) =$	2.5E-06
								$K_h / K_v =$	10

Note

WT: Water table (from the top of the casing)
Head: Water level in the piezometer once isolated
b: saturated section

Figure F3. Packer-test results for the TW3-Granville Ferry well.

Appendix G

Guelph permeameter results

Table G-1. Guelph permeameter results.

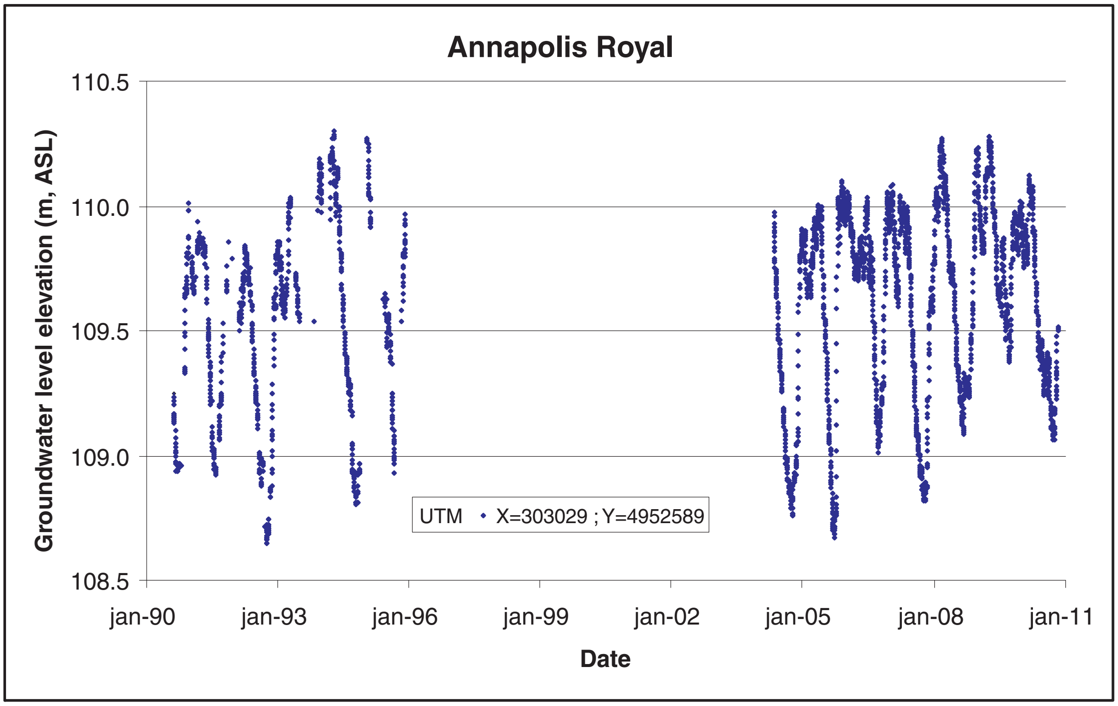
Unit	X	Y	K (cm/s)	K (m/s)
Annapolis	328567	4970935	4.08E-04	4.08E-06
Berwick	376393	4988550	2.61E-03	2.61E-05
Berwick	376331	4988553	2.93E-03	2.93E-05
Berwick 2	361305	4987689	1.91E-02	1.91E-04
Bridgetown	327824	4970113	8.86E-05	8.86E-07
Bridgetown	327824	4970115	1.65E-04	1.65E-06
Canning	299365	4955887	1.02E-03	1.02E-05
Canning	299354	4955868	4.54E-03	4.54E-05
Canning	299368	4955872	4.69E-03	4.69E-05
Cornwallis	375525	4994856	3.08E-03	3.08E-05
Cornwallis	375524	4994830	1.99E-02	1.99E-04
Cornwallis	375483	4994844	2.68E-02	2.68E-04
Cornwallis 2	345016	4984098	9.82E-03	9.82E-05
Cornwallis 2	345030	4984096	2.59E-02	2.59E-04
Cornwallis 2	345033	4984103	3.67E-02	3.67E-04
Cumberland	354998	4985243	1.89E-04	1.89E-06
Cumberland	354991	4985273	8.16E-04	8.16E-06
Debert (TB)	359798	4995089	8.30E-05	8.30E-07
Gibraltor	319751	4965402	5.08E-04	5.08E-06
Gibraltor	319736	4965405	6.86E-04	6.86E-06
Glenmont	361567	4992809	1.71E-05	1.71E-07
Glenmont	361567	4992809	3.62E-06	3.62E-08
Glenmont	361567	4992809	6.43E-05	6.43E-07
Glenmont	360999	4993591	3.94E-05	3.94E-07
Glenmont	360999	4993591	3.15E-05	3.15E-07
Glenmont	360999	4993591	5.08E-05	5.08E-07
Glenmont	360999	4993591	6.39E-06	6.39E-08
Glenmont	360979	4994682	5.01E-05	5.01E-07
Glenmont	360979	4994682	8.55E-05	8.55E-07
Glenmont	360979	4994682	6.81E-05	6.81E-07
Glenmont	360979	4994682	1.80E-04	1.80E-06
Kentville	384943	4993852	2.03E-04	2.03E-06
Kentville	361340	4990925	1.18E-05	1.18E-07
Kentville	361340	4990925	2.06E-05	2.06E-07
Kentville	361907	4992375	4.45E-05	4.45E-07
Kentville	361907	4992375	5.08E-04	5.08E-06
Kentville	360854	4992270	8.56E-05	8.56E-07
Kentville	360854	4992270	1.27E-04	1.27E-06
Kentville	361723	4992675	2.90E-04	2.90E-06
Kentville	361723	4992675	1.89E-04	1.89E-06
Kentville	361723	4992675	1.12E-03	1.12E-05
Kentville	361695	4990942	4.51E-04	4.51E-06
Kentville	361695	4990942	5.09E-04	5.09E-06
Kentville	362525	4991766	3.87E-04	3.87E-06
Kentville	362525	4991766	5.91E-03	5.91E-05
Kentville	362525	4991766	1.42E-04	1.42E-06

