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BULLETIN 589**

**Canadian Groundwater Inventory:
Regional hydrogeological characterization of
the south-central part of the Maritimes Basin**

**C. Rivard, Y. Michaud, C. Deblonde, V. Boisvert, C. Carrier,
R.H. Morin, T. Calvert, H. Vigneault, D. Conohan,
S. Castonguay, R. Lefebvre, A. Rivera, and M. Parent**



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PREFACE

Natural Resources Canada is currently developing a nationwide inventory of Canadian groundwater resources. This assessment, conducted at regional and national scales, is crucial for the effective management of groundwater resources from a sustainable development perspective. Indeed, increasing demands and costs to secure clean water and its decreasing availability in some areas have important social and economic consequences. The work presented here is a collaborative effort among municipal, provincial, federal, academic, and private stakeholders to address regional groundwater issues in a given region of eastern Canada.

Groundwater is a critical resource in the Atlantic provinces, where 91% of the rural population rely on it, compared with the national figure of 82%. In total, nearly 1.2 million people rely on groundwater for domestic needs, and municipal water use in the Atlantic provinces is increasing. Groundwater also supplies 90% of all water used for agriculture.

Over the last few years, there have been many concerns about the groundwater resources in Canada. These involve questions about their future sustainability and quality. The sustainability of groundwater resources faces a number of threats, of which overexploitation and surface contamination are certainly the most important. Depletion of groundwater reserves may be reflected in various ways, including water table decline, streamflow decreases, and loss of wetlands. Canadians want to ensure that there is an abundant, long-lasting supply of clean water for future generations. The Earth Sciences Sector of Natural Resources Canada is helping with the evaluation of available potable groundwater by mapping and studying major Canadian aquifers, and ensuring that there is a strong foundation of knowledge on which to base decisions.

The Maritimes Groundwater Initiative (MGWI) is a regional hydrogeological study that focuses on the south-central part of the Maritimes Basin. This basin includes some of the most productive aquifers in the country. The study area covered 14 000 km², including portions of three eastern Canadian provinces: New Brunswick, Nova Scotia, and Prince Edward Island. The MGWI project represents one of the largest regions characterized by the Earth Sciences Sector, and is a major contribution to the national inventory of groundwater resources.

The results of this study are aligned with a long-term mission to fill the knowledge gaps in the country's groundwater resources. Given its multiple scientific and institutional collaborations, this project is also well aligned with the priorities of the Earth Sciences Sector's Groundwater Program and the vision of the Canadian Framework for Collaboration on Groundwater. I would like to thank and 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

Ressources naturelles Canada élabore actuellement un inventaire national des ressources en eau souterraine du Canada. L'évaluation de ces ressources, aux échelles régionales et nationale, est cruciale pour leur saine gestion dans une perspective de développement durable. En effet, l'accroissement de la demande en eau et la hausse des coûts pour assurer un approvisionnement de bonne qualité peut avoir des conséquences économiques et sociales importantes dans les régions où la disponibilité de l'eau est limitée. Les travaux présentés dans ce bulletin sont le fruit d'un travail d'équipe considérable (incluant des groupes provenant des secteurs municipal, provincial, fédéral, universitaire et privé), visant à répondre aux questions relatives à l'eau souterraine dans une région donnée de l'Est du Canada.

L'eau souterraine est une ressource essentielle dans les provinces de l'Atlantique, étant donné que 91 % de la population rurale l'utilise, comparativement à la moyenne nationale qui est de 82 %. Au total, près de 1,2 million de personnes dépendent de la ressource pour leurs besoins domestiques, et la demande municipale de ces provinces ne cesse d'augmenter. L'eau souterraine fournit 90 % de toute l'eau requise pour le secteur de l'agriculture.

Depuis quelques années, des inquiétudes ont été émises au sujet des ressources en eau souterraine du Canada. Ces inquiétudes ont trait à la disponibilité continue et à la qualité de ces ressources dans l'avenir. La pérennité des ressources en eau souterraine fait face à plusieurs menaces, parmi lesquelles la surexploitation et la contamination de surface sont certainement les plus importantes. La diminution des réserves en eau souterraine peut se traduire de diverses façons, incluant la baisse du niveau des nappes, la réduction du débit des cours d'eau et la perte de milieux humides. Les Canadiens veulent pouvoir compter sur un approvisionnement abondant et de longue durée en eau propre pour les générations futures. Le Secteur des sciences de la Terre de Ressources naturelles Canada contribue à l'évaluation de la quantité disponible d'eau souterraine potable, en cartographiant et en étudiant les principaux aquifères du Canada, et en s'assurant que les connaissances nécessaires à une prise de décision éclairée soient disponibles.

L'« Initiative sur les eaux souterraines dans les Maritimes » (IESM) est une étude hydrogéologique régionale, s'intéressant à la portion centre sud du Bassin des Maritimes. Ce bassin recèle quelques-uns des aquifères les plus productifs du Canada. La zone d'étude couvrait 14 000 km², incluant des portions de trois provinces de l'Est du Canada : le Nouveau-Brunswick, la Nouvelle-Écosse et l'Île-du-Prince-Édouard. Le projet IESM représente une des plus vastes régions caractérisées jusqu'à maintenant par le Secteur des sciences de la Terre et constitue une contribution majeure à l'inventaire national des ressources en eau souterraine.

Les résultats de cette étude coïncident avec une mission à long terme de combler les lacunes dans nos connaissances concernant les ressources en eau souterraine du pays. Étant donné ses multiples collaborations scientifiques et institutionnelles, ce projet s'intègre bien aux priorités du programme « Les eaux souterraines » du Secteur des sciences de la Terre et à la vision du « Cadre canadien de collaboration en matière d'eau souterraine ». Je tiens à remercier et féliciter sincèrement les nombreux intervenants qui ont contribué à faire de ce projet un bel exemple de réussite collective.

Alfonso Rivera
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CONTENTS

Preface.	iii
Préface.	iv
Abstract/Résumé	1
Summary/Sommaire.	2
Introduction	8
Methodology	8
Selection of the study area	9
Data compilation	9
Fieldwork	9
Water-level measurements	9
Drilling	10
Geophysics	11
Borehole geophysics.	11
Electrical-resistivity soundings.	13
Ground-penetrating radar	14
Surface and marine surveys	14
Hydraulic testing	14
Pumping and slug tests	14
Packer tests	14
Permeameter and infiltrometer tests	15
Water, soil, and rock sampling	15
Water sampling.	15
Soil and rock sampling	16
Data analysis.	16
Reinterpretation of existing pumping tests	16
Groundwater recharge	16
Hydrograph-separation method	16
Water-balance method	17
Specific yields	18
Remote sensing.	18
Mapping	18
Numerical modelling	19
Description of the study area	19
Location	19
Physiography and hydrography	19
Climate	19
Land and water use.	20
Geology	21
Geological setting	21

Sedimentological and structural settings	22
Surficial sediments	22
Interpretation and presentation of existing and acquired hydrogeological data	25
Data from fieldwork	25
Piezometry and monitoring	25
Water-level surveys	25
Groundwater-level monitoring program.	25
Stratigraphy and fracturing	26
Drilling	26
Borehole geophysics.	26
Electrical-resistivity soundings.	29
Ground-penetrating radar	31
Hydraulic properties of the bedrock	31
Pumping tests	31
Packer tests	32
Hydraulic properties of Quaternary units	33
Pumping tests and slug tests in granular aquifers.	33
Permeameter and infiltrometer tests in glacial till	33
Slug tests in the peatland and underlying units	34
Saline intrusion.	34
Water and soil analysis, and rock-matrix porosity	36
Existing data	37
Groundwater recharge	37
Hydrograph-separation method	37
Water-balance method	38
Specific yields	39
Remote sensing.	40
Updating the regional geology	40
New compiled geological map	40
Regional representation of the upper three kilometres	40
Quaternary stratigraphy	42
Integration of hydrogeological information	42
General hydrogeological context	45
Hydrostratigraphic units of interest	47
Surficial sediments	47
Prince Edward Island Group	48
Richibucto Formation.	48
Boss Point Formation	49
Hillsborough Formation	49
Hydraulic properties of major aquifers.	49
Groundwater flow and water levels in bedrock aquifers	53
Monitoring wells and long-term behaviour	55
Hydrological budget	55
Aquifer recharge.	55

Groundwater use and specific capacity	56
Groundwater storage within the bedrock aquifers	59
Hydrological budget summary	59
Indication of aquifer vulnerability to surface contamination	59
Geochemistry	61
Overview of groundwater quality	61
Groundwater-quality issues	62
Regional picture of various chemical ions and parameters	63
Major and minor ions	63
Chloride	63
Fluoride	64
Iron	64
Manganese	64
Sodium	64
Sulphate	64
Trace metals	64
Arsenic	65
Barium	65
Lead	65
Selenium	65
Uranium	65
Nitrates	65
Acidity (pH), hardness, and total dissolved solids	66
Acidity (pH)	66
Hardness	66
Total dissolved solids	66
Summary	66
Seawater intrusion	66
Occurrence of saline intrusions in the Maritimes Basin	66
Location of the freshwater-saltwater interface	68
Case study: Beauséjour peatland near Shediac, New Brunswick	68
Hydrostratigraphic context	68
Potential interaction between the peatland and the regional aquifer	69
Potential groundwater contribution of the peatland to the regional bedrock aquifer	70
Hydrological impact study using modelling	70
Summary of potential interactions	70
Conceptual and numerical hydrogeological models	71
Hydrogeological conceptual model	71
Description of the numerical models and their properties	72
Two-dimensional models	75
General characteristics	75
Hydraulic properties	75
Boundary conditions	75
Results of 2-D modelling	76

Three-dimensional models	76
General characteristics	76
Hydraulic properties	77
Boundary conditions	77
Results of the 3-D modelling	78
Conclusions	79
Acknowledgments	81
References	82
Appendix A – Monitoring well locations and their fluctuations	87
Appendix B – Results obtained from packer tests	90
Appendix C – Water-level measurement variogram	93
Appendix D – Estimated recharge for the New Brunswick portion of the Maritimes Groundwater Initiative project	93
Appendix E – Cumulative distributions of specific capacity for major aquifer units	94
Appendix F – Log distributions of transmissivity for various geological formations	96

Figures

1. Location of the study area	9
2. Location of fieldwork sites	11
3. Core samples from diamond-drill hole, Légerville, New Brunswick	11
4. Location of sites investigated using borehole geophysics	12
5. Televiewer logs of sections of wells in a) Sackville, and b) Harcourt	13
6. Piezometer installation in Memramcook River valley, New Brunswick	15
7. Topography of the study area	20
8. Yearly average precipitation and air temperature, Moncton, New Brunswick	20
9. Spatial distribution of annual precipitation in the Maritimes	21
10. Location of subbasins of the Maritimes Basin and their stratigraphic succession	23
11. Hydrograph of Harcourt monitoring well, New Brunswick	26
12. Natural-gamma-activity and electrical-resistivity logs, Harcourt well, New Brunswick	27
13. Crossplot of gamma and resistivity data, Harcourt well, New Brunswick	27
14. Combined geophysical logs and packer test results, Harcourt well, New Brunswick	28
15. Rosette (strike) and equal-area stereographic plots of planar features in eight wells, Harcourt, New Brunswick	28
16. Location of Sackville, New Brunswick study	29
17. Rosette diagram of fracture strike, Sackville wells, New Brunswick	29
18. Pole-dipole-array electrical-resistivity survey, line 1, Sackville, New Brunswick	30
19. Pole-dipole-array electrical-resistivity survey, line 2, Sackville, New Brunswick	30

20.	Example of a pumping-test interpretation, Sackville, New Brunswick	31
21.	Comparison of transmissivity results, Fort Lawrence well, Nova Scotia.	32
22.	Location of electrical-resistivity lines, Shediac Bay, New Brunswick.	34
23.	Wenner-array electrical-resistivity survey, Cap Brûlé, New Brunswick	34
24.	Pole-dipole-array electrical-resistivity survey, Cap Brûlé, New Brunswick	35
25.	Location of electrical-resistivity lines, Rustico Bay area, Prince Edward Island	35
26.	Pole-dipole-array electrical-resistivity survey, Blue Bay Farms Road, Prince Edward Island . . .	36
27.	Visual estimation of porosity from thin-sections, Moncton Basin	37
28.	Comparison of three methods used for estimation of base flows	37
29.	Simplified geological map of the study area	40
30.	Simplified block diagram of a representative area of the Maritimes Basin	41
31.	Location of the detailed Quaternary-sediment study	43
32.	Location of drilling sites and geological cross-sections, Quaternary-sediment study	43
33.	Bedrock topography of the Moncton area, New Brunswick	44
34.	Geological cross-section A-A', northwest of Moncton, New Brunswick	44
35.	Geological cross-section E-E', Petitcodiac River, New Brunswick	45
36.	Geological cross-section B-B', Memramcook River valley, New Brunswick	45
37.	Distribution of good, variable, and poor potential aquifers in the study area.	48
38.	Hydraulic-conductivity values for hydrostratigraphic units in the Maritimes Basin	51
39.	Distribution of hydraulic-conductivity values in the study area.	52
40.	Distribution of storage-coefficient and specific-yield values in the study area	52
41.	Piezometric map of the bedrock aquifers in the study area.	54
42.	Monthly fluctuations of groundwater levels, Kensington provincial monitoring well, Prince Edward Island	55
43.	Regional picture of potential groundwater use in the study area	57
44.	Distribution of water use in New Brunswick	57
45.	Cumulative distribution of specific capacity for major hydrostratigraphic units	58
46.	Schematic annual hydrological budget for the Maritimes Basin	59
47.	Hydrological budget for the Maritimes Basin	60
48.	Aquifer-vulnerability indication map for the Maritimes	60
49.	Piper diagrams showing composition of groundwater for a) New Brunswick, and b) Prince Edward Island.	62
50.	Beauséjour peatland and surrounding region used for the case study	69
51.	Responses to precipitation events in the various layers of the Beauséjour peatland	70
52.	Schematic conceptual model of the Maritimes Basin, showing regional, local, and point scales.	72
53.	Distribution of hydrogeological units represented in the numerical model	74
54.	Modelled cross-section of Prince Edward Island	75
55.	Modelled piezometric map for the study area	79

Tables

1.	Summary of existing data for the study area	10
2.	Summary of field data acquired during the study	10
3.	Climatic conditions in the Maritimes	21
4.	Composite table describing lithological units of the Maritimes Basin	24
5.	Specifications of new boreholes drilled in bedrock during the study	26
6.	Specifications of wells where geophysical logs were recorded during the study	27
7.	Summary of pumping tests performed during the study	32
8.	Hydraulic conductivity values obtained from packer tests	33
9.	Annual recharge rates estimated using three methods of hydrograph separation	38
10.	Water-balance recharge estimates for geological units in the study area	38
11.	Estimation of specific yields, Prince Edward Island	39
12.	Aquifer potential of the main hydrostratigraphic units in the study area	47
13.	Summary of hydraulic-conductivity and storage-coefficient values	50
14.	Total water use and groundwater use by sector, New Brunswick	58
15.	Summary of groundwater-sampling results, New Brunswick and Prince Edward Island	67
16.	Main characteristics of the surficial sediments and rock units in the study area	73
17.	Characteristics of each conceptual model scale	74
18.	Characteristics and conditions of 2-D models	76
19.	Characteristics and conditions of 3-D models	77
20.	Combination of possible values for the numerical model	77
21.	Summary of recharge rates for the study area	78

Canadian Groundwater Inventory: Regional hydrogeological characterization of the south-central part of the Maritimes Basin

Abstract

The Maritimes Groundwater Initiative (MGWI) is a large, integrated, regional hydrogeological study focusing on a representative area of the Maritimes Basin in eastern Canada. The study area covers a land surface of 10 500 km², of which 9 400 km² are underlain by sedimentary rocks. This sedimentary bedrock is composed of a sequence of discontinuous strata of highly variable hydraulic properties, and is generally overlain by a thin layer of glacial till (mostly 4–8 m thick, but can reach 20 m). Depending on the area, 46 to 100% of the population relies on groundwater for water supply, either from municipal wells or from private residential wells. 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. This bulletin presents the current state of understanding of this hydrogeological system, along with the methodology used to characterize and analyze its distinct behaviour at three different scales.

This regional bedrock aquifer system contains confined and unconfined zones, and each of its lenticular permeable strata extends only a few kilometres. Preferential groundwater recharge occurs where sandy till is present. The mean annual recharge rate to the bedrock is estimated to range between 130 and 165 mm/a. Several geological formations of this basin provide good aquifers, with hydraulic conductivity in the range 5×10^{-6} to 10^{-4} m/s. Based on results of numerical flow modelling, faults were interpreted to have a key role in the regional flow. Pumping-test results revealed that the fractured aquifers can locally be very heterogeneous and anisotropic, but behave similarly to porous media. Work performed at the local scale indicated that most water-producing fractures seem to be subhorizontal and generally oriented in a northeasterly direction, in agreement with regional structures and pumping-test results. Almost all residential wells are shallow (about 20 m) open holes that are cased only through the surficial sediments.

Résumé

L'« Initiative sur les eaux souterraines dans les Maritimes » (IESM) est une vaste étude hydrogéologique intégrée à l'échelle régionale s'intéressant à une portion représentative du Bassin des Maritimes dans l'Est du Canada. La région à l'étude couvre approximativement 10 500 km², dont 9 400 km² possèdent une assise de roches sédimentaires. Ce socle sédimentaire est composé d'une succession de strates discontinues dont les propriétés hydrauliques sont très variables. Le socle rocheux est habituellement recouvert d'une mince couche de till glaciaire (d'une épaisseur de 4 à 8 m en général, mais qui peut atteindre 20 m). Selon le secteur, de 46 à 100 % de la population dépend de l'eau souterraine pour son approvisionnement en eau, que ce soit par l'entremise de puits municipaux ou de puits résidentiels privés. Les principaux objectifs du projet consistaient à améliorer la compréhension de la dynamique de l'écoulement de l'eau souterraine et à fournir de l'information de base et des outils pour l'évaluation des ressources en eau souterraine à l'échelle régionale. Ce bulletin présente l'état de compréhension actuel de ce système hydrogéologique, avec la méthodologie utilisée pour caractériser et analyser son comportement distinct à trois échelles différentes.

Ce système aquifère régional en milieu rocheux renferme des zones à nappe captive et des zones à nappe libre et chacune de ses strates perméables de forme lenticulaire s'étend sur seulement quelques kilomètres. Une recharge préférentielle se produit là où du till sableux est présent. Le taux de recharge annuel moyen a été estimé être de l'ordre de 130 à 165 mm/a. Plusieurs formations géologiques de ce bassin constituent de bons aquifères, avec des conductivités hydrauliques de 5×10^{-6} à 1×10^{-4} m/s. À partir des résultats des modèles numériques de l'écoulement, il est apparu que les failles jouent un rôle majeur dans l'écoulement régional. Les essais de pompage ont révélé que les aquifères en milieu fracturé peuvent localement être très hétérogènes et anisotropes, mais se comportent de manière semblable à un milieu poreux. Les travaux réalisés à l'échelle locale ont indiqué que la majorité des fractures dans lesquelles l'eau circule sont faiblement inclinées et présentent généralement une direction nord-est, en accord avec les structures régionales et les résultats d'essais de pompage. Presque tous les puits résidentiels sont constitués de trous ouverts peu profonds (environ 20 m), tubés seulement dans l'intervalle supérieur occupé par les formations superficielles.

SUMMARY

The Maritimes Groundwater Initiative (MGWI) is a large integrated hydrogeological study focusing on a representative area of the Maritimes Basin (eastern Canada), where some of the most productive aquifers in Canada are found. This project falls within the framework of the national inventory of groundwater resources in Canada, carried out by the Geological Survey of Canada (GSC) in co-operation with provincial authorities. The study area covers a land surface of 10 500 km², of which 9 400 km² are underlain by sedimentary rocks (from Middle Devonian to Early Permian), and includes parts of New Brunswick, Nova Scotia, and Prince Edward Island. In these Maritime provinces, groundwater is a very important source of water supply. Depending on the province, 46 to 100% of the population relies on groundwater, mainly from fractured-rock aquifers. Groundwater is exploited both by municipal wells and by shallow (20 m deep on average) private residential wells that are 15 cm (6 inch) open boreholes in the bedrock and cased only through the surficial sediments. The main objectives of the MGWI project were to improve the general understanding of groundwater-flow dynamics within the major aquifers of this basin and to provide baseline information for a regional groundwater-resource assessment. This bulletin presents the current state of understanding of this hydrogeological system, along with the methodology used to characterize and analyze its distinct behaviour at three different scales.

This study is based on a common methodology for regional hydrogeology characterization (i.e. mostly using existing data, as new fieldwork could not cover the entire study area in detail). A thorough review of available relevant reports and studies, provincial databases, thematic maps, and scientific papers was done in order to develop a preliminary understanding of the hydrogeological setting. All these data (once validated) were compiled into thematic databases (geochemical, hydrogeological, climatic), which ensured optimal data manipulation and integrity, and their availability for all stakeholders. Fieldwork was carried out during two summers to gather additional data on stratigraphy, hydraulic properties, fracturing, and groundwater characteristics in specific areas, to fill the main gaps in information coverage.

The Maritimes Basin is located at the eastern edge of the Appalachian physiographic region. The topography of the basin is relatively flat. Because of the low relief of the basin, the major influence on the climate is the distance to the sea. Precipitation varies from 900 to 1500 mm/a, and averages 1100 mm/a.

SOMMAIRE

L'« Initiative sur les eaux souterraines dans les Maritimes » (IESM) est une vaste étude hydrogéologique intégrée à l'échelle régionale s'intéressant à une portion représentative du Bassin des Maritimes dans l'Est du Canada, où sont situés quelques-uns des aquifères les plus productifs du Canada. Ce projet a été entrepris dans le cadre de l'inventaire national des ressources en eau souterraine au Canada mené par la Commission géologique du Canada (CGC), en collaboration avec les autorités provinciales. La région à l'étude couvre approximativement 10 500 km², dont 9 400 km² possèdent une assise de roches sédimentaires (s'échelonnant en âge du Dévonien moyen au Permien précoce), et inclut une partie du Nouveau-Brunswick, de la Nouvelle-Écosse et de l'Île-du-Prince-Édouard. Dans ces Provinces maritimes, l'eau souterraine est une source très importante d'approvisionnement en eau. Selon la province, de 46 à 100 % de la population dépend de l'eau souterraine, provenant principalement d'aquifères de roches fracturées. L'eau souterraine est extraite à l'aide de puits municipaux ainsi que de puits résidentiels peu profonds (20 m de profondeur en moyenne), qui consistent en trous ouverts de 15 cm (6 pouces) pénétrant le socle rocheux et tubés seulement dans l'intervalle supérieur occupé par les formations superficielles. Les principaux objectifs du projet IESM visaient à améliorer la compréhension de la dynamique de l'écoulement de l'eau souterraine à l'intérieur des principaux aquifères de ce bassin et à fournir de l'information de base pour l'évaluation des ressources en eau souterraine à l'échelle régionale. Ce bulletin présente l'état des connaissances actuelles de ce système hydrogéologique, avec la méthodologie utilisée pour caractériser et analyser son comportement distinct à trois échelles différentes.

Cette étude s'appuie sur une méthodologie couramment utilisée dans la caractérisation hydrogéologique à l'échelle régionale, soit une approche fondée principalement sur l'utilisation de données existantes, puisque de nouveaux travaux de terrain ne peuvent pas couvrir l'ensemble de la zone d'étude en détail. Une revue exhaustive des données existantes a donc été effectuée, incluant les rapports, études, bases de données provinciales, cartes thématiques et articles scientifiques, de façon à développer une compréhension préliminaire du contexte hydrogéologique. Toutes ces données (une fois validées) ont été compilées dans des bases de données thématiques (géochimie, hydrogéologie, climat) qui assuraient une manipulation et une intégrité optimales, et une disponibilité à tous les intervenants. Les travaux de terrain ont été effectués durant deux étés, de façon à acquérir des données additionnelles sur la stratigraphie, les propriétés hydrauliques, la fracturation et les caractéristiques de l'eau souterraine à des endroits spécifiques pour combler les lacunes dans la couverture de l'information.

Le Bassin des Maritimes est situé à l'extrême est de la région physiographique des Appalaches. La topographie de ce bassin est peu accidentée. En raison de son faible relief, l'influence majeure pour le climat est la distance avec l'océan. Les précipitations varient de 900 à 1 500 mm/a, avec une moyenne de 1 100 mm/a.

This basin is a composite post-Acadian successor basin consisting of a series of sedimentary subbasins, which unconformably overlie a complex collage of pre-Carboniferous terranes. Subbasins trend generally northeast to east and are separated by basement uplifts along large regional faults. The stratigraphic column is composed, from base to top, of the following main groups: Horton, Windsor, Riversdale-Mabou, Cumberland, Pictou, and Prince Edward Island.

The sedimentary bedrock of the Maritimes Basin is composed of a sequence of discontinuous (lenticular) strata of highly variable hydraulic properties, and is generally overlain by a thin layer of glacial till (mostly 4–8 m). These fractured rocks are highly stratified, consisting mainly of sequences of sandstone, shale, siltstone, and conglomerate that appear in varying proportions in each geological formation. Individual beds range in thickness from a few centimetres to several metres, and their extent is variable. Layer transmissivities are closely related to open-fracture densities. Fractures have been noted in all rock types but are encountered mainly in sandstone layers and along lithological contacts and bedding-plane partings. A moderate to high number of small vertical fractures likely intersects the latter. Variable hydraulic properties of the various strata imply that some bedrock units act as aquifers, whereas others behave more like aquitards.

Several bedrock formations were identified as major hydrostratigraphic units to be prioritized within this project, based on their productivity and proximity to main urban centres. These formations, from the youngest to the oldest, are those of the Prince Edward Island Group, the Richibucto Formation (Pictou Group), the Boss Point Formation (Cumberland Group), and the Hillsborough Formation (Windsor Group). The aquifer potential of these four units varies from good to ‘variable’.

Formations included in the Prince Edward Island Group have a high percentage of sandstone, therefore providing very good aquifers with reported hydraulic conductivities (K) ranging between 4.3×10^{-6} and 2.5×10^{-3} m/s. Variable proportions of siltstone, breccia, and conglomerate are also present. The Richibucto Formation is composed mainly of sandstone interbedded with red mudrock. This formation has a good aquifer potential, with K varying from 1.4×10^{-6} to 1.9×10^{-4} m/s. The Boss Point Formation comprises mostly buff or light grey sandstone and conglomerate, with subordinate sandstone and mudstone interbeds; it usually has good aquifer potential ($1.1 \times 10^{-6} < K < 3.8 \times 10^{-5}$ m/s), but poorer hydrogeological conditions can also be found. Lastly, the Hillsborough Formation consists mainly of red conglomerate, grit, and sandstone with minor mudstone; its aquifer potential is highly variable ($1.6 \times 10^{-8} < K < 1.2 \times 10^{-5}$ m/s).

Le Bassin des Maritimes est un bassin successeur composite post-acadien constitué d’une série de sous-bassins sédimentaires, reposant en discordance sur un collage complexe de terranes pré-carbonifères. Les sous-bassins présentent en général une direction nord-est à est, et sont séparés par des soulèvements du socle le long de grandes failles régionales. La colonne stratigraphique est constituée, de la base au sommet, des groupes suivants : Horton, Windsor, Riversdale-Mabou, Cumberland, Pictou et Prince Edward Island.

Les roches sédimentaires du Bassin des Maritimes sont composées d’une succession de strates discontinues (lenticulaires) ayant des propriétés hydrauliques très variables; elles sont généralement recouvertes d’une mince couche (le plus souvent de 4 à 8 m) de till glaciaire. Ces roches fracturées sont très stratifiées, étant principalement constituées de séquences de grès, de shale, de siltstone et de conglomérat qui apparaissent en proportions variables dans chaque formation. Les couches individuelles varient en épaisseur de quelques centimètres à plusieurs mètres, et leur étendue est variable. La transmissivité des strates est intimement liée à la densité de fractures ouvertes. Des fractures ont été observées dans tous les types de roches. Cependant, les fractures sont surtout observées dans les strates gréseuses, ainsi que le long des contacts lithologiques et des plans de litage. Une densité moyenne à élevée de petites fractures verticales intersecte vraisemblablement les structures parallèles à la stratification. La variabilité des propriétés hydrauliques des différentes strates implique que certaines unités agissent comme aquifères, alors que d’autres comme s’apparentent davantage à des aquitards.

Plusieurs formations du socle rocheux ont été identifiées comme unités hydrostratigraphiques majeures, et donc priorisées dans le cadre de ce projet, suivant leur productivité et leur proximité des centres urbains. Ces formations, de la plus récente à la plus ancienne, sont : les formations du Groupe de Prince Edward Island, la Formation de Richibucto (Groupe de Pictou), la Formation de Boss Point (Groupe de Cumberland) et la Formation de Hillsborough (Groupe de Windsor). Le potentiel aquifère de ces quatre unités varie de bon à « variable ».

Les formations incluses dans le Groupe de Prince Edward Island possèdent un fort pourcentage de grès, fournissant de ce fait de bons aquifères dont les valeurs de conductivité hydraulique (K) signalées s’étalent de $4,3 \times 10^{-6}$ à $2,5 \times 10^{-3}$ m/s. Différentes proportions de siltstone, de brèche et de conglomérat sont aussi présentes. La Formation de Richibucto est constituée principalement de grès interlités de mudrocks rouges. Cette formation possède un bon potentiel aquifère, les valeurs de K variant de $1,4 \times 10^{-6}$ à $1,9 \times 10^{-4}$ m/s. La Formation de Boss Point comprend principalement des grès et des conglomérats chamois ou gris clair, accompagnés de quelques interlits de grès et de mudstone. Le potentiel aquifère de cette formation est généralement bon ($1,1 \times 10^{-6} < K < 3,8 \times 10^{-5}$ m/s), mais des conditions hydrogéologiques moins favorables peuvent aussi être rencontrées. Enfin, la Formation de Hillsborough est majoritairement composée de conglomérats, de grès à granules et de grès ainsi que d’une faible quantité de mudstones de couleur rouge. Son potentiel aquifère est très variable ($1,6 \times 10^{-8} < K < 1,2 \times 10^{-5}$ m/s).

Surficial sediments of the Maritimes Basin are composed mainly of till and glaciofluvial deposits. The dominant till unit cannot be considered an aquifer due to its limited saturated thickness and relatively low permeability. Sandy and gravelly unconsolidated sediments, known to be excellent aquifers, are restricted to very limited locations within the study area. Nevertheless, the till layer plays a major role in the basin, as most of the recharge supplying bedrock aquifers infiltrates through this layer. Its thickness usually varies between 0 and 20 m, and its composition is closely related to the underlying geological formation. Very few data were available to characterize tills of this region. Their hydraulic conductivities were estimated in this project using a double-ring infiltrometer and a Guelph permeameter.

In terms of hydraulic properties, there are three main types of till. The first type, associated with a poorly permeable formation (Salisbury Formation), is characterized by a silty matrix and an average hydraulic conductivity (K) of 6.5×10^{-9} m/s. The second type, generally sandy, is associated with the Boss Point Formation and has an average K of 1.3×10^{-6} m/s. The third type of till corresponds to the deposits overlying the Richibucto Formation: the till layer presents about 40 cm of sandy till with a K of 1.4×10^{-6} m/s overlying a silty-sandy till unit with a K of 5.3×10^{-8} m/s.

Pumping-test results revealed that the aquifers can locally be very heterogeneous and anisotropic, resulting in significant channelling. The tests revealed, however, that the investigated sites behaved similarly to porous media. The presence of less permeable boundaries was detected after some or several hours of pumping in many cases, confirming the limited extent of the lenticular permeable layers. All techniques indicated that most water-bearing fractures seem to be subhorizontal (with a dip smaller than 30°) and generally oriented in a northeasterly (045°) direction, which is in agreement with regional structures. The large number of subhorizontal fractures striking in a northeasterly direction seems to impart a quasi-horizontal two-dimensional (2-D) flow, with a preferential component along strike. Indeed, during pumping, observation wells located close to 045° from the pumping well reacted very strongly. As this orientation drifted farther from 045° , the observation well drawdown decreased.

Three different approaches to evaluating the aquifer recharge were used in this study: hydrograph separation, the water-balance method, and modelling. Groundwater recharge values obtained from hydrograph separation vary widely, from 92 to 436 mm/a, but watersheds for which data were available are located only in the most permeable formations (i.e. Richibucto Formation, undivided Pictou Group, Boss Point Formation, and the formations of the Prince Edward Island Group). The water-balance method yielded values

Les formations superficielles du Bassin des Maritimes sont principalement composées de till et de sédiments fluvioglaciaires. L'unité de till dominante ne peut généralement pas être considérée comme un aquifère dû à sa mince épaisseur saturée et à sa perméabilité relativement faible. Les sédiments sableux et graveleux non consolidés, reconnus comme de bons aquifères, ne sont présents qu'en de très rares endroits de la zone d'étude. Néanmoins, la couche de till joue un rôle majeur dans le bassin, car la majeure partie de la recharge se fait par infiltration au travers de cette couche. Son épaisseur varie en moyenne de 0 à 20 m, et sa composition est étroitement liée à celle de la formation géologique sous-jacente. Très peu de données étaient disponibles pour caractériser les tills de cette région. Leurs conductivités hydrauliques ont été estimées durant ce projet en utilisant un infiltromètre à double anneau et un perméamètre de Guelph.

Du point de vue des propriétés hydrauliques, il existe trois types de tills. Le premier type est associé à une formation très peu perméable (Formation de Salisbury); il est caractérisé par une matrice silteuse et une conductivité hydraulique (K) moyenne de $6,5 \times 10^{-9}$ m/s. Le deuxième type, généralement sableux, est associé à la Formation de Boss Point et présente une valeur moyenne de K de $1,3 \times 10^{-6}$ m/s. Enfin, le troisième type correspond aux sédiments surmontant la Formation de Richibucto; la couche de till est formée d'un till sableux d'une épaisseur d'environ 40 cm présentant une valeur de K de $1,4 \times 10^{-6}$ m/s, qui surmonte un till silto-sableux avec une valeur moyenne de K égale à $5,3 \times 10^{-8}$ m/s.

Les résultats des essais de pompage ont confirmé que les aquifères peuvent être par endroits très hétérogènes et anisotropes, entraînant une canalisation importante. Cependant, les essais ont également révélés que le comportement relevé aux sites étudiés est semblable à celui d'un milieu poreux. Dans plusieurs cas, la présence de frontières moins perméables a été détectée après quelques ou plusieurs heures de pompage, confirmant l'étendue limitée des couches perméables lenticulaires. Toutes les techniques utilisées ont indiqué que des fractures dans lesquelles l'eau circule semblent être majoritairement subhorizontales (avec un pendage inférieur à 30°) et généralement dirigées vers le nord-est (045°), en accord avec les structures régionales. Le nombre élevé de fractures subhorizontales de direction nord-est tend à engendrer un écoulement quasi horizontal (2D), ayant une composante préférentielle à 045° . En effet, durant le pompage, des puits d'observation situés à proximité d'une ligne à 045° par rapport au puits de pompage ont réagi très fortement. À mesure que cette orientation s'éloignait de 045° , l'importance du rabattement dans les puits diminuait rapidement.

Trois approches différentes pour évaluer la recharge de l'aquifère ont été utilisées dans cette étude : la séparation de l'hydrogramme, la méthode du bilan hydrique et la modélisation. Les valeurs de la recharge obtenues à partir de la première approche varient entre 92 et 436 mm/a. Toutefois, les bassins versants pour lesquels on disposait de données étaient situés uniquement dans les formations les plus perméables (c.-à-d. la Formation de Richibucto, le Groupe de Pictou non divisé, la Formation de Boss Point et les formations du Groupe de Prince Edward Island). Les valeurs estimées avec la méthode du bilan hydrique varient entre 33 et 310 mm/a, en

varying between 33 and 310 mm/a, with minimum, mean, and maximum weighted averages over the study area of 114, 184, and 251 mm/a, respectively, depending on values attributed to each parameter during the process. Using piezometric surveys and vertical gradients, it was determined that between 11 and 29% of the region is probably under artesian conditions or represents discharge areas. Therefore, an average of 130 to 165 mm/a is considered representative of groundwater recharge for the study area.

Values estimated for the hydrological budget are as follows: the annual recharge corresponds to 13.5% of the annual total precipitation, while 48.5% goes to runoff and 38% to evapotranspiration. According to available data, the total groundwater withdrawal represents only 0.5% of the total precipitation or 4% of the recharge. In comparison with other parts of the country and worldwide, the Maritimes Basin seems privileged in regard to the annual aquifer recharge and, on a regional basis at least, exploitation of this resource is small compared to the mean recharge rate.

The piezometric map obtained from the kriging of water-level measurements showed that the piezometric surface generally follows the surface topography, and that groundwater within both surficial sediments and fractured bedrock can be considered hydraulically connected with surface water at the regional scale. Water levels, obtained from the most recent existing data (of the last 5 years) and GSC field campaigns, vary from artesian-flowing conditions to depths that can reach more than 50 m, with an average depth (median) of 6.7 m. This piezometric map shows that groundwater generally flows toward the ocean, but that watersheds of large rivers such as the Petitcodiac River have a significant influence on groundwater flow. The highest hydraulic heads for the study area are located in topographic highs. These major hydraulic domes do not necessarily correspond to major recharge zones, as their hydraulic conductivity is sometimes very low. Preferential aquifer recharge areas are instead associated with sandy-till covers. The horizontal hydraulic gradient is usually gentle, being smaller than 0.01. This regional potentiometric map thus provides a portrayal of the upper part of the system's bedrock aquifers, sometimes under confined and sometimes under unconfined conditions.

Geochemical data indicate that the great majority of wells located in both New Brunswick and Prince Edward Island (no data were available for Nova Scotia) have groundwater of very good quality in terms of major ions and trace metals, but nitrates are of concern in Prince Edward Island. Electrical-resistivity-sounding results for two distinct regions in New Brunswick and Prince Edward Island showed that the shallow salt-water-freshwater interface can be located anywhere between 0 and 100 m inland in New Brunswick but up

fonction des valeurs attribuées à chaque paramètre durant le processus, avec des valeurs minimale, moyenne et maximale des moyennes pondérées correspondant respectivement à 114, 184 et 251 mm/a. En utilisant les levés piézométriques et les gradients verticaux, il a été évalué qu'entre 11 et 29 % du territoire est probablement sous condition artésienne ou représente des zones d'émergence (décharge). Une fourchette de valeurs allant de 130 à 165 mm/a est donc considérée représentative de la recharge en eau souterraine pour la région d'étude.

Les valeurs estimées pour le bilan hydrologique sont les suivantes : la recharge annuelle correspond à 13,5 % des précipitations totales annuelles, tandis que 48,5 % de l'eau s'écoule par ruissellement et 38 % est perdu par évapotranspiration. Selon les données disponibles, le prélèvement d'eau souterraine ne représente que 0,5 % des précipitations totales ou 4% de la recharge. En comparaison avec d'autres aquifères canadiens et ailleurs dans le monde, le Bassin des Maritimes apparaît privilégié en ce qui concerne la recharge annuelle et, à l'échelle régionale à tout le moins, l'exploitation de cette ressource est faible comparativement au taux de recharge moyen.

La carte piézométrique obtenue à partir du krigeage des mesures de niveau d'eau a montré que la surface piézométrique suit généralement la topographie de la surface du sol et que l'eau souterraine circulant dans les sédiments de surface et le roc fracturé peut être considérée hydrauliquement connectée avec l'eau de surface à l'échelle régionale. Les niveaux d'eau, provenant des données existantes les plus récentes (les 5 dernières années) et des campagnes de terrain de la CGC, varient de plus de 50 m de profondeur à artésien, avec une moyenne (médiane) de 6,7 m. Cette carte piézométrique a aussi montré que l'eau souterraine s'écoule en général vers l'océan, mais que les bassins versants de rivières importantes telle que la Petitcodiac ont une grande influence sur l'écoulement de l'eau souterraine. Dans la région d'étude, les charges hydrauliques les plus élevées sont situées sur les hauteurs topographiques, mais ces dômes hydrauliques ne correspondent pas nécessairement à des zones de recharge majeures, car leur conductivité hydraulique est souvent très faible. Les aires de recharge préférentielles des aquifères sont plutôt associées aux zones couvertes de till sableux. Le gradient hydraulique horizontal est habituellement faible (inférieur à 0,01). Cette carte potentiométrique régionale nous fournit une image de la partie supérieure des aquifères rocheux du système, qui sont soumis tantôt à des conditions de nappe captive et tantôt à celles de nappe libre.

Les données géochimiques indiquent que la grande majorité des puits du Nouveau-Brunswick et de l'Île-du-Prince-Édouard (aucune donnée n'était disponible pour la Nouvelle-Écosse) a une eau de très bonne qualité en ce qui a trait aux ions majeurs et aux métaux traces, mais les concentrations de nitrates retrouvées à l'Île-du-Prince-Édouard sont inquiétantes. Les sondages de résistivité électrique effectués dans deux secteurs distincts au Nouveau-Brunswick et à l'Île-du-Prince-Édouard ont montré que l'interface entre l'eau salée et l'eau douce se situe entre 0 et 100 m à l'intérieur des terres au Nouveau-Brunswick, mais jusqu'à 200 m à l'intérieur

to 200 m inland in an estuary of Prince Edward Island, thus representing a potential problem of brackish water in nearshore wells in certain areas. Based on the till-layer composition and recharge rates, the territory investigated was assigned a low, moderate or high level of vulnerability. Only the formations of the Prince Edward Island Group and the Boss Point Formation were classified as highly vulnerable to surface contamination, due to their sandy matrix cover.

Because of the large area covered by this study and the inherent heterogeneity of the Maritimes Basin, only conceptual and simplified 2-D and 3-D numerical flow models were developed. A three-scale graphical conceptual model was created in order to integrate the knowledge acquired through this study: regional (the entire study area), local (scale of a pumping test), and point scales. Numerical models were developed in 2-D with SEEP/W[®] and in 3-D with FEFLOW[®], two finite-element numerical simulators, using steady-state conditions to obtain a quantitative representation of the hydrogeological-system dynamics. Even if the Maritimes Basin is a fractured porous medium, it was assumed (based on pump-test results) that fractures and faults are sufficiently connected to provide a relatively homogeneous flow system at the regional scale that can be treated as onto an equivalent porous medium.

The simplified 2-D and 3-D models were developed using only the dominant formation for a given region and a horizontally stratified medium with homogeneous properties for each layer (since hydraulic conductivities decrease with depth). The first layer of each hydrostratigraphic unit was assigned a hydraulic conductivity (K) value based on the geometric mean of pumping-test results. The subsequent layers were assigned K values according to reported porosities. Probable recharge rates were also assigned to each formation or group, based on results from the prior study on recharge. Due to a lack of information and uncertainty about the till thickness in many areas, a constant-thickness till layer was assumed at this scale, and K values obtained in the field were assigned. Modelling validated the estimated ranges of hydraulic conductivity and recharge values previously found, and confirmed the potentially important role of faults in the regional flow system. In addition, modelling indicated that quite deep sections (up to 750 m) had to be modelled in order to adequately represent the regional groundwater flow.

Owing to the large region covered by the study and the great complexity of the geology, this bulletin does not address local issues, such as well-protection areas and specific locations for new wells. Nevertheless, the study represents the first regional inventory of the groundwater resources of the Maritimes Basin at

des terres dans un estuaire de l'Île-du-Prince-Édouard, ce qui peut donc causer dans certaines zones un problème d'eau saumâtre dans les puits situés près de la côte. Selon la composition de la couche de till et les taux de recharge, le territoire à l'étude s'est vu assigner une vulnérabilité faible, modérée ou élevée. Seules les formations du Groupe de Prince Edward Island et la Formation de Boss Point ont été classifiées très vulnérables à la contamination de surface dû à la couverture de till sableux.

Parce que la région à l'étude est vaste et à cause de l'hétérogénéité intrinsèque du Bassin des Maritimes, seuls des modèles conceptuels et numériques 2D et 3D simplifiés de l'écoulement ont été développés. Un modèle conceptuel graphique à trois échelles a été créé de manière à pouvoir intégrer les connaissances acquises durant cette étude. Ce modèle comprend les échelles régionale (l'ensemble de la zone d'étude), locale (échelle d'un essai de pompage) et ponctuelle. Des modèles numériques ont été développés en 2D avec SEEP/W[®] et en 3D avec FEFLOW[®], deux logiciels de modélisation numérique par éléments finis. Les simulations réalisées en régime permanent ont permis d'obtenir une représentation quantitative de l'hydrodynamique régionale du système à l'étude. Bien que le Bassin des Maritimes constitue un milieu poreux fracturé, il a été supposé, d'après les résultats des essais de pompage, que les fractures et les failles présentaient une connexion suffisante pour produire un système d'écoulement relativement homogène à l'échelle régionale pouvant être traité comme un milieu poreux équivalent.

Les modèles simplifiés 2D et 3D ont été développés en utilisant uniquement la formation géologique dominante pour une région donnée et un milieu stratifié horizontalement ayant des propriétés homogènes pour chacune des couches (car les conductivités hydrauliques sont reconnues pour diminuer avec la profondeur). La première couche de chaque unité hydrostratigraphique s'est vue attribuer une valeur de conductivité hydraulique (K) correspondant à la moyenne géométrique des résultats des essais de pompage. Pour les couches subséquentes, les valeurs de K ont été attribuées en fonction des données de porosité disponibles. Des taux de recharge probables ont également été attribués à chacune des formations ou groupes, en fonction des résultats de recharge préalablement obtenus. À cause du manque d'information et des incertitudes sur l'épaisseur de la couche de till à plusieurs endroits, une valeur constante a été imposée à cette échelle, et les valeurs de K obtenues sur le terrain ont été attribuées. La modélisation a permis de valider les fourchettes de valeurs obtenues précédemment pour les conductivités hydrauliques et les taux de recharge et de confirmer le rôle potentiellement important des failles dans le système d'écoulement régional. De plus, la modélisation a indiqué que des coupes assez profondes (jusqu'à 750 m) devaient être prises en compte pour pouvoir modéliser adéquatement le système d'écoulement à l'échelle régionale.

L'étendue de la région étudiée et la grande complexité de sa géologie empêche d'aborder, dans le cadre de cette étude, des problèmes locaux, tels que la délimitation des périmètres de protection et la localisation de nouveaux puits de production. Néanmoins, cette étude représente le premier inventaire des ressources en eau souterraine du Bassin des Maritimes à une échelle de 1/250 000.

1:250 000 scale. Indeed, very little work had been done to delineate and characterize the aquifers and the till cover on a regional scale in this region. Through compilation of existing data, fieldwork, data analysis, and modelling, a general picture has been generated of the hydrogeological, hydrological, and geochemical characteristics prevailing in this vast aquifer system, thus providing valuable information to provincial and municipal authorities for the management of groundwater resources. Maps showing the geology, the regional piezometry, the spatial distribution of hydraulic properties, the vulnerability, the recharge rate, and geochemical data, as well as various other parameters that are relevant to a regional hydrogeological study, are presented in a companion atlas on CD-ROM (Rivard et al., 2005a).

En effet, très peu de travaux portant sur la caractérisation à l'échelle régionale des aquifères et de la couverture de till avaient été réalisés jusqu'à maintenant dans cette région. La compilation des données existantes, les travaux de terrain, l'analyse des données et la modélisation ont permis de caractériser la zone d'étude et de fournir un portrait des contextes hydrogéologique, hydrologique et géochimique prévalant dans ce vaste système aquifère, fournissant aux autorités provinciales et municipales des informations essentielles à la gestion des ressources en eau souterraine. Des cartes ont été produites pour la géologie, la piézométrie régionale, ainsi que pour la répartition spatiale des propriétés hydrauliques, de la vulnérabilité, du taux de recharge, de la géochimie et de plusieurs autres paramètres pertinents à une étude hydrogéologique régionale. Ces cartes sont présentées dans un atlas complémentaire à ce rapport sous forme de CD-ROM (Rivard et al., 2005a).

INTRODUCTION

Groundwater is a very important source of water supply in the Maritime provinces. Indeed, 67% of the population in New Brunswick, 46% in Nova Scotia, and the entire population of Prince Edward Island rely on groundwater (Environment Canada, 2004). Towns such as Sackville, Hillsborough, and Shediac in New Brunswick, and Amherst and Oxford in Nova Scotia are supplied only by groundwater, and the same holds for many smaller municipalities near coastlines. The bulk of this groundwater comes from fractured sedimentary rocks of the Maritimes Basin and, to a lesser extent, from the surficial sediment cover. This hydrogeological region represents one of the main aquifer systems in Canada.

The Maritimes Groundwater Initiative (MGWI) was a multidisciplinary and multiagency research project conducted by the Geological Survey of Canada within the framework of the national inventory of groundwater resources in Canada, as suggested in an early version of the Canadian Framework for Collaboration on Groundwater, finally published in 2003 (Rivera et al., 2003a). The MGWI project began in 2000 and extended over three years. The main goal of this project was to improve the general understanding of groundwater-flow dynamics within the major aquifers of the Maritimes Basin. The complex sequence of sedimentary rocks forming this large hydrogeological system induces distinct groundwater flow patterns due to the aquifer-aquitard stratification.

This bulletin aims to provide baseline information on hydraulic properties of the various units, groundwater recharge rates, and groundwater quality. However, due to the large geographic area covered and the great complexity of the geology, the study does not address local issues such as well-protection areas and water-exploration strategies. Nevertheless, it represents the first inventory or assessment of the groundwater resources in the Maritimes at the regional scale. Indeed, the only other regional hydrogeological study carried out within the same study area, published more than 40 years ago (Carr, 1964), focused only on the Moncton Basin (1100 km²). Many local studies have been conducted, however, by consultants. Considerable effort has been focused on relevant fieldwork in geographic regions or even fields where no data were available, analyses of existing data, and modelling, all aimed at enhancing knowledge of this important hydrogeological system. This work provides the basis for the development of long-term groundwater-resource management and protection programs by provincial and municipal authorities.

Two case studies, both M.Sc. theses, were undertaken within the framework of the MGWI project, in order to address important issues in this area. The first (Boisvert, 2004) focused on the stratigraphy and hydraulic properties of the Moncton Basin surficial sediments, since they were

poorly characterized. Indeed, they probably have been neglected due to the fact that sediments within the study area consist mainly of glacial till and are generally thin, so the water supply comes mainly from bedrock aquifers. This work consisted, among other things, of estimating hydraulic conductivities of granular units within buried valleys and of the various types of surficial till. The second study (Carrier, 2003) was dedicated to the investigation of the potential hydraulic connection between a peatland and the regional bedrock aquifers. This project was a special request from the province of New Brunswick, since some residents living close to the harvested bog were concerned about the impact of bog drainage on the groundwater availability in their wells. In the Maritimes, few data were available to address these concerns. The goal of this study was to estimate the link between a representative peatland in New Brunswick and the regional bedrock aquifer.