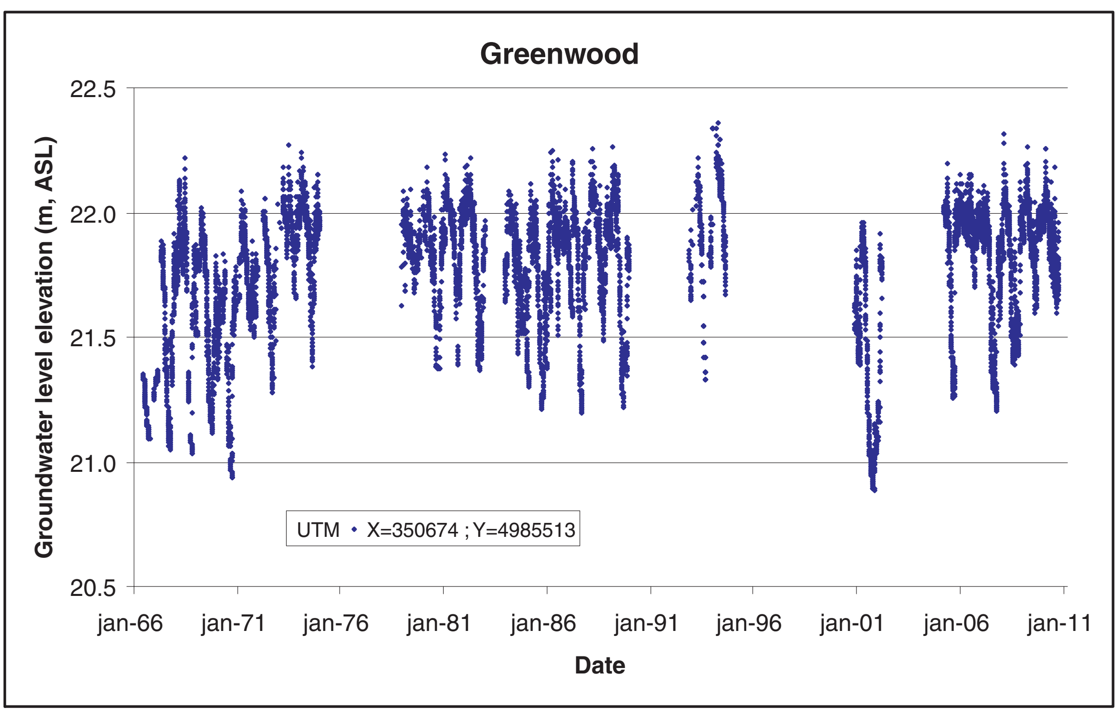
Table G-1. (cont.)

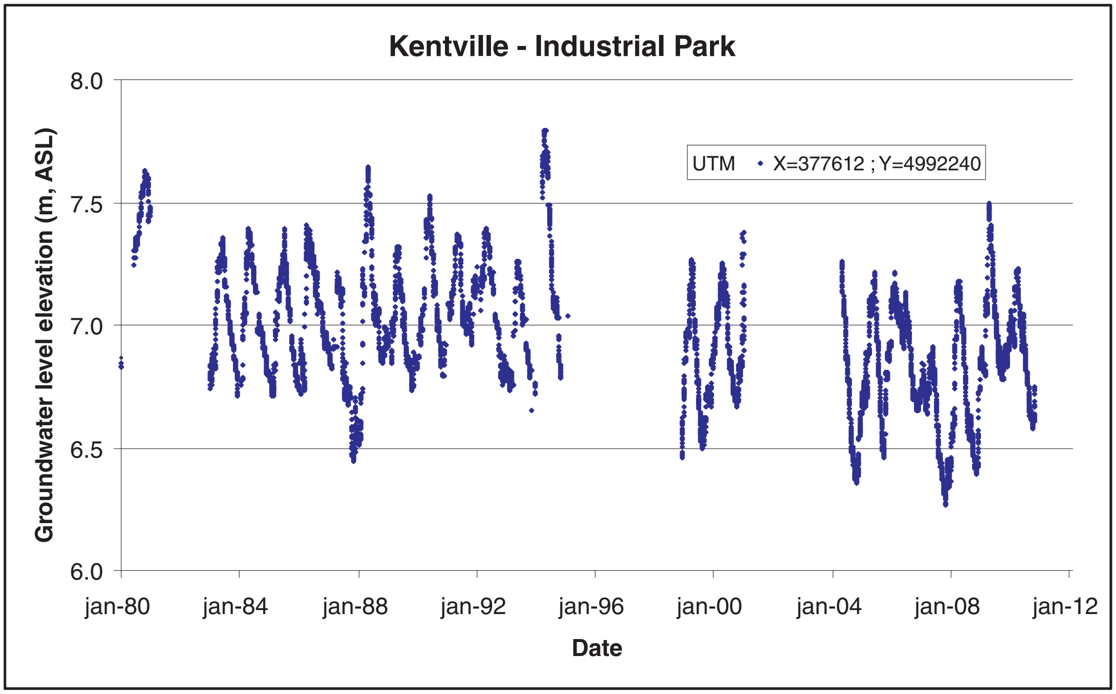
Unit	X	Y	K (cm/s)	K (m/s)
Kentville	362525	4991766	8.95E-03	8.95E-05
Kingsport (TB)	362131	4991021	1.30E-03	1.30E-05
Kingsport (TB)	362165	4991066	3.06E-03	3.06E-05
Lawrencetown (TB)	362117	4991020	6.40E-05	6.40E-07
Masstown	357422	4995927	3.32E-04	3.32E-06
Masstown	357984	4994132	1.29E-03	1.29E-05
Millar	361370	4991972	1.33E-04	1.33E-06
Millar	361381	4991950	3.97E-03	3.97E-05
Morristown	392519	4992032	5.75E-04	5.75E-06
Morristown	392520	4992031	9.04E-04	9.04E-06
Morristown	392511	4992038	2.03E-03	2.03E-05
Nictaux	377841	4992392	1.51E-03	1.51E-05
Nictaux	377797	4992403	5.79E-03	5.79E-05
Nictaux	377804	4992447	1.55E-02	1.55E-04
Nictaux 2	326445	4971139	1.19E-03	1.19E-05
Nictaux 2	326439	4971136	1.73E-03	1.73E-05
Nictaux 2	326446	4971105	1.56E-02	1.56E-04
Pelton (TB)	361591	4993887	8.30E-05	8.30E-07
Pelton (TB)	319736	4965405	6.86E-04	6.86E-06
Pelton (TB)	360692	4993538	6.50E-04	6.50E-06
Rossway	339654	4974438	1.02E-03	1.02E-05
Rossway	299365	4955887	2.78E-03	2.78E-05
Rossway	360869	4995417	4.92E-04	4.92E-06
Rossway	360613	4995275	3.55E-05	3.55E-07
Rossway2	300466	4963680	6.40E-05	6.40E-07
Rossway2	300458	4963692	1.28E-04	1.28E-06
Somerset (Sheffield Mills)	382686	4999223	1.65E-04	1.65E-06
Somerset (Sheffield Mills)	393151	4992707	1.31E-03	1.31E-05
Somerset (Sheffield Mills)	382875	4999171	1.50E-03	1.50E-05
Somerset (Sheffield Mills)	382879	4999208	6.09E-03	6.09E-05
Somerset2 (TB)	382879	4999208	6.45E-06	6.45E-08
Somerset2 (TB)	362420	4992837	3.32E-04	3.32E-06
Somerset2 (TB)	362468	4992924	6.50E-04	6.50E-06
Somerset2 (TB)	362360	4992846	4.49E-03	4.49E-05
Stewiake	361423	4990732	6.40E-04	6.40E-06
Stewiake	361395	4990713	1.20E-03	1.20E-05
Stewiake	361418	4990712	1.31E-03	1.31E-05
Stewiake	361393	4990710	4.73E-03	4.73E-05
Torbrook	385306	4991977	3.00E-03	3.00E-05
Wolfville	339654	4974438	1.02E-03	1.02E-05
Wolfville	339656	4974449	3.07E-03	3.07E-05
Woodsville	361368	4991973	6.40E-05	6.40E-07
Woodsville	360564	4991722	1.07E-04	1.07E-06
Woodsville	360536	4991661	1.17E-04	1.17E-06
Woodsville 2	387518	4995402	1.12E-04	1.12E-06
Woodsville 2	387559	4995433	3.32E-04	3.32E-06
Woodsville 2	387613	4995380	9.48E-04	9.48E-06