This bulletin is divided into eight sections (plus 'Introduction' and 'Conclusions'). A description of the methodology used to characterize the study area is followed by a summary of the general characteristics of the study area and the interpretation of existing and newly acquired data. The next three sections deal with the geological, hydrogeological, and geochemical characteristics, respectively, of the study area, based on existing information taken from reports and provincial databases, and on results of fieldwork and interpretation of data collected during this project. Results of the specific study regarding the hydrogeology of a peatland in New Brunswick are presented next. The final section provides a description of the conceptual and 2-D and 3-D numerical models integrating all available information, along with their results and a comparison with those obtained in the previous sections. An atlas containing maps that summarize the compiled information related to hydrology, geology, hydrogeology, geochemistry, and remote sensing was published in CD-ROM format (Rivard et al., 2005a).

METHODOLOGY

The MGWI project was based on a common methodology for regional hydrogeology characterization (i.e. mostly using existing data, as new fieldwork could not cover the entire study area in detail). This bulletin thus describes how this large fractured aquifer system was studied using a large number of nonuniformly distributed data of variable reliability, combined with well-targeted fieldwork and groundwater-flow numerical modelling. Based on the work of Michaud et al. (2004), this study includes the following steps: 1) selection of the study area, 2) data compilation, 3) fieldwork, 4) data analysis and interpretation, and 5) mapping. Numerical flow-modelling was added as a sixth step for this study in order to provide a more quantitative assessment of the regional groundwater resources.

Selection of the study area

The Maritimes Basin was selected for this study because it represents one of the key aquifer systems in Canada and because of the important role played by groundwater in supplying water for this part of the country. Because of the large area covered by the basin (46 000 km²), however, a smaller representative area was selected for the project (black rectangle in Fig. 1). Still, the study area covers 14 100 km² and parts of three provinces (New Brunswick, Nova Scotia, and Prince Edward Island), representing a standard 1:250 000 map sheet. Moreover, this area had to be enlarged for numerical modelling, in order to use natural limits for the model boundaries.

Data compilation

A thorough review of relevant reports and studies (from government and consultant reports, provincial water-well and water-chemistry databases, thematic maps, and scientific papers) was undertaken for an inventory of available data and in order to develop a preliminary understanding of the hydrogeological setting. Targeted information consisted primarily of borehole logs, weather and hydrological data, water-well (well depth, flow rate, static water level, etc.) and water-chemistry data, and pumping-test results. These documents, reporting mainly work conducted for municipalities, allowed first estimates of hydraulic properties of the geological formations. Provincial databases were the main source of information for geological logs, well descriptions, static water levels, and groundwater quality. Data were checked prior to their integration into the databases, and rejected mainly on the basis of their geographic location and aberrant or doubtful values. All these data were compiled into thematic databases (geochemical, hydrogeological, and climatic) to

ensure optimal data capture, manipulation, integrity, and dissemination. All geographic locations are in UTM NAD83 co-ordinates. Elevations were obtained from digital elevation models (DEM), constructed using 10 m topographic contours from 1:50 000 scale maps. These central databases are linked to a geographic information system (GIS) for statistical and spatial analysis, and for map representation. Table 1 summarizes the information obtained within the study area. Some of the data and stations used fall outside of the study area, but were kept because they provided valuable information, such as boundary values for the interpolation process. Almost no quantitative hydrogeological data were available for surficial sediments, as the great majority of wells are completed in fractured rocks.

One of the main additions to the provincial databases is the ability to link the borehole description to a given geological formation. This information was obtained through cross-references with the updated geological map (*see* 'Updating of regional geology' section) using ArcGIS®. An additional database dealing with weather and hydrological data was also developed in the course of a parallel project on climate-change impacts on groundwater recharge in eastern Canada (Rivard et al., 2003). This database contains hydrogeological, hydrological, and weather data for New Brunswick, Prince Edward Island, and Quebec.

Fieldwork

Fieldwork was carried out during the summers of 2001 and 2002 to gather additional data on stratigraphy, hydraulic properties, fracturing, and groundwater characteristics in specific areas, in an attempt to fill the main gaps in information coverage. Work performed and number of results in the fractured rocks, the surficial sediments, and the peatland are summarized in Table 2. The activities were performed within the various geological formations and surficial units representative of the Maritimes Basin and are described below. The selected sites for these activities are shown in Figure 2 (*see also* Rivard et al., 2005a, Plate 5-1).

Water-level measurements

Water levels within domestic and municipality wells were recorded during two summers (2001 and 2002) to obtain a regional estimation of the piezometric surface across the study area. Water levels were obtained from 433 wells tapping the bedrock and from 29 wells within surficial sediments, mainly domestic wells. Elevation measurements were also taken in rivers and creeks to complement the groundwater-level survey, in order to help understand the hydraulic connection between surface water and groundwater.

Five wells (Harcourt, Petitcodiac, Shediac, and Bureau-Beauséjour in New Brunswick, and Beecham Road in Nova Scotia) were equipped with loggers and pressure transducers, recording groundwater levels every 4 hours (*see* Fig. 2 for locations). The Petitcodiac monitoring well is occasionally

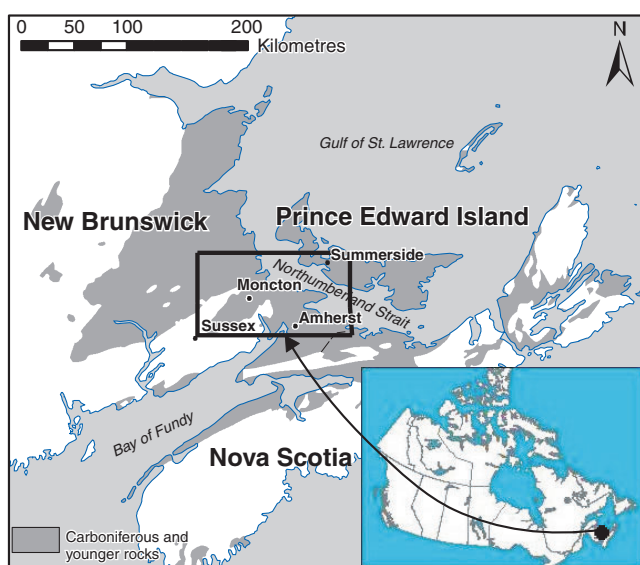


Figure 1. Location of the study area for the Maritimes Groundwater Initiative project (corresponding to a 1:250 000 map sheet).

used by the New Brunswick Department of Transportation, and the Bureau-Beauséjour well is used daily but only for sanitary purposes. Data were downloaded 2 or 3 times a year and batteries changed every year. This monitoring program allowed a close follow-up of annual fluctuations in ground-water level. The Petitcodiac and Harcourt wells have now been integrated into the provincial monitoring program.

Drilling

In 2002, boreholes were drilled to gain knowledge of the stratigraphy, to delineate units and formations, and to obtain information on hydraulic properties where no data were available using pumping and permeability tests. Six

boreholes were drilled within the sedimentary bedrock and seven were completed within the surficial sediments. Five of the boreholes in the bedrock were drilled using a destructive rotary-hammer method to depths ranging between 62.5 and 83.8 m. The only diamond-drill hole (with continuous core sampling) was completed to 91.5 m. Figure 3 shows typical core samples. Depths of boreholes drilled in surficial sediments using standard and hollow-stem augers ranged from 12 to 29 m. These were sealed in November 2002.

Extensive drilling was also performed through the peat and underlying units down to the bedrock beneath the Beauséjour peatland to establish the stratigraphy and understand the groundwater dynamics in this region. Twenty-seven holes were drilled to various depths and in three different sites using a percussion drill (Pionjär 120; 7 holes) and a

Table 1. Summary of existing data for the Maritimes Groundwater Initiative study area.

Data	Number
Description of wells in provincial databases and reports, including location, depth, yield, etc. (many fields missing)	188 700 wells (e.g. static water levels: 22 800 data)
Borehole logs for surficial geology	2997
Results of pumping tests (>4 hours; combined T, S)	50 for T, 24 for S
Water-sample analysis	1900 samples
Meteorological data	21 stations (1–95 year series)
Hydraulic data (stream hydrographs)	16 gauging stations (3–39 year series)
Grain-size analysis for till	75 (almost all in PEI)

Table 2. Summary of field data acquired during the Maritimes Groundwater Initiative.

Category	Activity	Number of data		
		Fractured rocks	Surficial sediments	Peatland
Survey	Measurements of water levels in wells	433	29	106
	Measurements of water levels in streams (80 locations)	-	-	-
	Topographic survey	-	-	209 locations
	Measurements of peat thickness	-	-	128 locations
Monitoring	Installation of data loggers in wells	5	-	4
Drilling	Rotary hammer and diamond drilling	6	-	-
	Standard and hollow-stem auger drilling	-	7	-
	Percussion drill, Russian peat sampler	-	-	7, 20
Hydraulic testing	Pumping tests and slug tests	10	7	19
	Permeameter and infiltrometer tests	-	26	2
	Packer tests	40 in 6 wells	-	-
Geophysics	Borehole geophysics	10 wells	-	-
	Electrical resistivity (11 lines, approx. 3.5 km)			-
	Ground-penetrating radar (approx. 2.2 km)	-	-	5 lines
Analyses	Water	17	5	14
	Soil (grain size)	-	80	27
	Undisturbed peat (grain size)	-	-	3
	Von Post decomposition index	-	-	3
	Plant macrofossils	-	21	6
	Rock (thin sections)	23	-	-
	¹⁴ C dating	-	3	1
Remote sensing	Validation process using ground-truth control points	-	-	-

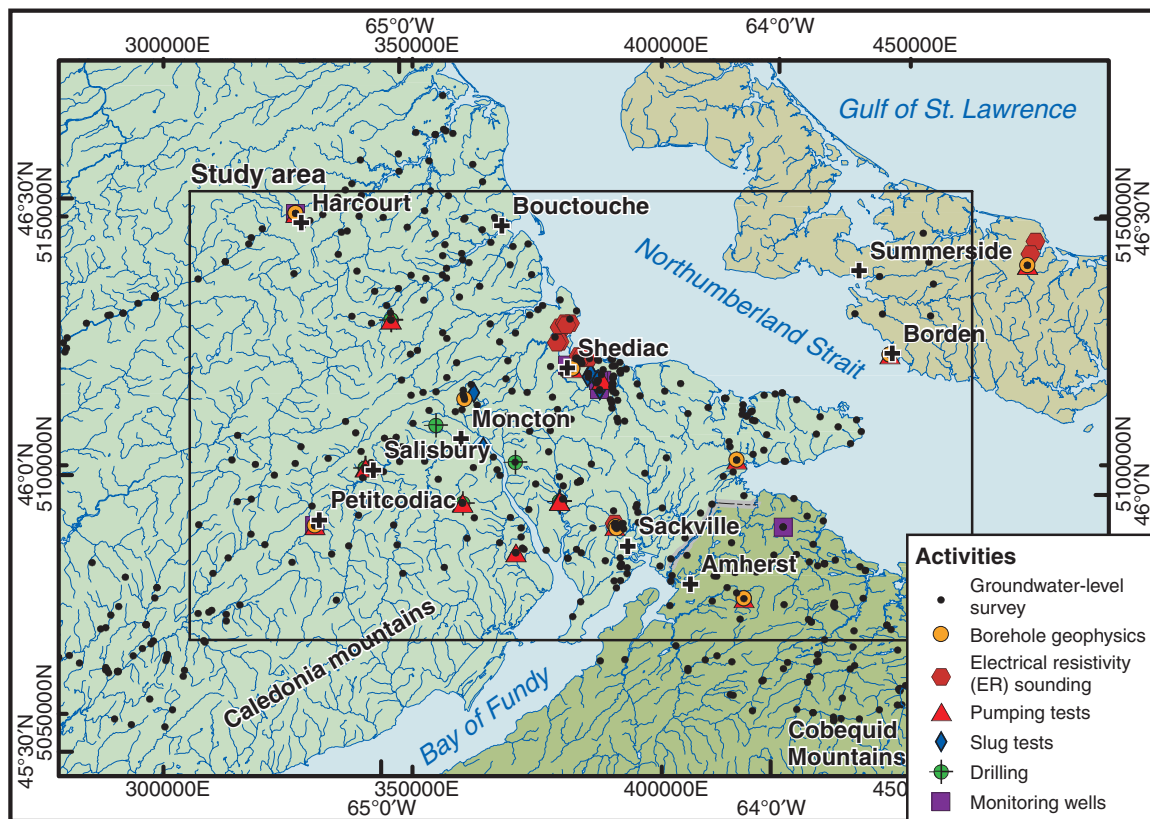


Figure 2. Location of Maritimes Groundwater Initiative study area, showing fieldwork sites.

Russian peat sampler (20 holes). These holes were used for material sampling at various depths (for grain-size and water-content analyses) and for the installation of 19 piezometers, in which a pressure transducer was introduced to record short- and long-term piezometric fluctuations. A telescopic rod was also used to estimate the peat thickness at 128 locations.

Geophysics

Geophysical surveys were carried out to identify changes in the stratigraphy of the upper 100 m and to locate and characterize fractures in order to contribute to the understanding of Quaternary and bedrock geology and hydrogeology. Electrical resistivity was also used to locate the saltwater-freshwater interface near the coast.

Borehole geophysics

As part of this multidisciplinary research effort aimed at understanding the surficial hydrogeological characteristics of these rock aquifers, comprehensive sets of geophysical logs were recorded in water wells specifically chosen because they penetrated several major hydrostratigraphic units. Geophysical logs were obtained in ten wells scattered throughout the region; their locations are shown in Figure 4. These logs were analyzed and interpreted in order to recognize



Figure 3. Core samples from diamond-drill hole, Légerville, New Brunswick. Core diameter 6.4 cm (2.5 inches).

important hydrogeological differences and similarities among rock types, from which a conceptual understanding of the regional hydrological system could be developed. Complementary packer tests, pumping tests, and surface geophysical surveys were conducted at a few selected sites in order to confirm and refine these general observations at a larger scale. A more detailed investigation, whereby pump tests and surface-resistivity measurements were integrated into the analysis, was conducted at a site in Sackville, New Brunswick (Morin et al., 2003).

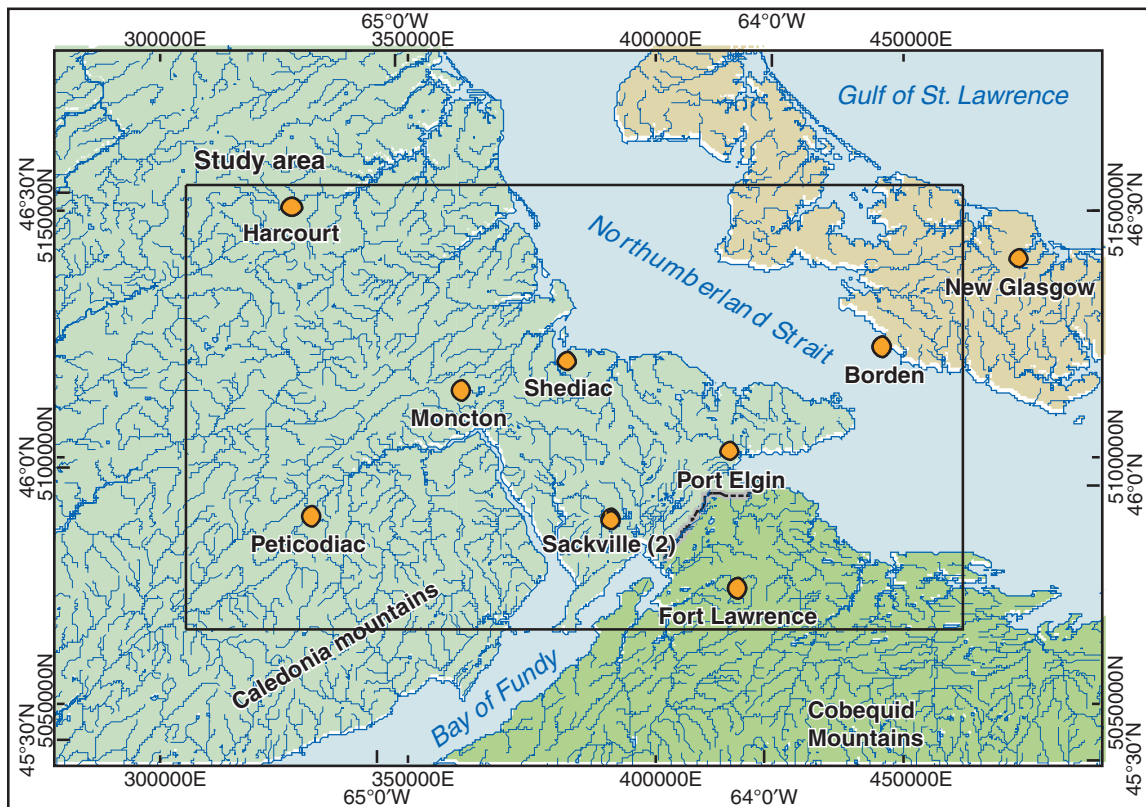


Figure 4. Location of sites where geophysical logs were obtained in water wells, Maritimes Groundwater Initiative study area.

Geophysical logging operations included the use of caliper, natural gamma, electrical resistivity, acoustic televiewer, and flowmeter under ambient as well as pumping conditions. Logging results proved to be indispensable for the successful implementation of packer tests by providing information regarding borehole geometry and fracture location (depth) and permeability; at times, these represented the only information available on stratigraphy and potential yield. Borehole geophysics also provides valuable information on orientation and frequency of water-bearing fractures, along with their individual flow rates.

When applying geophysical logging to the characterization of aquifer properties, the general approach consists of obtaining three primary categories of measurements: 1) logs that provide information related to lithology, such as natural gamma activity and electrical resistivity; 2) logs that measure borehole-fluid properties, such as temperature, specific conductance, and velocity; and 3) logs that generate magnetically oriented images of the borehole wall, from which structural features can be identified. All of these logs, as well as the caliper log, were recorded and processed on the 10 selected sites. Borehole-fluid velocity was measured under ambient conditions, and also under pumping conditions to locate specific productive intervals. Transmissivities are quantified from results of the vertical-flow distribution and the subsequent drawdown. By systematically combining all of these data into

a broad interpretive scheme, the structural features controlling flow can be distinguished from the general population of features intersected by the well. From trends in the orientation, distribution, and frequency of these features, a conceptual understanding of the groundwater system at the regional scale can be developed.

The two log types that are the most sensitive and responsive to lithological variations are the formation-resistivity and natural-gamma logs. An example of these logs obtained in the well that penetrates rocks of the Pictou Group (Harcourt well) is provided in the 'Interpretation of existing and acquired hydrogeological data and results' section. Electrical-resistivity logs respond to variations in pore-water specific conductance, porosity, and grain size. Typically, dense, coarser grained sandstone exhibits higher resistivities than do the finer grained deposits that are more efficient electrical conductors. On the other hand, high gamma activity, in counts per second (cps), is commonly associated with the presence of fine-grained units that tend to accumulate radioisotopes through adsorption and ion-exchange processes.

Fluid-property logs provide evidence of movement of the borehole fluid, which can help locate primary transmissive zones. Specific conductance and temperature logs qualitatively delineate fluid exchange, whereas flowmeter measurements not only verify these flow patterns but also quantify

flow rates. After fluid-property logs have been recorded under ambient conditions, flowmeter logs can be repeated during pumping to quantify the vertical distribution of transmissivity (T). According to this flowmeter-pumping field technique (Morin et al., 1988; Molz et al., 1989), a flowmeter log is obtained in the wells concurrently with pumping, once pressure conditions have approached a quasi-steady state; no packers are required. These data identify zones of fluid exchange between the borehole and the surrounding formation, and establish the change in hydraulic head required to produce the observed flow pattern. Transmissivities are computed using the relation developed by Cooper and Jacob (1946) for flow into or out of a well penetrating a series of idealized, layered aquifers.

This field technique identifies only the most permeable zones in the well and quantifies transmissivities over their uppermost 2 to 3 orders of magnitude. This limitation is due to the measurement range and resolution of the flowmeter (i.e. large flow rates associated with very permeable intervals are easily measured but tend to overwhelm any small contributions from less permeable zones). To acquire a broader range of direct transmissivity measurements, particularly in the less transmissive (lower T value) zones associated with the intact rock matrix, packer testing must be performed. Packer tests are complementary to the flowmeter-pumping technique in the sense that they not only confirm test results for the largest T values, but also expand this range of hydraulic measurements to less permeable zones. Moreover, the results of the preliminary flowmeter tests allow the operator to designate the proper placement of the inflatable packers, to coincide either with permeable fractures or with intact rock.

Once the primary productive zones had been located and their transmissivities quantified, structural features associated with these intervals were examined with borehole-imaging tools, such as optical and/or acoustic televewers. These instruments generate digital, magnetically oriented images of the borehole wall, from which the strike and dip of fracture planes can be computed by means of a simple geometric exercise (e.g. Plumb and Luthi, 1989). Examples of an acoustic televewer log from the Harcourt well and an optical televewer log from the Sackville number 7 well are shown in Figure 5, with the planar, magnetically oriented panels representing an unwrapped cylindrical view.

Electrical-resistivity soundings

The electrical-resistivity method was used to delineate saline intrusion and map subsurface stratigraphy at several locations in the MGWI study area: Shediac Bay, New Brunswick and Rustico Bay, Prince Edward Island for saline intrusion, and Sackville, New Brunswick for subsurface stratigraphy and fracture patterns. In this method, an electric current is applied to the surface through two electrodes and a potential difference is measured between two other electrodes. The current flow and the distribution of electrical potential in the subsurface are affected by the difference in

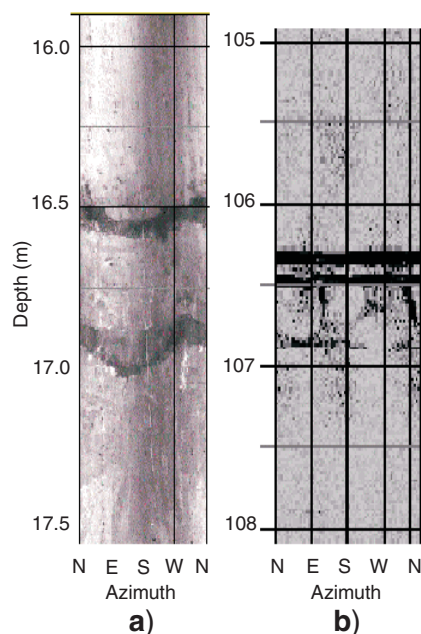


Figure 5. Televewer logs of sections of **a)** Sackville number 7 well (optical data), and **b)** Harcourt well (acoustic data). Digital, magnetically oriented images represent a planar view of a cylindrical borehole.

electrical resistivity of the geological materials encountered, which is controlled by porosity, salinity, and clay content of the various layers or units. Increasing the electrode separation increases the depth of investigation. Therefore, a 2-D electrical image can be obtained by making measurements with increasing electrode separations for each position along a survey line. The equipment used in this project was an Iris Instruments Syscal R1 Switch-48 resistivity-imaging system. This system has 48 electrodes spaced 5 m apart (240 m cable length) that can be selected automatically by computer control.

Two array types were used for the surveys. For detailed investigations, a Wenner array configuration was used. This array has four electrodes placed at equal separations along a line. The current is applied to the two outer electrodes and the potential difference is measured between the two inner electrodes. The depth of investigation is approximately one-half the electrode separation. For the equipment used, the maximum depth of investigations was approximately 40 m. For deeper investigations, a pole-dipole array was used. One current electrode was fixed at a location at least 1 km away from the beginning of the survey line and current was injected through a second current electrode that was selected from the multielectrode cable. The resulting potential difference was then measured between two adjacent electrodes on the cable. The spacing between the current and potential electrodes was increased to augment the depth of investigation. With this equipment, the maximum depth of investigation was approximately 80 m. The electrical-resistivity images were processed to obtain an electrical-resistivity model using the

inversion software RES2-DINV®, which uses a least-squares finite-difference method. The models were then interpreted to assess stratigraphy and potential for saline intrusion. A full description of this work, including Wenner and pole-dipole electrical-resistivity images and description of the stratigraphy, is given in Rivard et al. (2005b).

Ground-penetrating radar

An extensive ground-penetrating radar survey was carried out in the Beauséjour peatland, in order to evaluate the depth and spatial extent of the peat unit. In the exploited sector, a ground-penetrating radar survey was carried out along two north-south lines and three east-west lines (varying between 55 and 720 m in length, for a total of 2.2 km) using a Sensors & Software Inc. pulseEKKO® 100 with 50 MHz frequency antennas and a 1000 V pulser. Measurements were made every metre with an antenna separation of 2 m. Results were validated with borehole logs obtained with the Russian peat auger and a percussion drill (Carrier, 2003).

Surface and marine surveys

Surface seismic and marine surveys were also carried out in an attempt to assess the thickness and stratigraphy of Quaternary sediments in the Moncton area. Since drilling was prohibited close to the Petitcodiac River by provincial regulations, this could have been a good way of obtaining information in that area. Unfortunately, both of these geophysics techniques provided inconclusive results, as they were unsuited to the sediment type mantling the Petitcodiac River valley. For more details, see Boisvert (2004).

Hydraulic testing

Pumping and slug tests

Ten short- and long-term pumping tests were performed in the fractured aquifers in order to estimate their hydraulic properties in different parts of various geological formations. The pumping period ranged between 8 and 88 hours, and recovery periods between 6 and 25 hours, depending on equipment reliability and operational constraints. Eight of the wells were located in New Brunswick (Harcourt, Petitcodiac, Sackville, Riverview, Salisbury, Hillsborough, Shediac-Parlee beach, and Beauséjour peatland) and the others in Nova Scotia (Fort Lawrence and Beecham Road). Three of the pumping tests were done for municipalities (Sackville, Hillsborough, and Riverview). The Municipality of Sackville needed a long-term pumping test to develop a protection-area plan and a vulnerability analysis. The Village of Hillsborough wanted to test a well constructed in 1990, which had been previously only partially tested. The Town of Riverview, which is studying the possibility of using their own wells (the population is currently supplied by the Moncton aqueduct), was pleased to have one of their wells

tested. Harcourt, Petitcodiac, Fort Lawrence, and Beecham Road are wells belonging to provincial authorities. Three of them (Harcourt, Petitcodiac, and Beecham Road) were used during this project as monitoring wells. Raw data for these pumping tests are available in Rivard et al. (2005b; graph format only).

To characterize the hydraulic properties of the potential granular aquifers of the Moncton Basin, a multiple piezometer nest was installed in the Memramcook River valley (Fig. 6), located east of the Petitcodiac River in New Brunswick. A first nest, composed of three piezometers (one in each sand unit and one in the middle aquitard), was installed 160 m from the actual Memramcook riverbed. The second nest, including one piezometer in each sand unit, was installed 25 m from the first, but closer to the river. Each well was equipped with a pressure transducer to record the changes in water-table elevation. Two slug tests were performed in the top sand unit, one in the middle aquitard, and five in the bottom sand unit. Short-term pumping tests were also carried out in each sand unit.

Within the framework of the Beauséjour peatland study, 19 slug tests were conducted in 19 piezometers installed in the peat and underlying units to evaluate their hydraulic conductivity. Twelve tests were carried out in the peat, five in the silt unit, and two in the till layer (*see* 'Case study: Beauséjour peatland near Shediac, New Brunswick' section for details on the stratigraphy).

Packer tests

An efficient method for determining the vertical distribution of local transmissivities is the constant-head injection test using straddled packers. This method consists of injecting water at a constant flow rate (constant pressure) of an interval of rock isolated with two packers. The equipment can be used in various well diameters and allows measurements of permeability over several orders of magnitude, which is essential to calculate matrix or fracture hydraulic properties. The transmissivity of the tested zone can be obtained using the Thiem equation (e.g. Lohman, 1979; Todd, 1980), assuming steady-state flow conditions.

This technique seemed particularly appealing since all formations in the Maritimes Basin comprise a sequence of different layers of highly variable permeability. Therefore, a straddle-packer system was used for direct measurements of transmissivity in six wells (Harcourt, Port Elgin, Shediac, and Petitcodiac in New Brunswick; Fort Lawrence in Nova Scotia; Borden in Prince Edward Island) in order to evaluate the hydraulic properties of distinct rock types. In this technique, two packers are inflated to hydraulically seal and isolate a section of the borehole. Intervals varied from 2.14 to 3.90 m, but were typically 2.34 m long. Water was injected from tanks at the surface at a constant flow rate, while the pressure was constantly monitored. In total, 40 intervals were examined in the 6 wells. Zones of interest (i.e. more permeable units) for these detailed packer-test analyses had been

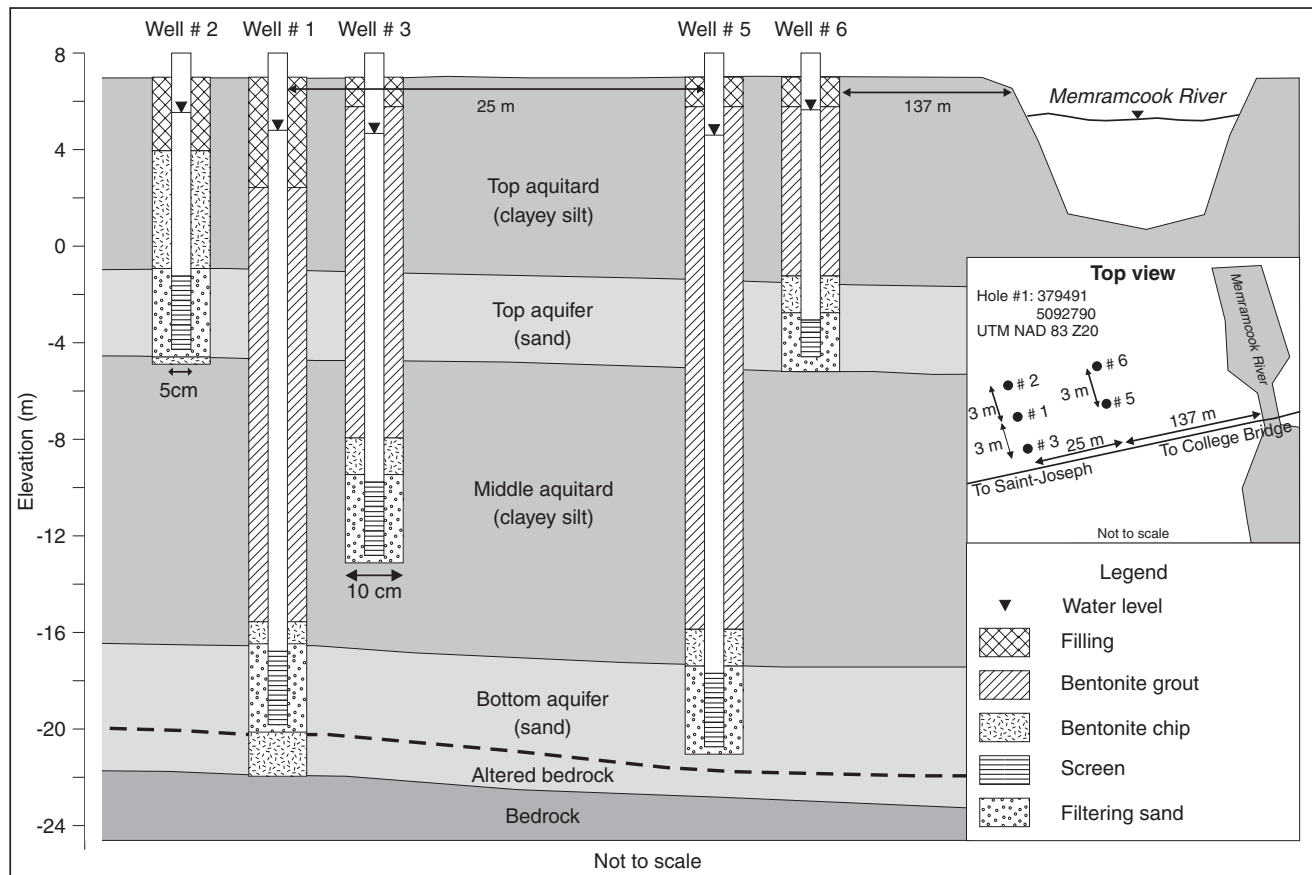


Figure 6. Piezometer installation in the Memramcook River valley, New Brunswick.

selected according to geophysical profiles obtained from bore-hole and flow logging. Thus, each distinct rock type in a well had at least one section isolated and tested to obtain a representative value of transmissivity.

Permeameter and infiltrometer tests

Because of the key role played by the till layer in aquifer recharge, estimation of hydraulic properties of the till was done using a Guelph permeameter and a double-ring infiltrometer (DR). In total, eight Guelph and three DR tests were conducted in the silty till unit at two different sites. Three Guelph and two DR tests were also conducted in the sandy till unit, and four Guelph and one DR tests were performed in the silty-sandy till unit. For details on the methodology of these tests, *see Boisvert (2004)*.

Two infiltrometer tests were also conducted in a bedrock quarry north of the Beauséjour peatland using a Guelph permeameter, in order to evaluate the saturated hydraulic conductivity of the till overlying the Richibucto Formation just outside the peatland. These values were used in the 2-D numerical model to simulate recharge of the bedrock aquifer (*see Carrier, 2003*).

Water, soil, and rock sampling

Water sampling

To improve knowledge of the geochemistry of the study area, 36 groundwater samples were collected during the summers of 2001 and 2002 and sent to the New Brunswick provincial laboratory for analysis of major and minor ions, nitrates, metals, and other parameters such as total dissolved solids, hardness, pH, and turbidity. The wells were selected to fill data gaps in certain areas (based on the provincial databases) and to complement the fieldwork to be performed. For example, wells selected for monitoring or pumping tests were sampled before the testing began. Also, samples were taken during pumping tests, when possible. Two water samples were collected for the surficial sediment study and, in the Beauséjour peatland, 22 water samples were collected in the 4 stratigraphic units (14 in the peat, 3 each in the till and the silt, and 2 in rocks) for physicochemical analysis in order to differentiate groundwater in the peatland from the regional groundwater. A YSI Incorporated probe was also used to measure salinity when residents complained about the salty taste of their water during the 2002 water-level survey.

Soil and rock sampling

Soil samples were collected within the framework of the two M.Sc. theses for the purpose of grain-size analysis. The soil composition helped with characterization of the material (e.g. sandy silt or silty sand) and was used as an additional way of estimating hydraulic conductivities of granular units (Boisvert, 2004). Twenty-three rock samples from the various formations were also collected in 2001, and estimation of porosity was carried out using thin sections.

Data analysis

Reinterpretation of existing pumping tests

When accessible, pre-MGWI pumping-test results were reinterpreted, although very few ‘raw’ pumping-test data were given in the various reports available. When drawdown versus time curves were provided, calculations using the Cooper-Jacob or Theis method (Todd, 1980; Kruseman and de Ridder, 2000) were used depending on the graphic presentation (semilog or log-log). Approximately 12 pumping tests (with and without observation wells) were reinterpreted. Results of the new interpretations were generally close to the previously reported results.

Groundwater recharge

Aquifer recharge is defined, in a general sense, as the amount of water vertically circulating through the unsaturated zone, eventually reaching the water table and thus representing a net contribution to the aquifer. Several techniques are available for estimating groundwater recharge, including hydrograph separation, groundwater fluctuations, 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. The range of recharge rates estimated using various approaches can be large and their reliability is variable, especially since some techniques provide ‘potential’ recharge and others ‘effective’ recharge. Uncertainties in each approach underscore the need for application of multiple techniques to increase the reliability of recharge estimates (Scanlon et al., 2002).

In this study, three approaches were used: hydrograph separation, the water-balance method coupled with a correction factor, and modelling. Well hydrographs (showing groundwater fluctuations) could not be used to estimate effective local recharge since specific yields were unknown. Rather, they were used to indirectly estimate specific yields, using recharge estimates determined with the other methods (*see* ‘Specific yields’ section). All techniques used for this project apply to the regional scale, or are at least representative of a large basin. Recharge estimates obtained from modelling are presented in the ‘Conceptual and numerical hydrogeological models’ section.

Hydrograph-separation method

River base flows, which represent an estimation of the aquifer contribution to the river (subsurface flow), are calculated from hydrograph separation using certain hypotheses. A river hydrograph is composed of water coming from four different paths: 1) runoff or surface flow, 2) hypodermic flow, which corresponds to the portion of infiltrated water circulating at shallow depths, lasting only shortly after a storm event and emerging as seepage flow, 3) groundwater flow, and 4) precipitation falling directly on the stream. In general, the stream surface being very small in comparison to the watershed area, this last contribution can be ignored. Also, hypodermic flows are often negligible compared to the contribution of the aquifer and are thus often not taken into account. Therefore, streamflow can be roughly divided into two components: the base flow (subsurface flow) and the surface flow (basically representing the runoff). Because of the slow velocity of groundwater, the base flow only plays a small role during a storm event, but generally supports the stream flow in the absence of rain and during dry periods. The groundwater recharge rate over an entire watershed thus roughly corresponds to the base flow measured at the outlet of the watershed, divided by the watershed area for a given period (month or year).

The hydrological response of a watershed (hydrograph shape) depends strongly on its physiographic features. The time of concentration (maximum time taken by a water drop during a storm event to exit the watershed), which characterizes the velocity and intensity of the watershed reaction, is indeed directly influenced by the shape, size, and slopes of the watershed. To these factors can be added the following: impacts of hydrometeorological parameters (such as precipitation, temperature, wind, and solar radiation), soil type (infiltration capacity, retention properties, and permeability), and land use. Anthropogenic factors, such as withdrawals (irrigation or pumping), hydraulic structures (e.g. dams), and effluents, also have a direct impact on the estimation of base flows. These quantities, however, usually cannot be quantified during the estimation and are thus included in the uncertainties associated with the method. Nevertheless, this method is commonly used to estimate quantities of infiltrated water, since it does not necessitate direct soil measurements (e.g. lysimeters), which are often uncertain and local, and it can integrate a substantial amount of information at the regional scale over several years (Scanlon et al., 2002).

In addition to the MGWI project, a parallel study on the potential impacts of climate change on groundwater resources in eastern Canada (Rivard et al., 2003) had, among other things, the objective of estimating recharge rates using hydrograph separation for New Brunswick, Prince Edward Island, and Quebec. Results for watersheds included within the study area were thus used for this project. Two approaches had been selected for hydrograph separation: graphical and digital filters.

The graphical approach assumes that, between two storm events, the base flow is equivalent to the total stream flow. Different techniques can be used to determine base-flow curves. In the climate-change project, the local minima method included in the HYSEP software developed by the United States Geological Survey (Sloto and Crouse, 1996) was used. In this method, daily streamflow rates are used to calculate base-flow rates. It is assumed that, between two storm events, the base flow is equivalent to the stream (total) flow. The runoff period is calculated with the empirical relation $N = A^{0.2}$, where N is the number of days after which runoff ceases and A is the watershed area (in square kilometres). The base flow is then estimated using a linear interpolation between local minima. This method is very simple to implement (once file formats are reorganized) and can provide relatively good estimates; it is therefore commonly used in practice. Nevertheless, even though graphical approaches are based on some physical reasoning, they are generally not well founded physically (Furey and Gupta, 2001).

The filter approaches are based on the fact that the actual base flow depends heavily on the previous calculated base flow and also on a component related to the previous and/or actual stream flow rates. The general equation to calculate the filtered base flow (q) is

$$q_k = \alpha \cdot q_{k-1} + \frac{(1-\alpha)}{2} (y_k + y_{k-1}) \quad (1)$$

where y is the stream-flow rate, α is a coefficient on the order of 0.9, and the index k represents the actual day and $k-1$ the day before. Two filter methods, one developed by Chapman (1991) and the other by Furey and Gupta (2001), were used. They employ physically based relations to determine proportionality coefficients. Furey and Gupta (2001) have slightly modified this equation by using only the streamflow data recorded some days (e.g. three) before for the second term, as they consider this lag necessary for the storm event to have an impact on the base flow. These filters do not rely on calibration and, unlike other filter applications, they do not include any constraints to restrict values of base flow in the equations (e.g. $0 < Q_{\text{baseflow}} < Q_{\text{total}}$). As no constraints are used in these filters, base flows can slightly exceed stream flows following a major event, but the error is small. It has been noticed that these inaccuracies diminish as the watershed size increases. Details for the application of these methods can be found in Rivard et al. (2003).

Eleven gauging stations in New Brunswick and five others in Prince Edward Island fall within the region under study. The New Brunswick stations are located near Sussex, Harcourt, Shediac (Haute-Aboujagane), Dorchester, Turtle Creek, and Petitcodiac, with the last five located approximately 7 km south of Petitcodiac. The stations in Prince Edward Island are all located between Summerside and Borden. Five other stations were also used because of their proximity to the study area. The earliest records date back to 1961.

Water-balance method

The water balance is calculated using the following simplified equation, taking into account the most significant factors:

$$I = P - R - ET - \Delta SWS, \quad (2)$$

where I is the infiltration, P is the precipitation, R is the runoff, ET is the evapotranspiration, and SWS is the soil-water storage for a given period (all in millimetres).

Weather data necessary for this recharge study were obtained from the database of the Meteorological Service of Canada (2002). Twenty-five stations were available within the study area or in the nearby region. The evapotranspiration was estimated using the Thornthwaite (Chow et al., 1988), Turc (1954), and Coutagne (1954) methods. The first method always yielded significantly higher values than the other two methods, since it provides a potential value (i.e. a quantity of water removed from the soil by evaporation and transpiration under conditions of unlimited supply). The last two were thus considered to provide more realistic values. Results for all three methods are presented on Plate 4-2 of Rivard et al. (2005a). The infiltration was calculated for each year where mean annual precipitation and temperature were available (between 1 and 95 years) at the 21 stations. Runoff was calculated using equations developed by the Soil Conservation Service (United States Soil Conservation Service, 1972; Steenhuis et al., 1995). The parameters needed for these equations are soil type, vegetation type, abundance of vegetation, and slope. Land-use and vegetation-cover maps were available from a remote-sensing pilot project (*see below*). Mean slopes were determined from DEM maps. Once these parameters are available for a given area, one can find the curve with which an equation is associated. The curve allows the determination of runoff as a function of precipitation.

Finally, soil water storage (SWS) is the amount of water available for plants. It was obtained by multiplying the estimated root depth (RD) by the available water-storage capacity of soils (AWSC)

$$SWS_{(mm)} = RD_{(m)} \cdot AWSC_{(mm/m)} \quad (3)$$

Root depth and available water-storage capacity were estimated based on the vegetation-cover map and coefficients taken from tables of a publication from the British Columbia Department of Agriculture, Food, and Fisheries (Nyvall, 2002). Averaged over many years, the change in storage should be negligible.

All components of equation 2 were interpolated with the inverse-distance method over the study area using 500 m by 500 m grid cells. This size was chosen to obtain a reasonable number of cells without losing precision on each parameter. Both Surfer® and ArcMap® software were used in this process. Development of programs was sometimes necessary to link results from the two software applications.

According to Hamel et al. (2001) and Hamel (2002), the water-balance method must be corrected based on known hydrogeological conditions. Because the sedimentary rocks are not homogeneous and the water table poorly known in the till cover, the formal Darcian approach could not be used for the correction. Therefore, three approaches were used to estimate the proportion of the area where recharge to bedrock is unlikely (discharge areas or artesian conditions), in order to reduce the potential water-balance values: 1) estimation of upward flow areas, indicated by vertical hydraulic gradients; 2) estimation of zones where the piezometric map is significantly above the ground surface; and 3) evaluation of the percentage of artesian wells among visited sites. For the first approach, the water table within the till layer was assigned a constant value (1.7 m) beneath the topographic surface, based on the geometric mean of the few available hydraulic-head data in the till layer (very few wells are supplied by ground-water circulating in the surficial sediments). The hydraulic-head data within bedrock were taken from the piezometric map (*see below*). For the second approach, the interpolated (bedrock) piezometric map was subtracted from the DEM. Negative zones indicate upward flow. For the last approach, bedrock wells among visited sites with a water level close to (<1 m) or above the ground surface were used to determine the percentage of wells having an upward gradient.

Specific yields

The equation that allows calculation of the recharge (W) from groundwater fluctuations in unconfined aquifers is

$$W = S_y \cdot \Delta h / \Delta t, \quad (4)$$

where S_y is the specific yield (equivalent to the drainage porosity, n_e) and Δh is the groundwater-level variation over a given time period Δt . This method is best suited for short periods in regions having shallow water tables with large fluctuations (Healy and Cook, 2002). This is the case for all six Prince Edward Island monitoring wells (distributed uniformly across the entire island).

The groundwater-level variation Δh was calculated graphically, by extrapolating down the recession curve of the well hydrograph until aligned with the curve peak. Indeed, this point corresponds to the level that would have been reached by the groundwater if no precipitation had occurred. The inherent difficulty with this method resides in the determination of the specific yield if no long-term pumping tests have been carried out in the well (or very close by), and in the impossibility of determining if groundwater-level fluctuations are due strictly to recharge and not to human activities such as pumping and irrigation (Healy and Cook, 2002). Furthermore, the value found is local, being representative of a radius of at most 100 m.

Since no specific-yield data were available for any wells in Prince Edward Island (pumping tests were too short in duration to provide reliable results), and since the evaluation

of recharge rates has provided a fairly reliable range of values, it was decided to use the six monitoring wells to estimate the specific yields throughout the province. Values of Δh were calculated for each year available, and their mean was used to provide minimum, mean, and maximum probable values of specific yield at each well. Indeed, annual Δh values had an approximately normal distribution. Water-level measurements in those wells were available for periods of 25 to 35 years.

Remote sensing

The MGWI project made innovative use of RADARSAT-1 radar imagery and Landsat-7 optical imagery within this regional hydrogeological project. This pilot project was conducted by TecSult Inc. with the support of the Canadian Space Agency, as part of the Earth Observation Applications Development Program (EOADP). Its aim was to evaluate the usefulness of RADARSAT-1 and Landsat-7 imagery as an input to groundwater-resource characterization and management projects.

The main scientific goal was to develop new tools to assist hydrogeologists and decision-makers in their work. In the context of regional studies, the use of satellite images and geomatics technologies, such as GIS, facilitates the mapping and analysis of natural resources, as well as data acquisition, monitoring, integration, and interpretation. Satellite images have proven to be very useful in providing vegetation maps; other applications are now being identified for groundwater-characterization purposes in temperate climatic regimes. The thematic information provides extra data layers that may contribute to the quantification of aquifer recharge and to the determination of major fracture systems, and thus to the overall understanding of groundwater-flow dynamics in the study area. Once validated, this information could also be used to help evaluate aquifer vulnerability with methods such as DRASTIC (Aller et al., 1985).

Mapping

Regional mapping of hydraulic properties, geochemical data, and hydraulic heads was carried out. Data for the first two categories were plotted discretely, as values showed no correlation (most likely due both to a lack of data pairs and to the system's strong heterogeneity). For the mapping, the hydraulic properties from wells located within 3 km were aggregated using a geometric mean. A piezometric map of the bedrock was produced using data from provincial databases, reports, and GSC water-level surveys. Since the GSC measurements were all taken within a relatively short period (in July and August of 2001 and 2002), they probably constitute a more representative and reliable source than other existing data collected in different months over a period of more than 40 years.

Numerical modelling

Due to the large area covered by this study and the inherent heterogeneity of the Maritimes Basin, only conceptual and simplified 2-D and 3-D numerical flow models were developed. Numerical models were developed in 2-D with SEEP/W[®] (GEO-SLOPE International, 1997) and in 3-D with FEFLOW[®] (WASY GmbH, 1998), two finite element numerical simulators, using steady-state conditions to obtain a quantitative representation of the hydrogeological-system dynamics. Even if the Maritimes Basin is a fractured porous medium, it was assumed that fractures and faults are sufficiently connected to provide a relatively homogeneous flow system at the regional scale that can be treated as an equivalent porous medium. Furthermore, the majority of pumping well results available in the provincial database and from the field campaigns showed a behaviour similar to that of a porous medium, following Theis-type curves (*see* 'Hydraulic properties of the bedrock' section).

DESCRIPTION OF THE STUDY AREA

Location

The Maritimes Basin covers the eastern part of New Brunswick, all of Prince Edward Island, the north-central part of Nova Scotia, and small parts of Newfoundland and Quebec. The study area, which encompasses parts of three provinces (New Brunswick, Nova Scotia, and Prince Edward Island), is represented by the black rectangle in Figure 1. It is approximately centred on the Moncton Basin, and covers a land surface of about 10 500 km², of which 9 400 km² are underlain by sedimentary rocks. The remainder consists either of the basement complex (pre-Carboniferous rocks, 1000 km²) or water bodies (3700 km²).

The study area is located between latitudes 45°45' and 46°30'N and longitudes 63°30' and 65°30'W (UTM 20, 305000–462000E and 4961000–5153000N). The major towns in the study area are Moncton, Sackville, Shediac, and Bouctouche in New Brunswick; Amherst in Nova Scotia; and Borden and Summerside in Prince Edward Island. This region is easily accessible through a well developed road network.

Physiography and hydrography

The Maritimes are part of the Appalachian physiographic region, which extends from Newfoundland to Alabama. The Maritimes Basin is located at the eastern edge of the region. The topography of the basin, illustrated in Figure 7, is relatively flat. Elevation generally ranges from sea level to about 150 m, although it may reach 300 m in the pre-Carboniferous rocks located in the southern part of the study area (the Caledonia mountains along the Bay of Fundy in New Brunswick, and the Cobequid Mountains in Nova Scotia). Elevations were calculated using 10 m topographic contours from 1:50 000

scale maps. Figure 7 also shows the locations of most gauging stations, weather stations, and Prince Edward Island monitoring wells used for the MGWI project.

Several major surface-water bodies are located within the study area. In general, watersheds are larger in New Brunswick and Nova Scotia than in Prince Edward Island, as its relatively low topography does not favour the development of large watersheds. In New Brunswick, approximately 200 watersheds drain toward the sea; the major rivers are the Petitcodiac and the St. John. Prince Edward Island has only a few shallow streams. Plate 4-3 of Rivard et al. (2005a) illustrates these watersheds. In New Brunswick and Nova Scotia, the occurrence of wetlands suggests a shallow water table or the presence of local perched aquifers.