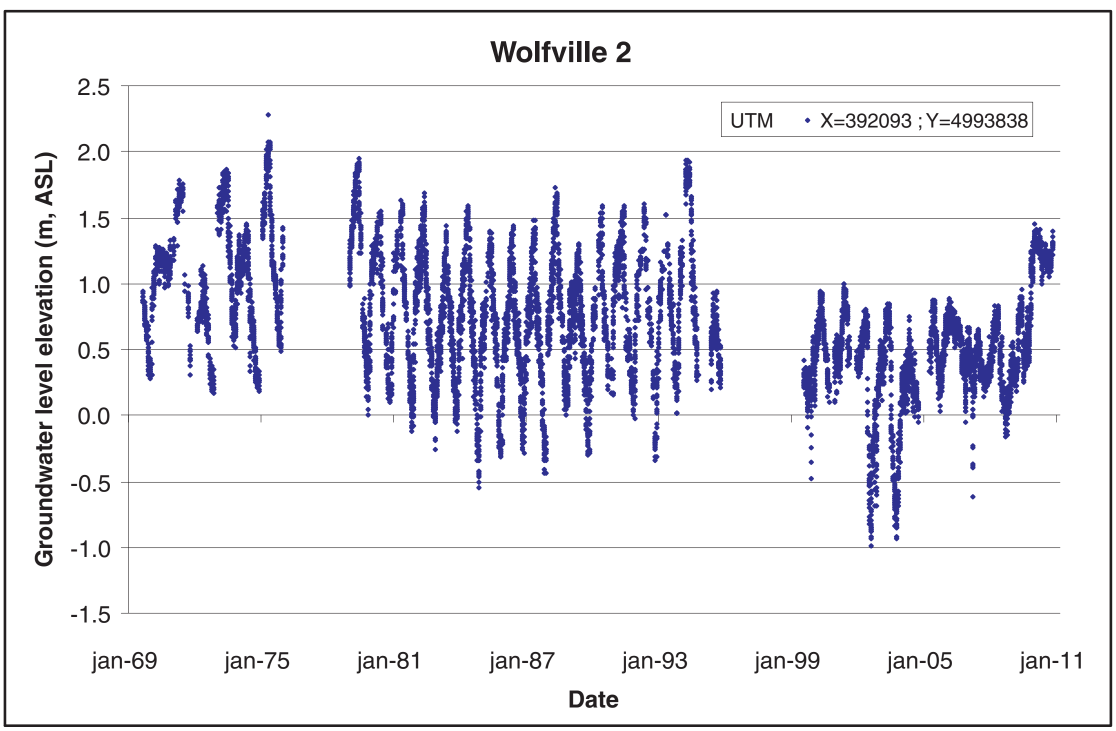
Appendix H

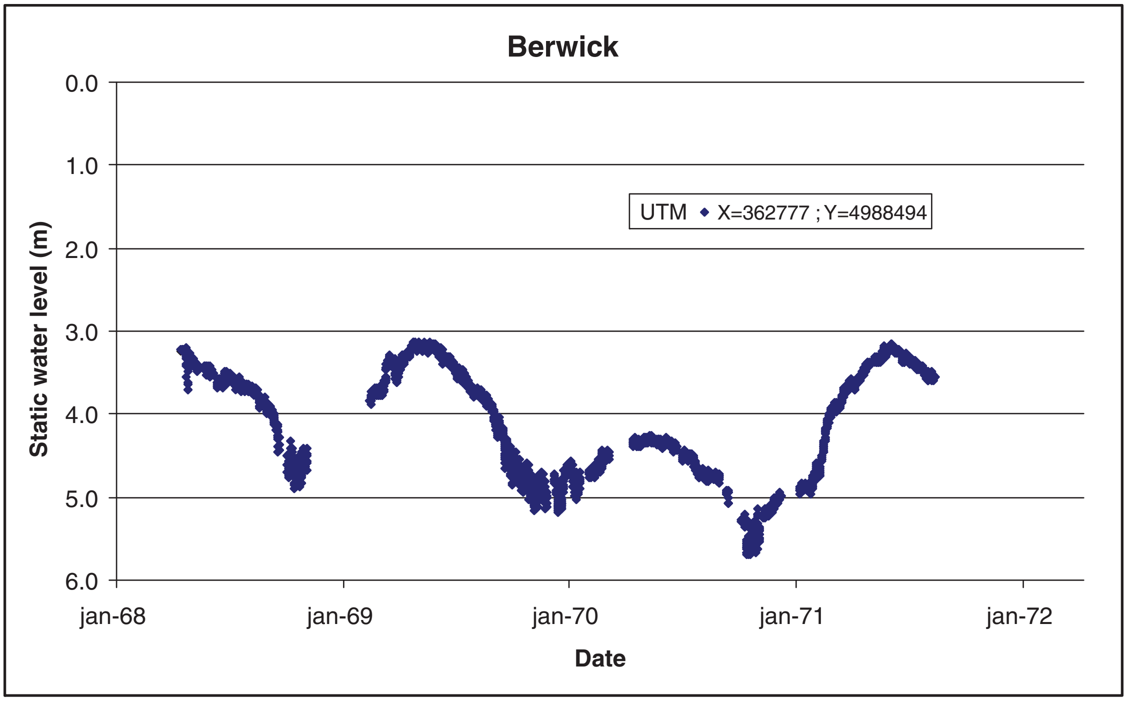
NSE monitoring-well hydrographs

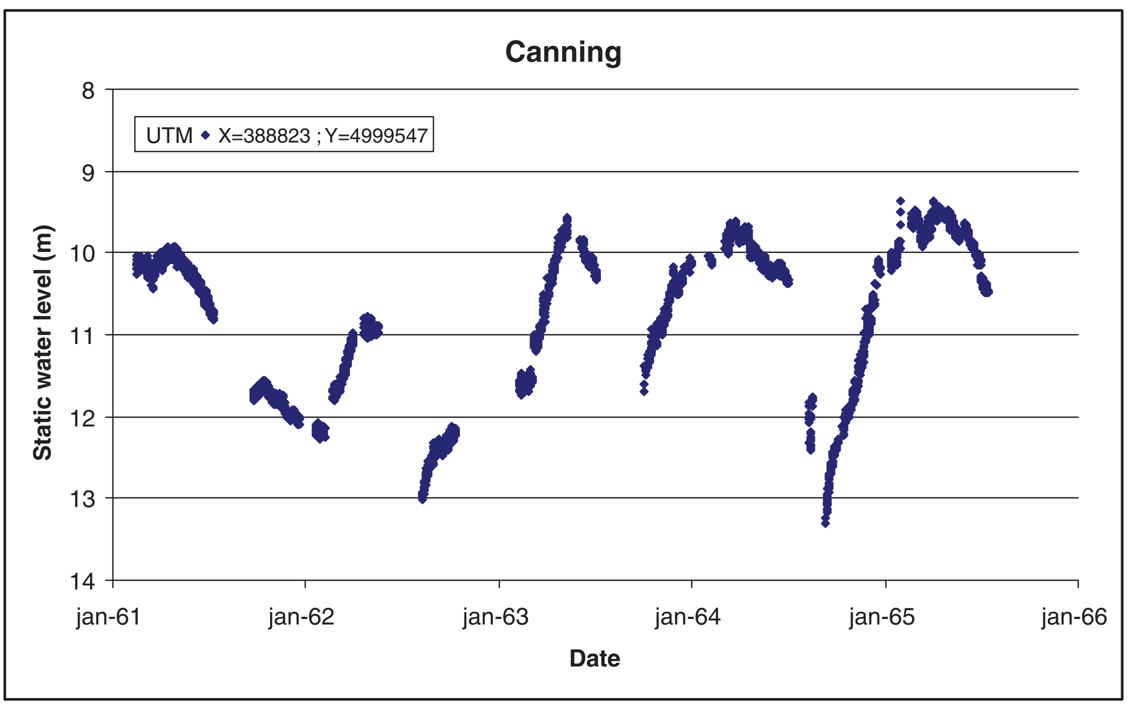


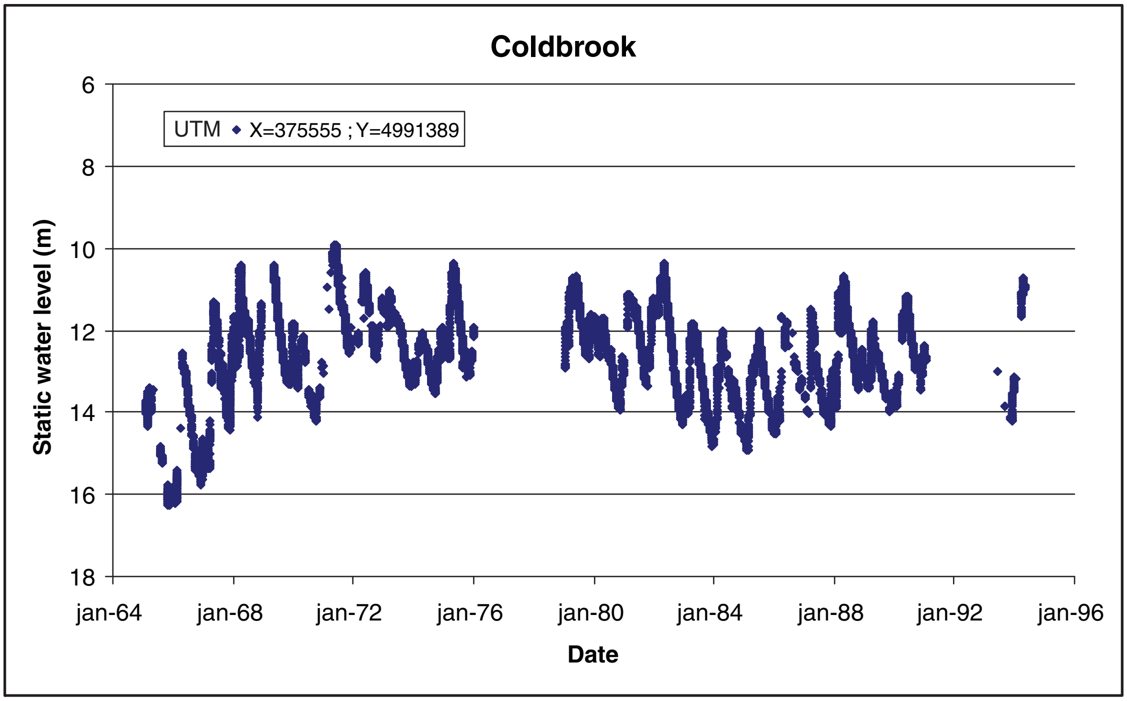


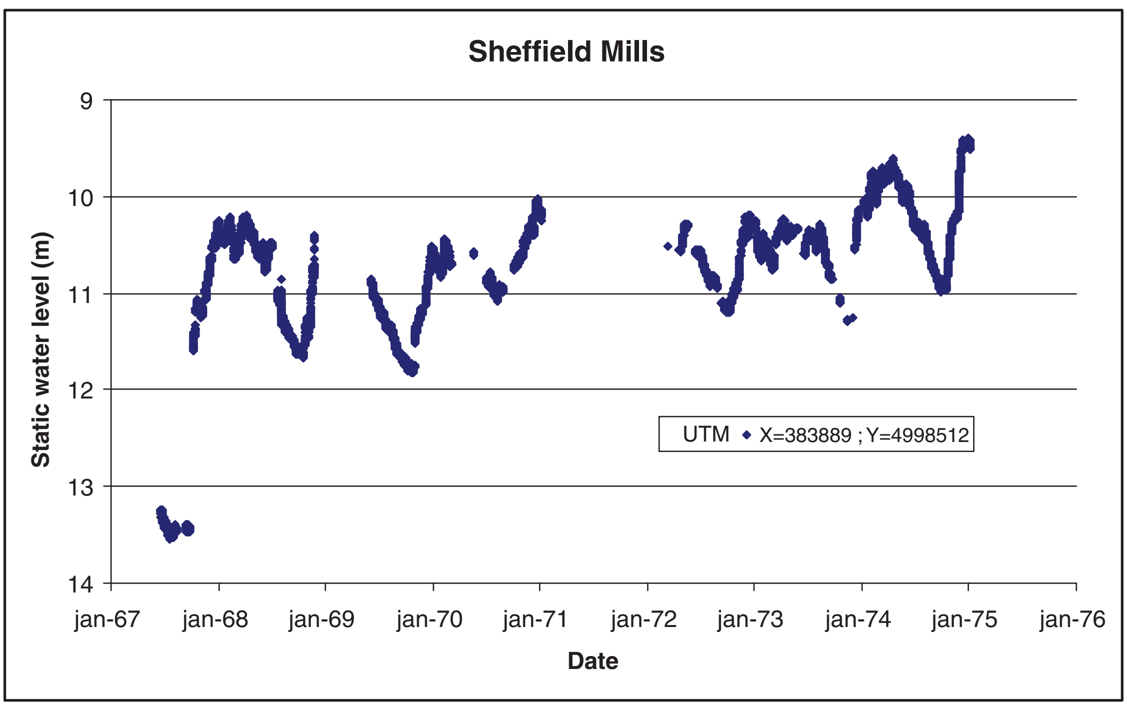

Kentville - Industrial Park