The surface drainage in the New Brunswick portion of the study area runs in two main directions, eastward into the Northumberland Strait and westward into the St. John River (located west of the study area), except for areas around the Petitcodiac and Memramcook rivers and along the Bay of Fundy. Coastal areas in the eastern portion of the basin are dominated by beaches to the north and by peat bogs and salt marshes to the southeast. Near the provincial boundary in Nova Scotia, the lowland plain is characterized by a series of roughly parallel ridges with a trend similar to that of the Cobequid Mountains but with lower elevations (Vaughan and Somers, 1980). These ridges become less pronounced farther to the north, the countryside in the Amherst area being essentially flat lying. Rivers occupying ancient river valleys broaden over extended flood plains as they flow north toward the coast.

Runoff could be important in some areas because of the relatively high rainfall rates and the presence of a continuous layer of till, which contains variable proportions of clay and silt. Nevertheless, the large forested zones and smooth slopes of the basin, together with the general till composition, do not really favour runoff generation. Indeed, bedrock outcrops are sparse and infiltration through the till layer is likely the only effective groundwater-recharge path to the bedrock aquifers.

Climate

The climate of the Maritimes is described as humid continental, with long and cold winters and warm summers (Brown, 1967). It is one of the wettest parts of Canada, where a substantial proportion (about 25%) of the precipitation occurs as snowfall. Because of the basin's low relief, the major influence on weather is distance to the sea. Indeed, the coastal areas of the Northumberland Strait are cooled in the summer and warmed in the winter by the ocean. The prevailing circulation of continental air masses from the west allows much wider fluctuations in temperature than would be expected in a purely maritime climate (Peters, 1981).

Daily-average air temperature varies between 17 and 24°C in the summer and between -12 and -4°C during the winter. Average precipitation ranges from 900 to 1500 mm/a.

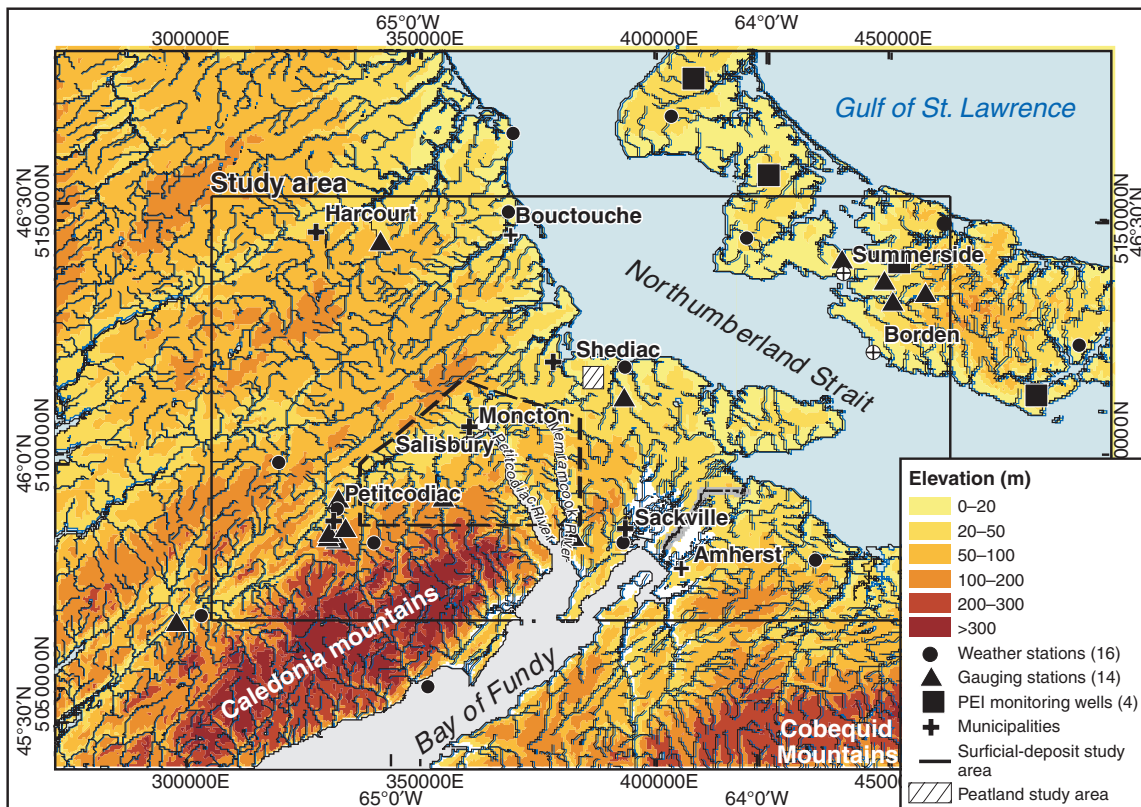


Figure 7. Topography of the Maritimes Groundwater Initiative (MGWI) study area (map in UTM co-ordinates, Zone 20, NAD83), showing the locations of weather stations, gauging stations, Prince Edward Island monitoring wells, and the two case studies carried out during the MGWI project.

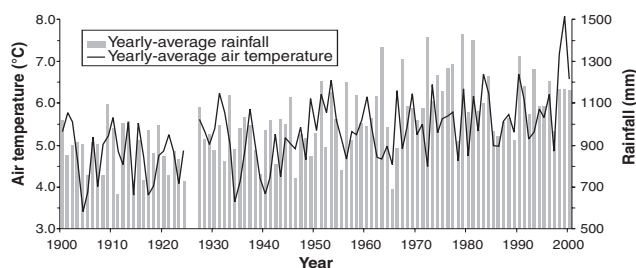


Figure 8. Yearly-average precipitation and air temperature, Moncton weather station, New Brunswick.

The highest values are observed along the Bay of Fundy. Figure 8 presents, as an example, yearly-average rainfall and air temperature recorded at the Moncton weather station (Environment Canada, 2002). Mean annual evapotranspiration varies between 345 and 440 mm/a (*see* 'Water-balance method' section above for details and Plate 4-2 of the atlas). Table 3 summarizes the climatic conditions and Figure 9 presents the spatial distribution of annual precipitation.

Land and water use

The population of the Maritime provinces is concentrated mainly along the seashore and inland close to major rivers. Large portions of inland New Brunswick and Nova Scotia are forested, with the remaining parts devoted to farming. A significant portion of the Maritimes is exploited for its natural resources. The economies of New Brunswick and Nova Scotia are based mostly on manufacturing (food processing, lumber products, paper, metals, and transportation products), tourism, forestry, fishing and aquaculture, mining (metals, peat moss, and salt), energy, construction, and agriculture. This distribution is also representative for most of Prince Edward Island, except that mining and energy are almost nonexistent. Most industries have a close relationship with water-resource management, specifically water-quantity and -quality issues. Indeed, their viability relies on having access to an adequate supply of good-quality water; in turn, they may have some environmental impacts on this resource.

Table 3. Climatic conditions in the Maritimes.

Province	Annual precipitation (mm/a)	Average temperature (°C) summer / winter	Mean evapotranspiration (mm/a)
New Brunswick	950 to 1450	20 to 24 / -12 to -7	382 to 430
Nova Scotia	1000 to 1400	17.4 / -4 to -6	345 to 440
Prince Edward Island	900 to 1250	18.5 / -6.6	359 to 428

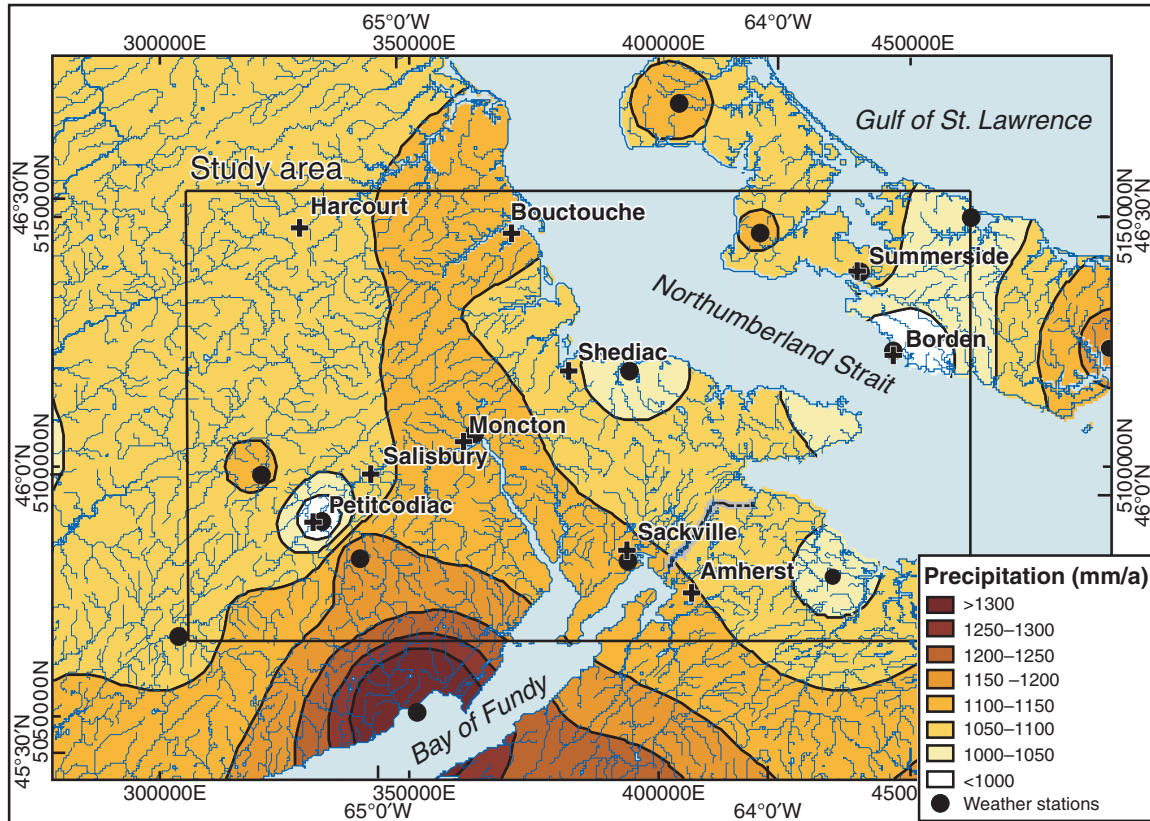


Figure 9. Spatial distribution of annual precipitation in the Maritimes (using 24 weather stations, shown as black dots).

Geology

Geological setting

The Maritimes Basin is a composite post-Acadian successor basin that consists of a series of sedimentary subbasins, which unconformably overlie a complex collage of Appalachian tectonostratigraphic terranes (for a synthesis, *see* van de Poll et al., 1995). Subbasins trend generally northeast to east and are separated by basement uplifts (e.g. Caledonia and Kingston uplifts) along large regional faults (e.g. Clover Hill–Poller River and Peekaboo–Berry Mills faults). The central part of the basin, often termed the ‘Maritimes Rift’, features a thick sequence (locally up to 12 000 m) of Late

Paleozoic sedimentary rocks that have been periodically deformed and reworked, resulting in a complex temporal and spatial pattern of erosion and deposition. The subbasin sedimentary sequences and the time of maximum subsidence are diachronous and range from late Middle Devonian to Westphalian C (St. Peter, 1993). Regional unconformities or disconformities in the stratigraphic records show that several periods of deformation and sea-level change have affected the Maritimes Basin during the course of its depositional history (St. Peter, 1993). Since the Carboniferous period, there has been little depositional activity (Vaughan and Somers, 1980). A relatively thin cover of unconsolidated Quaternary glacial deposits overlies these rocks. Most of the overburden is glacial till, but glaciofluvial and alluvial sediments occur along the banks of the large rivers.

The study area covers the Moncton, Sackville, and Cumberland subbasins, and a part of Prince Edward Island, as shown in Figure 10. The stratigraphic column comprises, from base to top (Fig. 10), the Horton, Windsor, Riversdale-Mabou, Cumberland, Pictou, and Prince Edward Island groups. The internal stratigraphy of these units is complex and often laterally discontinuous, as a result of different sedimentation rates, syndimentary faulting, and reworking. The main rock types of these groups and their respective formations are presented in Table 4. This table is composite and not representative of the lithostratigraphy of a particular subbasin.

Sedimentological and structural settings

The sedimentological setting of most units in the Maritimes Basin is essentially one of continental affinity (alluvial-lacustrine-fluvatile; St. Peter, 1993; van de Poll et al., 1995), except for a marine episode during deposition of the Windsor Group. The strata represent several alluvial-lacustrine or alluvial-marine cycles in the early basin fill (Horton, Windsor, and Mabou groups), which are covered by multiple stacked cycles of meandering fluvatile, inter-channel, and paludal deposits (Cumberland and Pictou groups; St. Peter, 1993).

The Late Devonian to Early Carboniferous is represented by the Horton and Windsor groups. The Horton Group consists of a sequence of continental sedimentary and volcanic rocks that rests unconformably on pre-Carboniferous units, and is overlain by the marine limestone and evaporite strata of the Windsor Group (Dyck et al., 1976). The marine beds are overlain by thick assemblages of continental origin, which correspond to the Riversdale-Mabou, Cumberland, and Pictou groups, during the Middle to Late Carboniferous. According to St. Peter (1993), the angular unconformity between Cumberland and Pictou strata implies structural inversions of the basin fill, causing uplift, tilting, and erosion of parts of the stratigraphic packages. Strata of the Early Permian Prince Edward Island Group are gradational above the Pictou Group. Rocks of Triassic age occur locally, especially along the Bay of Fundy in New Brunswick and along Cobequid Bay in Nova Scotia.

Four stages of deformation have affected and segmented the depositional history of the units of the Maritimes Basin (van de Poll et al., 1995 and references therein). The first deformation stage has mainly affected rocks of the Horton Group in the Moncton Basin and correlative units in surrounding areas. This resulted in folding, the development of faults in an environment controlled by dextral movement, and regional uplift, causing regional erosion prior to deposition of the Windsor Group.

The second stage of deformation was regional and initiated during deposition of the Riversdale Group; its upper age limit has not yet been defined. The deformation has affected rocks of the Windsor Group and created the creeping into

pillows, crests, and diapirs. This stage was followed by preferential erosion and a regional subsidence and covering of adjacent platform regions.

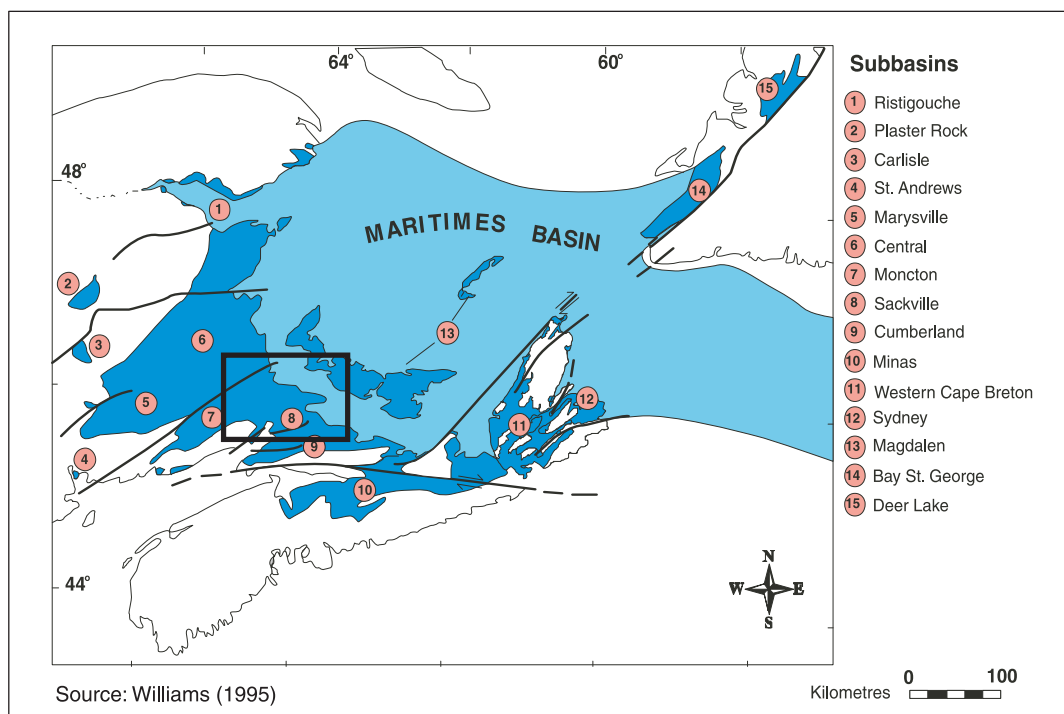
The third stage of deformation occurred between the Early Permian and the Late Triassic. It resulted in the regional uplifting and inversion of bedrock blocks along reactivated faults. This stage marked the beginning of the destruction of the Maritimes Basin, leading to its current structural configuration and horst-and-graben morphology. It produced regional open synclinal folds, limited by faults, thus creating grabens and half grabens that affect earlier-formed basins. The third stage also induced the complete inversion of the rock strata and created large open anticlines above deeply buried bedrock.

The last stage of deformation occurred during the Mesozoic. It is characterized by subsidence, inversion of strata, and the development of normal faults affecting Triassic and older rock units.

Surficial sediments

The surficial sediments of the Maritimes Basin consist mainly of till and glaciofluvial deposits (Vaughan and Somers, 1980; Rampton et al., 1984; MacDougall et al., 1988). Only a few small areas are covered by marine clay. Sand and gravel are restricted to narrow zones near major streams and to glaciofluvial complexes. Most of the recharge supplying the bedrock aquifers infiltrates through the till layer; however, very few data were available on its hydraulic properties. In addition, the hydraulic potential of sand and gravel units in bedrock valleys had never been tested.

For most of the study area in New Brunswick, the thickness of the glacial till varies from 0 to 20 m and averages 8 m; in Prince Edward Island, it ranges from 0 to 8 m and averages 4 m; and, in Nova Scotia, it averages 8 m. The matrix of the deposits is heterogeneous, varying from sandy to clayey. It usually reflects the composition of the underlying bedrock, indicating that surficial deposits have not been transported far (Carr, 1964). In the Moncton region (covering approximately 1000 km²), Carr (1964) found that the sand content of several samples of till ranged from 33 to 91% and averaged 62%. Surficial sediments of Prince Edward Island are also mostly glacial till, 70 to 80% of which is composed of sand and gravel derived from the local bedrock (Jacques Whitford and Associates Ltd., 1990b). Sand and gravel sediments, such as eskers, kames, and outwash plains, can be found as very thick deposits in some areas, but they are very limited in extent and restricted to valleys (e.g. near the Petitcodiac River in the Moncton region and near Sussex, both in New Brunswick). Most of the sediments were deposited during the Late Wisconsinan glaciation and deglaciation. The ice sheet retreated about 13 000 years ago and was followed by a marine transgression and a Holocene regression. The actual marine transgression began 4000 years ago, the result of



System	Stage	Time (Ma)	Groups	5	6	7	8	9	13
			NB & NS	Marysville	Central	Moncton	Sackville	Cumberland	Magdalen
Carboniferous	Permian Lower	270	Prince Edward Island						
					Clifton C				Unnamed
		290							
	Upper						Cape John	Cape John	Naufrage
							Tatamagouche	Tatamagouche	Cable Head
		300	Pictou						Green Gables
	Middle			Richibucto			Richibucto	Balftron	
				Minto	Clifton B	Salisbury		Malagash	Bradelle
			Cumberland					Ragged Reef	
								Spring Hill Mines	
								Polly Brook	
	Lower			Boss Point	Clifton A	Boss Point	Boss Point	Boss Point	Port Hood
		325	Riversdale-Mabou		Enragé			Claremont	Pomquet
				Shin	Bathurst			Shepody	Hastings-Shepody
	Viséan		Windsor			Hopewell	Hopewell Cape	Middleborough	
						Glover Hill	Lime-Klin Brk		
						Cassidy Lk	Pugwash		
Devonian	Upper					Upton	Upton	Windsor	Windsor
				Parleeville		Macumber Hillsborough	Macumber Hillsborough		
						Weldon		Nuttby	
	Middle					Albert	Albert	Greville River	Horton
								Rapid Brook	
								Falls	
	Lower	360	Horton						
				Kleef		Memramcook			
	Eifelian			Volcanics					
		376	Fountain Lake					Fountain Lake (Cobequid Highlands)	
		390							

Figure 10. Location of subbasins of the Maritimes Basin in the study area and their stratigraphic succession (*from van de Poll et al., 1995*). Abbreviations: Brk, Brook; Lk, Lake.

isostatic adjustment. Recent deposits can be found in a few areas on the eastern side of New Brunswick and on Prince Edward Island. They consist mainly of beach sand, tidal mud, and river alluvium. The soils consist mainly of Podzol, Gleysol, and Luvisol types. Organic soils are also encountered in some scattered areas.

Wetlands (especially peatlands and marshlands) are encountered in several areas throughout New Brunswick and in Nova Scotia near the provincial boundary. Marshlands are characterized by permanent, intermittent, or irregular flooding. They are usually located near the coastline and are therefore saltwater marshes. In scattered areas, peatlands have

Table 4. Composite table describing lithological units of the various subbasins of the Maritimes Basin (*from* van de Poll et al., 1995). Note that this table should not be interpreted as a lithostratigraphic column.

System	Group	Formation	Dominant lithology
Permian	Prince Edward Island	Egmond Bay	Red sandstone
		Orby Head	Conglomerate and coarse- to medium-grained wacke
		Hillsborough River	Wacke and conglomerate
		Idare Capes	Conglomerate, sandstone to mudstone
Carboniferous	Pictou	Undivided	Typically sandstone and mudstone
		Cape John	Sandstone and mudstone
		Tatamagouche	Conglomerate, sandstone and mudstone
		Balfour	Arkosic sandstone and mud-clast conglomerate; siltstone and mudstone; calcareous sandstone concretions abundant
		Richibucto	Sandstone, conglomerate, and siltstone; minor thin coal seams
		Minto	Fine- to medium-grained lithic and quartzose sandstone and minor pebbly sandstone; siltstone, mudstone, and very fine grained sandstone
	Cumberland	Salisbury	Mudstone, siltstone, and fine-grained sandstone; quartzose sandstone and pebbly sandstone, mud-clast and polymictic conglomerate
		Undivided	
		Malagash	Mudstone, sandstone; minor limestone and coal
		Ragged Reef	Black shale with coal and sandstone with coal
		Springhill Mines	Mudstone, fine-grained to pebbly sandstone; coal
		Polly Brook	Conglomerate and sandstone
		Joggins	Mudstone, minor fine-grained to pebbly sandstone, and coal
		Grande Anse	Medium- to coarse-grained sandstone and pebbly conglomerate; siltstone and mudstone; commonly fine- to very fine grained calcareous sandstone; minor fine-grained sandstone with plant detritus; minor silty mudstone
		Boss Point	Fine grained to granular sandstone; siltstone and mudstone; minor mudstone, locally with carbonate nodules or calcrete; minor very thin coal seams, petroliferous limestone
	Riversdale-Mabou	Undivided	Sandstone and polymictic conglomerate; siltstone and mudstone
		Shin	Very fine to coarse-grained sandstone and polymictic conglomerate; siltstone and mudstone
		Hopewell Cape	Very fine to coarse-grained sandstone and polymictic conglomerate; siltstone and mudstone
		Enragé	Arkosic sandstone and polymictic conglomerate; fine- to medium-grained sandstone, mudstone, sandy mudstone, and sandstone, commonly with paleosol and carbonate nodules
		Claremont	Conglomerate and sandstone
		Shepody	Sandstone and conglomerate
		Middleborough	
	Windsor	Lime-Kiln Brook	Sandstone and conglomerate; massive and granular gypsum; minor limestone and mudstone
		Pugwash	
		Clover Hill-Cassidy Lake	
		Upperton	Gypsum and anhydrite; minor limestone, mudstone, and sandstone
		Macumber	Fossiliferous, intraclastic, and/or pelletal limestone; minor breccia
		Parleeville	Locally highly fossiliferous, algal, and siliclastic limestone, sandstone, and mudstone
	Horton	Hillsborough	Polymictic conglomerate and lithic sandstone; minor mudstone
		Weldon	Polymictic conglomerate; fine-grained to granular sandstone; mudstone and shale
		Albert	Siltstone, mudstone, and shale; fine- to coarse-grained quartzose feldspathic arenite
		Nuttby	
		Memramcook	Sandstone, polymictic conglomerate, siltstone, and mudstone, commonly with paleosol and carbonate nodules
		Greville River-Rapid Brook Falls	Conglomerate, wacke, sandstone, siltstone, and argillite
Devonian	Fountain Lake	Undivided	Basalt, rhyolite, tuff, basalt sandstone, siltstone, and conglomerate

formed in former lake basins or other poorly drained areas. These deposits have formed from the accumulation of sphagnum peat and other wetland plants. The average thickness of the peat bogs is about 3 m (Vaughan and Somers, 1980; Keys and Henderson, 1987). Potential hydraulic connection between peat bogs and the regional bedrock hydrogeological system is not well documented. A case study of a peat bog near Shediac, including extensive fieldwork and modelling, was conducted by Carrier (2003) in order to understand the interactions between the systems (*see* 'Case study: Beauséjour peatland near Shediac, New Brunswick' section).

Boisvert (2004) evaluated hydraulic properties of Quaternary sediments in the Moncton area, their hydrogeological potential, their role in the regional groundwater-flow systems, and, in particular, their influence on aquifer recharge.

INTERPRETATION AND PRESENTATION OF EXISTING AND ACQUIRED HYDROGEOLOGICAL DATA

This section describes the interpretation methods used to analyze data from fieldwork carried out during this project and from other sources. Results are presented as tables, graphs, or figures. Maps developed using some or all the results obtained in this section are presented either in the following sections summarizing the geological or hydrogeological knowledge or in the atlas (Rivard et al., 2005a).

Data from fieldwork

Fieldwork carried out during this three-year project included water-level measurements, drilling, geophysics, hydraulic testing, and sampling (*see* 'Methodology' section). The results obtained were added to the hydrogeological database and have significantly contributed to the general understanding of this hydrogeological system.

Piezometry and monitoring

Water-level surveys

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). A piezometric map of the bedrock was produced through kriging by means of an exponential variogram with a correlation length of 21 km, using SURFER™ software by Scientific Software Group. A considerable amount of information on

groundwater depths was available from provincial databases and reports, but a high level of uncertainty was attached to the data, mostly because static water levels were often measured immediately after well construction. Moreover, fluctuations within a year or a decade can certainly be large. For this reason, only the most recent data (1998 or newer) from each provincial database were retained, giving more weight to the water-level survey. This also avoided dealing with long-term fluctuation patterns or trends. All bedrock wells were used, without consideration of their depths, since this information is not always available and most wells are probably open to the rock aquifer from immediately beneath the surficial deposits to the bottom of the well. To obtain a more realistic piezometric map when performing the interpolation, manual control points were added, especially in low-relief areas close to streams and along the coast, where a lack of measurements was noted. The piezometric map is presented in the 'Integration of hydrogeological information' section and on Plate 5-5 of Rivard et al. (2005a).

It is not clear from water-level measurements, taken in both rivers and wells, whether the 'average' bedrock piezometry is always related to groundwater within the surficial sediments and to surface water. Uncertainties related both to elevation of measurement points (land surface) and to bedrock sequence arrangements of the Maritimes Basin make conclusions regarding hydraulic connections difficult. In addition, a deep well close to a stream may not show similar water levels, although the same unit may further be connected to another stream due to the absence of overlying fine-grained sediments or beds. It appears from available data that major rivers are generally connected to neighbouring bedrock aquifers, and it is believed that both units should be hydraulically connected at the regional scale, even if local disconnection may be observed due to the lenticular character of the rocks. The very few data on groundwater within surficial sediments available for the area suggest that water circulating in this layer should also be connected to bedrock aquifers at the regional scale.

Groundwater-level monitoring program

All five MGWI monitoring wells are likely under semiconfined or confined conditions, since annual variations are small (on the order of 1 m or less) and the wells do not seem to react strongly to any major precipitation event. Hence, the well hydrographs could not be used to calculate recharge rates or specific yields. No long-term pumping-test results were available, however, to confirm the semiconfinement hypothesis. Figure 11 presents fluctuations of the Harcourt well from August 2001 to August 2004. This figure indicates relatively low levels for the year 2001; that year was indeed very dry. Other monitoring-well hydrographs, presented in Appendix A, all show a similar middle-term behaviour. The Shediac well hydrograph is strongly influenced by tides, with variations between recordings ranging from 0.6 to 1.3 m.

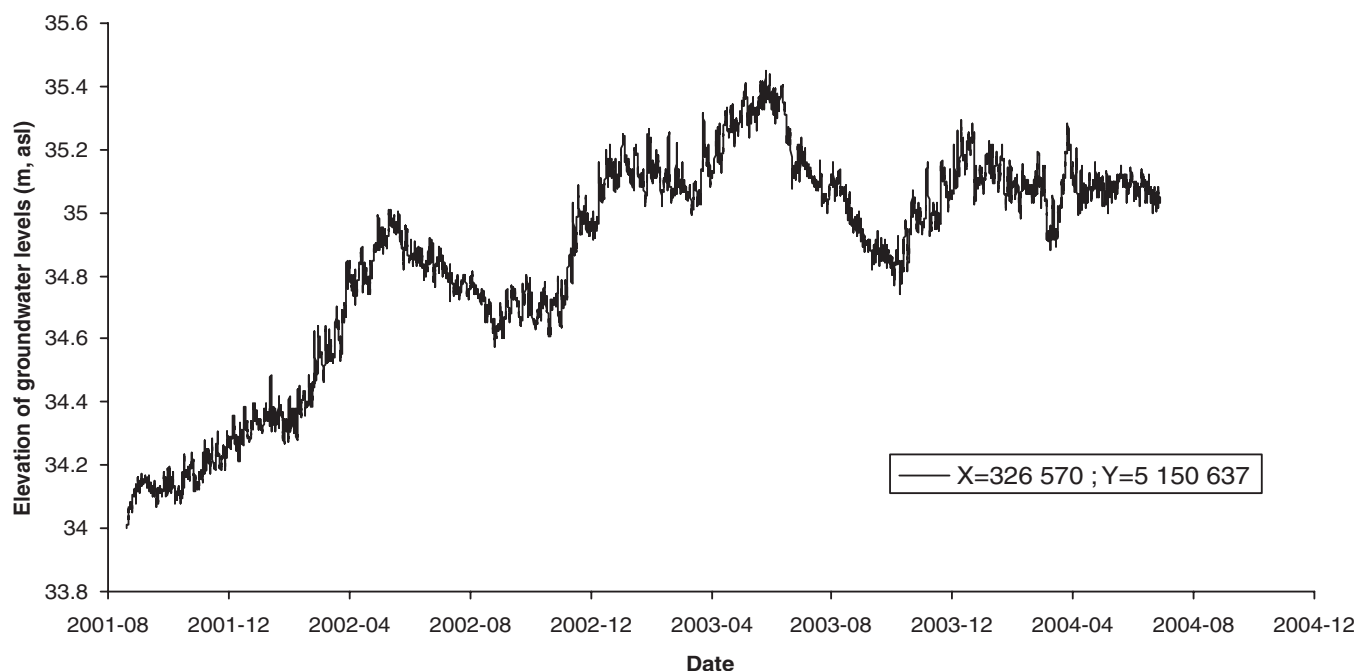


Figure 11. Hydrograph of the Harcourt (New Brunswick) monitoring well, August 2001 to August 2004.

Table 5. Specifications of new boreholes drilled in bedrock during the Maritimes Groundwater Initiative.

Site location	UTM (Zone 20, NAD83)		Well depth (m)	Diameter (mm)	Casing (m)	GW static depth (m)
	Easting (m)	Northing (m)				
Salisbury, NB	340460	5099498	62.5	150	0.45	5.11
	340601	5099513	62.5	150	0.1	1.97
Riverview, NB	360096	5092359	68.6	150	0.45	1.65
Dieppe, NB	370654	5100628	60.0	150	0.54	36.7
Légerville, NB	345747	5129191	83.8	150	0.72	10.15
	345710	5129262	91.5	64	0.47	3.59

Stratigraphy and fracturing

Drilling

The specifications of boreholes drilled in bedrock are summarized in Table 5. Core samples confirmed that fractures occur mostly in sandstone strata and at lithological changes. The Dieppe well revealed that, contrary to what the municipality had thought, this area is still in the Salisbury Formation and not in the Boss Point Formation. As such, the well provided very little water and drilling was abandoned after 60 m. Boreholes in Quaternary units confirmed the hypothesis that fairly thick deposits (up to 29 m) can be found in buried valleys as far as 10 km northwest of Moncton (and thus from the Petitcodiac River valley), and that they could include sand units. Borehole characteristics in surficial sediments are presented in Boisvert (2004).

The manual drilling in the Beauséjour peatland, performed using a percussion drill (Pionjär 120) and a Russian peat sampler, indicated that silt and till units were present between the peat and the bedrock. The investigation conducted with telescopic rods revealed that the peat thickness averages 3.2 m, but can reach 7 m. Maps showing the geometry of the peatland are presented in Carrier (2003).

Borehole geophysics

The 10 wells investigated with borehole geophysics are listed in Table 6. The logs displayed in Figure 12, typical of those obtained from most wells, reveal an inverse relation between individual traces, with fine-grained materials being identified by the combination of high gamma activity and low resistivity. Conversely, coarse-grained deposits are associated with low gamma activity and high resistivity. This inverse correlation roughly forms a mirror image between the two

Table 6. Specifications of the wells where geophysical logs were recorded during the Maritimes Groundwater Initiative.

Location	Total depth (m)	Approx. diameter (cm)	Casing depth (m)	Formation	Lithology
Petitcodiac, NB	113	Approx. 15.2 to 12.0	12.6	Salisbury	Shale, siltstone, conglomerate, sandstone
Borden, PEI	120	Approx. 15.5	12.2	Kildare Capes	Sandstone, siltstone
Fort Lawrence, NS	69	Approx. 16.3	6.1	Balfour	Sandstone, siltstone, shale
Harcourt, NB	145	Approx. 12.4 to 10.3	6.7	Undivided Pictou Gp	Sandstone, shale
Port Elgin, NB	44	Approx. 20.3 to 19.3	19.2	Richibucto	Sandstone, siltstone
Shediac, NB	61	Approx. 15.5	42.7	Richibucto	Sandstone, siltstone
Moncton, NB	88	Approx. 30.1 to 25.6	12.2	Salisbury; Richibucto	Sandstone, siltstone, shale
New Glasgow, PEI	83	Approx. 16.3	17.5	Kildare Capes	Sandstone, siltstone
Sackville #4, NB	24	Approx. 26.4 to 23.1	12.2	Boss Point	Sandstone, siltstone, shale
Sackville #7, NB	54	Approx. 22.1 to 17.5	10.1	Boss Point	Sandstone, siltstone, shale

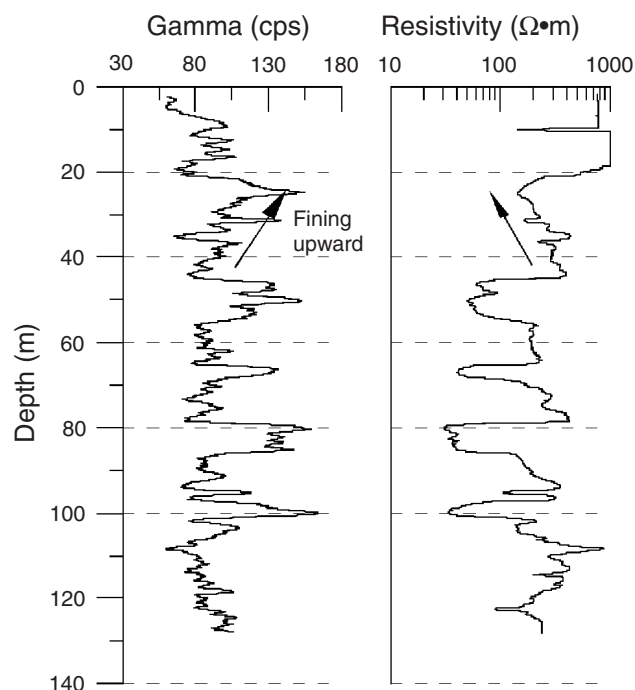


Figure 12. Natural-gamma-activity and electrical-resistivity logs recorded as a function of depth in the Harcourt (New Brunswick) well.

logs that is illustrated by the crossplot shown in Figure 13. These trends also delineate depositional processes, with specific intervals depicted as fining upward. As described below, groundwater movement through these aquifers is controlled predominantly by individual fractures. Therefore, lithological information such as grain-size distribution, gleaned from the gamma and resistivity logs, is not of primary importance when considering the hydrogeological characteristics of these sedimentary rocks. Nevertheless, these logs are significant in a secondary sense when considering fluid transport associated with matrix porosity and with fracture density related to rock type.

Figure 14 presents a summary of the geophysical logs obtained and transmissivity profiles resulting from packer tests in the Harcourt (New Brunswick) well, indicating

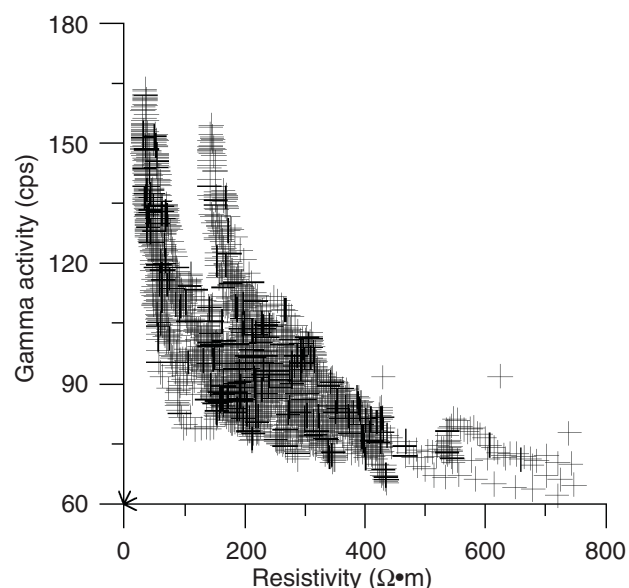


Figure 13. Crossplot of the gamma and resistivity data from the Harcourt (New Brunswick) well shown in Figure 12.

water-bearing fractures. Arrows superimposed on the caliper log in Figure 14a indicate groundwater flow direction, showing the downward circulation of the flow between the two fractures. Therefore, the transmissivity of this well is clearly determined by two permeable (aquifer) units separated by an aquitard, as shown on Figure 14b.

In total, 326 planar features were identified and oriented by careful inspection of televiwer logs from eight wells. This directional information is depicted on the rosette diagram (strike) and the equal-area, lower-hemisphere stereographic projection in Figure 15. These data indicate that most permeable intervals are associated with bedding planes and thin-bedded sequences of various rock types; a few productive fractures are detected in sandstone units. Furthermore, a large majority of these features, whether discrete fractures or bedding plane partings, are subhorizontal; very few steeply dipping features were identified in these logs, even when considering the sampling bias inherent in locating subvertical

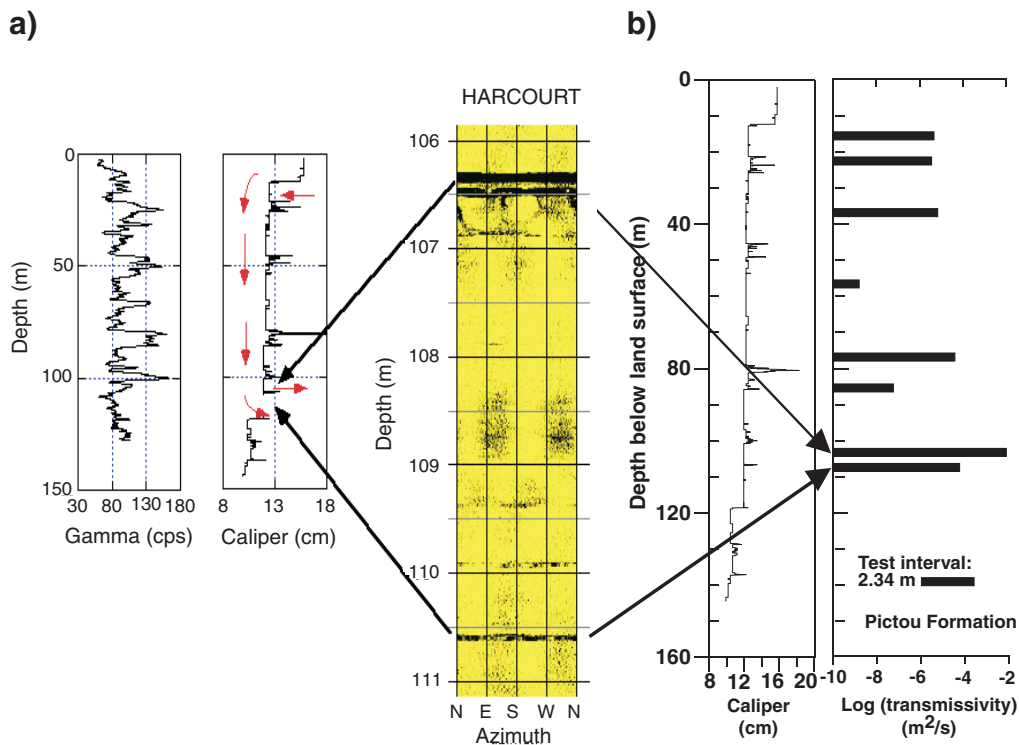


Figure 14. Combined geophysical logs and packer test results from the Harcourt (New Brunswick) well: **a)** example of borehole geophysical logging (gamma, caliper, and televiwer); and **b)** comparison between a caliper log and the results of packer testing.

fractures from vertical wells (Terzaghi, 1965). Only about 5% of all planar features have dips greater than 50° . Just seven fractures were found to intersect the Moncton well, all of them subhorizontal. The Harcourt well was distinctly different from the others in terms of structure. This is the only site among those investigated that lies north of the Kingston Uplift, and it is apparent that the bedrock here has been subjected to different tectonic forces. Fractures exhibit no clear trend in orientation and no correlation with other sites.

On a smaller scale, a site located 5 km northwest of Sackville, New Brunswick was selected for a more comprehensive testing strategy to confirm and refine the regional observations of the subbasins in more detail. This site is located at a municipal water facility and consists of seven wells (Fig. 16). Two wells (wells 4 and 7) were logged with geophysical tools; one well (well 5) was pumped and the other six were monitored as part of a long-term aquifer test; and pole-dipole surface-resistivity surveys were conducted along three transects (dashed lines in Fig. 16).

The general geological structure is gently dipping, coincident with fracture strike as determined from the image logs, and aligned northeast-southwest. A rosette diagram of directional data (strike) from Sackville wells 4 and 7 (Fig. 17) appears to be a matching subset of the general results derived from eight wells (Fig. 15). Analysis of the aquifer-test data demonstrates hydraulic communication among wells to be localized

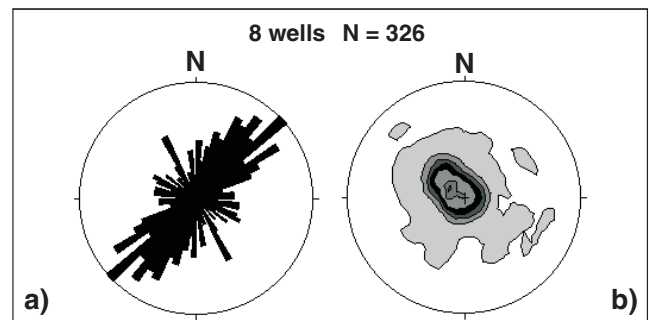


Figure 15. Plots of 326 fracture orientations for eight wells in Harcourt, New Brunswick, developed from inspection of televiwer logs: **a)** rosette (strike), with radius = 6% or 22 values; **b)** equal-area, lower-hemisphere stereographic projection.

east-west, with no discernible response north-south in the monitor wells (for the pump-test report, *see* Rivard et al., 2005b). Thus, flow is preferentially oriented subparallel to strike and associated transmissivities are on the order of $10^{-3} m^2/s$. The interpreted results derived from integrating all field measurements indicate that these local hydrostratigraphic characteristics are consistent with more regional results determined across a large portion of the basin. Consequently, this Sackville site serves as a useful microcosm for general basin hydrogeology within the shallow subsurface.

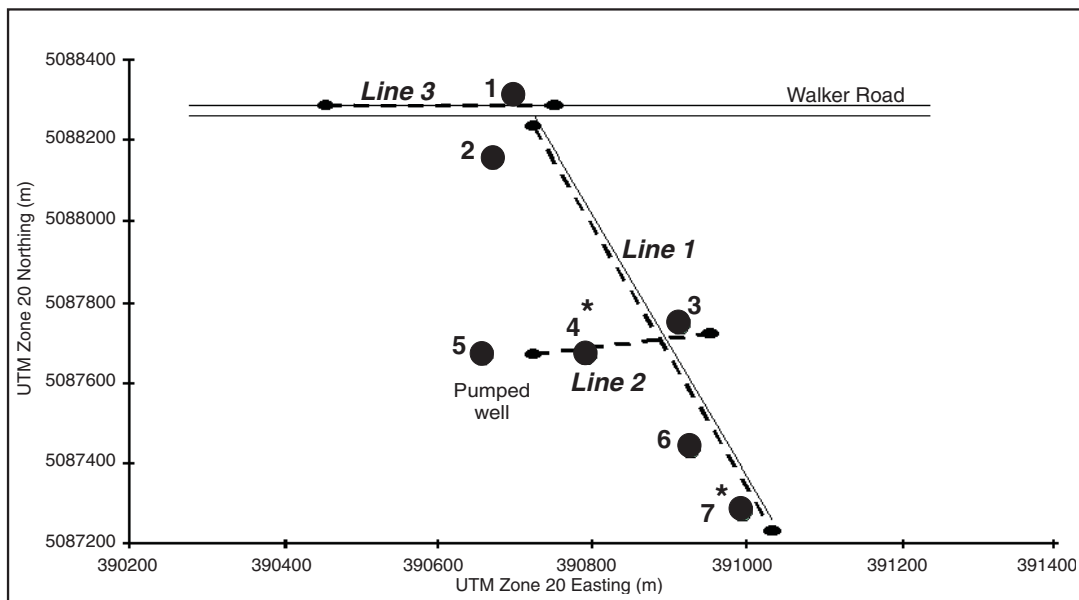


Figure 16. Site of Sackville study, with locations of seven water wells and three surface-resistivity surveys (dashed lines). Geophysical logs were obtained in wells 4 and 7 (indicated with '*'); the aquifer test was performed by pumping well 5 and monitoring the other six wells.

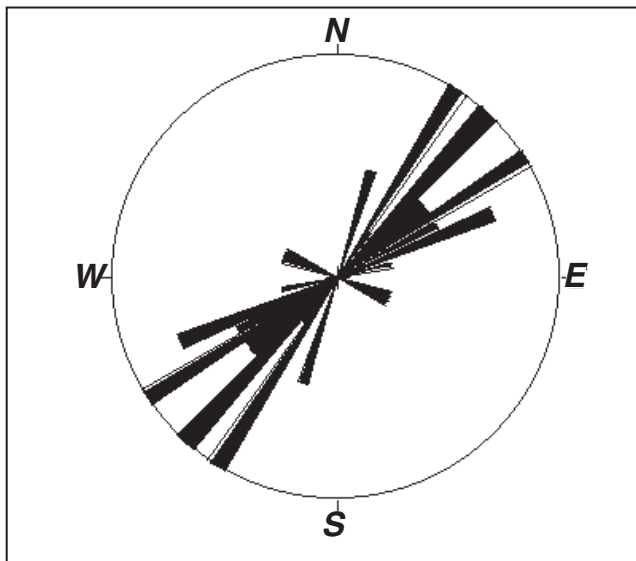


Figure 17. Rosette diagram of fracture strike for Sackville wells 4 and 7, developed from inspection of televiwer logs. N = 28; radius = 14% or 4 values.

Magnetically oriented televiwer images of the borehole walls (for an example, *see* Fig. 5) indicate that the vast majority of planar features intersecting the wells are subhorizontal, although they tend to have a consistent northeasterly strike that is aligned with the direction of the regional stress field and the major faults of the Maritimes Basin. Significant vertical flow was detected in four wells under ambient conditions (Port Elgin, Harcourt, and both Sackville wells), which indicates the presence of a hydraulic barrier to vertical fluid

movement within the fractured rocks that is short-circuited by the well itself (i.e. few permeable vertical fractures). These features infer a quasi-2-D flow in the horizontal sense, but with a preferential component along strike, as noted from the results of the Sackville study.

Electrical-resistivity soundings

The locations of the three electrical-resistivity images acquired at the Sackville water-supply well field are shown in Figure 16. The first image (line 1) was acquired along the main access road to the well field. The resulting electrical-resistivity image and two-dimensional model are shown in Figure 18. The northern part of the line is underlain by high-resistivity bedrock that contrasts sharply with a southward-dipping low-resistivity zone near station 480, which may be faulted and/or fractured. In the southern portion of the image, the high variability in the near-surface resistivity is likely due to variable thickness of overburden and the presence of rock fill along portions of the road. Resistive bedrock is interpreted to be at a depth of approximately 20 m. This is underlain by lower resistivity bedrock at a depth of 60 m.