UTM X=377612 ; Y=4992240
Groundwater level elevation (m, ASL)
8.0
7.5
7.0
6.5
6.0
jan-80
jan-84
jan-88
jan-92
jan-96
jan-00
jan-04
jan-08
jan-12
Date

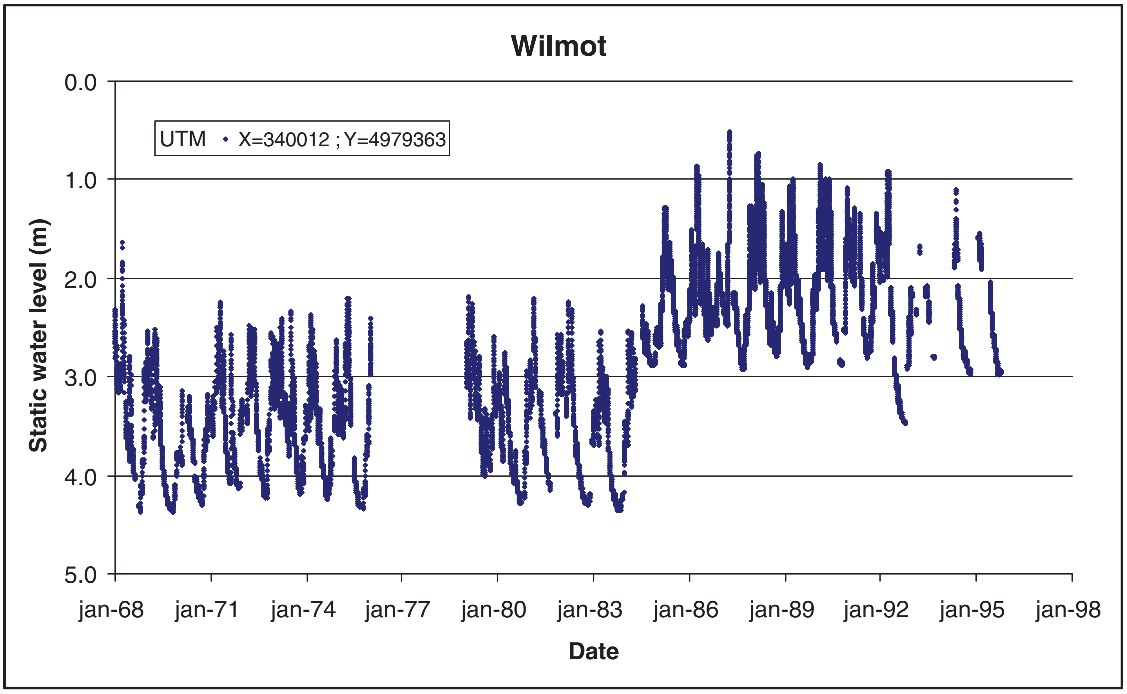

Wolfville 2
UTM X=392093 ; Y=4993838
Groundwater level elevation (m, ASL)