An electrical-resistivity image was also acquired along a line (line 2) that intersects production wells 3 and 5. The apparent resistivity image and results from modelling are shown in Figure 19. The resistivity of the upper 10 m is quite variable, likely due to changes in overburden composition. This is underlain by low-resistivity bedrock that increases sharply in thickness east of station 160, so that the resistive basement bedrock is too deep to image. This is interpreted to indicate that faulting and fracturing are present. The third

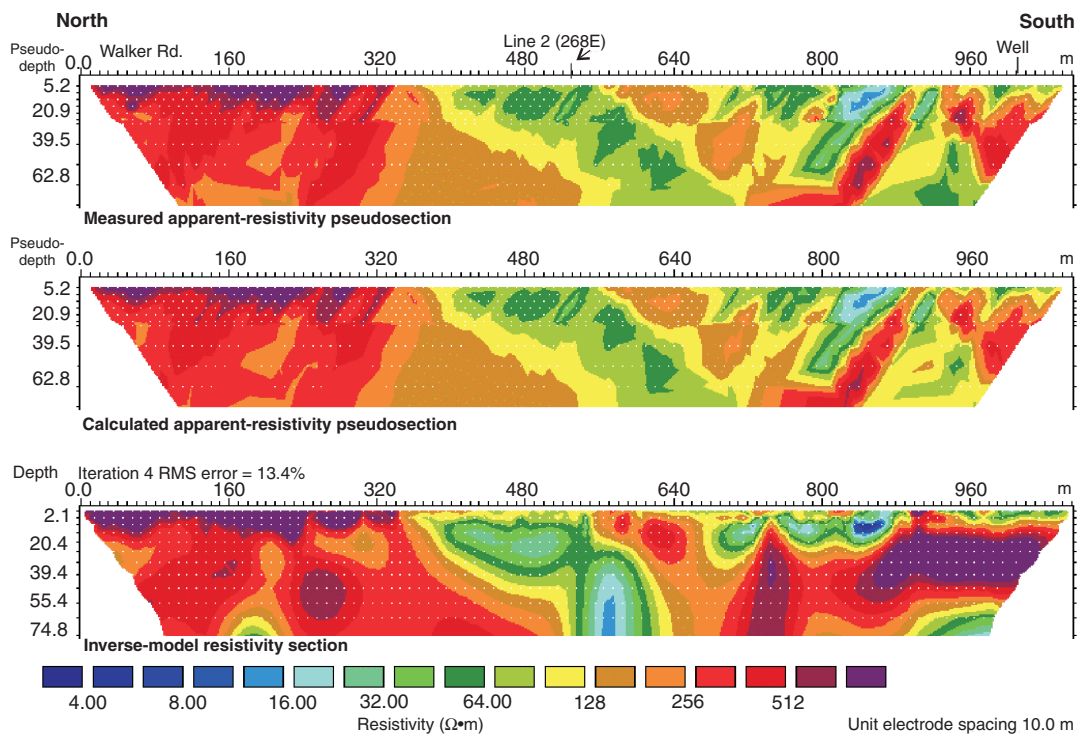


Figure 18. Pole-dipole-array electrical-resistivity survey for line 1, Sackville, New Brunswick.

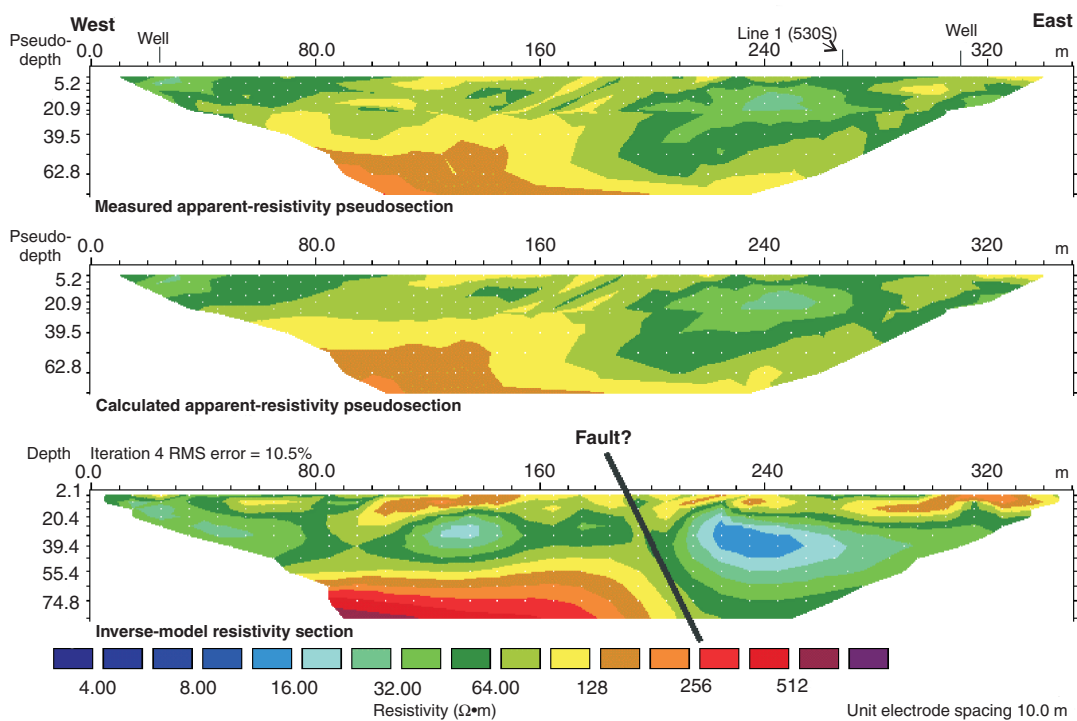


Figure 19. Pole-dipole-array electrical-resistivity survey for line 2, Sackville, New Brunswick.

electrical-resistivity image (line 3) indicated that the resistivity generally decreases slightly with depth, likely due to fractured bedrock.

The electrical-resistivity images from the Sackville well field indicate that there may be significant faulting and fracturing present, as detected by pumping tests (*see* 'Hydraulic properties of the bedrock' section) and borehole geophysics. Individual fractures are too narrow to detect with these techniques; only zones of fracturing can be identified, due to the lower bulk resistivity of the rock. On line 1, an apparent fracture zone dips south; on line 2, the apparent fracture zone dips eastward (or is faulted); and line 3 does not intersect the fracture zone. Therefore, the fracture zone likely dips southeast, suggesting a northeast strike, in agreement with results from borehole geophysics. This obviously can affect the interaction between wells during pumping, as confirmed by hydraulic testing. More electrical-resistivity imaging would be needed to develop a geological model of the well field, and a parallel line should have been implemented to accurately determine the strike, in order to correlate the images. A nearby parallel line was not feasible, however, due to the dense forest.

Ground-penetrating radar

Data retrieved from the Beauséjour peatland were processed with built-in software (developed by Sensors & Software Inc.) that uses spatiotemporal filters. The results revealed that there is a 30 cm thick layer of fine sand at the base of the peatland, followed by a continuous layer of till (of thickness varying from a very few centimetres to a few metres). Because of the strong attenuation of the signal in the fine till matrix, the signal failed to reach bedrock.

Hydraulic properties of the bedrock

Pumping tests

Interpretation of the pumping-test data was done using both the Theis and Cooper-Jacob methods (Todd, 1980; Kruseman and de Ridder, 2000). Although these two methods assume confined conditions and a fully penetrating well, they are commonly used in various contexts that deviate from these ideal conditions. The software package AqteSolv™ by HydroSOLVE, Inc. was used for the Theis curve match. In Riverview, one observation well reacted as if it were located in the same vertical fracture as the pumping well. These data were thus interpreted using the Gringarten and Ramey method (Kruseman and de Ridder, 2000). Observation wells were either unavailable or did not respond 'normally' at eight of the ten bedrock well sites.

The tests at the Harcourt, Petitcodiac, Fort Lawrence, Beecham Road, and Bureau-Beauséjour wells showed no evidence of boundaries (no abrupt change in the slope of the drawdown curves) during the test period. The other wells (Hillsborough, Riverview, Parlee Beach, Sackville, and

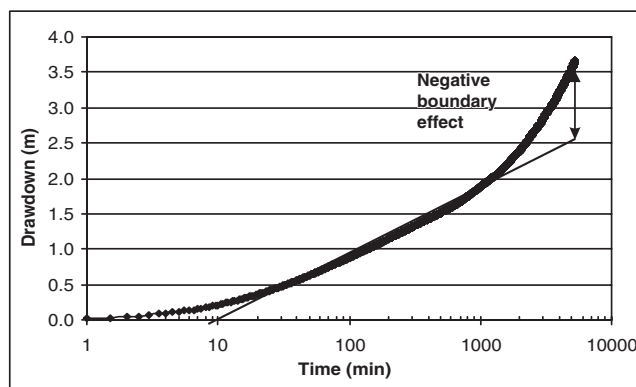


Figure 20. Example of a pumping-test interpretation, Sackville, New Brunswick.

Salisbury wells), however, revealed that, after a certain time (ranging from 3 to 24 hours), less transmissive boundaries were encountered. Indeed, the slopes of drawdown versus time curves departed significantly from infinite-aquifer-type curves (e.g. *see* Fig. 20).

To determine whether the behaviour of the second part of the curve was due to an impermeable boundary, the theoretical Theis curve was subtracted from the second part of the measured curve. These data also behaved according to the Theis curve, modified with a factor $1/t$ for the time shift, confirming the hypothesis. This is in complete agreement with the structure of the Maritimes Basin, which is composed of lenticular sedimentary strata of variable permeabilities and extents. The presence of an impermeable boundary indeed doubles the slope (rate of drawdown). As the slope sometimes more than doubled, it probably indicates that the well is bounded by more than one single linear impermeable boundary. In other words, it likely reflects the fact that the pumping well is close to one end of the lenticular stratum. As the lateral extent of permeable strata is generally small (on the order of 3 km or less), it is normal to occasionally reach their limits during a pumping test, even for pumping tests of relatively short duration and low flow rates.

Table 7 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 transmissivity range between 3.7×10^{-5} and $5.6 \times 10^{-3} \text{ m}^2/\text{s}$. Only two storage coefficient values were obtained due to the small number of observation wells or the lack of connection between pumping and observation wells.

These pumping tests provided evidence that fractured aquifers can be locally very heterogeneous, resulting in significant channelling. They also showed, however, that the investigated sites behaved like porous media and followed normal Theis-type curves, except that the Riverview well and its nearest observation well (34 m away) behaved as if they were located in the same vertical fracture. Nevertheless, the other observation well at Riverview (140 m away) had a

Table 7. Summary of pumping tests performed during the Maritimes Groundwater Initiative study.

Location / depth (m)	Formation	UTM (Zone 20, NAD83)		Flow rate (L/s)	Pumping duration (h)	T (m ² /s)	K = T/b* (m/s)	S
		Easting (m)	Northing (m)					
Harcourt / 125 m	Undivided Pictou Gp	326570	5150637	2.73	8	5.3×10^{-4}	4.2×10^{-5}	-
Petitcodiac / 125 m	Salisbury	330409	5087892	0.18	8	3.7×10^{-5}	3.0×10^{-7}	-
Fort Lawrence / 76.2 m	Balfroon	416558	5073190	1.36	8	6.0×10^{-5}	7.9×10^{-7}	-
Beecham Road / 48.3 m	Balfroon	424400	5087600	1.77	8	1.2×10^{-4}	2.5×10^{-6}	-
Sackville / 155.8 m	Boss Point	390652	5087664	36	88	5.6×10^{-3}	3.6×10^{-5}	1.3×10^{-4}
Riverview / 91 m	Boss Point	360003	5092463	7.5	53	1.2×10^{-3}	1.3×10^{-5}	1.2×10^{-4}
Salisbury / 62.5 m	Salisbury	340460	5099498	1.1	10	1.3×10^{-4}	2.1×10^{-6}	-
Hillsborough / 46 m	Boss Point	370776	5082470	4.1	15	2.6×10^{-4}	5.7×10^{-6}	-
Parlee Beach / 78.4 m	Richibucto	370776	5082470	3.4	16.5	1.2×10^{-3}	1.5×10^{-5}	-
Beauséjour peatmoss / 32 m	Richibucto	388040	5117146	0.93	20	5.3×10^{-5}	1.7×10^{-6}	-

* b is the open section, estimated by subtracting the casing length from the well depth.

porous media reaction. Observation wells located close to a strike direction of 045° from the pumping well tended to react very strongly during pumping, a behaviour that is consistent with regional structures. As this orientation drifted farther from 045° , the observation well drawdown tended to decrease. For instance, four wells in Sackville, located north and southeast of the pumping well (between 360 and 650 m away) never reacted. Detailed analysis and raw data for the 2002 pumping tests are provided in Rivard et al. (2005b).

Packer tests

Three of the wells investigated using packer tests (Harcourt, Port Elgin, and Shediac, New Brunswick) intersect the Richibucto Formation and one (Fort Lawrence, Nova Scotia) intersects the Balfroon Formation, which is very similar, comprising primarily sequences of sandstone, conglomerate, and siltstone. Another well intersects the Salisbury Formation (Petitcodiac, New Brunswick), which contains mostly shale with some fine-grained sandstone. The well tested in Borden, Prince Edward Island is located in the highly permeable Kildare Capes Formation. The length of each interval was 2 to 4 m and the number of sections per well depended on its total depth.

Generally speaking, zones of high transmissivity ($>5 \times 10^{-5} \text{ m}^2/\text{s}$) correspond to rocks dominated by fracture flow, whereas zones of lower transmissivity ($<10^{-6} \text{ m}^2/\text{s}$) indicate the presence of few fractures. The major water-bearing structures identified in the geophysical logs usually exhibited high transmissivity values. For instance, a zone of high transmissivity (approximate depth 106.5–110.5 m), identified from the results of geophysical logging in the Harcourt well (Fig. 14a), also returned high values during the packer tests (Fig. 14b). Seven intervals were tested in this well, of which five were located in sandstone, one in siltstone, and one in a mix of sandstone, siltstone, and conglomerate.

Transmissivity values determined in the Fort Lawrence well by means of both the flowmeter-pumping tests and the packer tests (Fig. 21) demonstrate how these two techniques can be complementary. There is good agreement between these methods for four of the five most permeable zones (corresponding to depths of 9, 17, 22, and 31 m), where T values

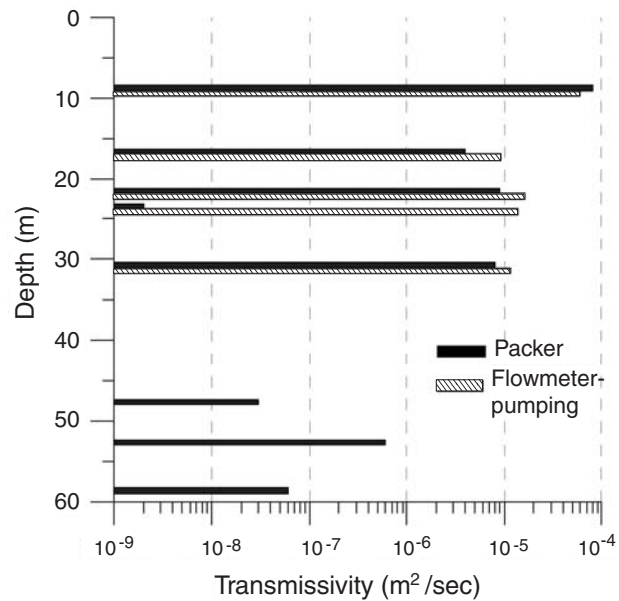


Figure 21. Comparison of transmissivity results in the Fort Lawrence (Nova Scotia) well, obtained from packer tests and flowmeter-pumping tests. Transmissivities determined from packer tests at depths greater than 35 m are below the resolution of the flowmeter-pumping method.

range from about 3×10^{-6} to $8 \times 10^{-5} \text{ m}^2/\text{s}$. At a depth of 24 m, however, the flowmeter identified a highly transmissive interval ($T = 1.4 \times 10^{-5} \text{ m}^2/\text{s}$) that was missed by the packer test ($T = 2.2 \times 10^{-9} \text{ m}^2/\text{s}$). The packers thus apparently failed to straddle the permeable fracture or were inflated directly over it. Consequently, the transmissivity of the intact rock matrix was measured. The packer system successfully measured the transmissivities of the three lowermost zones shown in Figure 21, whereas these intervals were below the resolution limitations of the flowmeter-pumping method and therefore not detected. In general, the highest hydraulic conductivities determined from the flowmeter-pumping measurements and from the packer tests are in good agreement, reaching roughly 10^{-4} m/s in these wells. According to the packer-test results, hydraulic conductivities decrease dramatically to about 10^{-8} to 10^{-7} m/s for the intact rock matrix.

Table 8. Horizontal and vertical hydraulic-conductivity values obtained from packer tests on six wells in the Maritimes Groundwater Initiative study area.

Location	UTM (Zone 20, NAD83)		Number of intervals	K_h (m/s)	K_v (m/s)	K_h/K_v	K pumping test (m/s)
	Easting (m)	Northing (m)					
Harcourt, NB	326568	5150634	7	1.4×10^{-4}	5.1×10^{-8}	2707	4.2×10^{-6}
Petitcodiac, NB	330031	5087718	10	2.2×10^{-7}	5.1×10^{-8}	4	3.0×10^{-7}
Port Elgin, NB	415092	5101077	3	1.9×10^{-5}	1.1×10^{-7}	166	-
Shediac, NB	382119	5119431	3	6.9×10^{-6}	1.24×10^{-7}	59	-
Fort Lawrence, NS	416558	5073190	8	9.9×10^{-6}	6.9×10^{-8}	143	7.9×10^{-7}
Borden, PEI	445794	5122226	7	5.2×10^{-6}	6.4×10^{-8}	80	5.6×10^{-5} *

* This value comes from the New Brunswick database.

Table 8 presents results of horizontal and vertical hydraulic conductivities for the six wells, along with the K_h/K_v ratio and the number of intervals tested. Since the investigated intervals were only the most transmissive ones, the hydraulic conductivities of the wells were calculated using an average matrix value of 5×10^{-8} m/s in nontested intervals. This might have slightly underestimated the K_v in these intervals, because some fractures might be present. The anisotropic ratio varies from 4 to 2707, with an average (geometric mean) of 105. Hydraulic conductivities obtained from pumping tests are also shown for comparison. Results are fully described in Morin et al. (2002) and Thériault (2001), as this work was completed for an undergraduate thesis. A summary of results obtained at each interval is presented in Appendix B.

Values obtained from packer tests (K_h) are sometimes quite different than those from pumping tests (by up to two orders of magnitude), and can be either larger or smaller. These differences are due to the fact that packer tests are very 'local' (within 10 m), whereas pumping tests have a radius of influence on the order of a few hundred metres. In addition, numerous problems are associated with the implementation of packer tests, including the transportation and manipulation of numerous pieces of the large, heavy, fragile equipment required; the location of the interval top and base and its perfect isolation; and the duration of the operation. Moreover, very small and large values are not particularly reliable. For instance, for a very transmissive zone, reaction to the water injection is sometimes difficult to quantify, since the water is very easily dissipated within the formation. This was the case for one of the intervals in the Port Elgin well. This technique, however, has the great advantage of allowing the estimation of hydraulic conductivities of individual beds.

Hydraulic properties of Quaternary units

Pumping tests and slug tests in granular aquifers

Results of the slug tests performed in the Memramcook River valley (see Fig. 6) were interpreted with the Bouwer and Rice (1976) or Butler and Garnett (2000) method,

depending on the type of response obtained. The results for the pumping and observation wells were interpreted with the Theis solution. The average hydraulic conductivities obtained were estimated to be 3×10^{-8} m/s for the top sand unit, indicating a very poor hydraulic potential; 6.6×10^{-10} m/s for the confining silt unit; and 2.2×10^{-5} to 9.1×10^{-4} m/s for the bottom sand unit. Hydraulic conductivities within the sand layers of the Petitcodiac River valley could not be evaluated because drilling in this area was not possible. Based on the Wheeler et al. (1985) report, however, the grain size of the Petitcodiac bottom sand unit seems coarser than the Memramcook one, suggesting a higher hydraulic conductivity. In conclusion, the results tend to show that the sand units, at least for the Memramcook River valley and likely also for the Petitcodiac River valley, cannot provide a substantial supply of water due to their limited thickness and extent, and indications of poor water quality (see 'Water and soil analysis, and rock-matrix porosity' section below).

Permeameter and infiltrometer tests in glacial till

The results of Guelph permeameter and double-ring infiltrometer (DR) tests were interpreted with the Elrick et al. (1989) solution and with Darcy's law, and compared so as to get a good estimation of the till hydraulic conductivity. The surficial-sediment mapping reveals the presence of three types of till, in terms of hydraulic properties. The till's composition is generally related to that of the underlying geological formation. The first type, associated with the Salisbury Formation, is characterized by a silty matrix and an average hydraulic conductivity (K) of 6.5×10^{-9} m/s. The second type, generally sandy, is associated with the Boss Point Formation and has an average K value of 1.3×10^{-6} m/s. The third type of till is associated with the Richibucto Formation: it consists of about 40 cm of sandy till with a K value of 1.4×10^{-6} m/s overlying a silty-sandy till unit with a K value of 5.3×10^{-8} m/s. The geometric means of the results from the two types of equipment were used as typical values for the materials. In general, tills are poorly compacted and, in some places, contain freeze-thaw or drought fissures, thus favouring infiltration.

Slug tests in the peatland and underlying units

The permeability (slug) tests were interpreted using the Cooper et al. (1967) and Bouwer and Rice (1976) methods. The average hydraulic conductivity values for the peat, sandy silt, and till were found to be 1.8×10^{-6} , 2.3×10^{-8} , and 4.4×10^{-9} m/s, respectively.

Saline intrusion

The primary goal of geophysical surveys in Shediac Bay, New Brunswick and Rustico Bay, Prince Edward Island was to determine the location of the saltwater-freshwater interface. Six locations were selected around Shediac Bay and two in the Rustico Bay area. The locations of the six lines in the Shediac Bay area are shown in Figure 22. Both Wenner and pole-dipole electrical-resistivity images were acquired.

Images obtained along Cap Brûlé Road are shown in Figures 23 and 24. The Wenner image in Figure 23 indicates high resistivity near the surface, due to the presence of dry sand, underlain by lower resistivity clay and/or silt and a poorly defined lower layer of resistive material. Zones of very low resistivity were not detected, suggesting that saline water does not occur within 40 m of the surface. The corresponding pole-dipole image is shown in Figure 24. The differences between the Wenner and pole-dipole measured apparent resistivity pseudosections are due to the differing array geometries and maximum depths of investigation. The greater depth of investigation of the pole-dipole

array (80 m versus 40 m) results in better definition of a resistive lower layer that is interpreted to be bedrock. A decrease in resistivity at the north end of the image may indicate brackish water at depths greater than 60 m, suggesting that the saltwater-freshwater interface is located approximately 80 m inshore.

The results at Parlee Beach indicated very low resistivity sand on the beach due to infiltration of seawater during the tidal cycle. This is underlain by a higher resistivity layer

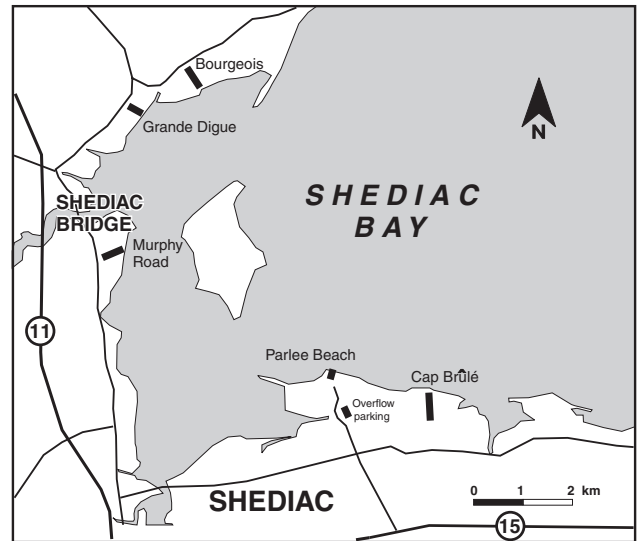


Figure 22. Location of the six electrical-resistivity lines around Shediac Bay, New Brunswick.

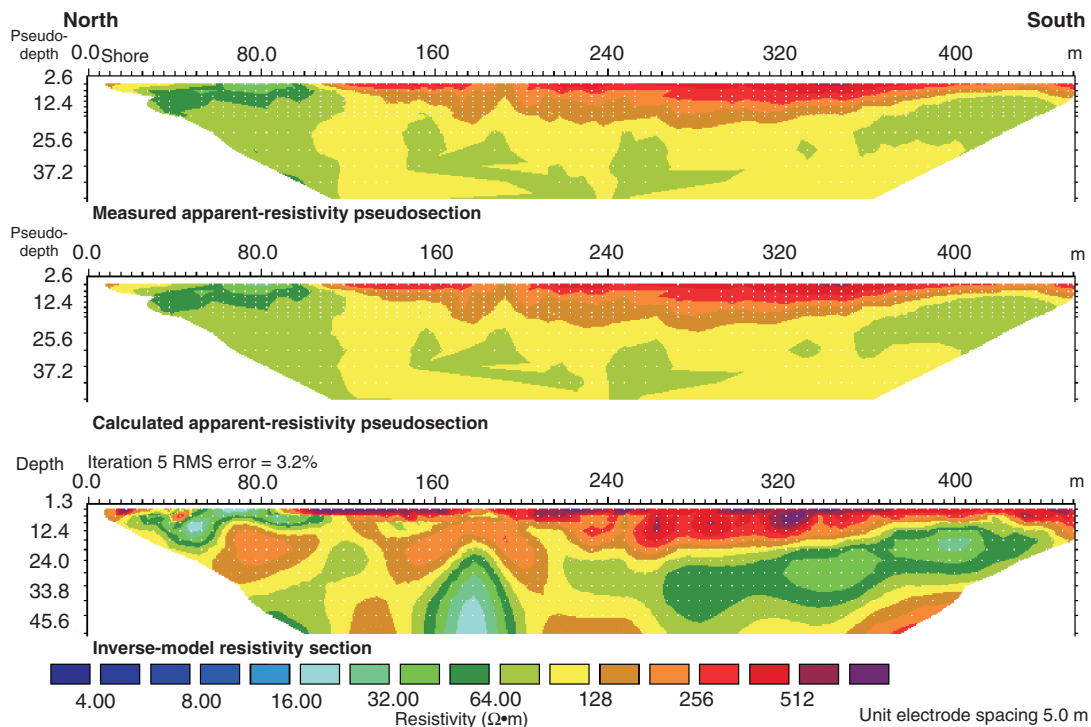


Figure 23. Wenner-array electrical-resistivity survey, Cap Brûlé, New Brunswick.

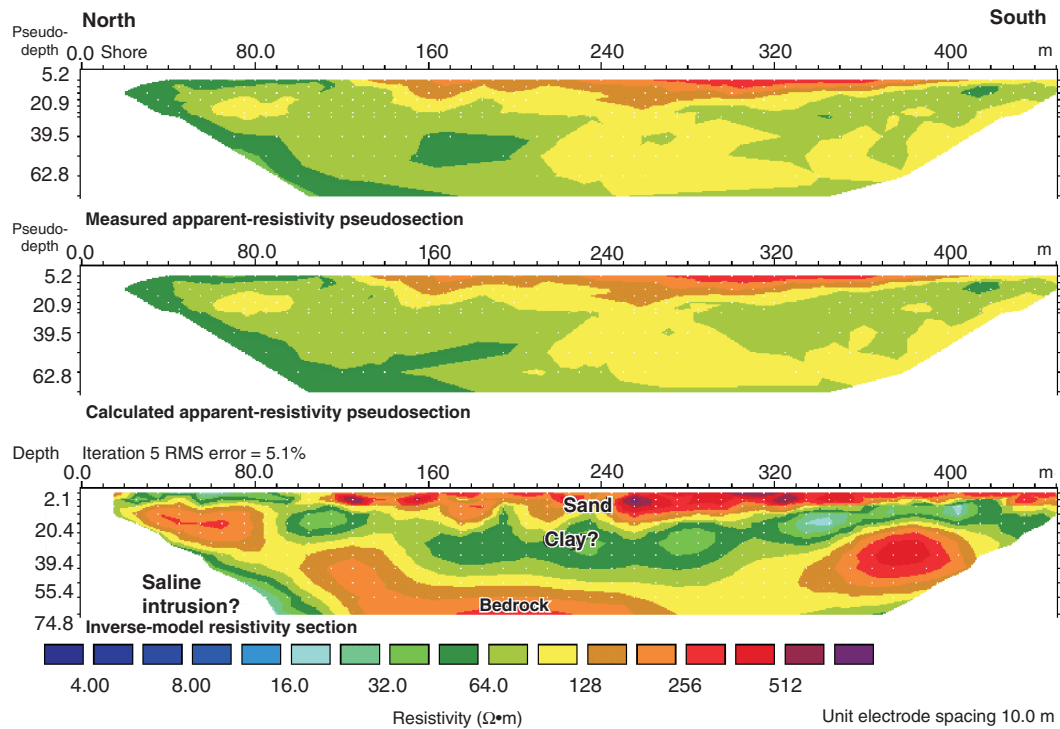


Figure 24. Pole-dipole-array resistivity survey, Cap Brûlé, New Brunswick.

likely containing fresh water that is discharging into the sea (see Rivard et al., 2005b). Saline intrusion from both the sea and the lagoon toward the dune is indicated by very low resistivities at depths of 20 to 30 m. A high-resistivity zone, located 20 m below the dune, suggests the presence of a fresh-water lens. Along Murphy Road, perpendicular to the beach, a very low resistivity zone was found at a depth of 20 m, indicating saline or brackish water and suggesting that a saltwater-freshwater interface is located approximately 70 m inshore. Results at Grande-Digue indicate a probable saltwater-freshwater interface located approximately 100 m inshore at a depth of 40 m. Finally, in Bourgeois, images acquired perpendicular to the shore indicate a possible saltwater-freshwater interface dipping sharply from the shoreline. Therefore, interpretation of the Wenner and pole-dipole electrical-resistivity images indicates that the saltwater-freshwater interface in the Shediac Bay area is always located fairly close to the shoreline, the distance varying from 0 to 100 m inland, and dips steeply inland, so it is not likely to be encountered by water wells.

In the Rustico Bay area of Prince Edward Island, Wenner and pole-dipole electrical-resistivity images were also acquired along two roads (Cemetery and Blue Bay Farms roads). The location of these lines is shown in Figure 25. Along Cemetery Road, none of the lower resistivity zones were of a magnitude that would indicate saline intrusion. The bedrock was found to consist of subhorizontal, southward-dipping layers with moderate and high resistivity. Wenner images acquired at Blue Bay Farms indicate a highly resistive bedrock layer near the surface that thickens westward to

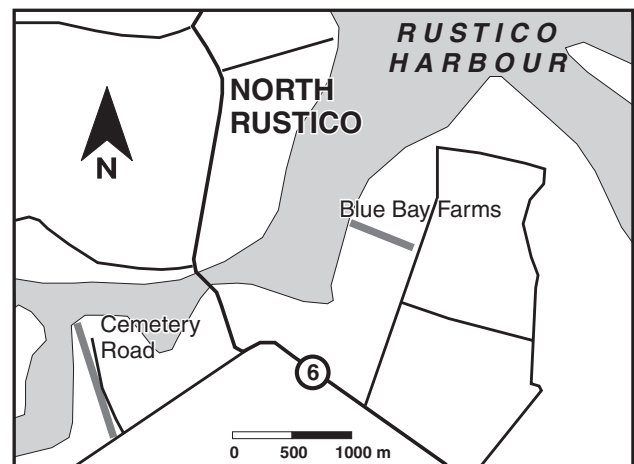


Figure 25. Location of the electrical-resistivity lines in the Rustico Bay area, north-central Prince Edward Island.

approximately 20 m. This is underlain by lower resistivity bedrock that decreases sharply in resistivity to the west, indicating the presence of a saltwater-freshwater boundary. The results from the pole-dipole array are similar and indicate that the saline intrusion may be confined to a permeable layer between 10 and 50 m in depth, 200 m inland (Fig. 26). Thus, in Rustico Bay, saline intrusion may present more of a concern, as it may occur farther inland and at shallower depths than in the Shediac Bay area.

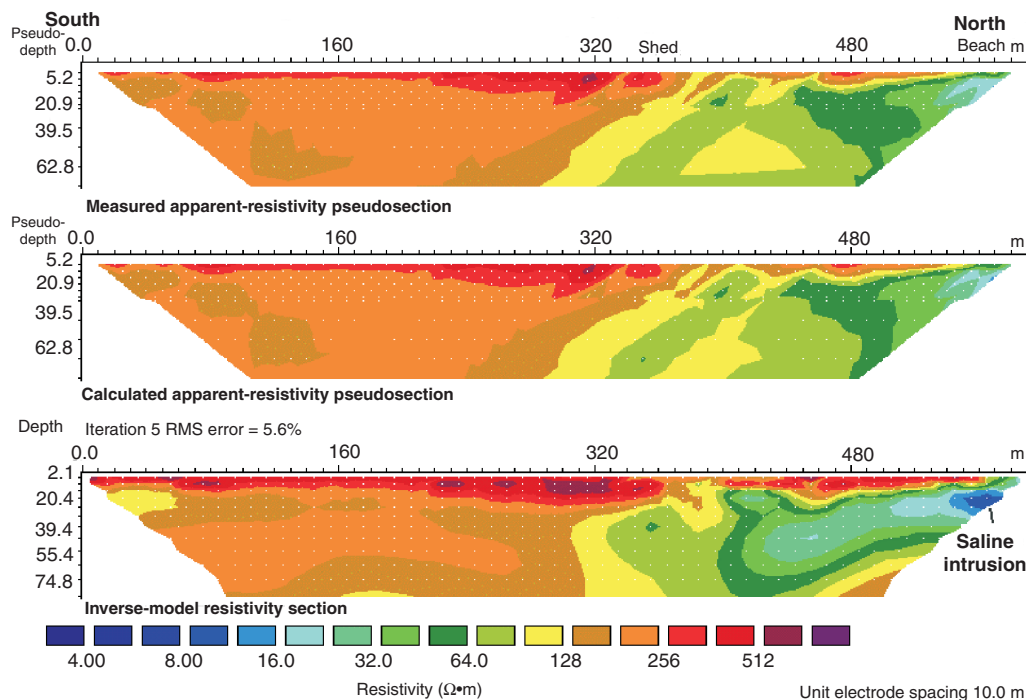


Figure 26. Pole-dipole-array electrical-resistivity survey, Blue Bay Farms Road, Prince Edward Island.

Water and soil analysis, and rock-matrix porosity

Analyses of inorganic components in water samples revealed that most parameters were below the health advisory limit (HAL) for drinking water (Health Canada, 2003). Nevertheless, turbidity exceeded the HAL in 7 out of 17 samples and the aesthetic criterion of 0.05 mg/L for manganese (Mn) and 0.3 mg/L for iron (Fe) were exceeded 10 and 2 times respectively. Of the seven wells suspected to have salinity problems (out of 237), only three could be sampled and tested with the YSI probe, since the groundwater was treated in the other cases. The three samples had salinities varying between 2 and 8 ppt (above 1 ppt, the water is considered brackish and, above 10 ppt, is considered saline). The water from the bottom granular sand unit of the Memramcook River valley was also tested with the YSI probe to test for salinity and pH. Two samples collected in piezometers 1 and 5 indicated saline and brackish groundwater (with salinities of 17 and 5 ppt). Geochemical analysis indicated that, in addition to high chloride and sodium contents, this water had exceptionally high values of iron, manganese, total dissolved solids, hardness, and turbidity.

All parameters in water samples taken in the peatland were below the health advisory limit for drinking water, except for iron and manganese. Half of the 22 samples exceeded 0.3 mg/L Fe and 37% of them exceeded the limit for Mn, which correspond to aesthetic criteria. Only 31% and 15% exceeded these criteria for samples taken in the peat, but

all three samples taken in the silt unit exceeded both criteria. Turbidity in one rock sample was found to be seven times the acceptable limit.

One hundred and seven grain-size analyses were performed for the two M.Sc. theses, the results of which are presented in Carrier (2003) and Boisvert (2004). Results of thin-section analysis of 23 rock samples are illustrated with coloured dots in Figure 27. This figure shows that total porosity can vary widely within a geological formation, mainly due to the presence or absence of calcite or other cements within the pores. Background values, including entire range, interquartile range, and median (black dot), come from a compilation for the Maritimes Basin (Bibby and Shimeld, 2000). Compiled and estimated total porosities of the formations range between 0 and 20%, and average between 5 and 10%. Earlier work had shown that porosity of the formations in the Prince Edward Island Group decreases significantly with depth, from 20% at the surface to 12% at 1 km depth, with some samples showing values close to 0% due to cementation (Chi et al., 2003). Other reported values for average matrix porosity of the Prince Edward Island Group range from 16 to 23% (Van der Kamp, 1981; Jacques Whitford and Associates Limited, 1990a).

These relatively high porosity values could lead one to expect that the Maritimes Basin flow system would react hydraulically like a double-porosity medium. However, well tests do not exhibit such a double-porosity behaviour but rather show drawdown curves representative of equivalent

porous media. This is interpreted to be caused by the presence of a very well developed fracture network with sufficient storage capacity to act as an equivalent porous medium.

Existing data

Existing data were used to calculate recharge rates and specific yields, and to verify results obtained in previous work, as in the case of the pumping tests. Since the reinterpretation of pumping tests used common methods, such as Theis or Cooper-Jacob, and because results were generally close to

previously determined values, no results are presented here. Interpretation of RADARSAT-1 radar imagery and Landsat-7 optical imagery was also carried out in a parallel project to extract information relevant to this regional hydrogeological study.

Groundwater recharge

Hydrograph-separation method

An example of the base-flow calculation, using the Chapman (1991), Furey and Gupta (2001), and HYSEP (Sloto and Crouse, 1996) methods, is presented in Figure 28. It illustrates mean monthly flows calculated using the three methods for the Petitcodiac River near Petitcodiac (gauging station 01BU002) for the year 1995. The main contributions to the river can be observed after the snowmelt period (April–May) and, to a lesser extent, in the rainy season (November). During these periods, the contribution of the two components (surface and subsurface flow) can be almost equal, whereas the surface flow during the rest of the year is distinctly smaller than the base flow or even negligible. For this particular example, annual recharge for the year 1995 was estimated to be 24, 25, and 27% of the annual total precipitation, using the Chapman, Furey and Gupta, and HYSEP methods, respectively.

Annual recharge rates for the 16 gauging stations are summarized in Table 9. All three methods were intensively tested within the framework of the project on climate change. The general conclusions were that 1) the local-minima method from HYSEP generally overestimates flows related to snowmelt, and thus annual recharge rates; and 2) even if both filter methods provide similar results for annual base flows, the Furey and Gupta method sometimes overestimates the base flow during recession periods. Thus, only the Chapman method was retained for future comparison, as it is

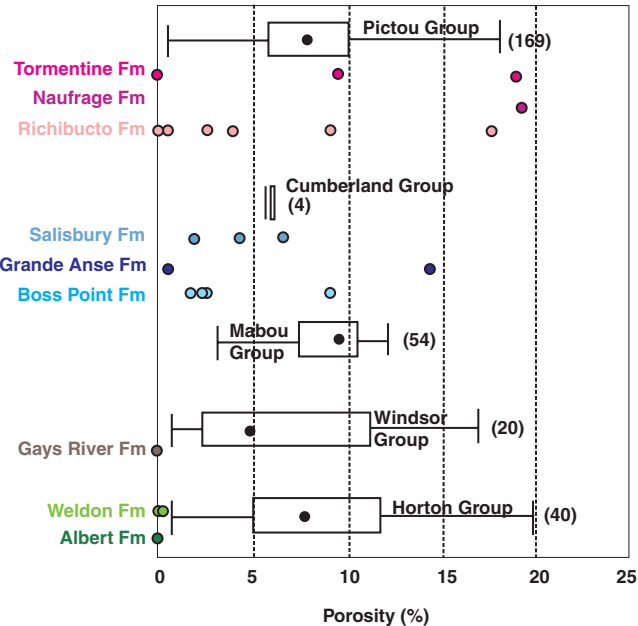


Figure 27. Visual estimation of porosity (thin sections, 300 counts per sample) of samples from the Moncton Basin. Background values, including entire range, interquartile range, and median (black dot), are from the literature.

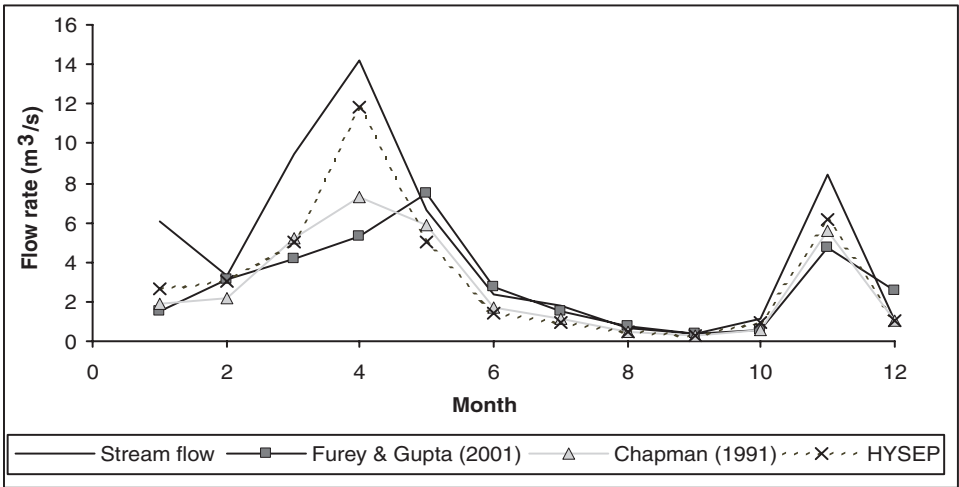


Figure 28. Comparison of the Chapman (1991), Furey and Gupta (2001), and HYSEP (Sloto and Crouse, 1996) methods used for estimation of mean and annual base flows for the Petitcodiac (New Brunswick) gauging station in 1995.

Table 9. Annual recharge rates estimated using the Chapman (1991), Furey and Gupta (2001), and HYSEP (Sloto and Crouse, 1996) methods of hydrograph separation.

Gauged river	UTM (Zone 20, NAD83)		Watershed area (km ²)	Period covered	Annual recharge rates (mm/a)		
	Easting (m)	Northing (m)			Furey and Gupta (2001)	Chapman (1991)	HYSEP (Sloto and Crouse, 1996)
Kennebecasis River, NB	297490	5064219	1100	1961–1999	376.6	359.4	412.2
Coal Branch River, NB	341364	5145409	166	1964–1997	362.1	345.3	389.4
Kinnear River, NB	393052	5111957	32.1	1985–1993	363.8	348.2	344.7
Petitcodiac River, NB	331779	5090071	391	1961–1997	332.0	316.7	341.7
Turtle Creek, NB	354403	5091108	129	1962–1997	457.4	436.2	546.4
Palmer's Creek, NB	382344	5082633	34.2	1966–1985	452.3	431.6	467.9
Hayward Brook, NB	332489	5081346	4.3	1995–1997	283.2	270.2	447.7
Hayward Brook, NB	330782	5082816	1.4	1995–1997	257.4	246.0	255.4
Hayward Brook, NB	330420	5082081	6.5	1995–1997	340.7	324.3	495.9
Hayward Brook, NB	330208	5082276	2.3	1995–1997	294.7	281.5	440.6
Hayward Brook, NB	333488	5083821	15.2	1995–1997	97.0	91.8	139.3
		Sum:	1882		Mean:	353	
River Platte, PEI	440280	5141374	4.5	1970–1982	180.2	172.6	179.5
Wilmot River, PEI	449281	5137937	45.4	1972–1997	333.4	318.2	482.5
North Brook, PEI	451308	5132786	12.9	1971–1987	324.8	310.0	458.0
Emerald Junction, PEI	457066	5134132	5.6	1974–1992	274.7	262.2	387.8
Dunk River, PEI	451199	5132665	114	1961–1997	370.7	353.7	519.3
		Sum:	182.4		Mean:	334.5	

Table 10. Water-balance recharge estimates for the various geological units in the Maritimes Groundwater Initiative study area.

Formation or group	Area (km ²)	Percentage of total area	Potential recharge (mm/a)			Percentage of discharge area*	Corrected mean (mm/a)
			Min.	Mean	Max.		
Prince Edward Island Group	1560.3	13.5%	224	300	387	22%	234
Undivided Pictou and Cumberland groups, Richibucto and Balfron formations	5923	51.3%	122	192	245	33%	128
Boss Point Formation	1272.9	11.0%	198	310	403	24%	236
Salisbury Formation	884.4	7.7%	0	40	118	31%	28
Horton, Mabou, and Windsor groups	1460.1	12.6%	0	51	120	18%	42
Basement complex	443.4	3.8%	0	33	106	35%	22
Weighted average :			115	184	251	29%	
Spatially averaged over entire study area (29%) :			81	131	178		

* Estimated using a vertical-gradient map

considered the most representative method for estimating annual recharge rates from hydrograph separation. Moreover, this method is very easy to implement with a spreadsheet (e.g. Excel). As can be seen in Table 9, the values vary widely, from 92 to 436 mm/a over the study area. The mean values found are 353 mm/a for NB and 335 mm/a for Prince Edward Island.

Water-balance method

Annual recharge rates estimated using the water-balance method are presented in Table 10 as a function of the various geological formations or groups in the study area (see 'Updating of regional geology' and 'Integration of hydrogeological information' sections), since the composition of the till cover generally correlates with that of the underlying bedrock. The weighted average over the entire study area gives

minimum, mean, and maximum recharge rates of 114, 184, and 251 mm/a, respectively, depending on the values attributed to each parameter during the process.

To correct the recharge rates obtained using the water-balance method, the proportion of the study area exhibiting discharge or artesian conditions (where recharge to bedrock does not occur) was determined based on three approaches: 1) the estimation of vertical gradients, 2) the subtraction of the piezometric map from the DEM, and 3) the piezometric surveys (see 'Methodology' section). The resulting vertical-flux map indicated that regions where recharge is impossible due to an upward gradient represented 18 to 35% of each area, depending on the geological unit as indicated in Table 10, with a weighted average of 29% over the entire study area. Nevertheless, the amount of recharge applicable in some quite large regions was very low. For the second approach, the interpolated (bedrock) piezometric map was subtracted

Table 11. Estimation of specific yields (S_y) as a function of probable recharge for wells in Prince Edward Island.

Location	UTM (Zone 20, NAD83)		Mean $\Delta h/\Delta t$	Minimum S_y (using 250 mm/a)	Mean S_y (using 300 mm/a)	Maximum S_y (using 350 mm/a)
	Easting (m)	Northing (m)				
Bloomfield	406814	5180638	7	3.6%	4.3%	5.0%
Caledonia	522408	5101094	7.25	3.4%	4.1%	4.8%
Kensington	451315	5141434	4.2	6.0%	7.1%	8.3%
Mount Pleasant	423335	5160399	6.08	4.1%	4.9%	5.8%
New Dominion	480701	5112997	12.44	2.0%	2.4%	2.8%
St. Charles	546107	5137988	16.94	1.5%	1.8%	2.1%

from the DEM. Accounting for the precision of interpolated water levels and DEM, areas with negative values represented 26%, 18%, and 11% for precisions of 2, 5 and 10 m, respectively. For the third approach, it was estimated that 12.5% of visited sites during the water-level survey corresponded to artesian wells, wells with shallow water levels (<1 m), or springs. As a confirmation, the percentage obtained when using the New Brunswick and Nova Scotia provincial databases was similar (12%). The Prince Edward Island water-well database, however, indicated that this percentage should be on the order of 5% for the island. Therefore, it was decided to consider a range of 11 to 29% of the total study area (except for Prince Edward Island, for which a minimum of 5% was used) that could be under conditions where recharge is impossible, providing a range of possible values for the mean recharge rate. This analysis led to a mean weighted average over the study area of 130 to 165 mm/a, considered most likely representative of the groundwater recharge for the study area.

The mean groundwater recharge obtained using the water-balance method (184 mm/a) is significantly smaller than that obtained with the hydrograph-separation method (300 mm/a). This could be due to the fact that streamflows at the watershed outlet were available only for highly permeable formations: they were located in the Richibucto Formation, Boss Point Formation, all formations of the Prince Edward Island Group, and undivided Pictou Group. If a comparison is made between recharge values only for these permeable formations, the correlation between the two methods is, in fact, quite good (92–436 mm/a versus 192–310 mm/a). These recharge estimates correspond to the total amount of water that infiltrates into the till cover. However, a significant portion of the recharge is likely to reach streams by hypodermic flow before infiltrating into the bedrock aquifer system. The reaching of streams by hypodermic flow is facilitated by a well developed hydrographic network. The authors believe, therefore, that the values determined using the water-balance method, corrected with the plausible proportion of artesian and discharge areas (130–165 mm/a), are representative of the study area.

Groundwater recharge was also quantified independently over the Moncton area using a combination of the water-balance and Darcian approaches (for details, *see* Boisvert, 2004). The water balance was also evaluated for every 500 m by 500 m cell of the study area. The infiltration obtained from the water

balance alone ranged from 0 mm/a in the urban area to more than 500 mm/a in the sandy till (Boss Point Formation). In this limited area, the topography is relatively flat and the entire region is well covered by water-level measurements, since it is generally more densely populated than the MGWI study area. Therefore, the Darcian approach provided reliable results and was very useful in correcting the potential recharge obtained with the water-balance method.

The vertical-flux map obtained using the Darcian approach showed that only 55% of the total area is likely to contribute to the recharge. This low percentage is indeed plausible for this particular region. It can be explained by the presence of two major rivers acting as discharge zones and also by the presence of buried bedrock valleys northwest of Moncton that confine the aquifers and cause artesian conditions. Most of the area contributing to the recharge seems highly favourable for infiltration, except for the Petitcodiac lowlands, where a silty till is present (Salisbury Formation). The recharge through the sandy till is three times higher than through the silty till. The recharge distributed over the Moncton area was found to range from 177 to 198 mm/a and average 192 mm/a. This recharge is higher than in the case of the MGWI study area (130–165 mm/a), since the sandy till overlying the Boss Point Formation represents a great proportion of the area studied (*see* Boisvert, 2004).

Specific yields

Values of specific yield (or drainage porosity) estimated using six well hydrographs in Prince Edward Island ranged from 1.5 to 8.3% when using a recharge interval of 250 to 350 mm/a, which is highly probable for this province. Using an average recharge rate of 300 mm/a, values of specific yield (S_y) vary throughout the province between 2 and 7%. These values, summarized in Table 11, show a significant storage capacity that is consistent with total porosity estimates. Indeed, they lie within the range of compiled and estimated total porosities (*see* 'Water and soil analysis, and rock-matrix porosity' section), and are in agreement with values used by the Prince Edward Island Department of Environment, Energy and Forestry, which generally utilizes S_y values ranging between 4 and 6% for its simulations.

Remote sensing

A valuable contribution to the project was achieved through the creation of maps showing land use, slopes, and vegetation cover that were used for the calculation of recharge. Refinement of units for the Quaternary geology map was also carried out. In addition, this study was able to detect regional bedrock structures (lineaments). The map showing the plotted fractures and faults was sent to a structural geologist with the New Brunswick Department of Natural Resources for verification. His conclusions were that most of these lineaments should indeed correspond to regional structures. Furthermore, the rosette diagram obtained indicates a plausible average trend close to 045° , in agreement with geophysics, pump-test results, and regional structural patterns. Identification of springs (resulting from temperature differences) could not be done, due mainly to the spatial resolution of the images and because they were taken in periods when temperature differences do not show enough contrast. The land-use and vegetation map was obtained by combining imagery interpretation and ground-truth control points, so as to validate the information and obtain a better understanding of the vegetation types present in this area, the proportion of species, and their development stages. These two maps are available in Rivard et al. (2005a). Details of this study are available on a poster (Chalifoux et al., 2003) and in an executive report for the Canadian Space Agency (Tecsult Inc., 2003).