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
jan-69
jan-75
jan-81
jan-87
jan-93
jan-99
jan-05
jan-11
Date

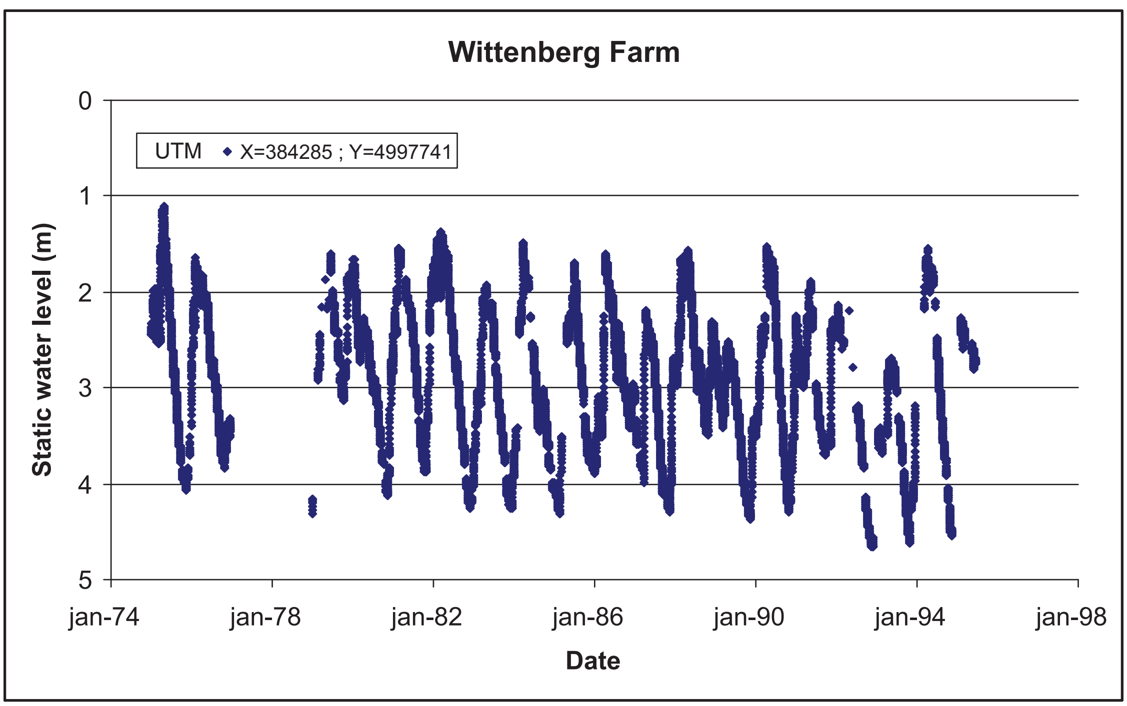

Berwick
UTM ◆ X=362777 ; Y=4988494
Static water level (m)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
jan-68
jan-69
jan-70
jan-71
jan-72
Date

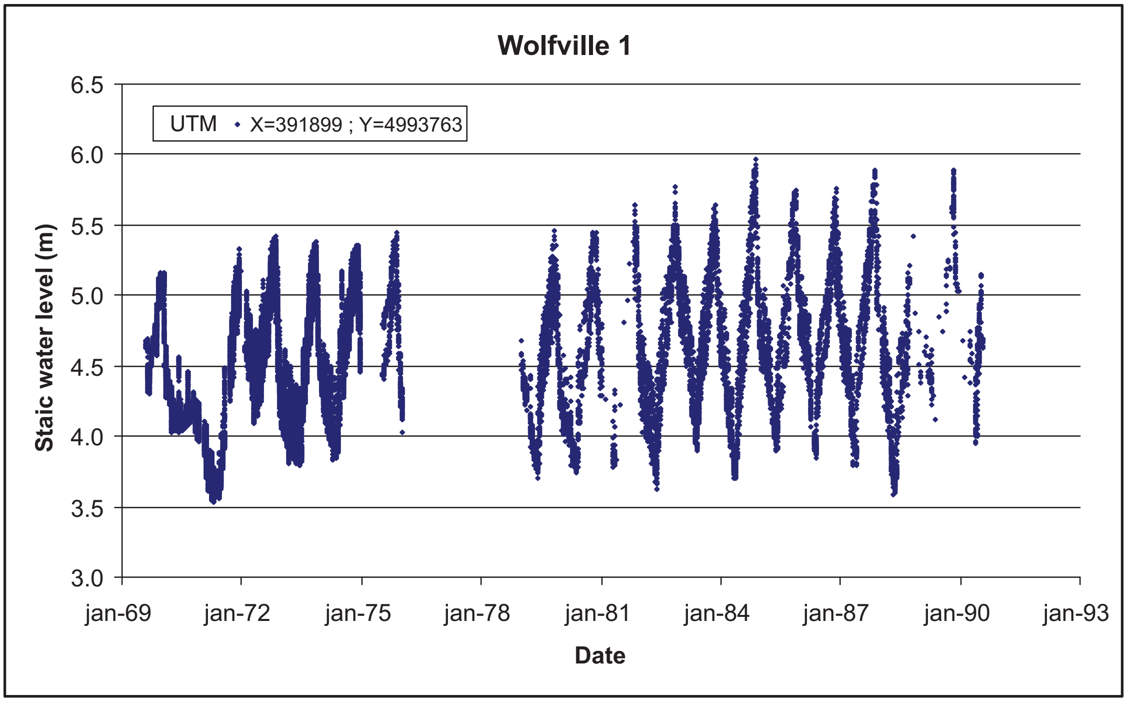

Canning
UTM ◆ X=388823 ; Y=4999547
Static water level (m)
8
9
10
11
12
13
14
jan-61
jan-62
jan-63
jan-64
jan-65
jan-66
Date

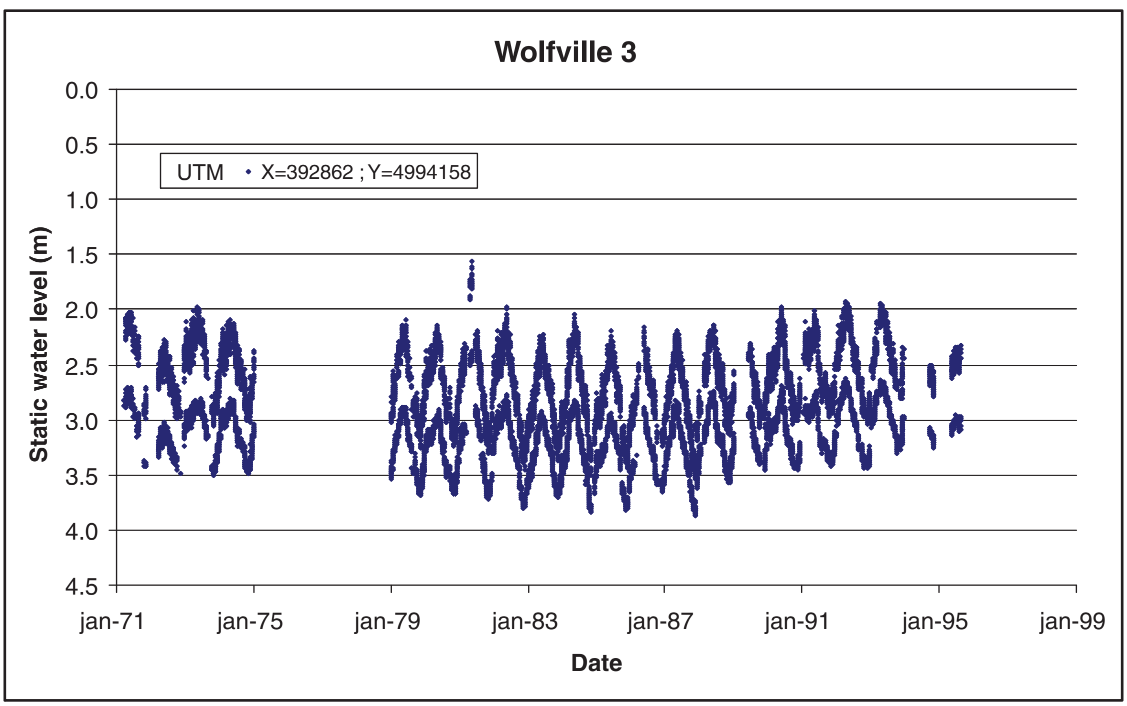

Coldbrook
UTM X=375555 ; Y=4991389
Static water level (m)
6
8
10
12
14
16
18
jan-64
jan-68
jan-72
jan-76
jan-80
jan-84
jan-88
jan-92
jan-96
Date


Sheffield Mills
UTM X=383889 ; Y=4998512
Static water level (m)
9
10
11
12
13
14
jan-67
jan-68
jan-69
jan-70
jan-71
jan-72
jan-73
jan-74
jan-75
jan-76
Date


Wilmot
UTM X=340012 ; Y=4979363
Static water level (m)
0.0
1.0
2.0
3.0
4.0
5.0
jan-68
jan-71
jan-74
jan-77
jan-80
jan-83
jan-86
jan-89
jan-92
jan-95
jan-98
Date


Wittenberg Farm
UTM X=384285 ; Y=4997741
Static water level (m)
0
1
2
3
4
5
jan-74
jan-78
jan-82
jan-86
jan-90
jan-94
jan-98
Date