UPDATING THE REGIONAL GEOLOGY

New compiled geological map

A regional geological map was developed using 1:50 000 scale New Brunswick Department of Natural Resources maps 95-22F, G, H, and J (St. Peter, 1995a–d); 95-8, 95-9, and 97-9 (Johnson, 1995b, c, 1997); 97-7 (Johnson and St. Peter, 1997); 99-23 and 26 (McLeod and Johnson, 1999a, b); and 1:250 000 scale maps by Lynch et al. (1998). Updates were based on the latest information provided by the provincial authorities. Figure 29 presents a simplified version of this updated map. The complete colour map is available in Rivard et al. (2005a).

Regional representation of the upper three kilometres

The hydrogeological properties corresponding to the hydrostratigraphic units described in Table 4 are quite variable. This results from the high variability and recurrence of bedrock types (conglomerate, sandstone, siltstone, and mudstone) within the different geological formations. Therefore, some bedrock units can act as aquifers, whereas others behave more like aquitards. Assessment of the lateral

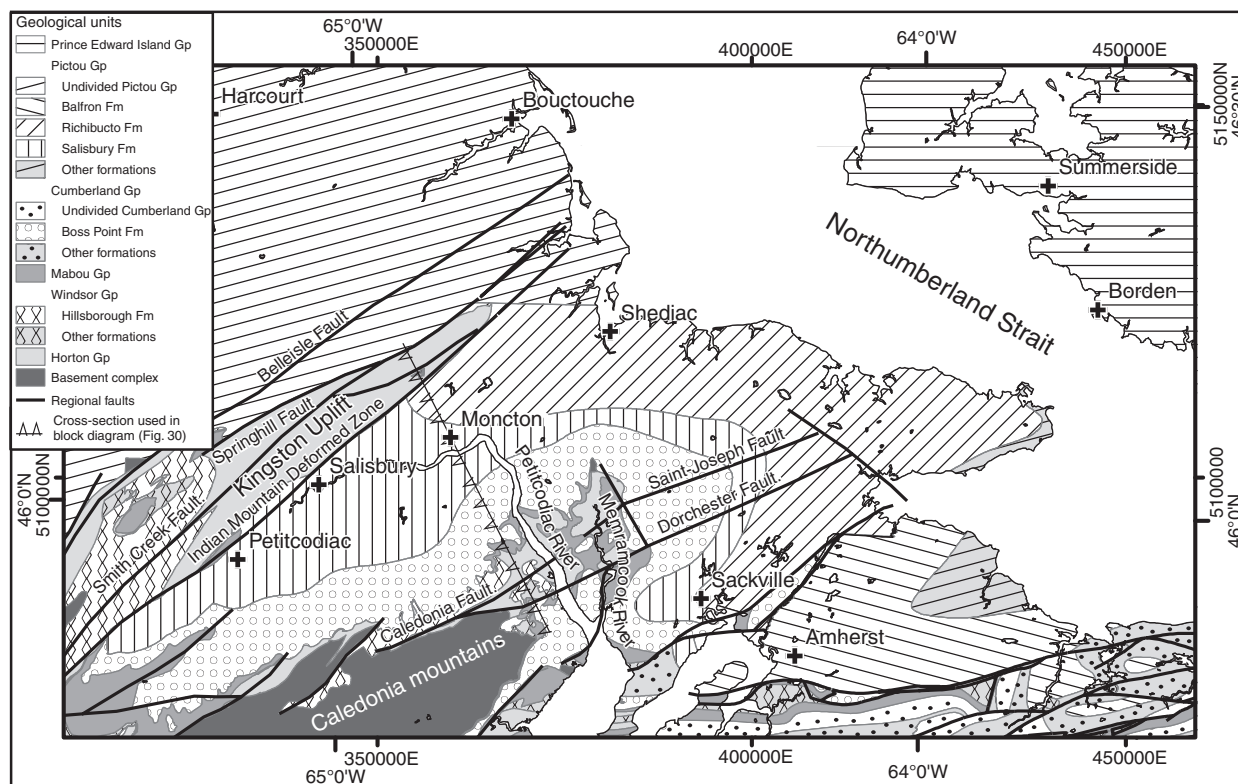


Figure 29. Simplified geological map of the Maritimes Groundwater Initiative study area, compiled from maps by New Brunswick Department of Natural Resources and Lynch et al. (1998). See Rivard et al. (2005a, Plate 2-1) for the complete map.

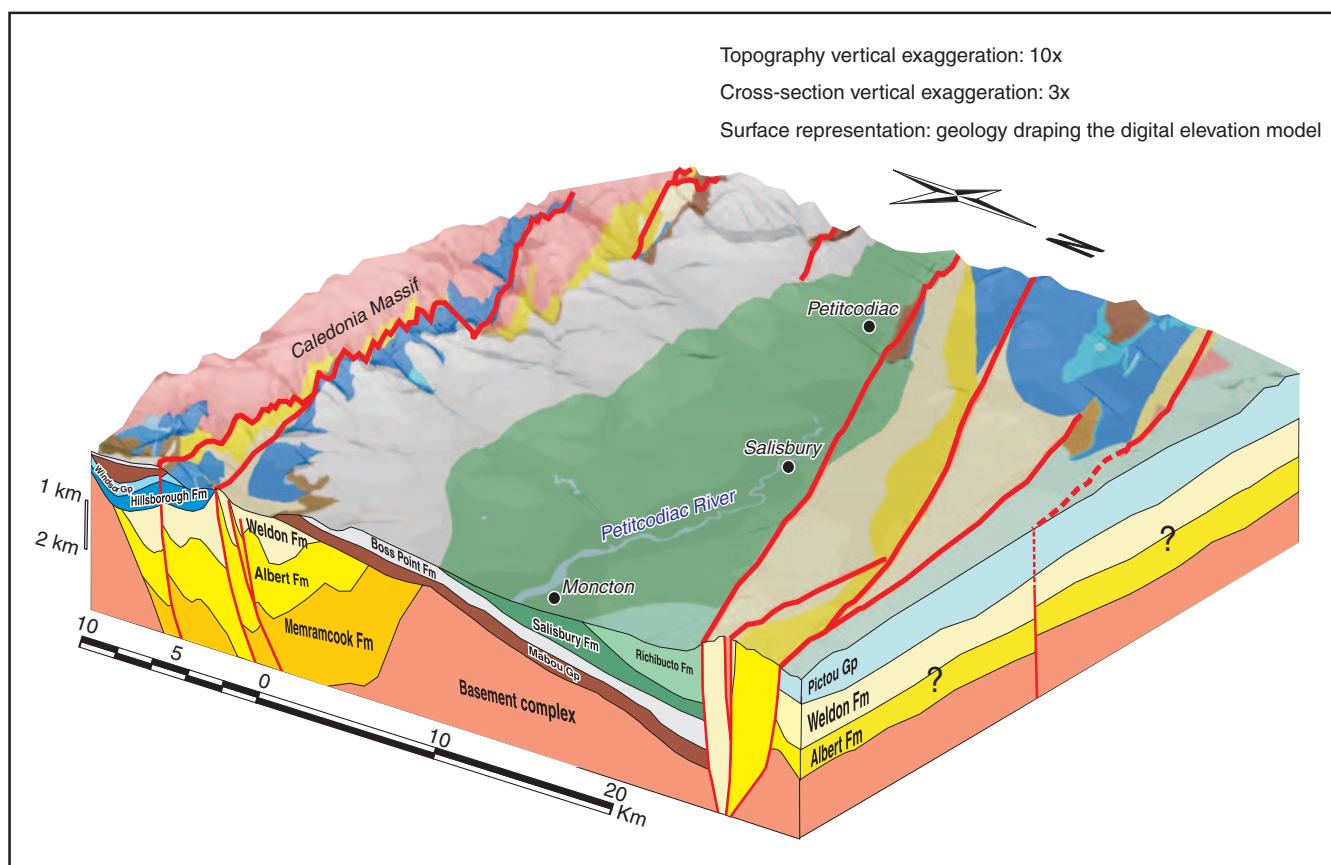


Figure 30. Simplified block diagram of a representative area of the Maritimes Basin. See Rivard et al. (2005a, Plate 2-2) for the full-colour map.

extent and thickness of aquifer and aquitard units within stratigraphic formations, and their correlation across subbasins, are hindered by extensive lateral discontinuity created by sudden facies changes, ‘pinch-outs’, erosional unconformities, and the absence of basin-wide markers. Lenticular bodies of sandstone in the lower Pictou Group, for example, are thought to be generally less than 3 km wide and of highly variable lengths (Hacquebard and Barss, 1970; St. Peter, pers. comm., 2002). The regional gentle northeast dip of units toward the Northumberland Strait adds further constraints in trying to establish regional-scale correlations in the shallow subsurface. Consequently, construction of cross-sections showing the individual rock types within units is an impossible task at the regional scale. Rather, statistical determination of the percentage of each rock type in the well database of targeted areas (e.g. where no data are available) would have been considered a viable alternative, at least to provide a general idea of the hydrogeological properties in various regions. Adequate borehole information for the upper 500 m, however, is generally not available for the construction of reliable cross-sections. Indeed, there are very few areas where descriptions of the first few hundred metres are comprehensive, and many areas (extending sometimes for several kilometres) do not have any description available for the upper part of the Maritimes Basin.

Therefore, a cross-section was compiled based on the cross-sections of Gussow (1953) and improved using various geological maps from Barss et al. (1977), C. St. Peter and S. Johnson (geologists with the New Brunswick Department of Natural Resources), and the Ph.D. thesis of Nickerson (1994). Information coming from different seismic lines and boreholes was also used to update the section. This cross-section is located along the Petitcodiac River between the Bay of Fundy and the Kingston Uplift, as shown on Figure 29. This 42.4 km cross-section was selected because of the degree to which it represents the geological formations and structures of the Maritimes Basin. The perpendicular section is an approximation of the New Brunswick platform geology north of the Kingston Uplift, based on the surface bedrock geology. Nevertheless, it should not be far from reality, since rocks north of this uplift have not been tectonized and should be quite homogeneous to depths of 1 to 2 km. Figure 30 presents the bedrock interpreted in this way, as a schematic block diagram. The view shown in this figure was selected so as to emphasize the relief.

This block diagram should be viewed as a simplified regional representation of an upper section of the Maritimes Basin. Although uncertainty can locally be high, it provides information on the main formations across a major segment

of the study area. Based on current knowledge, this is the first time that such a representation has been presented, mainly due to the numerous difficulties associated with the scale and variability of units (rock type and thickness) and structures.

Quaternary stratigraphy

Due to the large area covered by the MGWI project, a smaller area was selected for the M.Sc. thesis focusing on surficial sediments (Boisvert, 2004). This area, approximately centred on the city of Moncton, New Brunswick, covers about 1300 km² and includes the Petitcodiac and Memramcook River valleys (Fig. 31), which have the highest potential for hosting granular aquifers because of their thick Quaternary sediment fill. Two primary objectives of this investigation were to determine the architecture of the Quaternary sediments filling the Petitcodiac and Memramcook River valleys, and the contribution of the regional late Quaternary events to the architecture and stratigraphy.

The sediment architecture was determined using a series of geological cross-sections that intersect the main Quaternary stratigraphic units. The subsurface information needed to construct these sections was extracted from available borehole databases provided by provincial departments and consultants. The quality of these boreholes was validated using the methodology of Ross et al. (2001). After the validation process, a total of 2997 boreholes of variable quality remained for the study area. Because very few of these boreholes were in the Petitcodiac and Memramcook River valleys, 120 m of drilling was carried out on two sites, northwest of Moncton and near Memramcook. Since drilling was not possible in the Petitcodiac River valley due to provincial regulations, 11 km of land-based geophysics were performed to obtain additional information on the subsurface of the Petitcodiac River valley (*see* 'Geophysics' section). Using this information, five geological cross-sections (*see* Fig. 32 for locations) and thirty topographic cross-sections were drawn to get a more precise picture of the Quaternary sediment stratigraphy; all cross-sections can be found in Boisvert (2004). A detailed map of the bedrock topography (Fig. 33) was also prepared, based on earlier work by Hobson and Carr (1967).

Many of the tributary valleys to the Petitcodiac River are incised in bedrock, forming a network of deep Quaternary-sediment-filled valleys connected with the Petitcodiac River valley (Boisvert et al., 2002). These valleys are generally filled with a variable thickness of till, reaching more than 20 m in some areas. Drilling was carried out in order to validate the presence of a sandy confined unit beneath the till in the Jonathan Creek valley, located 10 km northwest of Moncton (Fig. 34). This sand unit is present in some of the borehole logs compiled for the MGWI project, but only 60 cm (2 feet) were found during the drilling. Thus, no conclusion can be drawn on the presence of an aquifer beneath the till on the southern flank of the Kingston Uplift.

Nevertheless, these valleys have a major impact on groundwater recharge, since the semiconfining units considerably limit infiltration.

A geotechnical study and the land-based geophysics performed between Moncton and Riverview suggest that the Petitcodiac River buried valley is more than 40 m deep and 750 m wide. The sides of the buried valley generally consist of 2 to 10 m of till, forming an aquitard (Wheeler et al., 1985). The postglacial marine invasion in the area did not have a significant impact on the hydrogeological context because of the minor sedimentation associated with it (Boisvert, 2004). The till is thus immediately overlain by a thick sand and gravel unit, probably deposited during the sea-level lowstand. This sand unit is also present in other cross-sections of the Petitcodiac River and Memramcook River valleys, suggesting that this aquifer is of regional extent (Boisvert, 2004). This unit is confined or semiconfined by a relatively thin layer of clay or clay and gravel. The origin of this layer is difficult to ascertain because the description of the material in Wheeler et al. (1985) is not very clear and drilling was not possible in this valley. Boisvert (2004) suggested that the deposition of this clay is the result of sea-level fluctuations during the Holocene transgression. The second sand unit is thinner than the underlying one and its extension is unknown. Finally, all these units are confined by a thick silty sand to clay unit associated with the Holocene transgression. According to Bray et al. (1982), deposition of the upper 8 m of clay was caused by the construction of the causeway in 1968. An example of a cross-section through the Petitcodiac River valley is presented in Figure 35.

The Memramcook River valley has a stratigraphy similar to that of the Petitcodiac but not as deep (29 m; Fig. 36). The bottom of this valley is composed of a sand and gravel unit, but this aquifer includes a variable thickness of weathered bedrock, which does not seem to be present in the Petitcodiac River valley. This unit is confined by a thick silt to sandy silt unit associated with the Holocene transgression. The middle clay unit found in the Petitcodiac River valley does not seem to be present in that of the Memramcook. The fine sand unit found within the sandy silt of the Memramcook River valley probably corresponds to the paleomarch level prior to construction of the College Bridge causeway. Thus, the upper part of the sandy silt unit has probably been deposited since the construction of this causeway.

INTEGRATION OF HYDRO- GEOLOGICAL INFORMATION

This section presents the hydrogeological context of the Maritimes Basin, its major hydrostratigraphic units, and the hydraulic properties of these units. The piezometric map obtained from water-level measurements is then presented; it provides 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.

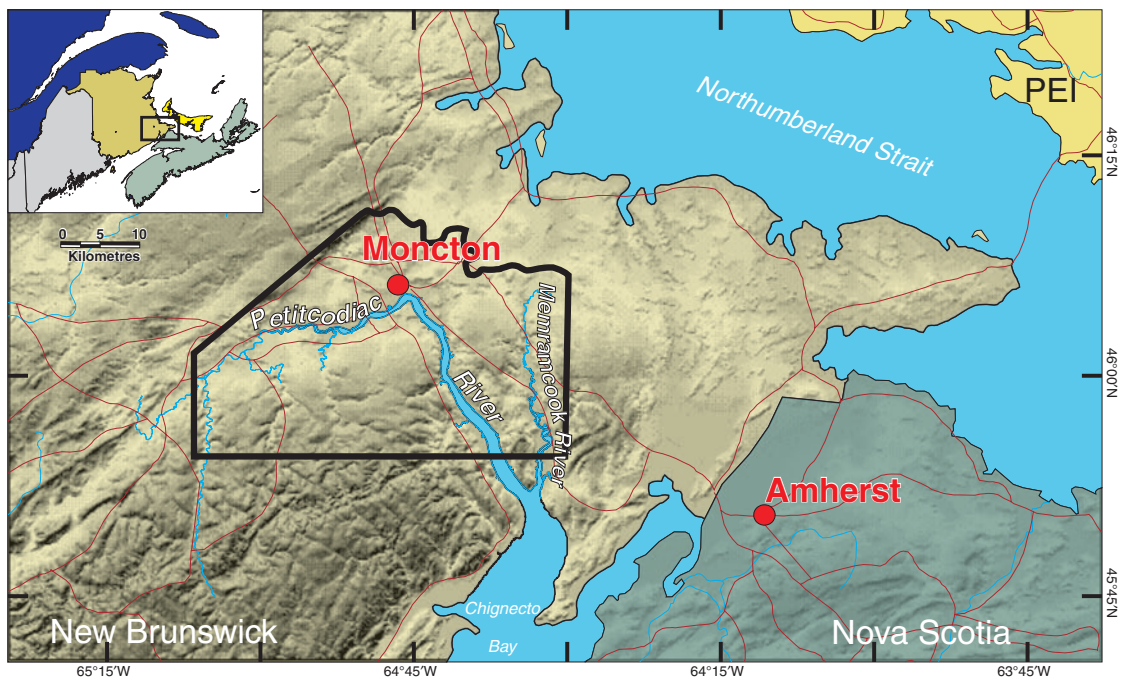


Figure 31. Location of the detailed Quaternary-sediment study (outlined in black).

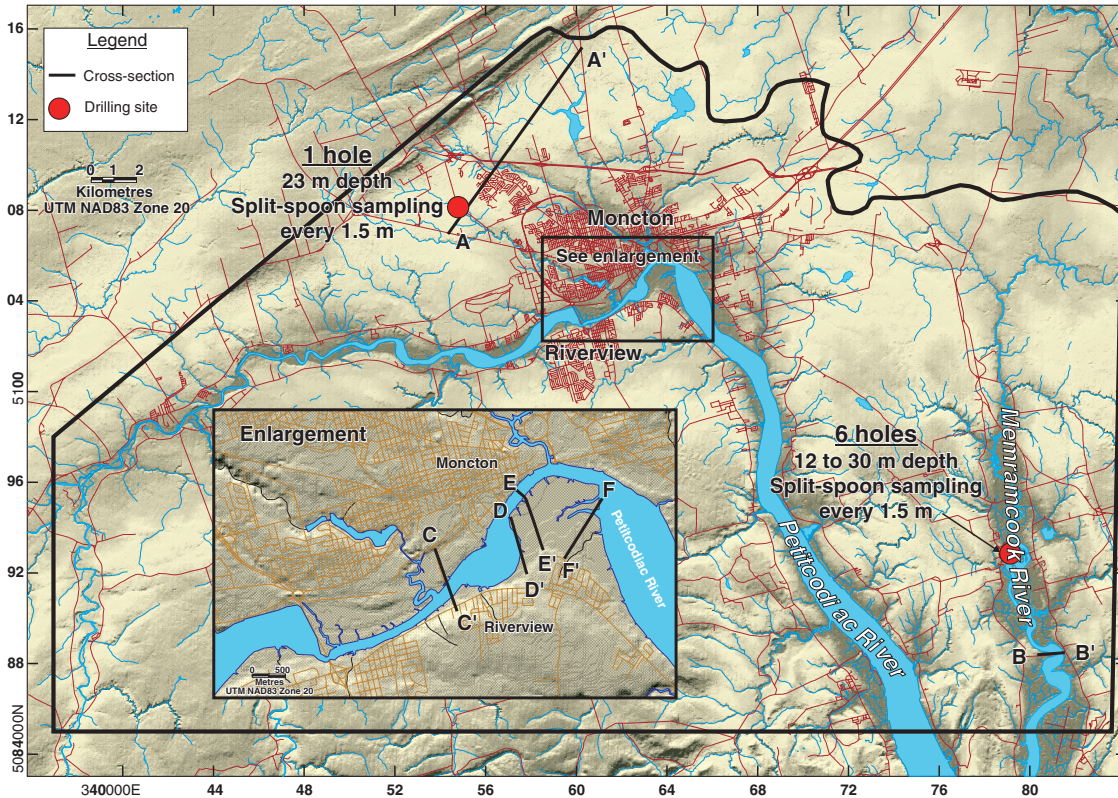


Figure 32. Location of drilling sites and geological cross-sections for the detailed Quaternary-sediment study.

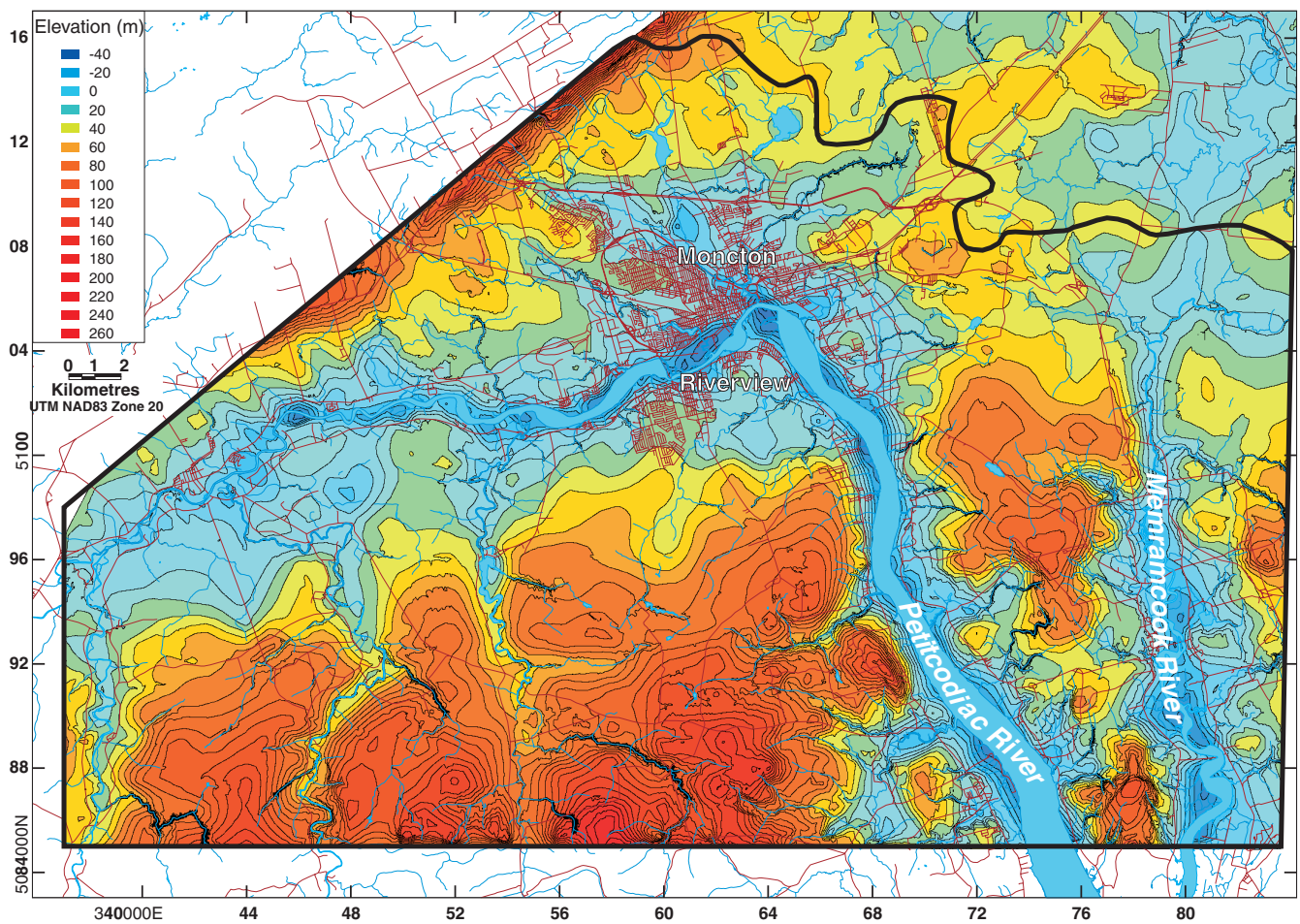


Figure 33. Bedrock topography of the Moncton, New Brunswick area, compiled for the detailed Quaternary-sediment study.

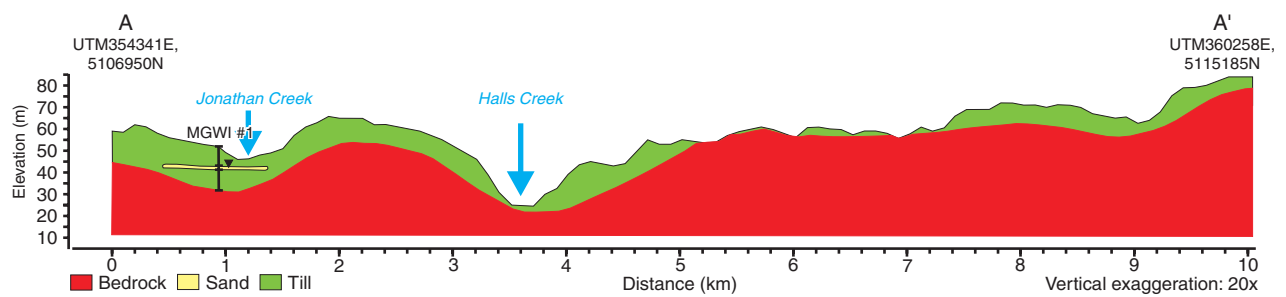


Figure 34. Geological cross-section A–A', northwest of Moncton, New Brunswick.

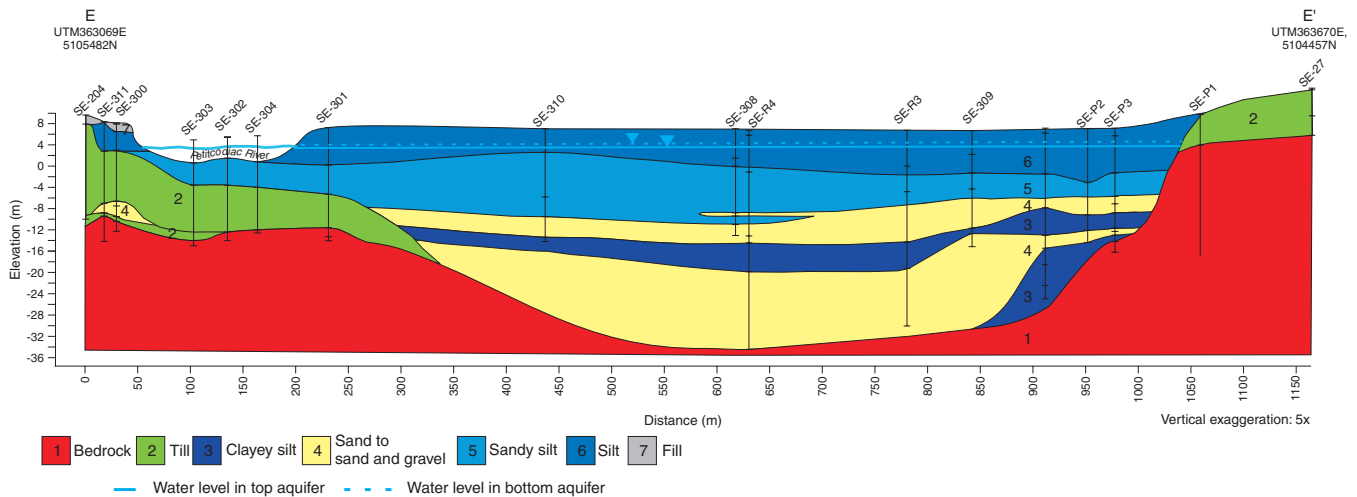


Figure 35. Geological cross-section E–E', Petitcodiac River valley, New Brunswick.

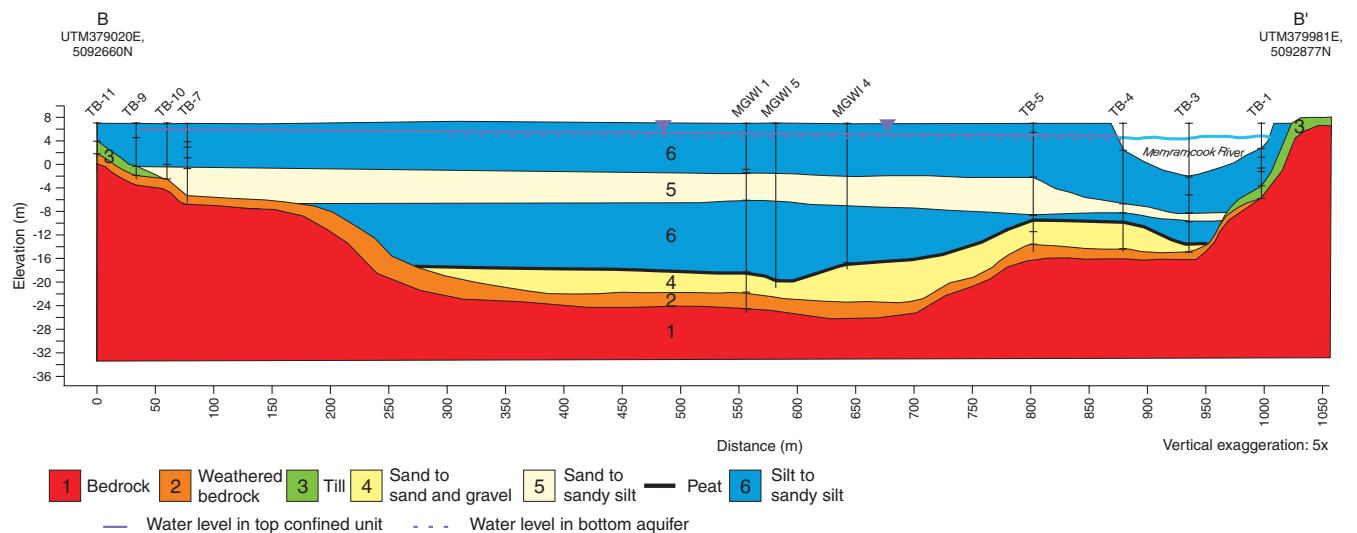


Figure 36. Geological cross-section B–B', Memramcook River valley, New Brunswick.

General hydrogeological context

The Maritimes Basin consists of a series of sedimentary subbasins containing Middle Devonian to Early Permian sedimentary rocks. These subbasins form part of the Appalachian Orogen and generally trend northeast to east along regional faults (McCutcheon and Robinson, 1987; Williams, 1995). The fractured sedimentary rocks of the basin are highly stratified and lenticular in nature, consisting of sequences of sandstone, shale, siltstone, and conglomerate that appear in varying proportions in each geological formation. The stratigraphy of the basin is complex due to differential sedimentation rates, syndimentary uplifting, and remoulding of previous deposits. As a result, the hydrogeological properties within each stratigraphic unit appear to be quite heterogeneous, due both to the occurrence of the lithological variation and to fracturing.

Groundwater can be exploited in relatively high quantities in the Maritimes Basin. It flows mostly in the bedrock and, to a lesser extent, in the surficial sediments. The data compilation and work performed during this three-year project have underscored the great complexity of this hydrogeological system. Individual beds range in thickness from a few centimetres to several metres, and their lateral extent is highly variable. As mentioned above, this sequence of discontinuous strata of highly variable hydraulic properties results in an aquifer/aquitard layering within the same geological formation. Groundwater flows within the bedrock through fractures and interconnected pore spaces between individual grains. Since fractures have a much higher permeability than the matrix around them, groundwater flows predominantly through fractures. Nevertheless, significant quantities of water, especially in sandstone and conglomerate layers, can

be stored in the matrix pores, as confirmed by total-porosity and specific-yield values (*see* 'Water and soil analysis, and rock-matrix porosity' and 'Specific yields' sections).

Fractures have been observed in all rock types; however, they are encountered mainly in sandstone and conglomerate layers and at lithological contacts (between two strata). Field measurements indicate that movement of groundwater is indeed predominantly controlled by fractures, although patterns in the distribution of these permeable features vary with rock type. Where the rock is composed primarily of sandstone like that of the Pictou Group, permeable intervals are limited to only a few distinct fractures within these units. Where rocks consist of highly variable lithological sequences, such as those identified in the Cumberland Group, permeable zones are much more dispersed and occur mostly along lithological contacts and bedding-plane partings. Fieldwork clearly revealed the spatially consistent pattern of fracture orientations dipping to the southeast and striking approximately 045°, south from the Kingston Uplift. This structural correlation among wells extending through most of the study area is in good agreement with the orientation of local faults and the regional stress regime. Borehole geophysics confirmed that most planar features intersecting the wells are shallow dipping (<30°), with a distribution of orientations that is fairly broad but still in general agreement with the regional structure. Only about 5% of fractures are found to be steeply dipping (>50°), but these have a stronger directional focus that better reflects local faulting characteristics. Because of this preferential fracture orientation and lenticular arrangement of beds, fractured aquifers can locally be anisotropic and very heterogeneous, resulting in significant channelling of the groundwater flow. Nevertheless, pumping tests revealed that investigated sites behaved similar to porous media at a large scale, as drawdown followed Theis-type curves (*see* 'Hydraulic properties of the bedrock' section).

In summary, the Maritimes Basin hydrogeological system is a fractured porous medium, having a total porosity typically ranging from 5 to 10%, but that usually follows porous-media Theis-type curves when pump tests are conducted. The lenticular nature of the different rock types and the great influence of lithology on fracturing have a large impact on the flow-system behaviour at the local scale. Fieldwork confirmed the limited extent of its permeable facies, and indicated a fractured-driven anisotropy. However, at the regional scale, the fractures are considered to be sufficiently connected to impart a behaviour typical of an equivalent porous medium.

According to water-well drillers, provincial hydrogeologists, and some reports (e.g. Francis and Gale, 1988), fractures in every stratum decrease in both number and aperture with depth. As a result, the permeability of the aquifers should generally decrease with depth. Many wells in recharge areas drilled deeper than 100 m yield little or no water beyond

this depth (Carr, 1964). This suggests that fractures, which account for a large part of the aquifer permeability, tend to close with depth or be less connected, perhaps due to the increasing overburden pressures. Carr (1969) observed in Prince Edward Island that, during dry spells, fractures in the siltstone and claystone strata yielded water, but those in the overlying and underlying sandstone strata were dry, attesting to the more rapid movement of groundwater in the coarser grained (sandstone) layers. The groundwater flowing laterally along the top of a poorly permeable stratum can produce springs, which have been observed at contacts between different rock types (Carr, 1969).

Most of the Maritimes Basin sequence is overlain by a relatively thin layer of till, whose composition may vary widely, as mentioned in the previous sections. This till is likely not an effective confining layer, and groundwater recharge to the rock aquifer system occurs through it. Indeed, since bedrock outcrops are rare, most of the recharge must occur through surficial sediments. Large-diameter wells dug in the till characteristically have much lower yields than those drilled in the bedrock (Carr, 1964). These wells yield just enough water for domestic use. Potential recharge rates between 92 and 436 mm/a have been determined for the most permeable regions (corresponding to the Richibucto Formation, undivided Pictou Group, Boss Point Formation, Balfron Formation, and all formations in the Prince Edward Island Group; *see* 'Groundwater recharge' section).

According to Carr (1964, 1969), the till and the bedrock likely form one hydrogeological system in the Moncton Basin of New Brunswick and in Prince Edward Island. A similar conclusion was reached by Brown (1971) for formations of the Pictou Group in the Shippagan region, located north of the study area. These observations might apply to the entire Maritimes Basin as well, because of the similarities between geological units across the basin. In Prince Edward Island, where the drainage courses are only small creeks and brooks, it was observed that neighbouring creeks dried out during pumping in bedrock wells (Prince Edward Island Department of Environment, Energy, and Forestry, pers. comm., 2003). Nevertheless, interactions between surface water and groundwater from both types of layers (surficial sediments and bedrock) are not well known throughout the Maritimes Basin. Measurements made during the 2002 field season showed that water levels are not always at the same elevation in aquifers and streams, despite proximity. This is an indication that all types of conditions (confined, semiconfined, and unconfined) may be found within the study area. As explained above, this is due to the sequential occurrence of strata of varying permeabilities. At a regional scale, however, there should be sufficient groundwater exchange between lenticular layers to provide a hydraulic connection between surface water and groundwater. The surface water-groundwater interactions are being investigated on a local scale in the Fredericton area, just west of this study area (Butler et al., 2002).

The following sections introduce the major hydrostratigraphic units encountered within the study area, along with their characteristics (extent, colour, thickness) and properties (conductivity, storage coefficient, yields).

Hydrostratigraphic units of interest

Geological formations may be classified into hydrostratigraphic units according to their hydraulic properties and water quality, which depend upon their lithology. Hydrostratigraphic units can be categorized as aquifer or aquitard, depending on the amount of water that can be drawn from them. An aquifer is defined as a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs (Todd, 1980). An aquitard is defined as a layer of more or less impermeable material (i.e. that cannot yield appreciable quantities of water). Table 12 presents the classification of the distinct geological groups into hydrostratigraphic units for the study area, based on available data and the information found in Carr (1964). The classification ‘variable aquifer’ has been used when good hydraulic potential can be found in certain areas, while poor transmissivities (or low yields) are observed in other parts of the formation, likely where fractures and sandstone layers are less abundant. Figure 37 presents visually all of the formations that are more likely to provide moderate to

high yields (i.e. those with a good or variable aquifer potential). This figure indicates that good aquifer units cover a large part of the region.

Four rock formations were identified as hydrostratigraphic units to be prioritized for hydraulic characterization during the MGWI project: 1) the Prince Edward Island Group, 2) the Richibucto Formation, 3) the Boss Point Formation, and 4) the Hillsborough Formation. These units were selected based on their productivity and proximity to main urban centres and water needs. Surficial sediments were also identified as being of major importance because of their role in aquifer recharge and the current poor level of knowledge regarding their hydraulic properties. These hydrostratigraphic units are described in the following sections.

Surficial sediments

Sandy and gravelly unconsolidated sediments are generally known to be excellent granular aquifers. They are, however, restricted to very limited locations within the study area. The cases of Sussex Corner (unofficial name) and Fredericton, (just outside the study area) New Brunswick exemplify the large aquifer potential of glaciofluvial sediments. Individual wells can yield as much as 53 L/s (697 gal./min. or Igpm). The glacial till that overlies most of the sedimentary rocks of the Maritimes Basin is considered a poor aquifer, however, since

Table 12. Aquifer potential of the main hydrostratigraphic units encountered in the Maritimes Groundwater Initiative study area.

Geological group	Hydrostratigraphic unit of interest	Aquifer potential
Surficial sediments	Till	Poor
Prince Edward Island	Orby Head, Hillsborough River, Kildare, Egmond Bay formations	Good
Pictou	Undivided Pictou Group	Generally good
	Richibucto Formation	Generally good
	Balfron Formation	Variable
Cumberland	Salisbury Formation	Poor
	Undivided Cumberland Group	Variable
	Boss Point Formation	Variable
Mabou	Undivided Hopewell Formation	Poor or bad (aquitard)
Windsor	Undivided Windsor Group	Poor
	Macumber Formation	Bad (aquitard)
	Hillsborough Formation	Variable
Horton	Weldon Formation	Poor (plus poor water quality)
	Albert Formation	Poor (plus poor water quality)
Basement complex	Pre-Carboniferous	Bad (aquitard)

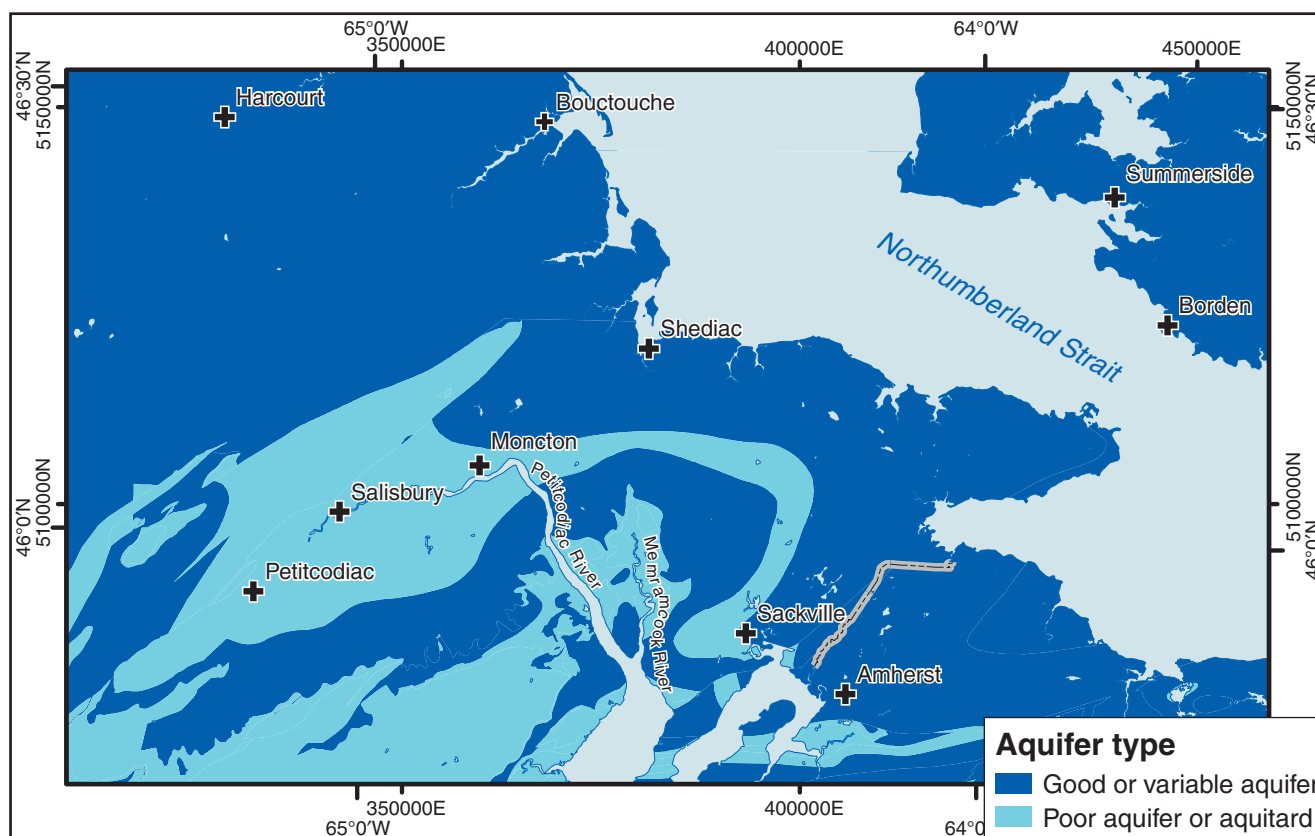


Figure 37. Distribution of good, variable, and poor potential aquifers in the Maritimes Groundwater Initiative study area.

it generally provides barely enough water for a family. Nevertheless, infiltration through till provides most of the recharge to the bedrock aquifers.

The study by Boisvert (2004) allowed the identification of layers of fine sand within the buried rock valleys of the Memramcook and Petitcodiac rivers in the Moncton Basin. The thickness of the sand layers is limited, however, and the groundwater quality was found to be poor at one location in the Memramcook River valley (with high concentrations of iron, manganese, chloride, and sodium). Thus, no significant source of water supply was found within surficial sediments in the Moncton area.

Prince Edward Island Group

Formations of the Prince Edward Island Group are the youngest in the Maritimes Basin, overlying those of the Pictou Group. Like all formations in the basin, they are made up of multiple layers of sedimentary rocks, but they are unique in their high proportion of ‘redbed’ sandstone, which is by far the most common rock type encountered. When less fine grained (mudstone) beds are present, these redbed sandstone layers form very good aquifers with high transmissivities. These rocks are also composed of variable proportions of siltstone, breccia, and conglomerate. Near the surface, the sandstone is highly fractured and altered, and

vertical joints can be encountered. Some intergranular permeability has also been noted in these rocks. The study of well hydrographs showed that specific yields (or, equivalently, drainage porosity) can locally be quite variable, averaging between 2 and 7% (*see* ‘Specific yields’ section).

Examples of good yields provided by these formations are the Union well field, which has a total withdrawal rate of about 75 L/s (989 Igpm), and the Brackley well field, also at about 75 L/s, both in the Charlottetown area; and the Linkletter well, close to Summerside, which can yield 97 L/s (1275 Igpm). At least 100 high-capacity wells ($Q > 10$ L/s) can be found on the island, and approximately 20 000 to 25 000 private wells supply the population. According to the Prince Edward Island Department of Environment, Energy, and Forestry, their total withdrawal would not represent a substantial proportion of the total recharge, except in very limited areas.

Richibucto Formation

The Richibucto Formation covers a large portion of the study area located to the north, northwest, and east of Moncton, New Brunswick. It is composed mainly of grey sandstone with numerous beds, interstratified with red-mudrock-dominated sequences (Johnson, 1995a). The sandstone is usually crossbedded, although it is occasionally massive

and some channels occur. The grains of sandstone are poorly sorted, equigranular, and subrounded (Carr, 1964). These rocks seem poorly consolidated. It is thought that bedding heterogeneity and sandstone porosity are responsible for the high water-bearing capacity of the Richibucto strata. Secondary joints and fractures allow the formation to have a good hydraulic potential.

The Richibucto Formation is highly exploited for water supply along the coastline from Port Elgin to Shediac, New Brunswick. Important zones of recharge and discharge are present and confined conditions are often encountered. Six of the most productive wells in this formation have a combined pumping capacity greater than 104 L/s (1370 Igpm; St. Peter, 2000). The wells of the town of Shediac have mean capacities of 10 to 27 L/s (132–355 Igpm). Other towns, such as Port Elgin, also have high-yield wells.

Boss Point Formation

Aquifer quality of the Boss Point Formation varies from good to poor; however, it was considered the best aquifer within the Moncton Basin by Carr (1964). It comprises mostly buff or light grey sandstone and conglomerate, with subordinate lithic and feldspathic sandstone and mudstone, and minor coaly shale, coal, and limestone (St. Peter, 1993). The sandstone varies from strongly crossbedded to massive, and some occurs as channel structures; it is mostly medium grained and fairly well sorted (Carr, 1964). The conglomerate is typically polymictic but quartz dominated (Johnson, 1995a). The beds have widely spaced, steeply dipping joints that likely contribute to the formation permeability. This formation is present in New Brunswick and Nova Scotia. Carr (1964) noticed that the base of the Boss Point Formation is often a source of springs, as groundwater permeating the sandstone intersects the claystone of the underlying formations of the Riversdale-Mabou Group and flows laterally on top of the claystone until it comes to the surface in a river valley. It has been observed that, on average, wells tapping this formation in Nova Scotia have lower transmissivities and yields than those in New Brunswick.

The pumping rate of the municipal well in Hillsborough, New Brunswick, is 11 L/s (150 Igpm). Other test wells that tap this formation in the same area, however, have been abandoned due to insufficient yield (ADI Limited, 2000). Wells of the town of Riverview, New Brunswick, also have good yields ($Q > 7.5$ L/s each). The average pumping rates for wells in the Boss Point Formation in Nova Scotia vary from 0.8 to 10 L/s (10–130 Igpm; Vaughan and Somers, 1980).

Hillsborough Formation

Exposure of the Hillsborough Formation is restricted to small areas located near the towns of Hillsborough and Sussex Corner in New Brunswick and just south of Amherst in Nova Scotia. The formation comprises mainly red conglomerate,

grit, and sandstone with minor mudstone; the coarse conglomerate and grit of the formation are typically poorly sorted and include polymictic granules to boulders set in a sandy or muddy sand matrix (St. Peter, 1993). Both conglomerate and grit are commonly grain supported and have tabular crossbeds.

The town of Sussex Corner is supplied by groundwater from this unit. Yields of 8 and 11 L/s were estimated by air lift during the development of the two wells. Five test boreholes have been drilled in this rock unit for the village of Hillsborough and abandoned afterwards, due to either insufficient supply or poor-quality water (ADI Limited, 2000). Yields vary over a wide range, from less than 0.1 to 11 L/s.

Hydraulic properties of major aquifers

Hydraulic properties of geological formations were estimated based on values compiled from various reports and measured using hydraulic testing (*see* ‘Methodology’ and ‘Interpretation of existing and acquired hydrogeological data and results’ sections). In particular, hydraulic conductivity (or transmissivity) is a critical parameter in hydrogeological investigations because it provides a quantitative estimate of groundwater availability and the well capacity needed for exploitation. Transmissivities and storage coefficients (for relatively large areas) are best estimated from observed water-level drawdown and recovery during a long-duration pumping test (> 72 hours), but these tests are expensive. Total porosities and specific yields (drainage porosity) in Prince Edward Island were also evaluated based on thin sections and well hydrographs, respectively.

Considering the very large extent of the study area, relatively few long-duration pumping tests have been carried out. Moreover, they have rarely been implemented using observation wells other than the pumping well. Consequently, very few storage coefficient data could be estimated and their reliability is questionable. The data compilation of reports from consultants and provincial governments provided several values of transmissivity and storage coefficient. Of these, only the results from pumping tests that lasted more than 4 hours were kept. Since several wells were very close to one another (relative to the regional scale of the study), results from wells within an arbitrary 3 km radius were aggregated using a geometric mean. From the 109 results on hydraulic conductivity (K) and the 43 results on storage coefficient (S) available to characterize the fractured aquifers in the vicinity of the study area, only 50 K values and 24 S values fell within the study area itself. Sixteen additional K values and two S values were acquired through fieldwork during the 2001 and 2002 seasons, as the GSC performed new short- and long-term pumping tests, packer tests, and borehole flowmeter-pumping tests, in an effort to fill the gaps in the existing knowledge. Some wells, however, were investigated using both pumping and packer tests, resulting in 10 new combined values being obtained for the study area.

In most cases, complete (raw) data from existing (pre-MGWI) pumping tests are not available and often even the duration is not indicated. Moreover, many wells are neither properly located nor subjected to a pumping-test period long enough to be considered representative (a threshold was imposed at 4 hours). Therefore, some tests had to be discarded. Where no other data were available, values with missing information on duration were kept. As far as possible, wells without geographic location were assigned an approximate location using maps and available information. At the regional scale, this approximation should have a negligible impact. Some values of K and S were found using hydraulic testing for the surficial sediments in the reports, but only three such K values and one such S value were located within the study area. They correspond to pumping tests done in very permeable granular units in the Sussex and Springhill areas. Permeameter and infiltrometer test results obtained during the 2002 field season are the only source of quantitative information regarding hydraulic properties of the till layer overlying the various geological formations of the Moncton Basin. Additional pumping tests were conducted in granular aquifers close to the Memramcook River (*see* 'Hydraulic properties of Quaternary units' section). They showed that these units could not serve as water supplies due to their limited extent and poor groundwater quality.

Carr (1964) found that one of the five pumping tests carried out during his Moncton Basin study had to be interpreted with a leaky artesian-type curve. It is not known if other wells necessitated this kind of interpretation (or if this characteristic has been taken into account), since complete pumping-test data are seldom available. In addition, most pumping tests

probably did not last long enough to see potential behaviour related to semiconfined or unconfined aquifer conditions on drawdown versus time graphs. Indeed, the 'plateau' and the second curve typical of those aquifers could simply have been missed.

Table 13 and Figure 38 summarize the collected and acquired values for K and S. All available data for Prince Edward Island were kept, since there is no clear differentiation between hydraulic properties throughout the island. Values for the Boss Point Formation are differentiated for New Brunswick and Nova Scotia, as K values found in Nova Scotia are generally an order of magnitude smaller than those in New Brunswick. No values are available for the Horton Group and the basement complex. Five other sites with hydraulic property values (five K and two S values) could not be included in this table, because they are located in a highly tectonized region and it was not clear from their location and the borehole description (when available) to which geological formation they belong. Hydraulic conductivities were obtained by dividing the transmissivities (values generally provided in databases and reports) by the open section (b) of the well, since $T = K \cdot b$, assuming that the flow is horizontal close to the well. The open section was estimated by subtracting the casing length from the well depth. When the casing length was unknown, the surficial-sediment thickness was used as an approximation; when even these data were not available, the mean value of surficial-sediment thickness data from provincial databases was used. Hence, hydraulic conductivities for individual wells are average values obtained from all rock strata over the entire (noncased) borehole depth. This allowed the estimation of representative hydraulic conductivity values

Table 13. Summary of hydraulic-conductivity (K) and storage-coefficient (S) values obtained from hydraulic testing of typical formations of the Maritimes Basin within or close to the Maritimes Groundwater Initiative study area.

Hydrostratigraphic unit or group	K (m/s)*			S ¹			Number of values ¹	
	Minimum	Maximum	Mean	Minimum	Maximum	Mean	K	S
Surficial sediments: Till Sand units	1.1x10 ⁻⁹ 1.5x10 ⁻⁸	1.9x10 ⁻⁴ 1.8x10 ⁻³	1.9x10 ⁻⁶ 1.3x10 ⁻⁶	- 8.4x10 ⁻⁴	- 1.1	- 1.4x10 ⁻³	52 8	0 (all) 4 (all)
Prince Edward Island Group ²	4.3x10 ⁻⁶	2.5x10 ⁻³	1.2x10 ⁻⁴	4.6x10 ⁻⁴	4.4x10 ⁻²	4.1x10 ⁻³	43	21
Balfour Formation (Pictou)	1.1x10 ⁻⁷	3.8x10 ⁻⁵	3.3x10 ⁻⁶	-	-	2.1x10 ⁻⁴	6	1
Richibucto Formation— undivided Pictou Group	1.4x10 ⁻⁶	1.9x10 ⁻⁴	2.2x10 ⁻⁵	7.4x10 ⁻⁵	3.7x10 ⁻³	5.0x10 ⁻⁴	18	10
Salisbury Formation (Pictou)	3.2x10 ⁻⁷	3.4x10 ⁻⁶	1.4x10 ⁻⁶	4.0x10 ⁻⁴	2.2x10 ⁻³	9.5x10 ⁻⁴	4	2
Boss Point Formation (Cumberland Group): New Brunswick Nova Scotia	3.3x10 ⁻⁶ 1.1x10 ⁻⁶	3.8x10 ⁻⁵ 8.5x10 ⁻⁶	1.1x10 ⁻⁵ 2.8x10 ⁻⁶	1.2x10 ⁻⁴ -	1.1x10 ⁻² -	4.8x10 ⁻⁴ -	5 9	4 0
Undivided Cumberland Group	8.1x10 ⁻⁷	5.5x10 ⁻⁶	4.9x10 ⁻⁶	1.0x10 ⁻⁴	8.7x10 ⁻²	2.2x10 ⁻⁴	18	3
Windsor Group (Hillsborough Formation)	1.6x10 ⁻⁸	1.2x10 ⁻⁵	4.1x10 ⁻⁷	1.4x10 ⁻⁴	2.1x10 ⁻²	1.7x10 ⁻³	5	2
Mabou Group	-	-	5.1x10 ⁻⁶	-	-	-	1	0
Horton Group	-	-	-	-	-	-	0	0

¹May represent combined values. Includes all types of aquifer: confined, unconfined and semiconfined
²Values for the entire island are included

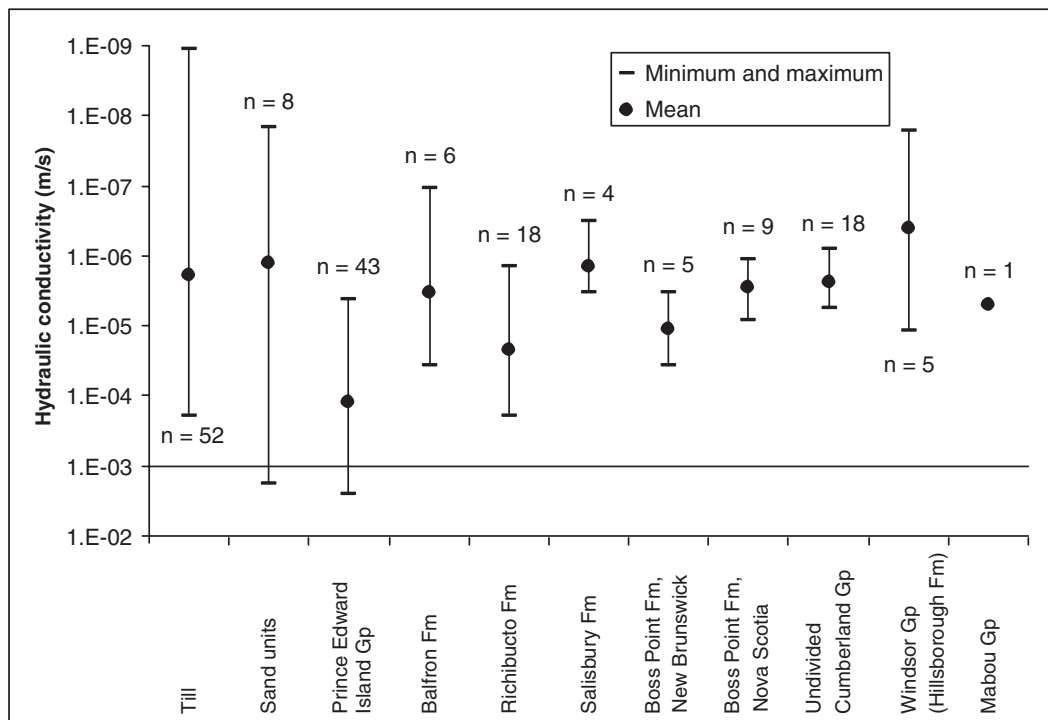


Figure 38. Hydraulic-conductivity (K) values for each hydrostratigraphic unit in the Maritimes Basin within or close to the Maritimes Groundwater Initiative study area.

for the bedrock aquifers as a whole (rather than for specific fractures). These values are usually smaller than K values found in sandstone strata alone (in which most of the flow occurs), as shown by borehole geophysics and packer-test results, on the order of 10^{-4} m/s for some intervals.

Minimum and maximum values are shown in Table 13 and in Figure 38 to demonstrate the wide ranges of values that can be encountered in each geological formation. As a general rule, the higher the percentage of sandstone present within (or neighbouring) the borehole, the higher will be the transmissivity (Carr, 1964). Because of the formations' inherent heterogeneity (stratification and fracturing), a well may have a totally different response than another well located within a few kilometres. For instance, 9 of the 14 test wells put down by the Town of Hillsborough in the Boss Point and Hillsborough formations have been abandoned due to low yields. A corollary of this is that the distribution of K could be overestimated due to the fact that only wells with promising high yields are tested. Indeed, completed wells with little or no hydraulic potential are abandoned without being tested, thus biasing the results.

Figures 39 and 40 show the distribution of hydraulic conductivity and storage coefficient data divided into three categories based on magnitude. A circle may represent either a single value or a geometric mean of several values located in a small area (within 3 km). Hydraulic conductivity values could not be interpolated, since values depend mostly on the local geological formations and, consequently, the gradual

transition between data would not be realistic (K values showed no spatial correlation). Data are quite scattered in certain parts of New Brunswick. They are mostly concentrated along the coast and rivers, where the population is denser. As expected, K data exhibit large variations between hydrostratigraphic units and even within a specific unit. These internal variations attest to the strong heterogeneity of each formation (succession of discontinuous layers of varying permeabilities) and reflect the strong influence of fracturing. In general, the hydraulic conductivity values seem to increase toward the north and east in the study area. The Richibucto Formation, undivided Pictou Group, and Boss Point Formation, and especially all formations of the Prince Edward Island Group, usually exhibit the largest values, typical of high-capacity formations. Other formations, however, can still yield sufficient quantities of water to supply small communities and locally provide high yields. No differentiation regarding depth was made, because of the shortage of data and the lenticular nature of the basin.

High storage-coefficient values ($>10^{-2}$) can indicate unconfined conditions, whereas low values ($<10^{-4}$) generally suggest that the aquifer is confined. Most pumping tests, however, have not been performed over long periods and raw data were generally not available for reinterpretation; therefore their reliability is low. Nevertheless, values found within the Maritimes Basin generally range between 10^{-4} and 10^{-3} , but values as low as 7×10^{-6} and as high as 0.4 have been reported. This, in conjunction with drilling logs, knowledge of hydraulic conductivity of the till, and grain-size analysis,

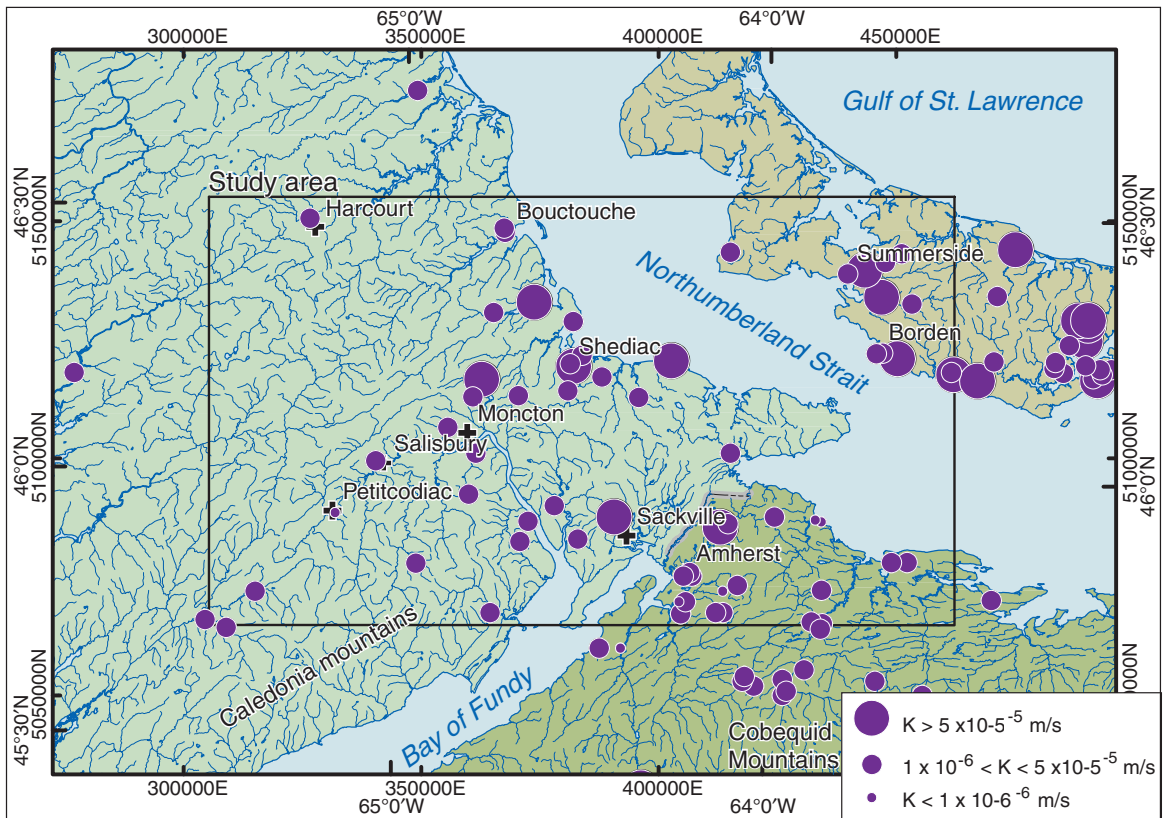


Figure 39. Distribution of hydraulic-conductivity (K) values in the Maritimes Groundwater Initiative study area.

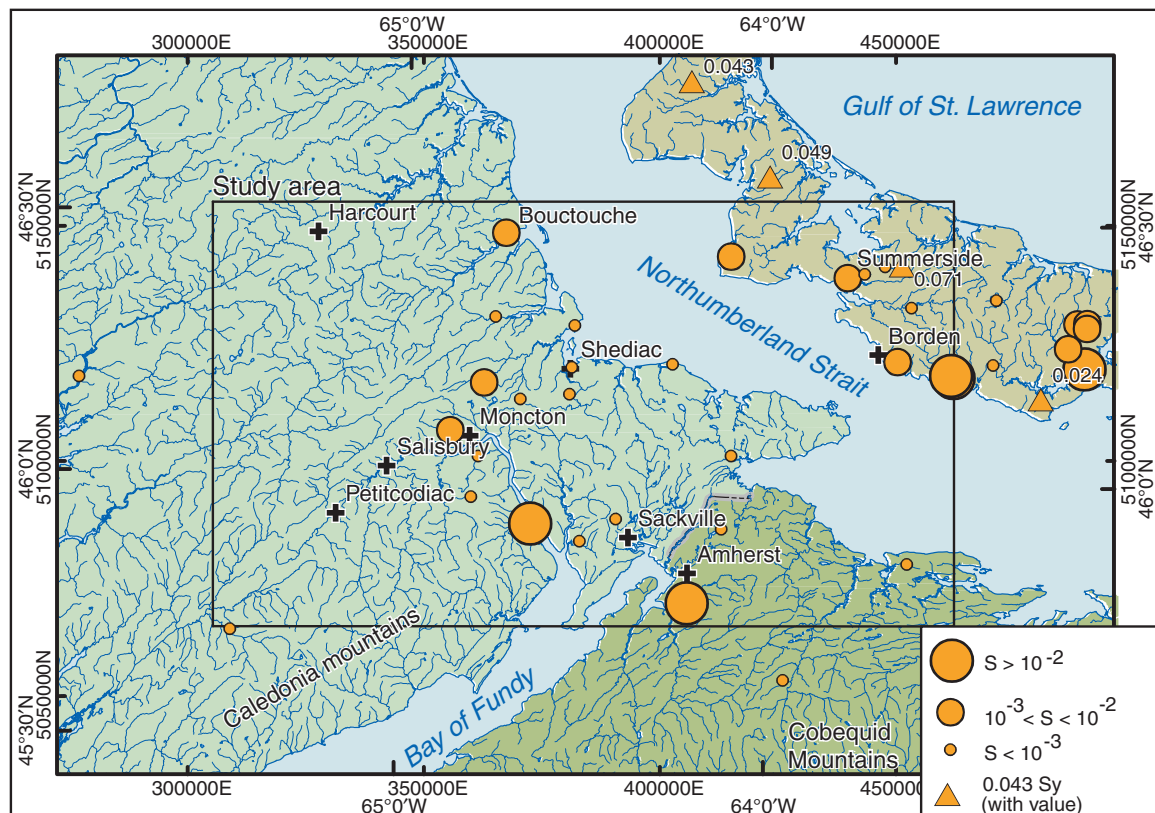


Figure 40. Distribution of storage-coefficient (S) and specific-yield (S_y) values in the Maritimes Groundwater Initiative study area.

confirms that the hydrogeological system is sometimes under confined and sometimes under unconfined conditions. Variations in hydrogeological conditions may be explained by the variability in thickness and composition of the surficial sediments, as well as by the fracturing condition of overlying fine-grained layers (siltstone, claystone, or shale). It is reasonable to assume that leakage could have been detected in some pumping-test curves, if the tests had been run for a sufficiently long period. Therefore, due to the short duration of the pumping tests and the difficulty in interpreting storage coefficients, Figure 40 must be viewed with caution and used only as an indication of a possible distribution of storage coefficients.

To get an idea of the drainage porosity values, specific yields (S_y) were calculated using six well hydrographs available for Prince Edward Island, where conditions are assumed to be unconfined (or very close to). Indeed, the till layer on the island is very sandy (grain-size analysis usually indicates 70–80% sand particles) and generally thin. As described in the ‘Specific yields’ section, S_y values for these six monitoring wells uniformly distributed over the island ranged between 2 and 7% using a representative mean total infiltration of 300 mm/a. These values, four of which can be seen on Figure 40, are in agreement with total porosities obtained from thin sections (5–10% on average; *see* ‘Water and soil analysis, and rock-matrix porosity’ section), thus confirming that water can easily circulate through this very well fractured and porous medium.

Groundwater flow and water levels in bedrock aquifers

The groundwater dynamics within the Maritimes Basin are not fully understood because the hydrogeological system is very heterogeneous, being composed of several formations that are themselves made up of an alternating sequence of sedimentary rocks, as mentioned in previous sections. Mapping of groundwater-level data is therefore a first step toward understanding the system hydrodynamics.

Information on groundwater levels across the study area was obtained from various provincial documents (mostly from databases) and through the GSC fieldwork. Data uncertainty is somewhat high because 1) most wells from water-well databases were not precisely located, and 2) static water levels were often measured only once, immediately after well completion (at different times of the year). Fluctuations within a year or a decade can certainly be large. For this reason, only the most recent data (1998 or newer) from each provincial database were kept, thus giving more weight to the water-level survey. This also avoided dealing with long-term fluctuation patterns or trends.

Groundwater elevations are calculated by subtracting the water depth from the topographic elevation. Data were rejected when negative elevations larger than 3 (i.e. 3 m below sea level) were obtained, since either the topographic

elevation or the water depth must be considered unreliable. A piezometric map was then produced using all the remaining data acquired during the GSC water-level survey (433 data points, of which 351 fall within the study area), plus 219 data points from the New Brunswick database, 225 from the Nova Scotia database and 153 from the Prince Edward Island database (all within the study area). Several additional points from the provincial databases were used, however, as the interpolation process had to rely on values located outside the study area. To obtain a more realistic piezometric map when performing the interpolation, manual control points were also added to the map because incoherent hydraulic heads were noted (mainly due to a lack of measurements), especially in low-relief areas close to streams and in the ocean along the coast. The piezometric map (Fig. 41) was produced through kriging using an exponential variogram (*see* ‘Piezometry and monitoring’ section and Appendix C). Uplifts are not well represented, as few points were available. The map in the atlas (Rivard et al., 2005a, Plate 5-5) presents, in addition, measured and manual control points used for kriging.

All bedrock wells have been used for this map without considering their depth, due to the fact that these wells are usually open over the entire depth interval below the surficial sediments, and well depths and casing lengths are often unknown. Moreover, a classification based on well depth would not have been representative for the entire study area, since each permeable stratum is lenticular and no correlation can be made beyond 3 km. Despite problems related to uncertainty of geographic locations, elevations (obtained from DEMs; *see* ‘Data compilation’ section), data reliability, temporal variations, depth disparities, and the large area covered, data from these various sources seem in good agreement and provide a coherent map at the scale of the study. The authors therefore consider this map to be accurate to within 5 m in the study area. Due to the inherent uncertainty of the data and their low density, this regional piezometric map should not be used as a reference for local studies. In addition, localities outside the study area are highly uncertain, as few data were generally available.

Figure 41 shows that groundwater generally flows toward the ocean, but that watersheds of large rivers such as the Petitcodiac and the St. John have a significant influence on groundwater flow. The groundwater levels generally follow the surface topography. The highest hydraulic heads for the study area are indeed located beneath topographic highs, for instance 1) in the Caledonia and Cobequid mountains; and, to a lesser extent 2) in the Kingston Uplift; 3) in the uplands halfway between the St. John River and the ocean north of the Kingston Uplift in New Brunswick; 4) between Amherst, Springhill, and Oxford in Nova Scotia; and 5) in the centre of Prince Edward Island (*see* Fig. 41 for locations of these areas). These major hydraulic domes do not necessarily correspond to major recharge zones, as their hydraulic conductivity is sometimes very low, as in the case of the Caledonia and Cobequid mountains and the Kingston Uplift. Preferential aquifer recharge areas are instead associated with sandy till

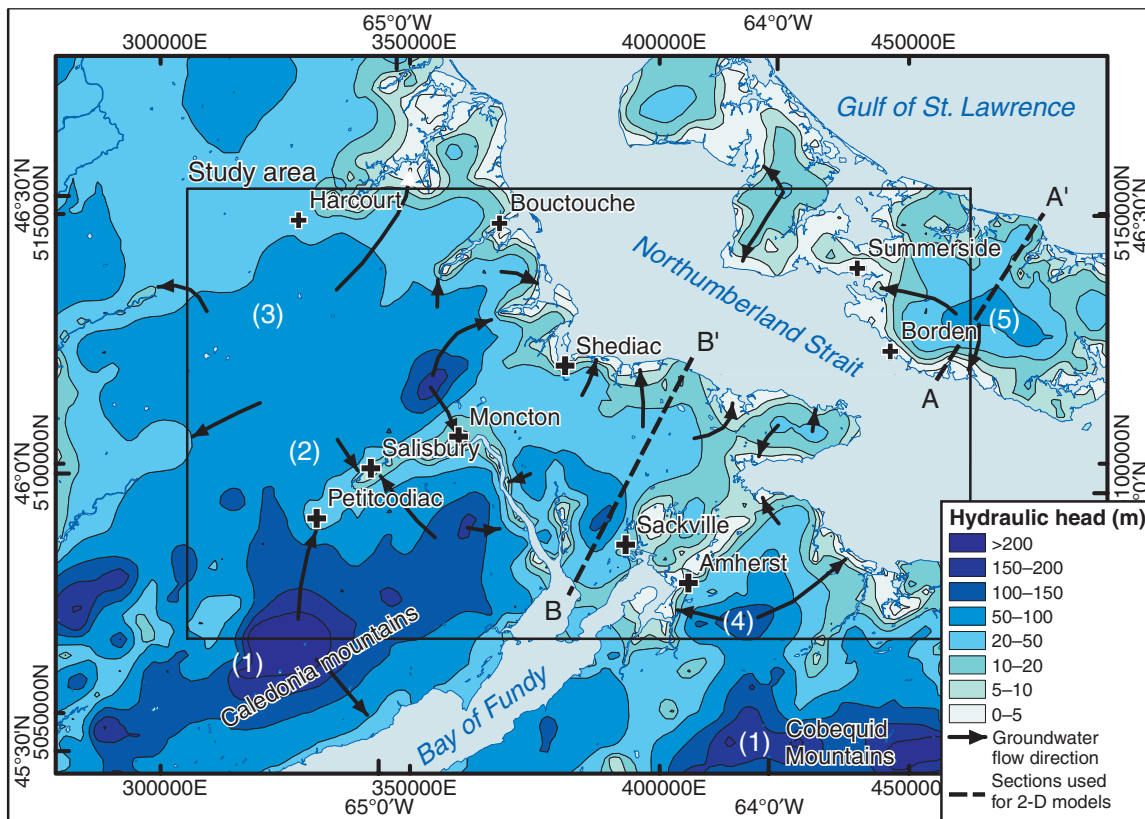


Figure 41. Piezometric map of the bedrock aquifers in the Maritimes Groundwater Initiative study area. Arrows indicate general flow directions. Numbers refer to locations discussed in the text. Cross-sections A-A' and B-B' correspond to 2-D model locations.

covers, such as in the Boss Point Formation and the formations of the Prince Edward Island Group. In the atlas (Rivard et al., 2005a), the surface watersheds were added to this map for comparison. Both surface water and groundwater are generally flowing in the same direction. Nevertheless, even if uncertainty is high in some areas, it is believed that groundwater and surface-water flows are not always in agreement. For instance, in New Brunswick, a fraction of the groundwater circulating from the hydraulic dome located between Hillsborough and Sackville seems to cross surface watersheds to reach the Shediac area. The horizontal hydraulic gradient, represented by the difference in hydraulic head between two contours divided by their distance, is usually gentle, being smaller than 0.01 over most of the study area. Very low gradients are observed in certain areas, such as between Shediac and Port Elgin. Prince Edward Island shows no high dome, as a result of the great permeability of the rock and the flat topography.

The water levels measured in wells located in the study area vary from artesian-flowing conditions to depths that can reach more than 50 m. The water-level depth averages (median) 6.7 m, being generally shallower (and even artesian) near the coast. Artesian conditions, springs, and water levels close to the surface (within 1 m) have been found almost uniformly over the area investigated during the 2001 and 2002 field seasons; they represent 54 sites or 12.5% of the 433 wells

visited. In addition, many residents mentioned nearby artesian wells or springs, but they often could not be precisely located because the land owners were not home. These frequent artesian conditions might seem awkward in this flat area. They can be explained, however, by the fact that fractures are gently dipping toward the Northumberland Strait, and that overlying fine-grained beds or accumulations of fine-grained sediments (in areas close to streams or the ocean) act to confine aquifers. Due to the absence of confinement, few artesian wells are expected on Prince Edward Island, and none were identified during field surveys.

Since the groundwater flow in recharge and discharge areas often has significant vertical components, the flow patterns cannot all be accurately represented in two-dimensions on a map. Since only mean water-level values over the entire borehole length are available (no wells are equipped with loggers and packers providing measurements at various depths), Figure 41 provides only indications of the regional groundwater-flow patterns (direction). Despite its limitations, this regional piezometric map provides valuable information because it portrays the upper part of the bedrock flow system, sometimes under confined and sometimes under unconfined conditions. Even if conditions are changing within this flow system, connected permeable zones ensure the hydraulic continuity regionally.

Monitoring wells and long-term behaviour

A groundwater-level monitoring network (six wells) is still active in Prince Edward Island, and a network in New Brunswick was active from 1977 to 1991 (34 wells, of which 26 are installed in the bedrock). Only a few wells from these monitoring sites (six in New Brunswick and one in Prince Edward Island), however, fall within the study area. Continuous water-level records in inactive wells allow the description of natural seasonal fluctuations. The available hydrographs usually showed typical water-level responses to seasonal patterns: a major spring-recharge event, followed by a decline in the water table during the summer; a smaller recharge event during the fall; and, finally, a decline during the winter. Mean annual water-level fluctuations generally range within 1 to 4 m, (McIntosh, 1984; Francis, 1989; New Brunswick Department of Environment, 1992; Valsangkar and Gregory, 2001; and scattered data from other reports). Long-term records, however, show that minimum and maximum water levels can be separated by up to 10 m. As an example, Figure 42 shows water levels of the only Prince Edward Island monitoring well located in the study area. The five loggers installed in wells located at strategic locations in the Maritimes Basin (Harcourt, Shediac (2), and Petitcodiac, New Brunswick; Beecham Road, Nova Scotia; *see* 'Water-level measurements' section) allowed the study of natural water-level fluctuations. They have shown little annual variation, on the order of 1 m or less, suggesting they are all under (semi)confined conditions. The Petitcodiac and Harcourt wells now belong to the New Brunswick monitoring program. Over the years, these data will also permit the detection of trends. Appendix A presents the locations of these wells and the water-level fluctuations in them during the monitoring periods.

As previously mentioned, the potential impacts of climate change on groundwater recharge in eastern Canada were studied in a parallel project (Rivard et al., 2003). Due to the length of the data series, stream base flows were used, rather than groundwater hydrographs, to estimate the recharge and

calculate statistical trends. Indeed, a strong relationship was established between base-flow time-series and groundwater-level-fluctuation data from the nearest well. The results revealed that, despite the fact that total precipitation has increased for the past century, groundwater recharge seems to have decreased over the last 30 years. Nevertheless, further investigation is required to determine if this decline can be attributed to 1) change in precipitation patterns; 2) increase in evapotranspiration; and/or 3) anthropogenic activities, such as groundwater withdrawals. Future projections seem to imply that shallow wells, as well as small rivers, creeks, and wetlands, may be more at risk.

Hydrological budget

The hydrological budget of the MGWI study area, including results of groundwater recharge rates, as well as calculation of groundwater use and storage in the rock aquifer system, is presented in this section. This budget will help to provide a good general picture of the regional hydrological cycle.

Aquifer recharge

Groundwater recharge rates were calculated using streamflow-hydrograph separation and the water-balance method with a correction factor, as described earlier ('Groundwater recharge' section). Piezometric fluctuations recorded in monitoring wells could not be used because the wells were under (semi)confined conditions or because specific-yield values were not known for unconfined aquifers. Instead, they were used for the evaluation of the specific yield (S_y), using estimated recharge rates, as described in the 'Specific yields' section. Estimates of recharge rates based on modelling will be provided in the 'Conceptual and numerical hydrogeological models' section. Values found in various reports are described below, and compared afterwards with values estimated from existing data.

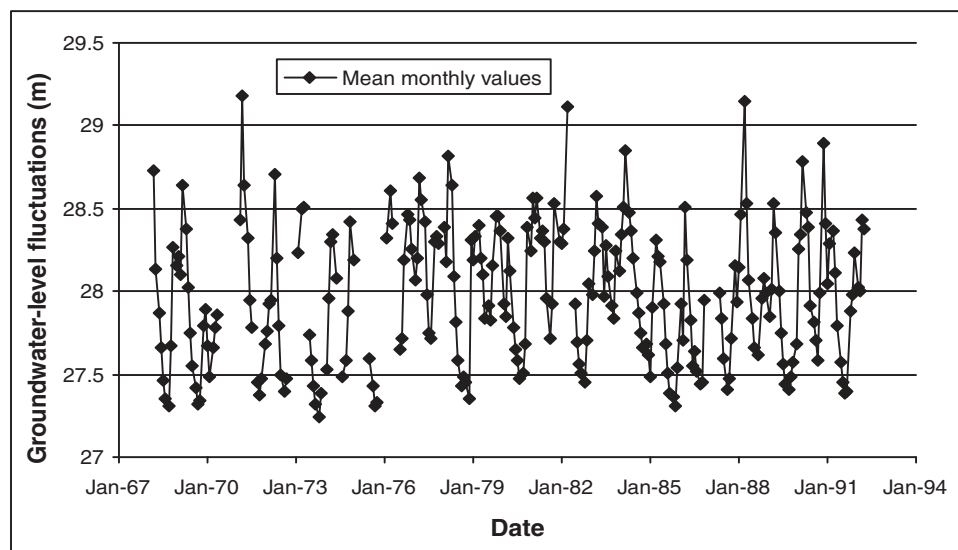


Figure 42. Monthly fluctuations of groundwater levels for the Kensington (Prince Edward Island) provincial monitoring well. Months with less than 25 days were excluded.

Aquifer recharge in the study area occurs mostly in locations where the till layer is sandy (as bedrock outcrops are sparse). Once the groundwater has infiltrated the till, it can either penetrate the fractured aquifer immediately if sandstone layers are in contact with the surficial sediments, or circulate laterally within the surficial layer at the top of 'mudstone' (siltstone, claystone, or shale) beds until it reaches a more permeable underlying layer. A fraction of the water can also infiltrate rock aquifers through fractures in the mudstone layers.

For New Brunswick, a broad range of groundwater-recharge rates has been suggested or reported, depending on the region. According to Peters (1981), the proportion of the total precipitation that infiltrates the Maritimes Basin varies from 1 to 50%, and as much as half of this infiltration is expected to occur during the spring period. In a report produced for the town of Sussex Corner focusing on the delineation of protection areas for the porous aquifer, the area had been assigned a recharge rate of 15% of precipitation in the model, even though the upper sand and gravel layer is very transmissive (Jacques Whitford Environment Ltd., 1995). In the Fredericton area, just west of the study area, the annual recharge rate of the granular aquifer was estimated to be 13% of precipitation (Gemtec Ltd. and FGA Ltd., 1994). Finally, Brown (1971) estimated the recharge rate near Shippagan (Taylor Island, in northern New Brunswick) to be 500 mm/a, based on specific yields and groundwater hydrographs. This value is surprisingly high, but the till in this area is generally very thin (0.5 m) or absent, and rocks are highly fractured and weathered in the uppermost part.

Despite the lack of precise information for Prince Edward Island, recharge is probably very significant because the till layer is generally thin (ranging from 0 to 8 m and averaging 4 m) and, for the most part, very sandy. Francis (1989) estimated, using hydrograph separation, that the recharge rate of the central portion of the island should be between 21 and 43% of annual precipitation. Jacques Whitford and Associates Ltd. (1990b) suggested 30% as a mean value for the entire island.

In Nova Scotia, hydrograph separation for the Kelley River (located 26 km southwest of Springhill) for the years 1971 to 1978 has shown that the recharge rate may vary between 14 and 34% of total precipitation, and average 21% (Vaughan and Somers, 1980). The authors of the study suggested that, as a great proportion of Cumberland County (the central part of the study area in Nova Scotia) is underlain by sedimentary rock similar to that found in the Kelley River basin, these ratios should be representative of a large region. Because the till layer of New Brunswick and Nova Scotia averages 8 m in thickness and is less sandy than in Prince Edward Island, it is normal to record lower recharge rates in these provinces.

Using existing data (*see* 'Existing data' section), hydrograph separation provided values varying from 92 to 436 mm/a, and averaging 353 mm/a for New Brunswick and 335 mm/a for Prince Edward Island (*see* Table 8). Watersheds

in New Brunswick for which data were available, however, were located only in the most permeable formations (Richibucto Formation, undivided Pictou Group, and Boss Point Formation). Nova Scotia was not part of the Rivard et al. (2003) study, so no base flow results were available. The water-balance method provided mean values ranging from 33 to 310 mm/a, depending on the geological formation, with minimum, mean, and maximum weighted averages over the study area of 114, 184, and 251 mm/a, respectively (*see* Table 9). Values of 122 to 403 mm/a were obtained for the most permeable formations (considering minimum and maximum values), with means ranging between 192 and 310 mm/a, which is in agreement with the hydrograph-separation method. Values from these two approaches can be considered maximum plausible values, since both methods calculate the amount of potential infiltration (not only the quantity that reaches the bedrock). Neither of these two approaches explicitly considers hydrogeological conditions. To compensate for this shortcoming, a correction factor was applied over the region, so as to rectify potential groundwater-recharge values obtained from the water-balance method. Indeed, no infiltration should be assigned where groundwater flow is upward. Hence, it can be assumed that recharge rates over individual formations are smaller than the values obtained from the water-balance and stream-hydrograph methods. Based on the water-level survey, the piezometric map and DEM, and an estimation of areas with upward gradients, the correction factor was estimated to range between 11 and 29% (except for Prince Edward Island, where 5% was used). Therefore, an average of 130 to 165 mm/a is considered a plausible representative value for the groundwater recharge over the entire study area (*see* 'Water-balance method' section for more details). In general, average values seem to be in fairly good agreement with reported values. These values are summarized in the 'Conceptual and numerical hydrogeological models' section.

Groundwater use and specific capacity

A review of the available information on well yields allowed the development of a general picture of the potential groundwater use from fractured aquifers. Figure 43 presents the spatial distribution of reported yields. In reports and databases, the data generally correspond to estimates based on short development tests following well completion. These data thus represent only a potential use over an undetermined period during the day. They usually do not correspond to the maximum acceptable well yield, nor are they representative of the actual use. In addition, as these data correspond, in many cases, to residential wells, they do not necessarily reflect the aquifer productivity (the aquifer could probably provide much more water). This is very evident in areas where no important municipalities or industries are present. As a result, Figure 43 provides only an indication of the actual use of aquifers, which may not always reflect the full potential of the aquifers in all locations.

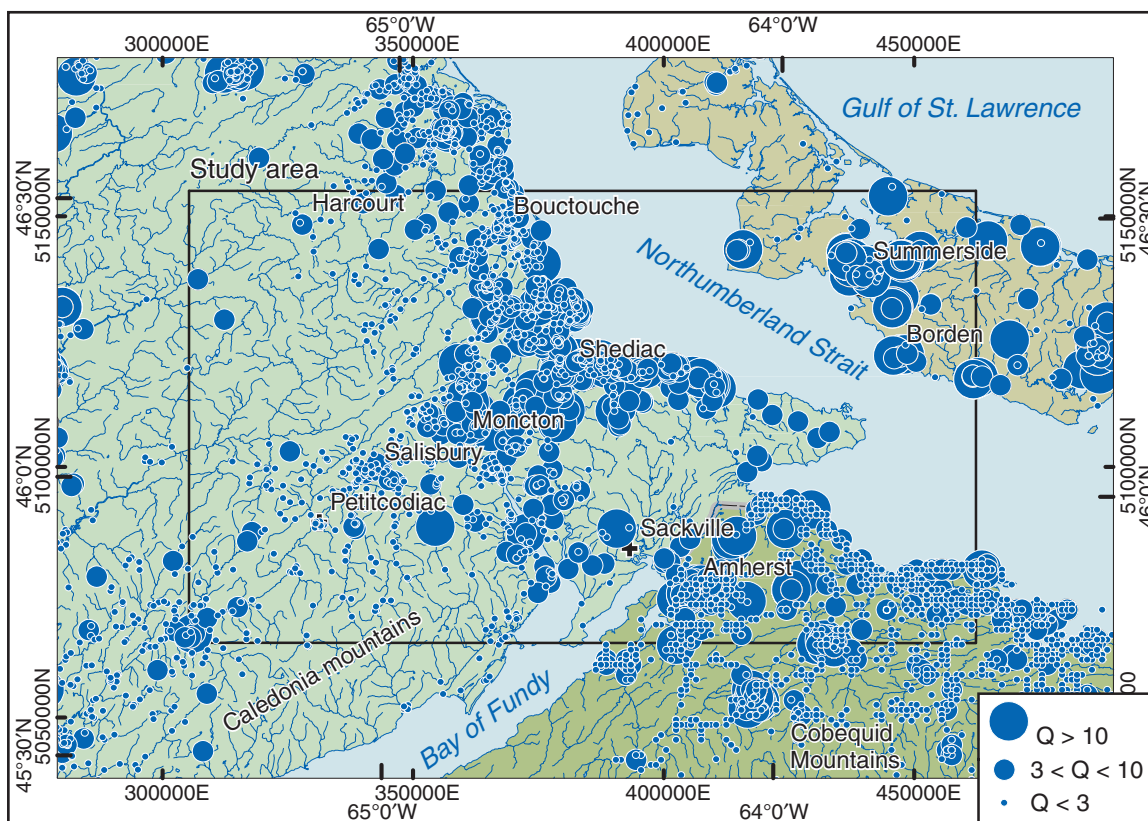


Figure 43. Regional picture of potential groundwater use based on well yields, Maritimes Groundwater Initiative study area. Abbreviation: Q, reported yield (L/s; from provincial database).

Yields have been divided into three categories: 6811 locations had flow rates less than 3 L/s (likely corresponding to residential wells), 976 had flow rates between 3 and 10 L/s, and 344 had flow rates greater than 10 L/s. Not all wells in the databases had an associated flow-rate. For instance, Prince Edward Island has approximately 20 000 to 25 000 residential wells, but only 470 flow rate values were available. Even though the municipality and industry yields are likely not all listed, Figure 43 shows that parts of the study area have a very good hydraulic potential. This yield distribution seems to be mostly in agreement with the map prepared by the New Brunswick Department of Environment and Local Government (2000), which shows three different zones according to estimated probable yields. Their high-capacity well zone is found all along the coastline, except for the extreme eastern point, including Port Elgin and Cape Tormentine.

To date, no problems have been reported regarding overexploitation of the resource in the study area. Nevertheless, some local usage conflicts have occurred between well owners. A study of groundwater use by sectors was conducted in New Brunswick by the New Brunswick Department of Environment (Johnson, 2002). In the municipal sector, groundwater supplies only 33% of the New Brunswick population; however, it represents 70% of the total water used. The distribution for domestic, industrial, commercial, agricultural, and aquacultural uses is shown in Figure 44. These percentages were determined for the entire

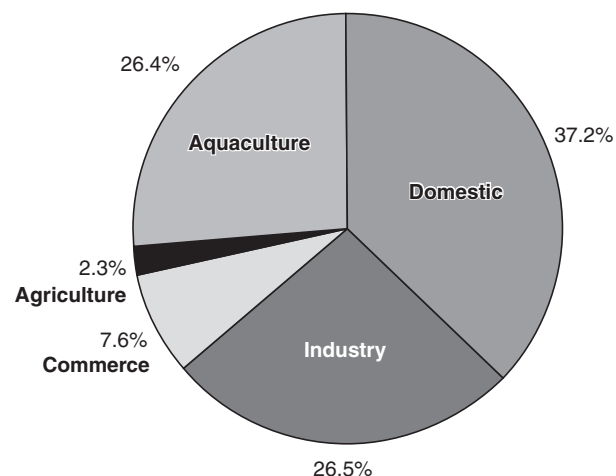


Figure 44. Distribution of water use in New Brunswick (data from Johnson, 2002).

Table 14. Total water use and groundwater use by sector in New Brunswick (*based on Johnson, 2002*).

Sector	Based on	Water use in New Brunswick		Approximate groundwater use for the MGWI study area (m ³ /d)
		(m ³ /d)	(%)	
Domestic	76 municipalities	340 000	37.2	51 000
Industry	Based on effluent flows (241 000 m ³ /d and 7 bottled water facilities (700 m ³ /d)	241 700	26.5	36 255
Commerce	25 municipalities	70 000	7.6	10 500
Agriculture	Major agricultural water users (irrigation, livestock, and cranberries)	21 000	2.3	3 150
Aquaculture	18 sites	241 000	26.4	36 150
Total :		913 700		137 055

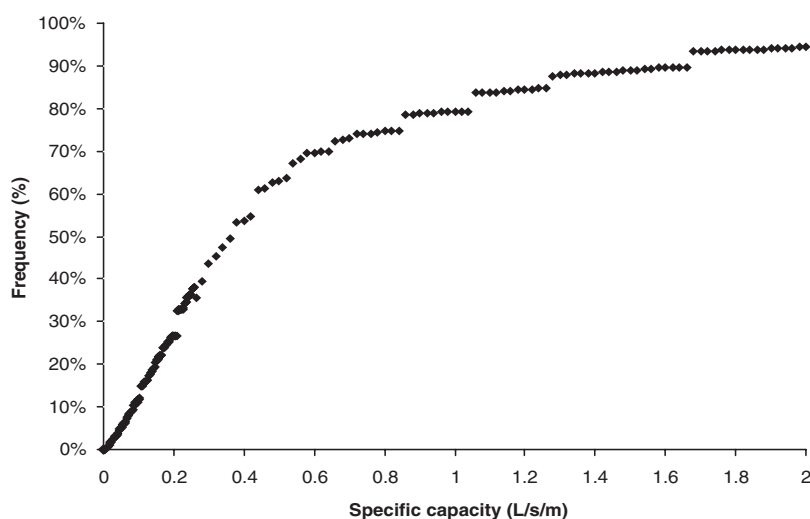


Figure 45. Cumulative distribution of specific capacity for major hydrostratigraphic units.

province, but they should also be representative of the MGWI study area. If the population of the study area is considered to be roughly 25% of New Brunswick's total population (based on a 1999 municipal-population survey) and if an average of 60% of the total water use is estimated to come from aquifers, then the distribution of groundwater use can be approximated as shown in Table 14. Annual withdrawal would thus be on the order of $50 \times 10^6 \text{ m}^3$ (137 000 m³/d), corresponding to 6.4 mm/a (the surface area being 7866 km²; see Appendix D). Recharge for the New Brunswick portion of the study area is estimated to be at least $2.43 \times 10^6 \text{ m}^3/\text{d}$, based on recharge rates in Table D-1 (Appendix D). Therefore, groundwater use would represent only a very small part of the total aquifer recharge (<5.6%). These numbers, however, are only global estimates, representative at the regional scale. For exploitation purposes, local studies need to be conducted. Furthermore, the representativeness of the percentages used (for population, sector distribution in the MGWI study area, and groundwater use) should be further investigated before a reliable withdrawal/recharge ratio is determined.

For an indication of the hydraulic capacity of the various geological formations, cumulative frequency graphs of the specific capacity values (Q/s , where Q is the pumping rate and s is the total drawdown) were also plotted. The graph,

including major hydrostratigraphic units (all formations of the Prince Edward Island Group, the Richibucto Formation, the undivided Pictou Group, the undivided Cumberland Group, the Boss Point Formation, and the Hillsborough Formation), is illustrated in Figure 45. Graphs for individual formations or groups are presented in Appendix E. Cumulative curves for the six hydrostratigraphic units are presented on a single graph in Rivard et al. (2005a) for comparison. Very few data are available for Nova Scotia, as the water-well database does not contain this information. Also, no data are available for the Balfron Formation. Again, as these graphs were obtained mostly with domestic wells, they do not provide an accurate picture of the aquifer potential, which is likely underestimated. Hence, Figure 45 is probably very conservative. Nevertheless, taken together, the data provide valuable general information on the aquifer capacity of the Maritimes Basin. Specific-capacity values for all aquifer units range from nearly zero to 20 L/s/m for high-capacity wells. However, as 94% of all wells have values smaller than 1.9 L/s/m, the graph of Figure 45 was stopped at 2 L/s/m. Only 1.4 and 0.5% of the wells have specific capacity values greater than 5 L/s/m and 10 L/s/m, respectively. Half of the wells were estimated to have specific capacities less than 0.35 L/s/m.

Groundwater storage within the bedrock aquifers

For the upper 100 m of fractured rocks, the groundwater storage was calculated based on total porosities and the mean percentage of coarse-grained rocks within hydrostratigraphic units. As mentioned above, the water is essentially stored in the rock matrix; porosity of fractures can therefore be neglected. It was considered that only sandstone and conglomerate allow water to be stored in appreciable quantity and be retrievable. The other rock units (shale, siltstone, etc.) do contain a non-negligible quantity of water, but that cannot be easily extracted due to the presence of fine-grained particles and their low permeability. To estimate the total amount of water available in the study area, 1) a mean percentage of sandstone and conglomerate has been estimated for each geological formation or group; and 2) minimum and maximum porosity values of 5 and 10%, respectively, have been assigned, based on average porosities found using thin sections and from the literature (*see* 'Water and soil analysis, and rock-matrix porosity' section). Using these assumptions, the quantity of water within the first 100 m of the fractured aquifers was found to be between 29 and 58 km³ (corresponding to 3.7 and 7.4 m over the study area).

These values correspond only to rough estimates of the groundwater quantity circulating within the study area. They are based on many assumptions and therefore have a high uncertainty attached to them. In addition, it must be said that all this water cannot be exploited and that only a certain percentage of the recharge should be extracted. For example, if 30% of the recharge was to be considered as a maximum usable quantity, the acceptable 'regional' withdrawal should not exceed 0.57 km³/a or 1.56 x 10⁶ m³/d for the entire study

area (using an estimated recharge ranging from 130 to 165 mm/a or, in terms of volume, 1.5–1.9 km³/a). However, on a local basis, this value could vary greatly.

Hydrological budget summary

Using the average values estimated for groundwater storage, recharge, runoff, evapotranspiration, and groundwater use, a regional hydrological budget was established for the entire MGWI study area. For withdrawal quantity, the groundwater use in New Brunswick was considered representative of the usage in the other two provinces since no other data were available. All mean values are given in millimetres/year and millimetres in Figure 46, and as percentages in Figure 47.

Comparison with another hydrogeological study in Quebec can be made for the upper 100 m layer of sedimentary fractured rocks. That study (Nastev et al., 2006a, b), focusing on a smaller study area (1500 km²) north of Montréal, found a recharge rate of 55 mm/a, a groundwater storage of 6 km³ (4 m), and a withdrawal of 1.8 x 10⁷ m³/a (12 mm/a). The rock-matrix porosity in that study was, however, very low and a thick layer of clay covers a large part of the study area. The Maritimes Basin seems privileged in regard to its annual aquifer recharge and, on a regional basis at least, exploitation of this water resource is small.

Indication of aquifer vulnerability to surface contamination

Regional characterization allows a preliminary assessment of groundwater vulnerability. Despite not having all the necessary information to strictly apply a method such as DRASTIC, the main parameters controlling vulnerability can be used to draw an approximate picture of the hydrogeological

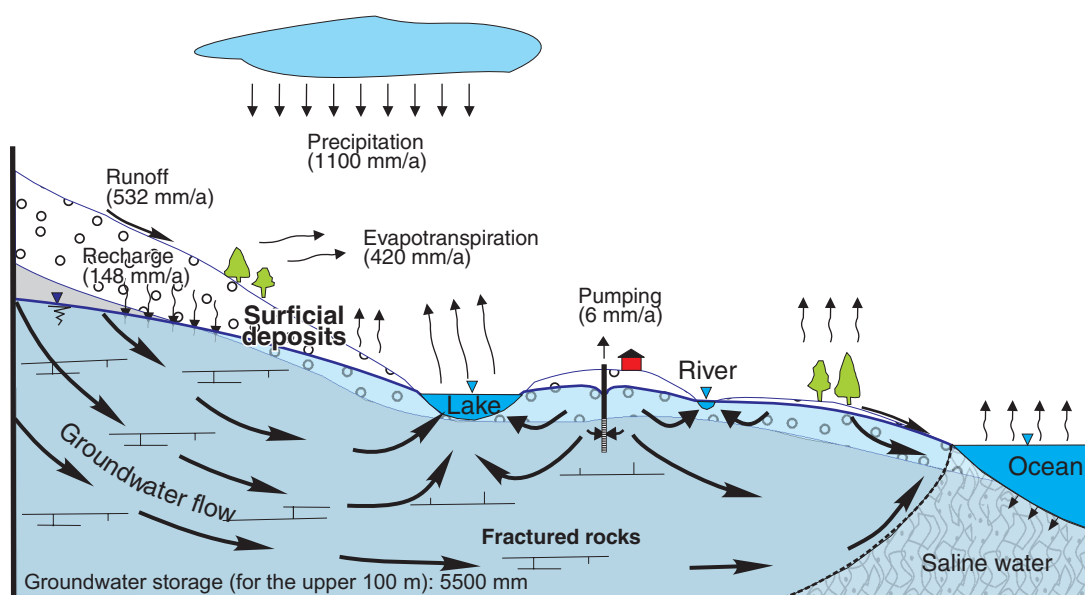


Figure 46. Schematic annual hydrological budget for the Maritimes Basin.

system’s vulnerability to surface contamination. DRASTIC uses the following parameters for its calculation: D for depth to the groundwater table, R for groundwater recharge, A for aquifer media, S for soil media, T for topography (slopes), I for impact of the vadose zone, and C for hydraulic conductivity of the aquifer.