Wolfville 1
UTM X=391899 ; Y=4993763
Static water level (m)
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
jan-69
jan-72
jan-75
jan-78
jan-81
jan-84
jan-87
jan-90
jan-93
Date


Wolfville 3
UTM X=392862 ; Y=4994158
Static water level (m)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
jan-71
jan-75
jan-79
jan-83
jan-87
jan-91
jan-95
jan-99
Date

Appendix I

Statistical distributions of hydraulic properties

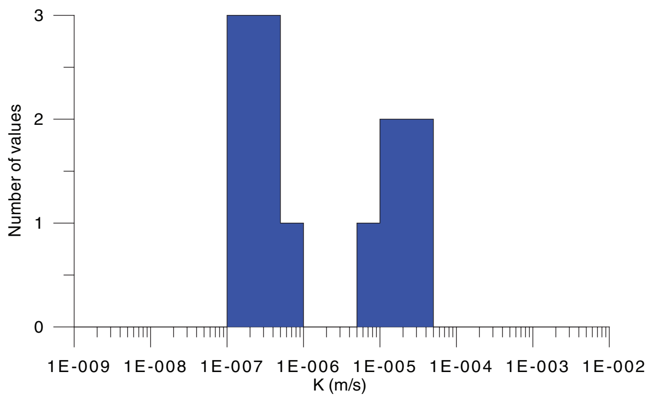


Figure I1. North Mountain Formation (7 values).

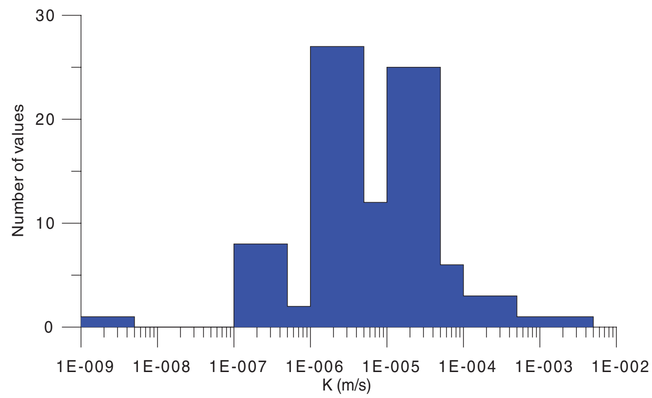


Figure I3. Wolfville Formation (86 values).

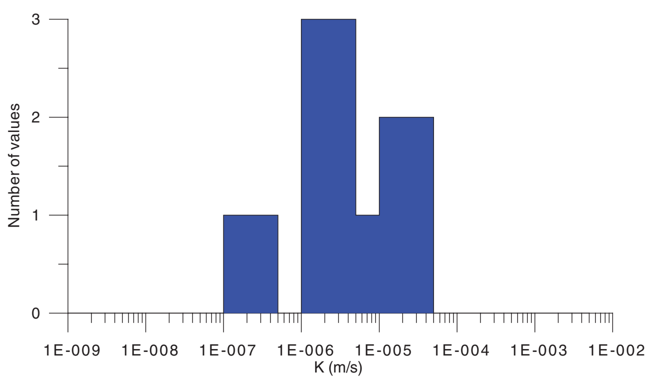


Figure I2. Blomidon Formation (7 values).

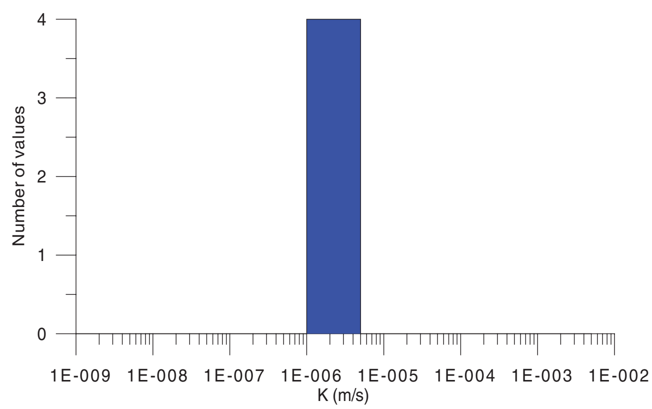


Figure I4. Horton Group (4 values).

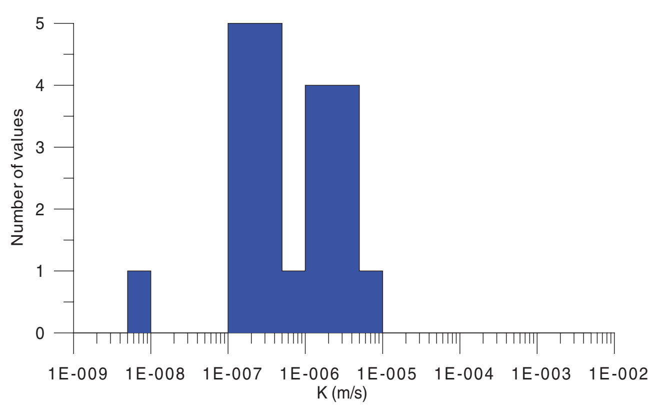


Figure I5. Meguma Group (10 values) and Annapolis Supergroup (2 values).

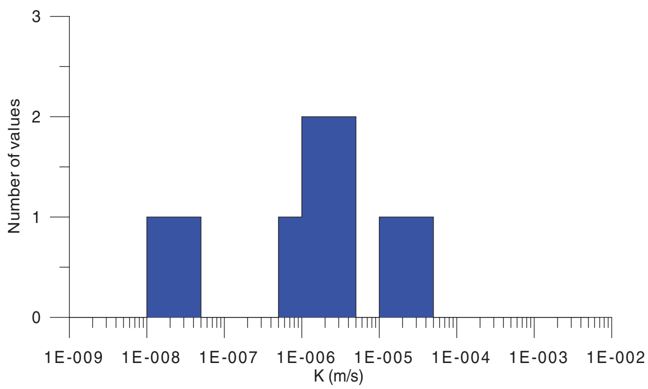


Figure I6. South Mountain batholith (5 values).

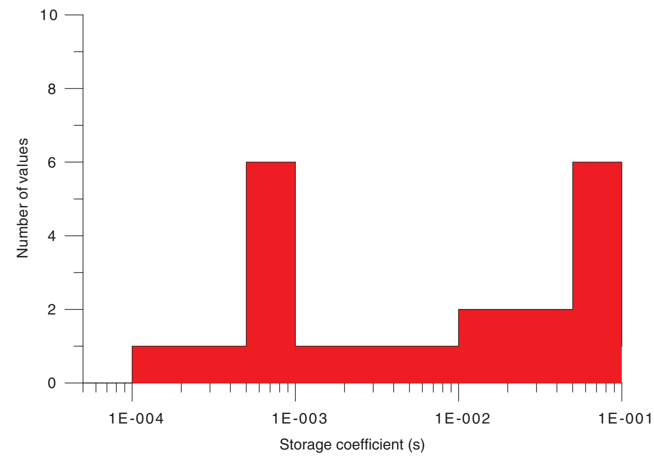


Figure I8. Storage coefficient - Sand and gravel units (18 values).