In this project, depth to the water table is relatively well known in many areas, thus allowing preparation of the piezometric map (*see* Fig. 41; Rivard et al., 2005a, Plate 5-5).

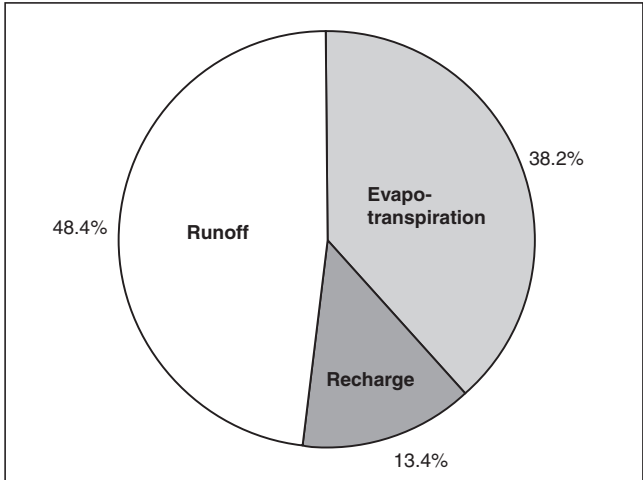


Figure 47. Hydrological budget for the Maritimes Basin, illustrated using percentages. Precipitation averages 1100 mm/a.

Even though depth of the groundwater table varies from 0 to 50 m, it is generally between 0 and 12 m (75th percentile) and averages nearly 7 m. With an uncertainty of ± 5 m in the DEM elevations at the regional scale, this parameter would not significantly affect the evaluation of the relative vulnerability. Furthermore, till thickness is almost everywhere less than 20 m and generally (75th percentile) less than 10 m, and the study area is relatively flat. Therefore, key properties related to vulnerability for the study area are the aquifer recharge rates and the hydraulic conductivity of the till layer, since it is directly related to the bedrock composition. Three categories were used for the till layer, as determined from fieldwork (*see* ‘Permeameter and infiltrometer tests in glacial till’ section), and two categories for recharge rates, based on results presented in Table D-1 (good if $R > 60$ mm/a, poor if $R < 60$ mm/a). These were combined to generate three levels of aquifer vulnerability: low, moderate, and high. Because the till-layer texture is strongly correlated with the underlying rock types, the resulting map (Fig. 48) is similar to a bedrock permeability map and also reflects the aquifer potential of the various units (more permeable formations are also more vulnerable to surface contamination). These results indicate that the most vulnerable formations are the Boss Point Formation and those of the Prince Edward Island Group, due to their sandy till cover that favours recharge. Only the Salisbury Formation and pre-Carboniferous rocks (basement complex) are classified as having low vulnerability. This simplified vulnerability assessment allows a representative delineation of the general areas that are the most vulnerable to contamination. Nevertheless, it must be emphasized that the classes

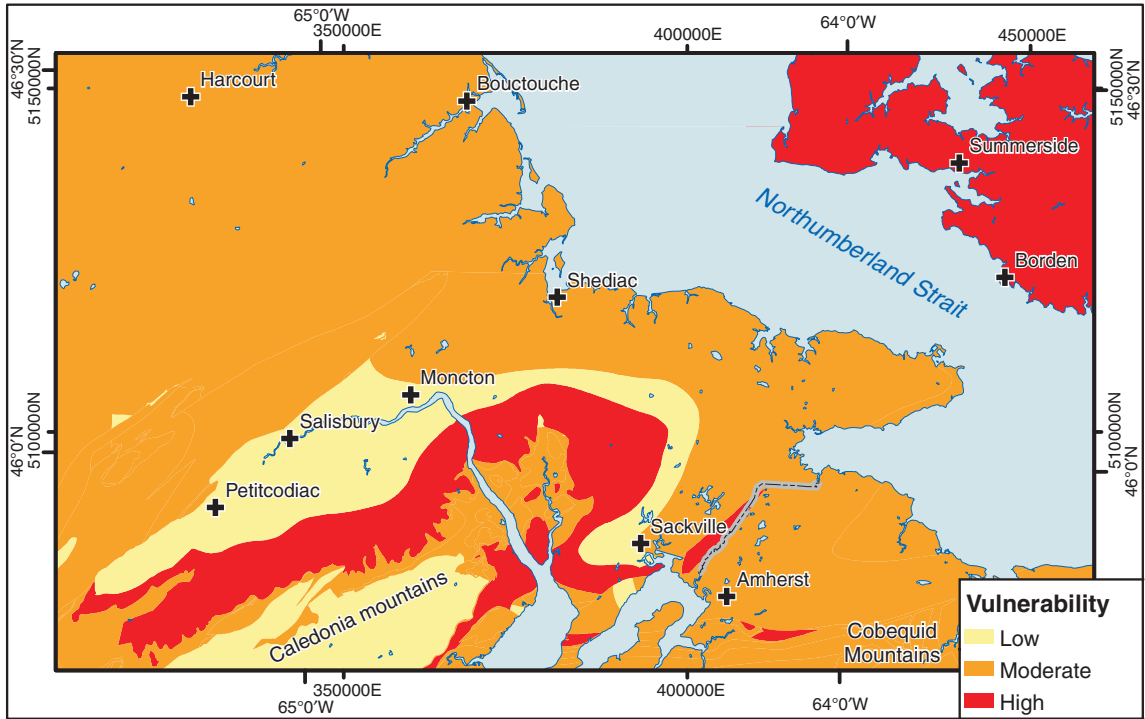


Figure 48. Aquifer-vulnerability map, Maritimes Groundwater Initiative study area.

used here are relative, and that the sandy till probably protects the underlying formations better than a sand cover alone would have done.

GEOCHEMISTRY

A regional hydrogeological study that aims to characterize the groundwater resource so as to support its protection and management cannot overlook groundwater quality. Aquifers with excellent supply potential but yielding poor-quality water are severely limited in use. Regional and detailed groundwater multiparameter geochemical surveys can be of considerable help to health and environmental officials in planning various types of land-use and regulatory studies (Boyle, 1991). Indeed, groundwater scientists and officials from all levels of government responsible for urban and rural development and health care must work closely in order to avoid activities that have costly and detrimental effects on the water resource. Furthermore, a detailed geochemistry study, including the identification of geological, hydrogeological, geochemical, or anthropogenic factors responsible for the chemical composition of groundwater, can greatly contribute to the understanding of hydrogeological system dynamics, as well as shed light on specific or potential problems (deterioration) of this resource. This section, which presents a general picture of the hydrogeochemistry of the study area, can be considered a first step in this direction.

Hydrogeochemical data for the study area come from two main sources: the New Brunswick Department of Environment and Local Government and the Prince Edward Island Department of Environment, Energy, and Forestry. In New Brunswick, data were obtained from the provincial well database, regional health districts, school boards, and municipalities. For Prince Edward Island, data were taken from the provincial well database. The geochemical database also includes samples collected during the 2001 and 2002 GSC fieldwork seasons. Data are mostly related to domestic wells, but municipal and industrial wells are also included. New Brunswick data contain analytical results dating from 1994 to the present, while Prince Edward Island data cover mainly the period from 1998 to 2002; however, results from five high-capacity wells are older (1986–1994). Within the study area, 1549 samples were available for New Brunswick and 353 samples for Prince Edward Island. Seventeen samples were added from the GSC fieldwork. No organic substances or bacteriological analyses were available for this study. Groundwater-quality data from Nova Scotia were not available. The following sections describe the general characteristics of the Maritimes Basin groundwater, and include both specific quality issues and an assessment of the spatial distribution of various chemical ions and parameters.

Overview of groundwater quality

The groundwater quality of the Maritimes Basin is generally excellent and, in almost all cases where it is exploited for water-supply purposes, meets the Canadian Guidelines for Drinking Water Quality (Health Canada, 2003). The major-ion characteristics of these waters can be attributed to dissolution of the dolomitic cement binding the sandstone that dominates the stratigraphy (Peters, 1981). The lowland sedimentary sandstone and interbedded aquifers of the Pictou, Cumberland, and Riversdale-Mabou groups exhibit similar water-quality characteristics (Vaughan and Somers, 1980). This groundwater is mineralized, with total dissolved solids (TDS) usually ranging between 100 and 300 mg/L and hardness generally between 50 and 150 mg/L. Water with this composition can be considered moderately hard. The most important dissolved ions in these units are calcium, carbonate, bicarbonate, and, to a lesser extent, sodium and chloride. The pH is slightly alkaline (usually ranging between 7 and 9).

A graphic representation of the overall chemical composition of groundwater of both New Brunswick and Prince Edward Island is presented in Figure 49 as Piper diagrams, showing the relative concentrations of major ions. A separate diagram was used for each province so as to characterize its general type of groundwater based on the major-ion chemistry. For a given well with multiple samples, only the most recent data were used. All values, without consideration of their location within the province, were utilized. In Prince Edward Island, the alkalinity (or, equivalently, HCO_3^-) was available only for the 17 high-capacity wells; therefore, bicarbonate ions (HCO_3^-) for residential wells were approximated assuming a perfect cation-anion balance. This assumption should not lead to a high percentage of error. Indeed, a verification made using data from the 17 high-capacity wells and 1532 samples from New Brunswick showed that, on average, the error is only 5 to 7%. Both diagrams show that groundwater in New Brunswick and Prince Edward Island is mainly of the calcium-bicarbonate type, but that the sodium-chloride type may also be encountered, especially in New Brunswick.

Conohan (2002) made two different plots for inland and coastal communities, and found that water samples from coastal areas were dominated by high chloride and sodium values, whereas samples from inland locations were dominated by higher carbonate (CO_3), calcium, and magnesium values. This difference could reflect the influence of seawater on groundwater systems near the coast through saltwater intrusion within the aquifers or the effect of groundwater geochemical changes during the course of its flow from recharge to discharge areas.

The occurrence of evaporite deposits in the Windsor Group often results in excessive amounts of sulphate, hardness, and total dissolved solids (Vaughan and Somers, 1980). Windsor Group evaporites may also influence the water quality of underlying and overlying units. For instance, surficial sand and gravel aquifers located west of the town of Oxford,

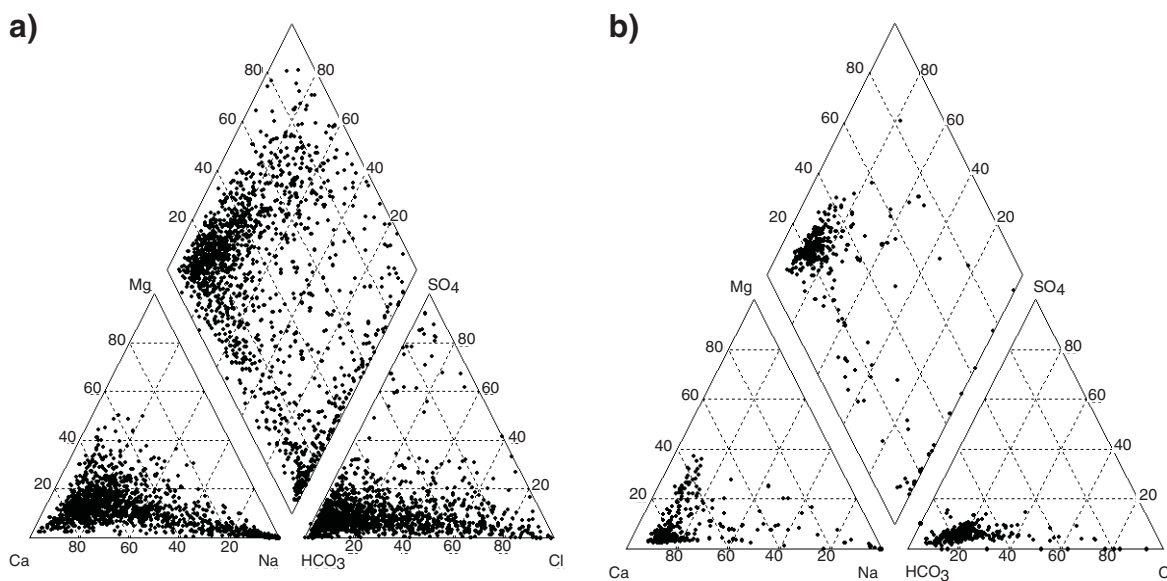


Figure 49. Piper diagrams showing the composition of groundwater, based on major-ion chemistry, for **a)** New Brunswick, and **b)** Prince Edward Island.

Nova Scotia, are saturated with chloride salts (>1000 mg/L). According to Vaughan and Somers (1980), there is a possibility that salts may influence the water quality of aquifers now in use in the towns of Amherst and Oxford, Nova Scotia if the resource is not properly managed. In some areas, however, wells in Windsor Group sedimentary rocks are known to yield groundwater of acceptable quality. Salty water in wells tapping the Boss Point Formation was also reported near Moncton, New Brunswick (Carr, 1964). In Nova Scotia, sediment and associated high turbidity are commonly reported by local residents as their most pressing water-quality problem (Vaughan and Somers, 1980). Most sediment problems occur in areas dominated by shale bedrock. Groundwater in contact with shale can also contain a wide range of dissolved salts.

The thickness of the calcium-(bi)carbonate facies is typically on the order of 100 m, although this thickness increases toward the centre of the Maritimes Basin. At depth, sodium-chloride-type water is ubiquitous. The thickness of the sodium-bicarbonate facies is reported to range generally between 0 and 300 m. This water type is considered a transitional facies between the calcium-(bi)carbonate and sodium-chloride types (Peters, 1981). The change of facies from sodium-bicarbonate water to sodium-chloride water occurs at a chloride value of approximately 1000 mg/L.

Groundwater-quality issues

There have been environmental concerns raised during the past few years regarding groundwater quality in the Maritimes. Groundwater in various parts of the Maritimes Basin can contain high concentrations of As, Ba, F, Rn, U, Fe, Mn, Na, and SO_4 (Boyle, 1991). Areas characterized by one or a number of these anomalous elements can be of

considerable concern to health officials and groundwater-resource managers. Apart from the natural occurrences of these parameters, concerns are mostly related to pollution due to agricultural practices, leaks from petroleum-storage tanks, sewage and waste disposal, seawater intrusion, and road de-icing activities. The only case of groundwater contamination of municipal wells by human activities (perchloroethylene) reported close to the study area is in Sussex Corner (unofficial name), New Brunswick (Jacques Whitford Environment Ltd., 1995), where wells tapped a sand and gravel aquifer in the valley. Populated areas (mostly located along coastlines and rivers) are, of course, more at risk. For instance, many municipalities located along the coastline see their population significantly increase during the summer due to tourism-related activities. Therefore, salt-water intrusion also represents a potential problem. The 'Sea-water intrusion' section is devoted to this specific subject.

In Prince Edward Island, problems related to agriculture are of great concern, especially for nitrates and pesticides, as nearly half of the land base in the province is devoted to agriculture, with row-crop production accounting for the largest portion of this activity. One of the main crops is potatoes. The Aldicarb pesticide (insecticide) is vigilantly observed, as it was commonly applied to potato crops since 1978. Aldicarb is highly toxic, mobile (high water solubility), and persistent in the environment. Analysis of groundwater samples from 103 domestic wells in 1983–1984 showed that only 20 wells contained Aldicarb traces, with concentrations below the drinking-water limit (maximum concentration detected being 5.4 ppb and the majority of the measured values falling between 1.3 and 2.2 ppb; Mutch et al., 1992). Atrazine, Chlorothalonil, and Mancozeb were also investigated. Of the 74 samples, only 13 recorded the presence of pesticide residue. All values were well below the Canadian Drinking

Water Quality Guidelines (Mutch et al., 1992). Samples containing both nitrates and detectable pesticides had a nitrate concentration higher than the overall average.

In a recent document (Young et al., 2002), authorities in Prince Edward Island indicated that evidence suggests that nitrate levels in groundwater are increasing in many areas. The situation on the island is quite alarming, since 4.5% of the wells across the province show nitrate concentrations above the drinking-water limit (10 mg/L), indicating that a non-negligible groundwater-quality degradation is underway. Within individual watersheds, nitrate levels and the number of contaminated wells can vary significantly. For instance, the part of the island included in the MGWI study area is one of the most problematic, with 78% of the tested wells exceeding 2 mg/L, the level at which groundwater quality can be conservatively considered altered by anthropogenic activities. Almost half (45%) of the tested wells had nitrate concentrations higher than 5 mg/L, and 8.6% exceeded the 10 mg/L criterion for drinking water. This is likely due to the intensive agricultural activity, combined with the sandy till layer that covers the very transmissive rock units of the Prince Edward Island Group and cannot effectively protect the groundwater from pesticides and nitrate pollution. Young et al. (2002) highlighted the fact that, while potato production has been stabilizing (and even showing a slight decline) since 1996, nitrate concentrations are still progressively increasing, suggesting a considerable time lag between modifications of land use and associated changes in groundwater quality.

Regional picture of various chemical ions and parameters

Several ions and parameters (pH, turbidity, hardness, and TDS) are regularly analyzed in private and municipal/industrial wells in New Brunswick and Prince Edward Island 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, 2003): 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 criterion (AC), when the limit is not related to health problems but to unpleasantness or technical nuisance.

The geochemical database contains inorganic water-quality analyses, including major cations and anions, trace metals, and other parameters, such as hardness, turbidity, and pH. Spatial distributions of these ions and parameters were drawn, and maps of most interest are presented in Rivard et al. (2005a), mostly for problematic substances 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 criterion, 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 substance, and percentage of samples above this limit, were calculated and added to the maps to provide a better representation of the groundwater quality. Statistics were first calculated individually for each province, but have been aggregated in Rivard et al. (2005a). Specific parameters that were chosen include chloride (Cl), fluoride (F), iron (Fe), manganese (Mn), sodium (Na), sulphate (SO₄), nitrate (NO₃), arsenic (As), barium (Ba), lead (Pb), hardness, pH, and total dissolved solids (TDS).

It must be emphasized that water-quality analyses in private wells can be biased in two ways: 1) groundwater samples are often taken only when owners suspect a problem (if the analyses are not obligatory), and 2) wells with poor water quality have sometimes been abandoned and are therefore probably not part of this database. Nevertheless, it is believed that these numerous sample analyses provide a representative picture of the groundwater within these Carboniferous and younger rocks.

Major and minor ions

Five ions (chlorides, fluorides, iron, manganese, and sodium), were particularly examined due to their potential occurrence in the study area (as in the case of sodium and chloride, since a great part of the study area is surrounded by the ocean) or a widespread presence in relatively high concentrations. There is no evidence of adverse health effects specifically attributed to calcium, bromide (being only an indication for bromate), magnesium, phosphorus, or potassium in drinking water. Guidelines for these elements have therefore not been defined and, as such, they are not discussed here.

Chloride

High concentrations of chlorides originate only to a limited degree from natural settings (e.g. dissolution of evaporitic rocks, seawater intrusion); important sources of chloride are mainly sewage, effluents from chemical industries, de-icing salts, and induced seawater (from pumping). Ingestion of a great quantity of chlorides is not known to be very harmful; however, its presence is undesirable, since it gives a bad taste to water. The aesthetic criterion is thus limited to 250 mg/L. In New Brunswick, 3.1% of the samples exceeded this limit and, surprisingly, only 0.6% of the samples in Prince Edward Island exceeded it. Saltwater wells related to fish and seafood industries (Jacques Whitford and Associates Ltd., 1990b) have not been included in the statistics or maps from this study because they are not representative of groundwater-quality problems (as they have been deliberately drilled adjacent to the ocean). Plate 7-1 in Rivard et al. (2005a) shows that most values exceeding the advisory levels are located along the New Brunswick coastline and the Petitcodiac River.

Elevated concentrations can also be encountered, however, in the Windsor Group (containing evaporites) and, surprisingly, in the Horton Group on the Kingston Uplift.

Fluoride

At low concentrations, fluoride efficiently decreases dental cavities, whereas concentrations greater than 2.0 mg/L may lead to teeth staining. For this reason, the MAC was fixed at 1.5 mg/L. Of the 1538 samples available for New Brunswick, 6.2% showed a concentration higher than this criterion. No data were available for Prince Edward Island. High concentrations of fluorides occur mainly along the Petitcodiac River and in the Salisbury Formation. Scattered high concentrations can also be found in the Pictou and Horton groups.

Iron

Iron is one of the major elements of the earth's crust and especially of sandstone (as oxide, carbonate, sulphide, 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 found in groundwater. At concentrations greater than 0.3 mg/L, however, iron may stain laundry and give a red-brown colour and a bad taste to the water. Moreover, iron can stimulate (iron) bacteria in the piping, creating a viscous thin layer. The aesthetic objective is thus to maintain concentrations below 0.3 mg/L. This element is present in relatively high concentrations almost everywhere in New Brunswick and, to a lesser extent, Prince Edward Island. Of the 1536 wells in New Brunswick and 337 wells in Prince Edward Island, 31.6% and 7.4%, respectively, exceeded this criterion. It is normal to have a lower percentage for Prince Edward Island, since aquifers in this part of the study area are mostly unconfined and therefore have a higher oxygen content. Elevated concentrations do not seem to be associated with a specific formation or group.

Manganese

Manganese can be found in more than a hundred minerals, as well as in soil and rock salts (halite). Reducing conditions in aquifers favour the dissolution of this element, which explains why it is significantly more abundant in groundwater than in surface water. Its presence is generally associated with that of iron. 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 are formed in the piping. It is technically difficult to reduce concentrations below 0.05 mg/L; thus, this value corresponds to the aesthetic criterion. Of the 1530 samples from New Brunswick, 44.3% exceed the limit, whereas the percentage drops to 3.0% of the 336 samples from Prince Edward Island. As with iron, elevated manganese concentrations can be found almost

everywhere in the study area and do not seem to be associated with a specific formation or group; the less reducing environment of Prince Edward Island aquifers does not favour its presence.

Sodium

Sodium is not toxic at concentrations found in the environment. Nevertheless, 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 element, a concentration of 175 to 185 mg/L usually being considered unpleasant. The aesthetic criterion was set at 200 mg/L. In New Brunswick, 2.9% of the 1542 samples exceeded the limit; only 0.3% of the 348 samples from Prince Edward Island exceeded it. Very high concentrations of sodium are generally correlated with those of chlorides (NaCl); they are therefore encountered mainly along the New Brunswick coastline and the Petitcodiac River, and in the Windsor and Horton groups.

Sulphate

Sulphate ions can be found in a natural state in numerous minerals and are not very toxic. At concentrations higher than 1000 mg/L in drinkable water, they can have a laxative effect among adults (600 mg/L for children). The taste of their various salts can be detected at around 500 mg/L, so the aesthetic threshold has been fixed at this level. Sulphates exceeded this level in 0.9% of samples in New Brunswick, whereas none of the 348 samples from Prince Edward Island exceeded it. Elevated sulphate concentrations in coal-mining areas of south-central New Brunswick may result from the oxidation of pyrite that is associated with coal deposits (Conohan, 2002). 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 here. Elevated concentrations are exclusively found in the Windsor, Horton, and Mabou groups. High values from wells drilled within the Windsor Group could be associated with the dissolution of evaporitic rocks.

Trace metals

Metals such as arsenic, barium, and lead, which could lead to serious health problems even at very low concentrations, were considered in this study because some samples showed elevated concentrations. Other trace metals, such as aluminum, boron, cadmium, chromium, copper, selenium, uranium, and zinc, are also occasionally or regularly analyzed by the provinces. There is no recommendation or criterion for aluminum in drinking water because it has not been proven harmful to human health. Boron, cadmium, copper, and zinc have never exceeded the limits for drinking water in either province. Chromium exceeded the 0.05 mg/L criterion only once in New Brunswick, with a value of 0.057 mg/L. Most of

the time, only six samples were available from Prince Edward Island; only copper, lead, and zinc are regularly tested in private wells.

Arsenic

Arsenic is a metalloid that can reach groundwater in two ways: 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 IMAC was established to 25 µg/L. In New Brunswick, 1.4% of the 1526 samples exceeded this criterion; none of the six samples from Prince Edward Island did. Plate 7-8 in Rivard et al. (2005a) shows that the highest concentrations of arsenic are located in the Windsor Group, except for one value in the undivided Pictou Group. Several values exceeding the IMAC are also encountered in the Horton Group on the Kingston Uplift. Their occurrence does not seem to be correlated with the presence in large quantity of sulphates or other metals, such as lead or zinc. These other substances, however, sometimes have much higher advisory levels or have been less monitored. In addition, their solubility could be different, so no conclusion can be drawn regarding the presence of arsenic in the rocks of the Maritimes Basin.

Barium

Barium can be found in nature in certain minerals, such as barium sulphate and carbonate. The MAC has been fixed at 1.0 mg/L. Analyses have shown that Prince Edward Island and New Brunswick samples exceeded this limit in 0 and 1.8% (for 1532 samples), respectively, of the cases. Elevated concentrations are scattered throughout the study area and do not seem to be related to any particular formation or group.

Lead

The presence of lead in potable water generally originates from the dissolution of lead from natural sources or within piping. The MAC is set at 10 µg/L. Samples from New Brunswick and Prince Edward Island have exceeded the limit in 3.8% of 1531 and 1.8% of 332 samples, respectively. High concentrations of lead are mainly located in the Pictou Group (Richibucto Formation and undivided Pictou Group), the Salisbury Formation of the Cumberland Group, the formations of the Prince Edward Island Group, and, to a lesser extent, the Boss Point Formation of the Cumberland Group. Galena (lead sulphide), a very common metallic mineral that was found in limestone of the Windsor Group, could be considered one of the natural sources of lead in the Maritimes.

Selenium

A MAC of 0.01 mg/L for selenium in drinking water has been established on the basis of health considerations. Food is the main source of intake for individuals who are not occupationally exposed (Health Canada, 2003). Drinking water containing the maximum allowable concentration of selenium would represent 10 to 25% of total selenium intake; the MAC is thus considered to provide a reasonable factor of safety from adverse effects of selenium. Nineteen of the 1313 New Brunswick samples (1.4%) and none of the Prince Edward Island samples exceeded this MAC criterion. Elevated selenium values are strangely well correlated with those of chlorides and sodium ($R^2 = 0.74$ and 0.61); they are therefore mainly encountered along the New Brunswick coastline and the Petitcodiac River.

Uranium

The new guideline published in April 2002 provided a lower IMAC value of 20 µg/L (compared to the previous value of 0.1 mg/L). Of the 571 New Brunswick wells tested for this metal, 1.1% showed the presence of uranium, with the highest value being 36.9 µg/L. Two of the six samples from Prince Edward Island were quite close to this limit (15 and 16 µg/L). As very few wells have shown values exceeding the advisory level, no conclusion can be drawn regarding potential relations with the bedrock geology. Nevertheless, three of the six New Brunswick wells that showed the presence of uranium are located on the Kingston Uplift (Horton Group).

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. Nitrate corresponds to a stable phase within the nitrogen cycle. Because nitrites are usually found in very low concentrations under typical aquifer conditions, only nitrates are of general interest in this project. Sources of groundwater contamination come from organic-matter decomposition and domestic sewage water, but mostly from inorganic fertilizers and manure.

The *Canadian Drinking Water Quality* guideline for nitrates, expressed in milligrams per litre of nitrogen ($\text{NO}_3\text{-N}$), is 10 mg/L. Analysis of nitrates showed that only 1.0% of the 1558 samples from New Brunswick exceeded the guideline for drinking water, but 8.6% of the 347 samples from Prince Edward Island exceeded it. Percentages of tested wells exceeding a 2 mg/L concentration, however, would probably provide 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). In this case, the situation is cause for even more concern, with 11% of the tested wells in New Brunswick and 78% of those in Prince Edward Island exceeding this threshold concentration. The portion of Prince

Edward Island included in the study area is indeed intensively cultivated, and presents the highest concentrations on the island. In New Brunswick, high nitrate concentrations also correspond to agricultural areas.

Acidity (pH), hardness, and total dissolved solids

Acidity (pH)

Generally, a pH value between 6.5 and 8.5 is targeted for drinking water. Corrosion may become significant below 6.5, and the frequency of encrustation and scaling problems, as well as inefficiency of chlorine disinfection, can worsen above 8.5 (Health Canada, 2003). In New Brunswick, 2.7% of the 1538 samples had pH values lower than 6.5 and 13.7% had values higher than 8.5. These percentages decrease rapidly to 0.9% and 3.7% for values lower than 6 and higher than 9, respectively. No data related to this parameter were available for Prince Edward Island. Wells showing alkaline and (lightly) acidic waters are surprisingly often very close. Wells with water having a pH lower than 6.5 seem to be mainly located within the Pictou Group.

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 its adverse action with soap, hard water is unsatisfactory for domestic purposes. Water is classified as soft if the total hardness (H_t) is below 75 mg/L CaCO_3 , hard if it is between 150 and 300 mg/L, and very hard if it is greater than 300 mg/L (Todd, 1980). Water in excess of 500 mg/L CaCO_3 is considered unacceptable (Health Canada, 2003). In New Brunswick, water from 16.6%, 3.5% and 1.6% of the wells can be considered, respectively, hard ($H_t > 150$ mg/L), very hard ($H_t > 300$ mg/L) and unacceptable. For Prince Edward Island, hardness had to be calculated (using the approximation $2.5\text{Ca} + 4.1\text{Mg}$; Todd, 1980, p. 282); the results are 33.9% hard, 1.2% very hard, and 0.3% unacceptable. The few wells having unacceptable water due to hardness ($H_t > 500$ mg/L) can be found in almost all formations and groups; however, one-third of these wells are concentrated in the Horton Group.

Total dissolved solids

Total dissolved solids (TDS) include 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, 2003). The presence of dissolved solids in water can affect its taste; more than 500 mg/L is considered undesirable for drinking water. In New Brunswick,

5.3% of the 694 samples available exceeded this aesthetic criterion. This parameter was not available for Prince Edward Island samples. High values of TDS can be found in all formations and groups. Because of elevated concentrations of certain ions (among other things, sodium and chlorides) along the New Brunswick coastline and the Petitcodiac River, these areas show high TDS concentrations.

Summary

Table 15 summarizes the ions and parameters analyzed, the type of limit (criterion) and its value, and the number and proportion of samples exceeding the limit for drinking water from both provinces. This table shows that, in fact, a very low percentage of wells tested exceeds the limits, except in the case of nitrates for Prince Edward Island and iron and manganese, especially for New Brunswick.

Seawater intrusion

Variations in ocean tides and in the rate of recharge due to seasonal and long-term fluctuations enable seawater to penetrate aquifers along coastlines and in estuaries. Fresh groundwater beneath land discharges near the coast and mixes with saline groundwater beneath the sea floor (Fetter, 1980). Fresh groundwater grades into saline water in a zone called the interface or zone of diffusion. Pumping can cause saltwater intrusion by reduction of the potentiometric head in the aquifer, allowing inland movement of the saltwater wedge, or by inducing leakage from overlying or underlying aquifers affected by saltwater intrusion. The shape and position of the zone of diffusion is controlled primarily by the volume of fresh water discharging from the aquifer and, to a lesser extent, by the hydraulic conductivity of the aquifer. For instance, a multiple saltwater intrusion pattern may develop where separate wedges of brackish water invade each of the most permeable beds. This may occur where a coastal aquifer consists of different horizontal beds with widely differing hydraulic conductivities, as in the case of the Maritimes Basin.

Occurrence of saline intrusions in the Maritimes Basin

Saltwater intrusion problems due to pumping have been reported in some areas of New Brunswick, Nova Scotia, and Prince Edward Island, but do not seem to be of concern in most of the study area. Some detailed studies on saltwater intrusion were conducted in the Maritimes, especially in Prince Edward Island. For instance, interesting studies were done by Brown (1971) for New Brunswick and by Carr (1969), van der Kamp (1981), Jacques Whitford and Associates Ltd. (1990b), and Jacques Whitford Environment (1998) for Prince Edward Island. Brown (1971), Carr (1969) and van der Kamp (1981) studied specific areas, whereas Jacques Whitford and Associates Ltd. (1990b) and Jacques Whitford

Table 15. Summary of groundwater-sampling results in New Brunswick and Prince Edward Island.

Ion	Type of limit	Limit (mg/L)	Number of samples		Percentage of wells exceeding the limit	
			PEI	NB	PEI	NB
Aluminum	none	-	6	1530	-	-
Arsenic	IMAC	0.025	6	1526	0	1.4%
Barium	MAC	1	6	1532	0	1.8%
Boron	IMAC	5	6	1528	0	0
Bromides	none	-	6	1252	-	-
Cadmium	MAC	0.005	6	1529	0	0
Calcium	none	-	0	1542	-	-
Chlorides	AC	250	6	1553	0.6%	3.1%
Chromium	MAC	0.05	353	1510	0	0.1%
Copper	AC	1	348	1526	0	0
Iron	AC	0.3	6	1536	7.4%	31.6%
Fluorides	MAC	1.5	337	1538	-	6.2%
Lead	MAC	0.01	337	1531	1.8%	3.8%
Magnesium	none	-	0	1542	-	-
Manganese	AC	0.05	332	1530	3.0%	44.3%
Nitrates (NO ₃ -N)	MAC	10	348	1558	8.6%	1.0%
Phosphorus	none	-	336	0	-	-
Potassium	none	-	344	1532	-	-
Selenium	MAC	0.01	331	1313	0	1.4%
Sodium	AC	200	348	1542	0.3%	2.9%
Sulphates	AC	500	6	1532	0	0.9%
Uranium	IMAC	0.02	348	571	0	1.1%
Zinc	AC	5	348	1528	0	0
Other parameters						
Hardness		500	337	1563	0.3%	1.6%
pH		6.5 to 8.5		1538	-	16.4%
TDS		500	345	694	-	5.3%

Environment Ltd. (1998) looked at the possibility of finding saline groundwater for the fishing industry throughout Prince Edward Island. The regional spatial and temporal variations of the location of the freshwater-saltwater interface have never been investigated.

The stratified nature of the bedrock of the Maritimes Basin, resulting in a succession of very distinct horizontal permeabilities, combined with confined and unconfined conditions and the fact that the water flows mainly through fractures, makes prediction of the location of the saltwater-freshwater interface very difficult (e.g. Carr, 1969; van der Kamp, 1981). Consequently, information on the saline water (or brine) distribution comes mainly from listed discrete occurrences, and the phenomenon is poorly known and understood. Generally, it seems that the influence of saltwater intrusion is observed only within a few tens to hundreds of metres from the coast, and there are many areas where fresh groundwater occurs immediately adjacent to the coast, especially in Prince Edward Island (Jacques Whitford and Associates Ltd., 1990b). Carr (1969), however, noted the presence of saline swamps and springs far inland (up to 350 m), indicating that the zone of diffusion can encroach a considerable distance into the aquifer at shallow depths, even if this area has no large withdrawals of groundwater. Brown (1971) and van der Kamp (1981) observed that the groundwater salinity generally rose sharply in the dry period and fell during the autumn, as abundant precipitation recharged the aquifer and flushed out the saline water.

The Prince Edward Island Department of Environment has received several requests from operators of mussel and lobster holdings for assistance in obtaining saltwater well supplies (Jacques Whitford and Associates Ltd., 1990b). Saline groundwater is preferred over seawater because of its almost constant temperature and bacteria-free character. Attempts have been made to find saline groundwater, but many of them failed. Water from most existing coastal wells is, in fact, brackish or fresh rather than salty. Jacques Whitford and Associates Ltd. (1990b) identified hydrogeological factors conducive to development of high-yield saltwater wells, based on seven existing saltwater wells and five exploratory wells. Five criteria were found to be relevant for detecting potential zones for saltwater wells: surface elevation, distance from shore, seaward exposure, direction of structural dip, and freshwater hydraulic head. None of these criteria, however, was individually directly correlated to salinity; rather, an overall analysis attributing points to each criterion seemed to provide valuable information. Most of the saltwater wells were situated less than 5 m from the sea, where the land is less than 20 m in elevation and within a long and narrow point (land jutting into either the sea or saltwater estuaries). Because of the intrinsic heterogeneity of the Maritimes Basin, however, even wells constructed close to a saltwater well will not necessarily yield a water of similar chemical composition. Salinity can be improved by sealing off freshwater horizons with grouted casing, but this also results in a decrease in the overall yield.

Location of the freshwater-saltwater interface

The electrical-resistivity method was used to delineate saline intrusion at several locations in two regions: Shediac Bay, New Brunswick and Rustico Bay, Prince Edward Island. In the Shediac Bay area, six lines were run over an area covering approximately 20 km of coastline. The interpretation of these lines revealed that a relatively shallow saltwater-freshwater interface (less than 40 m deep) could only be found at short distances from the shoreline, generally less than 100 m (for more details, see the 'Electrical-resistivity soundings' section and Rivard et al., 2005b). Therefore, wells in this area are quite well protected against salt contamination. In addition, a 16.5 h pumping test performed in Parlee Beach, in a production well located 70 m from the high tide limit, showed that the salinity of the groundwater never increased.

Rustico Bay is probably representative of the many estuaries present on the island and was therefore selected for investigation. Results from the two survey lines indicated that, in one area, saline water could not be found at shallow depth, whereas, in the other area, located less than 400 m away, the interface was located 200 m inland. This is a good illustration of the great variability in conditions that can be encountered in the Maritimes Basin. Since the population is quite dense in the province, these findings, in agreement with Carr's (1969) conclusions (interface being located from 10 m to 1 km from the shore), suggest that salinity in groundwater might have been a problem for certain residents living along the coastline. The location and number of abandoned wells are, however, not known for Prince Edward Island.

Analytical methods, using two approximate equations for a homogeneous isotropic island (Todd, 1980, p. 507; Fetter, 1980, p. 143), confirm that salt water can be found close to the ocean only at considerable depths, even using very conservative parameter values (small recharge rates and high hydraulic conductivities). Based on these equations, the interface is approximately located more than 80 m below mean sea level (MSL) at only 200 m from the shoreline, and 120 m below MSL at 500 m inland. As previously mentioned, fractures, layering, and vertical anisotropy can greatly modify these depths.

Based on current knowledge, saline intrusions do not seem to threaten groundwater quality of coastal aquifers in the study area. Nevertheless, the situation could worsen if intensive pumping were to be carried out in the area, since pumping significantly modifies the flow pattern by reversing the hydraulic gradient, creating an encroachment of the zone of seawater. Therefore, before being able to draw conclusions and determine sustainable yields of fresh water (even during the dry season) in specific cases, studies must be performed at a local scale to take into account the characteristics inherent to each site, including heterogeneity (fractures and layering), location as a function of the shoreline configuration, and hydrogeological conditions (confined, semiconfined, or unconfined).

CASE STUDY: BEAUSÉJOUR PEATLAND NEAR SHEDIAC, NEW BRUNSWICK

The province of New Brunswick is Canada's first peat producer. Harvested peatlands are located mainly in the eastern part of the province, near the coast. Drainage of commercial peatlands is a prerequisite to harvesting peat. The impact of peatland drainage on groundwater resources, however, is not well documented. In eastern New Brunswick, some people living close to a harvested bog are worried about the impact of drainage on the groundwater availability in their wells. Thus, this case study was developed to improve the understanding of one aspect of groundwater-flow system dynamics in the Maritimes Basin, specifically groundwater interactions between an ombrotrophic peatland and the regional bedrock aquifers. The study first required the characterization of the peatland hydrogeology in local and regional contexts. Based on this characterization, a 2-D vertical numerical model was developed of the groundwater flow in the peatland in a regional hydrogeological context, allowing the evaluation of potential interactions between the two systems under various geological and climatic scenarios, so as to study the impact of peatland drainage (drawdown) on nearby wells.

The Beauséjour ombrotrophic peatland, selected for this study, is located 5 km southeast of Shediac, New Brunswick (Fig. 50). The peatland covers more than 4 km² and lies on the water divide between the Scoudouc River and the Aboujagane River watersheds. The mean elevation is about 32 m and the coastline is about 5 km away to the north. The peat started to accumulate in two depressions approximately 9040 ±130 years BP (*see* Carrier, 2003, sample UL-2469). Peat harvesting in this region began in 1991.

Understanding the groundwater interactions between the two systems required a good comprehension of the topographic, stratigraphic, and hydrogeological contexts. To accomplish this, work that included drilling, ground-penetrating radar and seismic studies, topographic levelling, soil and groundwater sampling, in situ permeability tests, a pumping test, piezometric measurements, and installation of water-level loggers in five piezometers was carried out during the 2001 and 2002 field seasons. The water-level loggers enabled the monitoring of piezometric fluctuations in each of the four stratigraphic units.

Hydrostratigraphic context

The stratigraphy of the peatland comprises 1) 3.2 m of peat, 2) 0.5 m of sandy silt, 3) 3.4 m of till with a fine matrix, and 4) highly fractured sandstone of the Richibucto Formation. Outside the peatland, the stratigraphy comprises only a till unit with a fine to sandy matrix overlying a sandstone or conglomerate unit. The till unit is characterized by a very compacted, fine sand to silty matrix and also by the presence of isolated, weathered sandstone cobbles. The hydrogeological

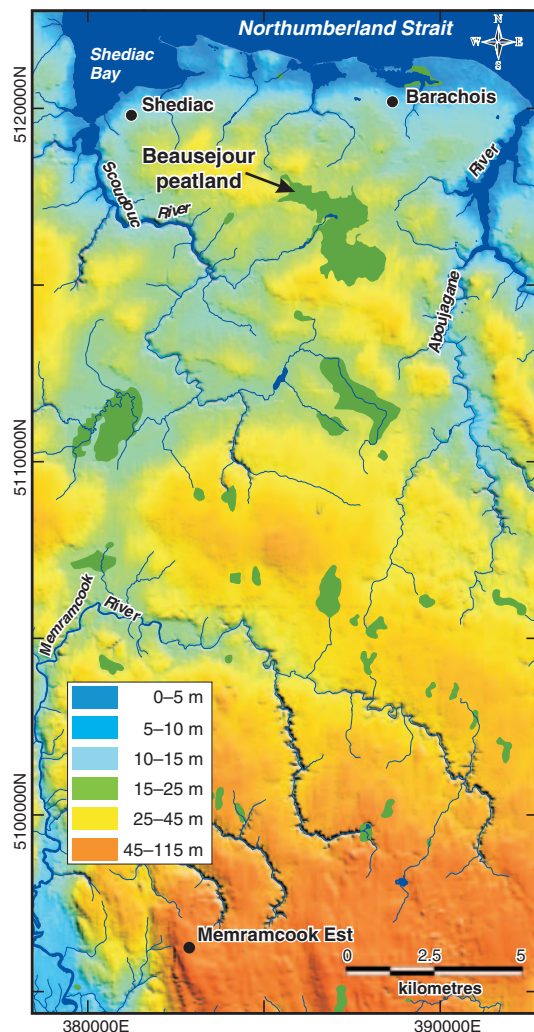


Figure 50. Beauséjour peatland and the surrounding region used for the case study.

properties of the units beneath the peatland were estimated using in situ permeability tests and a pumping test for the bedrock unit. The resulting hydraulic conductivity (K) values extend over four orders of magnitude (from top to bottom): 1.8×10^{-6} , 2.3×10^{-8} , 4.4×10^{-9} , and 5.3×10^{-5} m/s (see ‘Slug tests in the peatland and underlying units’ section).

The stratigraphy thus presents two relatively permeable units (the peat and bedrock) separated by an aquitard (the sandy silt and till units). Macrofossil and diatom analysis seemed to indicate that the underlying till has not been reworked by the sea or by marine eluviation, since all identified species were associated with freshwater environments (Bhiry, 2002).

Potential interaction between the peatland and the regional aquifer

Piezometry and geochemistry data were utilized to determine the potential hydraulic connection between the peatland and the regional bedrock aquifer. Piezometric maps showed that groundwater levels in the peatland are distinct from those of the bedrock aquifer in two major respects:

- 1) During the period of the case study, the water-table elevation in the peatland was maintained between 26.5 and 33.3 m, whereas the regional (bedrock) piezometric level was between 20 and 25 m.
- 2) In the peatland, the groundwater-flow pattern is radial and goes from peat domes toward their periphery. The water is discharged in a southwest direction through a brook, except in the drained part, where the flow is mainly circulating in a northeasterly direction. The general regional groundwater flow direction is however mainly toward the north (to the sea) and east-northeast (to the Aboujagane River).

On the other hand, fluctuations in piezometric level have been recorded for more than a year (August 2001–November 2002) in each stratigraphic unit. Many observations can be made regarding the profiles obtained from the peat and the bedrock. Fluctuations in the two units are generally similar: following precipitation, a rapid, synchronous rise is observed in both. This prompt reaction is illustrated by the sawtooth shape on the profiles, compared to the smoother profiles of the sandy silt and till units. Indeed, piezometric levels in the sandy silt and till units show an attenuated response (smaller amplitude) and a time lag. The lag of the water-level response in the sandy silt is 3 to 11 days compared to water levels in the peat. In the underlying till unit, the time lag can reach 2 months. Figure 51 shows the responses to precipitation for the various layers.

These results indicate that the rock units are clearly not strongly connected to the peat unit, and that the sandy silt and till units provide an effective barrier to limit groundwater exchanges. Indeed, the amount of groundwater that would potentially reach the bedrock vertically is significantly reduced and delayed by these less permeable units. The similarities in behaviour between the groundwater in the peat and in the sedimentary rocks could be explained by the presence of ‘windows’ in the till cover close to the peatland. The till layer could be thin or totally absent, or could have a coarser texture.

Samples of groundwater collected in the four stratigraphic units also enabled discrimination of the groundwater within the peatland from the regional groundwater. The pH field measurements showed a mean of 4.98 in the peat and 8.54 in the till, whereas the regional groundwater pH averages 7.67. In addition, specific conductivity measurements indicated that values in the till layer and in the peat are also quite different: 61 $\mu\text{S}/\text{cm}$ in the peat and 556 $\mu\text{S}/\text{cm}$ in the

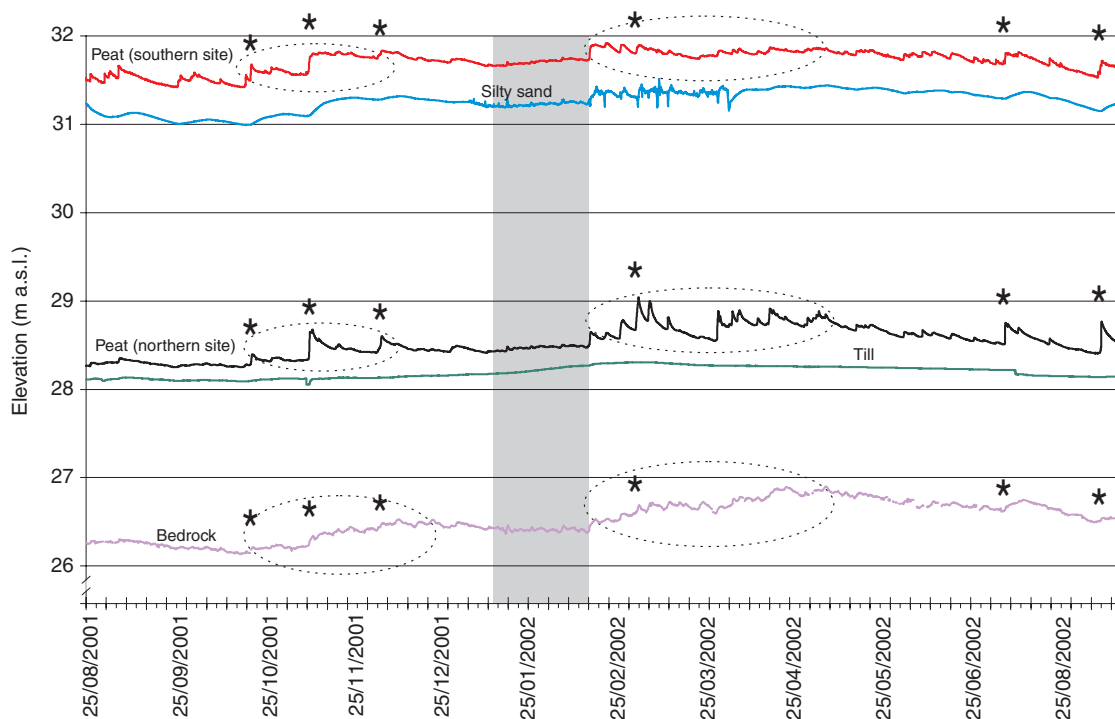


Figure 51. Responses to precipitation events in the various layers of the Beauséjour peatland; stars indicate the occurrence of rain events and the grey rectangle shows the probable period of the fall recharge in the till layer.

bedrock. Finally, chemical analyses showed very low ionic concentrations in the peat compared to the groundwater composition of regional bedrock aquifers.

Potential groundwater contribution of the peatland to the regional bedrock aquifer

Quantification of the potential recharge originating from the peatland was carried out using Darcy's law. The calculation is based on the measured groundwater levels from August 2001 to November 2002 and an equivalent hydraulic conductivity of 5×10^{-9} m/s (using the harmonic mean of the sandy silt and till units according to their respective thicknesses). The vertical flow obtained varies from 5 to 20 mm/a and has a mean of 12 mm/a. This recharge is very similar to that reported by Gemtec Ltd. (1991) in the Pigeon Hill peatland of northeastern New Brunswick (13 mm/a). This value only represents a potential recharge. In this case, it would correspond to about 1% of total precipitation and probably at most 10% of the bedrock aquifer recharge (values vary between 100 and 250 mm/a for the Richibucto Formation). In fact, the mass water content (w) measured in the till samples collected at various depths during the 2001 fieldwork indicated that w decreased significantly from the top to the base of this unit, being almost dry just above the bedrock ($w = 15\%$). Definitive conclusions cannot be drawn at this stage, but several pieces of evidence suggest that the groundwater contribution of the peatland to the bedrock is small, if not negligible.