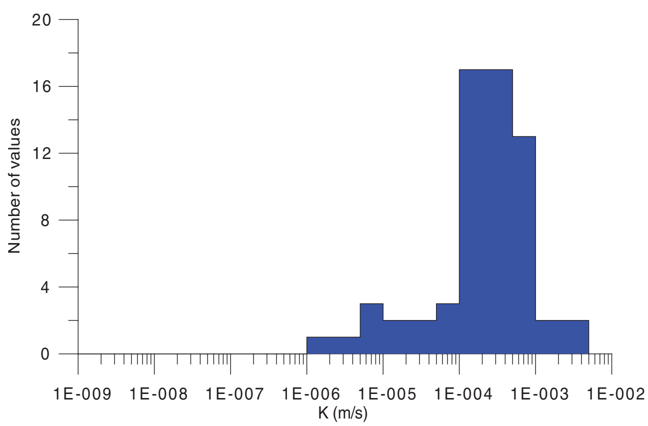


Figure I7. Hydraulic conductivity - Sand and gravel units (41 values).

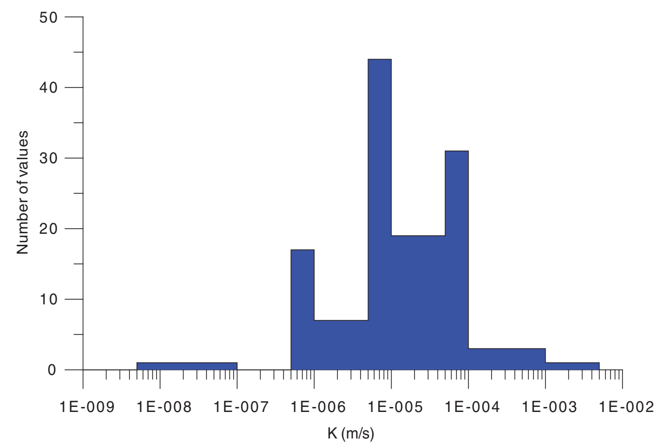


Figure I9. Hydraulic conductivity - All bedrock values (128 values).

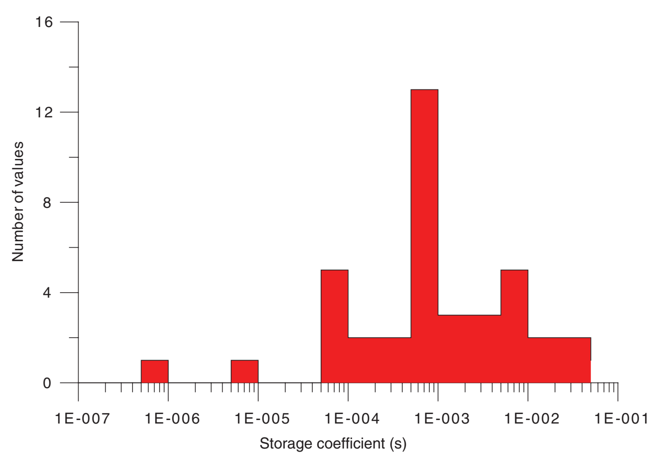


Figure I10. Storage coefficient - All bedrock values (33 values).

Appendix J

DRASTIC index ratings and weights

Table J-1. DRASTIC index ratings and weights for the 7 parameters (Aller et al., 1987).

Rating	Depth to water (m) D	Net Recharge (mm/a) R	Aquifer media A	Soil media S	Topography (% slope) T	Impact of the vadose zone I	Hydraulic Conductivity of the aquifer (m/s) C
1	30.5 +	0-50		Nonshrinking & Nonaggre-gated Clay	18 +	Confining aquifer	4.72E-07 – 4.72E-05
2	22.8-30.5		Massive shale (1 to 3)	Muck			4.72E-05 – 1.41E-04
3	15.2-22.8	50-102	Metamorphic / igneous (2 to 5)	Clay loam	12-18	Silt/clay (2 to 6) shale (2 to 5)	
4			Weathered metamorphic / igneous (3 to 5)	Silty loam		Metamorphic /igneous (2 to 8)	1.41E-04 – 3.30E-04
5	9.1-15.2		Glacial till (4 to 6)	loam	6-12		
6		102-178	Bedded sandstone, limestone & shale sequences (5 to 9) Massive sandstone (4 to 9) Massive limestone (4 to 9)	Sandy loam		Limestone (2 to 7) Sandstone (4 to 8) Bedded limestone, sandstone, shale (4 to 8) Sand & gravel with significant silt & clay (4 to 8)	3.30E-04 – 4.72E-04
7	4.6-9.1			Shrinking and/or aggregated clay			
8		178-254	Sand and gravel (4 to 9)	Peat		Sand & gravel (6 to 9)	4.72E-04 – 9.43E-04
9	1.5-4.6		Basalt (2 to 10)	Sand	2-6	Basalt (2 to 10)	
10	0-1.5	254 +	Karst limestone (9 to 10)	Thin or absent gravel	0-2	Karst limestone (8 to 10)	9.43E–04 +
Weight	**5**	**4**	**3**	**2**	**1**	**5**	**3**

Contents
This CD-ROM contains the full contents of Bulletin 598 in .pdf format, including any maps or oversized figures.

System requirements
PC with 486 or greater processor, or Mac® with OS® X v. 10.2.2 or later; Adobe® Reader® v. 6.0 (included for both PC and Mac) or later; video resolution of 1280 x 1024.

Quick start
This is a Windows®-based autoplay disk. Should the autoplay fail, navigate to the root of your CD-ROM drive and double-click on the autoplay.exe file. Mac® users must use this method to begin.

****

Contenu
Ce CD-ROM renferme le contenu intégral du Bulletin 598 en format .pdf, y compris les figures surdimensionnées ou les cartes, s'il y a lieu.

Configuration requise
PC avec processeur 486 ou plus rapide, ou Mac® avec OS® X v. 10.2.2 ou ultérieure; Reader® v. 6 d'Adobe® (fourni pour PC et Mac) ou version ultérieure; résolution vidéo de 1280 x 1024.

Démarrage rapide
Ceci est un disque à lancement automatique pour les systèmes d'exploitation Windows®. Si le lancement automatique ne fonctionne pas, allez au répertoire principal du CD-ROM et faites un double clic sur le fichier autoplay.exe. Les utilisateurs de systèmes Mac® doivent procéder de cette façon pour débuter la consultation.