Hydrological impact study using modelling

A 2-D numerical model was developed to study the interactions between the water stored in the peatland and the regional groundwater-flow system using various precipitation scenarios and, in particular, the possibility that water levels within the peatland were supported by the bedrock aquifer. To do so, two scenarios were compared: 1) using the model-calibrated parameters over 30 years; and 2) using the calibrated parameters over 20 years, then removing the recharge for the last 10 years. Hence, without precipitation, the only possibility for water gain or loss within the modelled peatland was through the underlying till layer. Results from numerical modelling using 14 virtual observation wells located within the peat and the bedrock aquifer showed that lowering of water levels in the peatland had little impact on water levels within the bedrock at 50, 100, and 1000 m outside the peatland. In addition, simulations indicated that lowering of water levels within the peatland could not be compensated by supplies from the regional aquifer. Therefore, conclusions from modelling agreed completely with fieldwork results: the hydraulic connection between the peatland and the regional aquifer is small to insignificant.

Summary of potential interactions

The existence of the peatland is attributed to the presence of the relatively impermeable till layer and to the morphology of the peatland bottom, and not to the discharge of regional

groundwater. Hence, the Beauséjour peatland likely represents an (almost) independent groundwater-flow system. Its contribution to the regional groundwater-flow system could be on the order of 0 to 1% of precipitation. This hypothesis is supported by several pieces of evidence, originating from the fieldwork performed and from the numerical modelling. Therefore, the impact of drainage on the groundwater resource should be very limited, or even negligible. Details of this study can be found in Carrier (2003).

CONCEPTUAL AND NUMERICAL HYDROGEOLOGICAL MODELS

Realistic hydrogeological models allow insights into the various components of hydraulic systems and thus help determine regions of high hydraulic potential and identify recharge areas. Indeed, numerical models represent useful tools for integrating all available information, verifying estimations of hydrogeological properties and hydrological parameters, and understanding the dynamics of the regional hydrogeological system. Numerical models were used in this project mainly to confirm the general flow directions and groundwater-recharge rates and hydraulic conductivities previously found with other theoretical and empirical approaches, as well as to obtain indications of the role of regional faults. These elements are all essential to support the development of a long-term groundwater-resource-management plan. Due to the large area covered by this study and the stratified and lenticular nature of the bedrock throughout the Maritimes Basin, only conceptual and simplified numerical models were developed. This section first describes the conceptual model and main characteristics of the till and bedrock units, in order to review and condense all the information and knowledge concerning the hydrogeological system. Then, the results of 2-D and 3-D numerical-flow models are presented.

Hydrogeological conceptual model

Present knowledge regarding the hydrostratigraphic units, regional and local groundwater-flow systems, hydraulic behaviour under pumping, groundwater quality, and hydrological budget of the MGWI study area is summarized in Figure 52 and Tables 16 and 17. Three scales were used so as to schematically describe the characteristics and conditions of the Maritimes Basin hydrogeological system: regional, local and point scales.

First to be presented is the regional-scale model, which encompasses the entire study area. Lenticular bodies of sandstone, shale, siltstone, and conglomerate form a discontinuous and layered aquifer-aquitard sequence within geological formations, which are composed of different percentages of these interbedded rock types. At the regional scale, these units cannot be taken into account individually, as they have highly variable lengths, lateral extents, and thicknesses. Regionally, each geological formation must therefore be

considered as a single hydrostratigraphic unit over the entire model thickness, though with stratified layers, as hydraulic conductivity decreases with depth. This homogeneity assumption for each layer is also supported by Brown (1971), who found evidence of hydraulic continuity throughout the layered aquifer-aquitard system of the Pictou Group in the Shippagan region, despite high permeability ratios between strata. In Prince Edward Island, Carr (1969) also came to the conclusion that all strata (including Quaternary sediments) could be considered as one large interconnected aquifer due to the number and distribution of fractures that connect the sandstone and 'mudstone' strata to the surface. Considering the similarities in rock properties throughout the Maritimes Basin, this conclusion can likely be extended to the entire study area. Above the bedrock aquifer, the upper part of the conceptual model is composed of unconsolidated glacial till, since the latter covers the great majority of the study area. Composition of the till layer is directly related to that of the underlying bedrock formation (the till matrix varying from silty to sandy). Due to a lack of information and to uncertainty about the till thickness in many areas, a till layer of constant thickness was assumed in the conceptual model. Infiltration occurs mainly through the till cover and, preferentially, through sandy tills, but a portion of this water probably never reaches the bedrock, instead reaching streams by hypodermic flow. Quite a large portion of the study area is likely under confined conditions. The system is thus said to be partly confined, as both confined and unconfined conditions can be found, depending on the till layer composition and fracturing of overlying beds. Regional faults are presumed to have an important influence on groundwater flow.

Next, the local scale illustrated in Figure 52 corresponds to the area being influenced by a pumping test, and is on the order of a few square kilometres. At the local scale, the layering and fracturing of the heterogeneous bedrock aquifers can strongly influence the hydraulic behaviour. The sketch in Figure 52 depicts a hypothetical sequence of the common sedimentary rock types encountered in the region. The proportion of each rock unit varies from one geological formation to another; unit thickness is also highly variable within each formation. Pumping tests revealed that aquifers can locally be very heterogeneous and anisotropic due to these discontinuities and fracturing, but behave as equivalent porous media, likely because fractures are well interconnected. In addition, they confirmed the limited extent of the aquifers by showing impermeable boundaries in many cases. Pumping-test results indicated mean hydraulic conductivities on the order of 5×10^{-6} to 1×10^{-4} m/s for aquifer units. Locally, the till layer is characterized by a variable thickness (ranging from 0 to 20 m) and texture.

Finally, the point scale presents the heterogeneity of the aquifer material, with plausible fracture patterns and matrix characteristics of the fractured rock aquifers. Mean matrix porosities range between 5 and 10%. Strata are generally subparallel to the surface, with bedding planes dipping gently toward the Northumberland Strait. The thick sedimentary rock sequence is highly fractured, showing a large number of

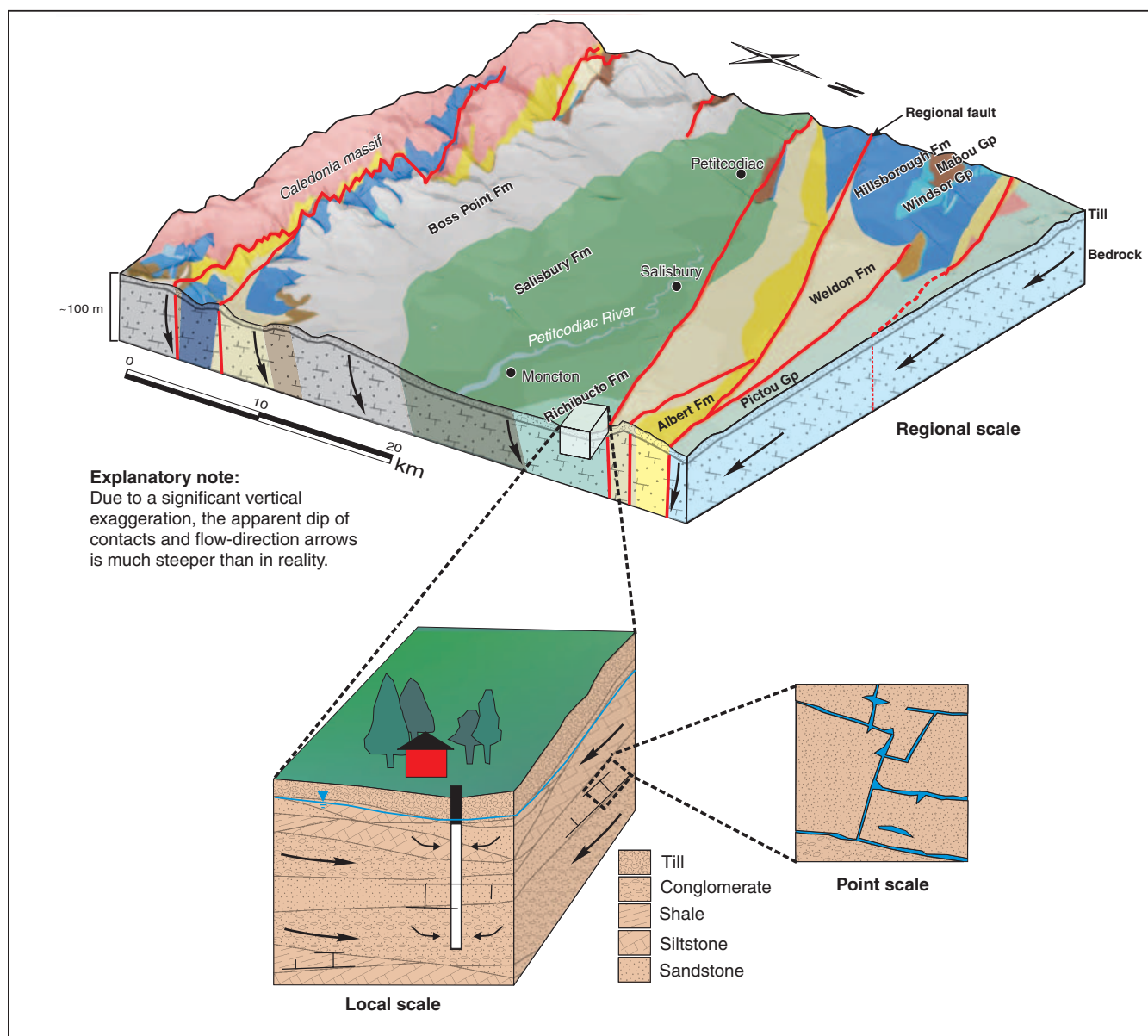


Figure 52. Schematic conceptual model of the Maritimes Basin, showing regional, local, and point scales. Arrows indicate general groundwater flow.

discontinuities along the bedding planes with some major vertical fractures, and likely a moderate to high number of small vertical fractures intersecting the bedding planes. Fractures are also more numerous in sandstone and conglomerate units. Most fractures seem to have a 045° strike, in agreement with regional structures (e.g. Caledonia and Kingston uplifts). These features seem to infer a quasi-horizontal 2-D flow, with a preferential component along strike. Permeabilities of the bedrock are closely related to the presence or absence of fractures. Hydraulic conductivities of individual sandstone and siltstone beds, estimated using packer tests, range from 3×10^{-8} to 5×10^{-3} m/s and from 6×10^{-8} to 3×10^{-5} m/s, respectively, depending on the fracture patterns encountered. Hydraulic conductivities of the sandstone matrix without fracturing would be on the order of 10^{-7} to 10^{-8} m/s.

Description of the numerical models and their properties

Numerical models were developed in 2-D with SEEP/W® (GEO-SLOPE International, 1997) and in 3-D with FEFLOW® (WASY GmbH, 1998), two finite-element numerical simulators, using the regional-scale conceptual model and steady-state conditions to obtain a quantitative representation of the hydrogeological-system dynamics. For the development of these models, the geology had to be greatly simplified in many areas due to the lenticular nature of permeable bodies and strong heterogeneity in the Maritimes Basin (Fig. 53). Models were thus developed using only the dominant formation

Table 16. Main characteristics of the surficial sediments and rock units of the Maritimes Groundwater Initiative study area. Abbreviation: GW, groundwater.

Unit	Role and characteristics
Till layer	Role: provide aquifer recharge Characteristics: Preferential GW recharge occurs through sandy till units Nature of tills depends on the underlying bedrock formation: ➤ permeable (sandy) matrix: PEI Gp and Boss Point Fm ($K = 1.3 \times 10^{-6}$ m/s) ➤ moderately permeable matrix: Richibucto Fm, Balfron Fm, undivided Pictou Gp, and Hillsborough Fm ($K_{40\text{ cm}} = 1.4 \times 10^{-6}$ m/s; $K_{>40\text{ cm}} = 6.5 \times 10^{-9}$ m/s) ➤ low permeability (silty) matrix: Salisbury Fm ($K = 6.5 \times 10^{-9}$ m/s) Thickness ranges from 0 to 20 m, but is generally <10 m (75th percentile)
Carboniferous rocks	Role: provide good quality GW (aquifers) Characteristics: Porous fractured media Main aquifer units: PEI Gp, Richibucto Fm, Balfron Fm, undivided Pictou Gp, Boss Point Fm, and Hillsborough Fm Main aquitard units: Salisbury Fm, Horton Gp and Mabou Gp Cyclic sequence of sandstone, siltstone, shale, and conglomerate Lenticular and discontinuous beds Some intergranular porosity present (5–10% on average) Fractures are mostly horizontal and related to bedding planes and lithological changes Vertical fractures are not as common but link horizontal fractures Fracturing better developed in conglomerates and sandstones Fractures show a very strong 045° preferential orientation; aquifers are thus locally very anisotropic Hydraulic properties (closely related to the presence or absence of fractures): ➤ $10^{-8} < K < 10^{-3}$ m/s with mean K for aquifer units varying from 5×10^{-6} and 1×10^{-4} m/s ➤ $10^{-4} < S < 1$, with mean S between 10^{-4} and 10^{-3} (for all types of conditions) ➤ for PEI, $1 < S_v < 8\%$, with mean values between 2 and 7% Typical well specific capacity: $0.2 < Q/s < 1$ L/s/m (for domestic purposes) Aquifer vulnerability: ➤ low where low-K till is present (Salisbury Fm) ➤ high where high-K till is present (especially all PEI formations and Boss Point Fm) Groundwater quality: ➤ naturally good, with elevated Fe and Mn contents; Moderate hardness ➤ predominant GW type is CaHCO_3 in upper 100–200 m and NaCl, below 300–500 m (and deeper inland) ➤ the only group with common natural GW quality problems is the Windsor ➤ areas more affected by anthropogenic degradation: PEI by nitrates and potential risks of saline intrusions along coastlines

for a given region, and a horizontally stratified medium with homogeneous properties for each formation (since hydraulic conductivities decrease with depth).

The first layer of each hydrostratigraphic unit was assigned a hydraulic conductivity (K) value based on the geometric mean of pumping-test results (*see* ‘Hydraulic properties of the bedrock’ section and Table 13). Indeed, K values could not be directly introduced and interpolated in the models, as they were too scattered (approximately 55 values to cover the entire study area after aggregating neighbouring points). The spatial distribution would therefore not be representative, since values probably depend mostly on the geological formations, and the gradual transition between data would therefore not be realistic (K values indeed showed no correlation). Therefore, hydraulic conductivity values were instead applied according to each individual geological formation or group. Groups (Riversdale-Mabou, Windsor, and Horton groups, and the basement complex) for which no or very few K values

were available were assigned values according to judgement, based on their dominant stratigraphic composition. In Prince Edward Island, pumping-test results did not allow differentiation of the hydrogeological properties between formations of the Prince Edward Island Group. The subsequent layers were assigned K values according to reported porosities (*see* ‘Hydraulic properties’ section below).

Probable recharge rates were assigned based on results from the prior study on recharge (*see* ‘Groundwater recharge’ section), also according to the underlying formation. The till layer was assigned hydraulic conductivity values according to those found using permeameters during the 2002 fieldwork (*see* ‘Hydraulic properties of Quaternary units’ section) and, where these were not available, based on their presumed composition, since they are related to the underlying rock formation.

Table 17. Characteristics of each conceptual model scale for the Maritimes Groundwater Initiative study area. Abbreviation: GW, groundwater.

Regional scale (characterization of the entire study area, 14 000 km²) GW recharge: ✓ Mainly occurs through till ✓ Preferential GW recharge zones where till is sandy ✓ GW recharge rates vary from 22 to 271 mm/a with a weighted average of 130 to 165 mm/a over the study area when using 11 to 29% of areas with upward GW flow where recharge cannot occur (discharge areas) General GW flow patterns: ✓ Lenticular discontinuous beds cannot be considered individually; therefore, each formation is taken as one hydro-stratigraphic unit over the model depth using average pumping-test results ✓ Gravity-driven system with flow from topographic highs toward the sea or major streams ✓ GW depth is on average 6.7 m, but varies from 50 m to artesian ✓ Major streams affect regional GW flow, thus mostly connected to aquifers but may be independent of aquifers locally (i.e. water elevations are different in wells and streams) ✓ K decreases with depth (connected fractures are sparser or not as open); main GW flow occurs in the upper 100 m ✓ Major faults seem to act as preferential GW flow zones (such 'drains' are required in the GW-flow numerical models to allow the drainage of estimated recharge volumes)
Local scale (hydraulic behaviour as observed during pumping tests, ~1 km²) ✓ Aquifer conditions depend on nature of overlying till partly confined in NB and NS, unconfined in PEI ✓ Frequent and well connected subhorizontal fractures (interspersed in low K matrix) infer a quasi-2D flow ✓ Behaviour as equivalent porous media under pumping (follow Theis-type curves) ✓ Lenticular and discontinuous beds; leads to frequent negative hydraulic boundaries for wells under pumping ✓ Very anisotropic; observation well response very dependent on orientation of main fractures (wells may not respond away from the preferential 045° orientation)
Point scale (scale of borehole, ~1 m²) ✓ Fractured porous media ✓ Strata are generally subparallel to the surface with bedding planes dipping gently toward the Northumberland Strait ✓ Small vertical fractures connecting main horizontal fractures ✓ Subhorizontal fractures mainly present along bedding planes and in sandstone beds ✓ Most fractures seem to be oriented in a 045° direction, in agreement with regional structures ✓ Low-K matrix; sandstone matrix without fracturing on the order of 10⁻⁷ to 10⁻⁸ m/s ✓ Typical matrix porosity (5–10%) for sedimentary rocks, allowing significant water storage

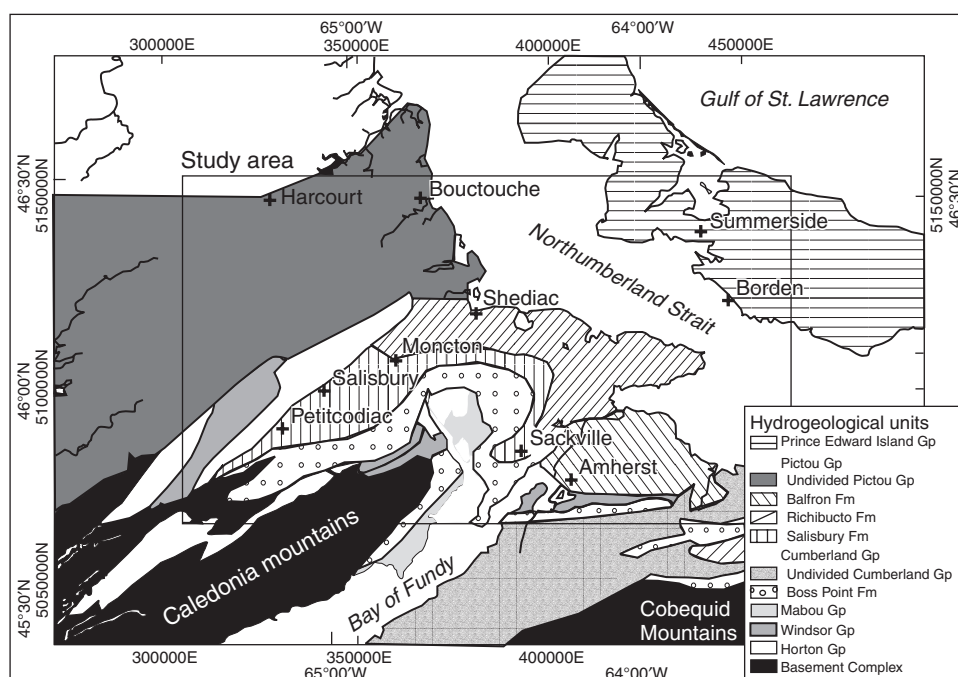


Figure 53. Distribution of the hydrogeological units represented in the numerical model of the Maritimes Basin.

Since simplified regions of the geological map use only the dominant formation, associated parameters of some areas are not always representative of individual specific formations. This is particularly obvious in the southern part of New Brunswick (e.g. near Hillsborough), where rock units have been extensively tectonized and are therefore tilted and exposed on their edge. This makes the regional modelling task difficult and certainly underscores the inadequacy of the model for local (500 km² or less) applications.

Two-dimensional models

General characteristics

As the bedrock is the only unit capable of providing substantial yields, only this layer was taken into account in the 2-D models. Two sections, one in the central part of Prince Edward Island (on Fig. 41, cross-section A–A') and the other between the Bay of Fundy and the Northumberland Strait in New Brunswick (Fig. 41, cross-section B–B'), were modelled. These two sections go through piezometric highs and approximately follow groundwater lines. As they are meant to represent a cut through an island (i.e. land surrounded by the ocean), the area to be modelled was first estimated using the approximate solution for an isotropic homogeneous island (Todd, 1980, p. 506). This first approximation indicated that fresh groundwater could flow as deep as 750 to 1000 m below MSL.

Hydraulic properties

Two-dimensional vertical sections were developed in SEEP/W[®] using a stratified medium, with hydraulic conductivity gradually decreasing with depth. Values of porosity with depth available for Prince Edward Island (Chi, pers. comm., 2001) showed that, for the upper 1000 m, total porosity decreases from 20 to 10%. Empirical relationships between porosity and permeability indicated that, for this range of porosity and type of rock, the permeability can decrease by about 1.5 to 2 orders of magnitude (Blatt et al., 1980). Figure 54 presents the Prince Edward Island section with the description of horizontal (K_x) and vertical (K_z) hydraulic conductivity used according to depth. The model employed four different values of K (including several rows of cells for each) and a conservative anisotropy ratio of 1/10 ($K_z = K_x/10$), based on packer-test results and reported information. Table 18 summarizes the characteristics and conditions of both 2-D models.

Boundary conditions

Since till was not represented in these 2-D models, the recharge assigned to the models represents the amount of water that effectively reaches the bedrock. The till hydraulic conductivity is, in any case, sufficient to easily allow infiltration of groundwater recharge. Variable recharge rates were assigned on top of both models according to the geological formation, based on previously determined values (*see* Table 9). A constant head was assigned to the first three nodes just below MSL to allow the fresh water to exit, and a no-flow boundary was attributed to nodes of the rest of the section

Figure 54. Modelled cross-section for Prince Edward Island, showing piezometric distribution and flow paths.

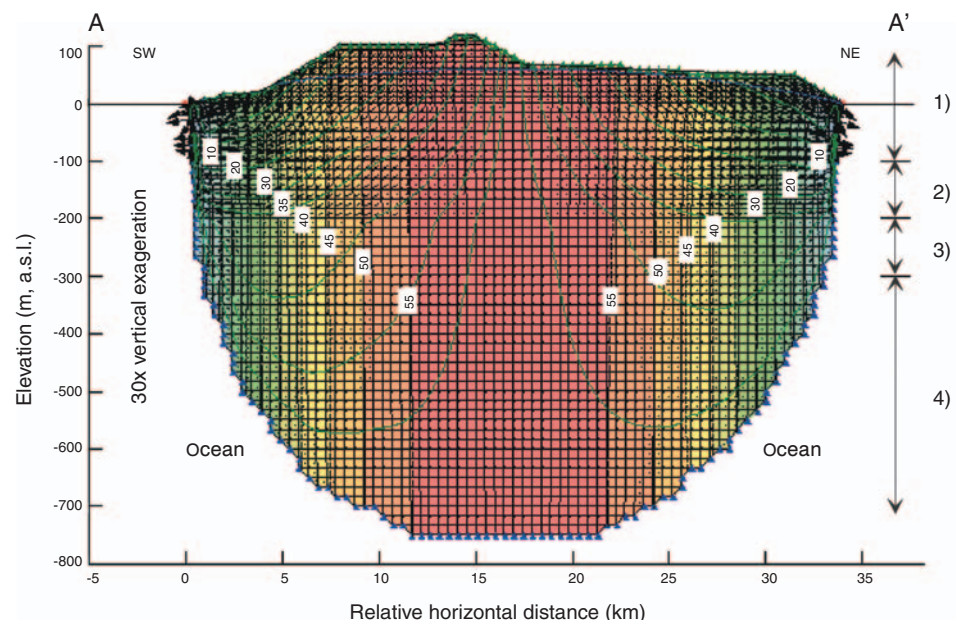


Table 18. Characteristics and conditions of 2-D model for Prince Edward Island.

Characteristic / condition	MGWI model
Conditions	Steady state Saturated
Model mesh	PEI: 3048 elements. NB: 7088 elements (mostly quadrilateral)
Hydraulic conductivities	Vertical anisotropy (K_z/K_x) Stratified media: four 'homogeneous' layers of 200 to 250 m thickness, with two orders of magnitude from top to bottom Upper K_x : PEI: $= 10^{-4}$ m/s NB: Boss Point $= 10^{-5}$ m/s; Richibucto $= 2 \times 10^{-5}$ m/s; Salisbury $= 10^{-6}$ m/s
Groundwater recharge	PEI: uniform. NB: according to geological formations (<i>see</i> Table 9 or 20)
Boundary conditions	Constant heads for first nodes close to the surface No-flow boundary ($Q = 0$) to represent the saltwater-freshwater interface

below MSL. Indeed, if the saltwater-freshwater interface is considered sharp (i.e. very little exchange occurs between the two types of water), this boundary also represents a no-flow ($Q = 0$) boundary. Even in Prince Edward Island, withdrawal from wells (mainly residential) should not represent a high percentage of the total recharge, except in a few local areas (G. Somers, pers. comm., 2003).

Results of 2-D modelling

Knowing the approximate hydraulic-head distribution across the sections from measurements, a sensitivity analysis was performed. Even if most of the flow occurs within the most permeable part of the section (<200 m, and especially in the upper 100 m), both models have shown that not considering the bottom section would result in a significant rise of the water table at elevations not representative of measurements. For the Prince Edward Island section, a combination of $K_x = 10^{-4}$ m/s in the upper portion and $W = 300$ mm/a gave a realistic water-table elevation based on the piezometric map drawn from water-level measurements. To have a similar water table across the island with $W = 350$ mm/a, the first K_x had to be set at 1.2×10^{-4} m/s and, with 250 mm/a, K_x had to be 7×10^{-5} m/s. A sensitivity analysis was also performed on the K_z/K_x ratio, using 1/5 and 1/50. It was found that, for these three cases ($W = 300, 350$, and 250 mm/a), the vertical anisotropy factor had a moderate impact on the water table, the latter varying a maximum of -3 m for $K_z/K_x = 1/5$ and +10 m for $K_z/K_x = 1/50$, relative to the reference case (K_z/K_x ratio of 1/10).

The New Brunswick section crosses three formations: Boss Point, Salisbury, and Richibucto. The Boss Point and Richibucto formations have relatively similar mean hydraulic conductivities (K_x of 1×10^{-5} and 2×10^{-5} m/s, respectively), but the hydraulic conductivity of the Salisbury Formation is an order of magnitude smaller. The first simulations showed that it was impossible to obtain the observed water-table profile using these K and probable (previously estimated) recharge values. In fact, the water table was either too low close to the

Bay of Fundy or much too high on the lowland side. The interpretation is that the Dorchester and Saint-Joseph faults likely act as conduits and drain a great quantity of groundwater for the region. These faults are located in topographic depressions and probably drain considerable groundwater down to the Port Elgin Fault, which exits into the ocean. The latter two faults, however, which are perpendicular to the section, cannot be adequately represented by the 2-D section model. In addition, it was hypothesized that the high water table on the Bay of Fundy side might also be attributable to the presence of shale beds, which can locally raise the water table, separating two sandstone and/or conglomerate aquifers. Indeed, within the Pictou Group and especially the Cumberland Group, these beds are quite common.

In conclusion, the 2-D models seemed to indicate that regional faults have a major impact and that sections as deep as 750 m must be modelled in order to adequately represent the regional groundwater flow.

Three-dimensional models

General characteristics

The 3-D numerical models cover a total area of 27 300 km². Due to this very large area, two separate models were developed: one for Prince Edward Island and one for New Brunswick and Nova Scotia. This allowed the simulations to be speeded up, since 11 layers (12 slices) were used for each model. This time, the till layer was included in the models, but with a constant thickness due to a lack of accurate information in several areas: 4 m for the Prince Edward Island model and 8 m for the New Brunswick and Nova Scotia model. These values were based on several thousands of data points contained in provincial databases. Each layer was defined so as to restrict the two following elements to be less than double in size. Approximately 3000 linear (three-node) triangular elements of similar area were used for each layer of the Prince Edward Island model. This number rises to 7000 for the New Brunswick and Nova Scotia model. Table 19 presents general characteristics and conditions of the models.

Hydraulic properties

As with the 2-D models, horizontally stratified media were used, with hydraulic conductivity decreasing with depth. Figure 53 illustrates the simplified geological map used to assign hydraulic conductivity (K) and recharge (W) values in the model. Table 20 provides the initial and calibrated K and W values used in the model for the upper part of the bedrock unit. For the till layer, hydraulic conductivity values of 10^{-6} , 5×10^{-8} , and 7×10^{-9} m/s, respectively, were used for sandy till (Boss Point Formation and formations of the Prince Edward Island Group), silty-sandy till (other formations), and clayey till (Salisbury Formation).

Boundary conditions

An area larger than the study area was used in the models, since it is preferable to utilize natural limits for the model boundary conditions and to impose other boundaries as distant as possible from the area under study to avoid ‘forced’ results. The Prince Edward Island model was developed using only first-type boundary conditions (constant head). A zero-elevation hydraulic head was used along the coastline to represent sea level, and constant heads were imposed along the Hillsborough River at the extreme east end of the modelled part of the island. The model for New Brunswick and Nova Scotia is limited in the northwestern part of New Brunswick by the Richibucto River, the Salmon River, Grand

Table 19. Characteristics and conditions of the 3-D models for Prince Edward Island, and for New Brunswick and Nova Scotia.

Characteristic/condition	MGWI model
Conditions	Steady state Saturated
Model mesh	PEI: 3000 elements/layer. NB: 7000 elements/layer (triangular) 11 layers
Hydraulic conductivities	Vertical anisotropy (K_z/K_x) Stratified media: four ‘homogeneous’ layers of 200 to 250 m thickness, with two orders of magnitude from top to bottom Upper K_x values, (see Table 20)
Groundwater recharge	PEI: uniform. NB: according to geological formations (see Table 9 or 20)
Boundary conditions	Constant heads for rivers and $h = 0$ along coastlines

Table 20. Combination of possible values of hydraulic conductivity (K) and recharge rate (W) for the main lithological groups used in the calibrated numerical models of Prince Edward Island, and of New Brunswick and Nova Scotia.

Group	Stratigraphic unit	K initial ¹ (m/s)	K model (m/s)	W initial ² (mm/a)	W model (mm/a)
Prince Edward Island	Undifferentiated	1.2×10^{-4}	10^{-4}	285	300 or 350
Pictou	Richibucto Fm and undivided	2.2×10^{-5}	3×10^{-5}	128	100
	Balfron Fm	3.3×10^{-5}	3×10^{-5}	128	100-150
	Salisbury Fm	1.4×10^{-6}	10^{-6}	28	20
Cumberland	Boss Point Fm NB	1.1×10^{-5}	3×10^{-5}	236	150
	NS	2.8×10^{-6}	3×10^{-6}	- ³	100
	General (undivided)	4.9×10^{-6}	5×10^{-6}	- ³	50
Mabou	Hopewell Fm	5.1×10^{-6}	5×10^{-6}	42	20
Windsor	Hillsborough Fm	4.1×10^{-7}	5×10^{-7}	42	20
Horton	Weldon Fm	-	10^{-7}	42	20
Basement complex	Pre-Carboniferous	-	10^{-9}	22	negligible <1
¹ Mean values taken from Table 13 ² Mean values taken from Table 9; water-balance-method values minus the percentage area where discharge likely occurs, except in PEI where a more plausible value of 5% based on GIS delineation was used ³ Recharge rates obtained from existing data were calculated only within the MGWI study area					

Lake, and the St. John River (and its tributaries). The rest of the model is limited by the ocean ($h = 0$), except for the eastern part of Nova Scotia where a no-flow boundary (along a stream line) was used based on the piezometric map (Fig. 41). The Petitcodiac River (New Brunswick) and rivers leading to Hillsborough Bay (in the extreme eastern portion of the modelled part of Prince Edward Island) were also included in the model as boundary conditions, since they are expected to serve as major discharge zones. Elevations for the different rivers were read from 1:50 000 scale maps.

Results of the 3-D modelling

Simulations using the Prince Edward Island model confirmed that the aquifer underlying the island is very permeable and that recharge is abundant. An overall recharge of 300 to 350 mm/a can be applied over the island to calibrate the model. This is in agreement with previously determined values (with the hydrograph-separation and water-balance methods), as well as with values reported in various documents and used for more local modelling by the province's Department of Environment. On a local basis, however, recharge could probably vary between 200 and 400 mm/a.

Initial simulations with the New Brunswick and Nova Scotia model, using probable values for hydraulic conductivity and recharge rate, showed unrealistic piezometric values, hydraulic heads being too high relative to the water-level measurements. Therefore, either recharge was overestimated, hydraulic conductivities were underestimated, or faults played a significant role as conduits within the hydrogeological system, as indicated by the 2-D model. It was therefore decided to introduce faults and keep the previously estimated values for mean recharge and hydraulic conductivity. To accomplish this, the following major faults (Fig. 29), listed in Williams (1995), were added to the model: the Lubec-Belleisle, Springhill, and Peekaboo–Berry Mills faults, situated north and south of the Kingston Uplift; the Clover Hill (Caledonia) Fault, north of the Caledonia mountains; and the Dorchester, Saint-Joseph, and Cobequid faults, south of the Cobequid Mountains. According to the New Brunswick Department of Natural Resources, they tend to be brittle structures and therefore fault zones rather than single structures, which seem to act as conduits. They have been integrated into the model using narrow segments of very high hydraulic conductivity ($K_{\text{fault}} = 1 \text{ m/s}$, an arbitrary value used only to observe the impact of a much larger K) in the bedrock layer. Another similar segment with high K value was added on the northern part of the Cobequid Mountains, since the unconformity with the Maritimes Basin likely provides a preferential path for infiltration. This modification greatly improved the results. Simulated hydraulic heads that were originally too high were therefore likely due to the fact that water could not be evacuated freely with the original model that did not account for the potential effect of major faults.

Over large areas such as geological formations or groups, some K and W values had to be modified relative to previously determined mean values. Numbers used in the models, however, were always within plausible values, recharge rates being included in the range of values (minimum and maximum) previously estimated (*see* Table 9) and K values taken from the log K distributions of the formations (*see* Appendix F). The combination of K and W values introduced in the model as a function of stratigraphic units is presented in Table 20. Mean values found using the corrected water-balance method, initially assigned in the model, are also included in Table 20 for comparison.

As noted in 'Hydraulic properties of major aquifers' section, hydraulic conductivities (and therefore recharge) generally decrease in New Brunswick and Nova Scotia in a southerly direction. Stratigraphic units such as the Richibucto and Balfron formations are probably more transmissive close to the coastline (as observed from transmissivity and pumping-rate data), but this feature has not been taken into account in this simplified model. Since only the dominant stratigraphic units were included in the model and no faults of lesser importance (or major fractures) are modelled, no corridor or flow channel is available for discharge at this scale. This does not mean that good local hydraulic potential cannot be found within these areas. At a local scale, of course, representation of small, permeable, connected formations and also differentiation of layers would allow the flow to circulate. These features, however, cannot be represented at the regional scale.

A summary of the mean recharge rates obtained with the three methods is presented in Table 21. The recharge rates used in the regional model for the most permeable regions (100–350 mm/a) lie in the range of values provided by hydrograph separations (92–436 mm/a) and are of the same order of magnitude as those found using the corrected water-balance method (138–241 mm/a). Recharge rates for most permeable units thus represent 10 to 30% of total precipitation. The highest values of K and W were attributed to rock units of Prince Edward Island. Recharge rates for this region had to be slightly increased compared to the initial value assigned (285 mm/a). Areas with relatively low hydraulic conductivity (10^{-6} – 10^{-7} m/s), as in the case of the Windsor, Mabou, and Horton groups and the Salisbury Formation, were given very low recharge values (20 mm/a, compared to 22–42 mm/a found with the corrected water balance). A weighted average

Table 21. Summary of recharge rates for the entire Maritimes Groundwater Initiative study area.

Method	Mean recharge rate (mm/a)	
	Most permeable units	Regional value
Stream hydrograph separation	92–436	–
Water balance	192–310	184
Corrected water balance ¹	138–241	130–165
Modelling	100–350	135
¹ using information from vertical gradients, DEMs, and piezometric surveys		

for the modelled region gives 135 mm/a, a value lying within the range obtained with the water-balance analysis, taking into account that 11 to 29% of the area corresponds to either discharge zones or confined conditions (130–165 mm/a). The only major difference between formation areas concerns Prince Edward Island, since the model incorporates a larger part of the island than is included within the study area. The water balance from these steady-state models shows that 100% of the recharge comes from infiltration through the overlying surficial-sediment layer. All boundaries, representing streams or the ocean, consequently act as discharge areas.

The simulated piezometric map is presented in Figure 55. The piezometric contours are simplified in comparison to the map drawn from water-level measurements (Fig. 41), but hydraulic heads are well reproduced with this simplified numerical model. Indeed, major hydraulic domes are depicted on both maps. The highest values are, of course, observed over the Caledonia and Cobequid mountains. Reliable piezometric data for these mountains are not available, however, since few wells have been drilled. Groundwater circulates mostly toward the ocean (since the sea constitutes the lowest hydraulic head), except near major rivers such as the Petitcodiac and St. John rivers (New Brunswick), where the influence of those watersheds is manifest. Local features, such as local domes on the piezometric map obtained with

observed water levels or observed artesian conditions, cannot be represented at this scale with the model. In addition, it should be emphasized that hydraulic gradients do not match perfectly. Differences in this parameter indicate that hydraulic conductivities are likely smaller or higher (e.g. along the New Brunswick littoral zone) than what was used as an average value for this geological formation. Lack of data did not allow the division of each formation into different zones.

This 3-D modelling validated the estimated ranges of hydraulic conductivity and recharge values, and confirmed the potentially important role of faults in the regional flow system. These fault zones would represent significant potential sources of groundwater available for exploitation, and therefore warrant further investigation.

CONCLUSIONS

The Maritimes Groundwater Initiative (MGWI) represents a first inventory of the regional groundwater resources in the Maritimes Basin, where some of the most productive aquifers in Canada can be found. The study area covers more than 14 000 km², including parts of New Brunswick, Nova Scotia, and Prince Edward Island. This large study area (equivalent to a 1:250 000 map sheet) was selected due to the critical need for characterization of regional aquifers in

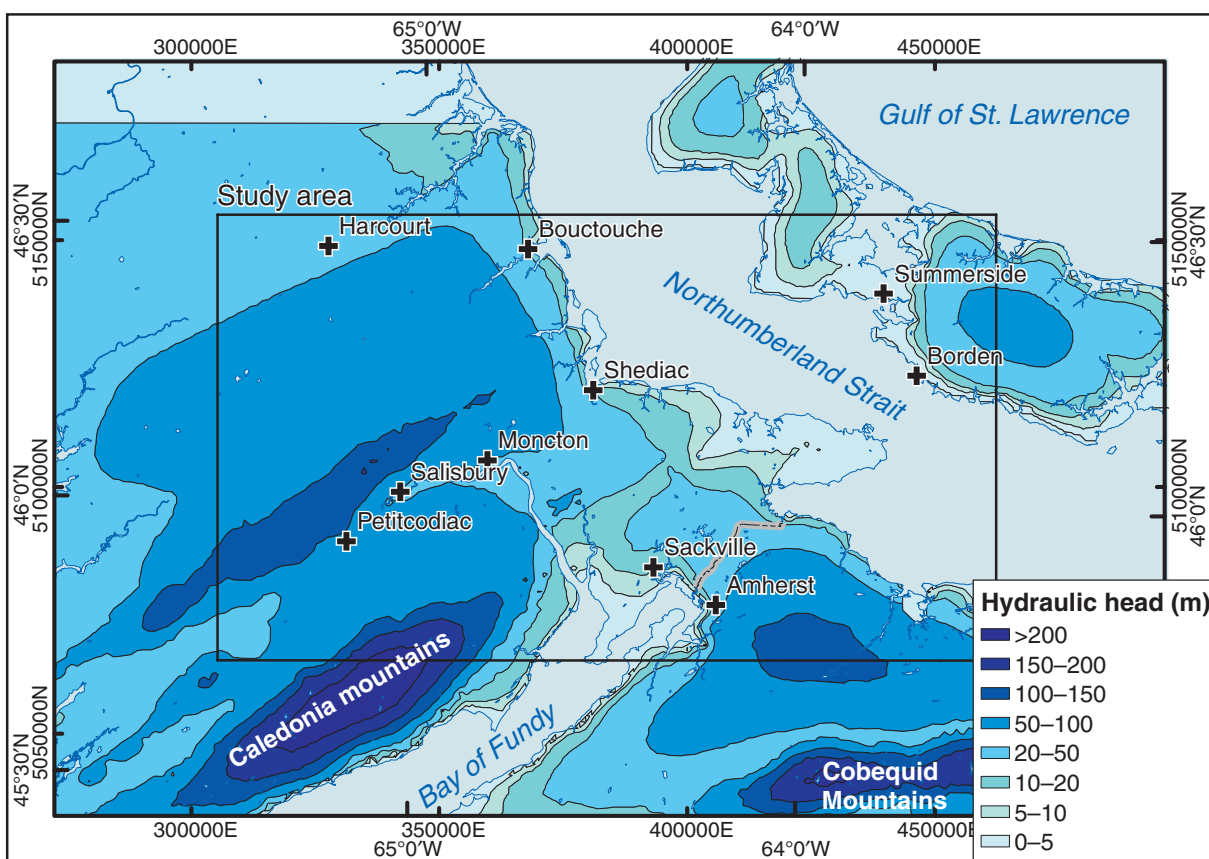


Figure 55. Modelled piezometric map for the Maritimes Groundwater Initiative study area.

Canada. One of the project goals was to provide baseline information for a regional groundwater-resource assessment, to support provincial and municipal groundwater management and protection. A series of activities was therefore carried out within the framework of the MGWI project for that purpose. These activities included data compilation and structuring into databases, fieldwork, data analysis, modelling, and interpretation.

The hydrogeological synthesis undertaken and the work performed underscored the great complexity of the hydrogeological system in the Maritimes Basin. Indeed, this basin includes several geological formations, each composed of a sequence of discontinuous (lenticular) layers of sedimentary rock of variable permeability (mostly sandstone, siltstone, shale, and conglomerate). Hydraulic conductivities, and therefore well yields, are closely related to the presence or absence of fractures. The bedrock is generally overlain by a thin layer of glacial till, whose composition varies according to the underlying geological formation. Good to variable aquifer units are present throughout most of the study area.

Due to the scale of the study and heterogeneity of the basin, three scales were proposed for the conceptual model in order to integrate the knowledge acquired through this inventory: regional scale (the study area), local scale (scale of a pumping test), and point scale. The regional system (scale of modelling) is characterized by geological formations that have homogeneous properties, though with stratified layers, as hydraulic conductivity decreases with depth. This hydrogeological system contains confined and unconfined zones, and its lenticular aquifer strata extend only a few kilometres. Since bedrock outcrops are rare, recharge results from infiltration through the till layer. Preferential infiltration occurs where sandy till is present (especially on formations of the Prince Edward Island Group and on the Boss Point Formation). Pumping-test results revealed that the system behaves as an equivalent porous medium and that the presence of less permeable boundaries can be detected after some or several hours of pumping in many cases, confirming the limited extent of the lenticular permeable layers. Preferential fracture patterns result in an anisotropic quasi-2-D flow system. Indeed, work performed at the point (aquifer material) scale indicated that most water-producing fractures seem to be subhorizontal (with a dip of less than 30°) and generally oriented in a northeasterly (045°) direction, in agreement with regional structures. They are encountered mainly in sandstone layers and at lithological changes. The matrix porosity is typical of that of porous clastic sedimentary rocks, allowing good groundwater storage where sandstone and conglomerate are predominant.

The piezometric map obtained from interpolation of water-level measurements showed that the piezometric surface generally follows the surface topography and that groundwater within both surficial and fractured aquifers can be considered hydraulically connected with surface-water bodies at the regional scale. The groundwater mainly flows

seaward and, in New Brunswick, drainage toward the Petitcodiac River and St. John River watersheds is also significant.

Groundwater within the Maritimes Basin is generally abundant and of good quality. High hydraulic conductivities (K), on the order of 5×10^{-6} to 1×10^{-4} m/s, can be found in many areas, and geochemistry data show that over 95% of wells usually have concentrations of major and minor ions (except for iron, fluorides, and manganese), nitrates, metals, and other parameters below the Health Canada advisory levels for drinking water. Iron and manganese are not considered a health problem, since recommended limits exist only for aesthetic reasons and these elements are quite easy to remove from water. Concentrations of naturally occurring fluorides in New Brunswick and nitrates on Prince Edward Island exceed advisory levels in 6.2% and 8.6% of the samples, respectively. Nitrate levels on Prince Edward Island are therefore of concern, as the guideline can also be viewed as an indication that the groundwater quality is well degraded in a given region. Indeed, a threshold of only 2 mg/L indicates that anthropogenic activities are affecting the resource. Considering this indicative threshold, the percentage of wells affected by nitrates in this intensive agricultural region reaches 78%, which is of serious concern. Studies focusing on the nitrogen cycle and the impact of climate change on its fate throughout the groundwater-flow regime in Prince Edward Island are currently being conducted by the GSC (Savard et al., 2004). Saline intrusion does not seem to be a major problem in this the study area. Nevertheless, electrical-resistivity sounding profiles showed that the system heterogeneity results in diverse patterns of intrusion, and that saline water can be found quite far inland (>200 m) on Prince Edward Island, corroborating results obtained from other studies.

The results of this study did not indicate overexploitation, as groundwater use for this area was estimated to be on the order of 5% or less, relative to recharge. Therefore, in many regions, groundwater extraction could probably be increased significantly without jeopardizing other activities and natural habitats. This percentage, however, is based on a preliminary water-use survey only in New Brunswick and on regional estimates. Furthermore, the predicted population increase and economic development will certainly put more pressure on the groundwater resource, especially in coastal areas. Based on the till-layer composition and recharge rates, parts of the study area were assigned either low, moderate, or high levels of vulnerability. Only the Prince Edward Island Group and the Boss Point Formation were classified as highly vulnerable to surface contamination.

Recharge rates (W) of 90 to 400 mm/a were estimated for the most permeable formations, using two different methods of evaluation: stream hydrograph separation and the water-balance method corrected for areas where recharge is considered impossible (using the vertical-gradient map, the piezometric map versus DEM, and water-level-survey data). Recharge rates for the other formations were much lower (22–42 mm/a), because of low bedrock transmissivities and

important runoff due to the till cover and slopes. The mean overall recharge rate for the study area was estimated to be on the order of 130 to 165 mm/a.

Two- and three-dimensional numerical models were developed using steady-state conditions and a simplified geological map. Recharge rates obtained both for individual formations or groups and for the entire study area (weighted average) lie within ranges estimated using the two previous methods. Indeed, recharge for the most permeable regions ranged from 100 to 350 mm/a (i.e. in the range of 10–30% of total precipitation), and the weighted average for the entire study area was 135 mm/a. Values of hydraulic conductivity used in the models also lie within the log K distributions of the formations. Agreement between the piezometric maps obtained from modelling and the one based on water-level measurements is quite satisfactory, since major characteristics were well reproduced. The modelling exercise was useful, since it validated the regional conceptual understanding of the hydrogeological system, confirmed probable combinations of previously determined values of K and W, and suggested the important influence of regional faults, which would act as drains.

This synthesis and characterization project allowed a regional understanding of the hydrodynamics within the Maritimes Basin. This work should therefore help the prediction of its behaviour at a given scale and, as a result, contribute to the development of long-term groundwater-resource management. It also shed light on several issues that could each become a project on its own, including 1) the system's anisotropy; 2) the continuity/discontinuity of the aquifers; 3) the specific role and extent of the faults on the regional flow; 4) the system's local behaviour where the presence of several boundaries is suspected from pumping tests; 5) the interpretation of geochemical anomalies in groundwater and their relation to the geology; and 6) the data uncertainty and its impact on the regional results. Indeed, a single value taken from the database will often poorly characterize the area. Regional studies generally assume that the entire dataset will provide a reasonably representative picture of the region. This qualitative argument should, however, be quantified.

Due to the size of the study area and the complexity of its geology, it is rather difficult to develop a groundwater-exploration strategy based on this inventory. Indeed, local studies must be performed to assess the hydraulic potential of a specific location. Of course, more permeable units, such as the formations of the Prince Edward Island Group, the undivided Pictou Group, and the Richibucto, Balfour, and Boss Point formations, can first be targeted for water exploration, but there are no guarantees of finding high yields. Conversely, formations of relatively low potential can yield surprisingly large quantities of water locally due to the presence of important fractures. Nevertheless, this project provided essential information for management purposes, such as hydrogeological and geochemical databases, a piezometric map, a mean annual hydrological budget, and conceptual and numerical models for this vast region. Furthermore, this project has already

proven beneficial to several municipalities (Moncton, Sackville, Riverview, Salisbury, and Hillsborough) for their groundwater exploration programs and the delineation of groundwater-protection areas.

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REFERENCES

ADI Limited

2000: Groundwater supply review — village of Hillsborough, New Brunswick; unpublished technical report prepared by ADI Limited, File (80) 1246-002.1, 33 p.

Aller, L., Bennett, T., Lehr, J.H., and Petty, R.J.

1985: DRASTIC: A standardized system for evaluating groundwater pollution potential using hydrogeologic settings; United States Environmental Protection Agency, Robert S. Kerr Environmental Research Laboratory, Ada, Oklahoma, Publication EPA/600/2-85/0108, 163 p.

Barss, M.S., Grant, A.C., Sanford, B.V., and Wade, J.A.

1977: Basement structure, eastern Canada and adjacent areas; Geological Survey of Canada, Map 1400A, scale 1:2 000 000.

Bhury, N.

2002: Analyse macrofossile d'un secteur d'une tourbière ombrotrophe située au sud-est du Nouveau-Brunswick, Canada; Université Laval, Département de géographie, Centre d'études nordiques, 6 p.

Bibby, C. and Shimeld, J.

2000: Compilation of reservoir data for sandstones of the Devonian-Permian Maritimes Basin, eastern Canada; Geological Survey of Canada, Open File 3895, 101 p.

Blatt, H., Middleton, G., and Murray, R.

1980: Origin of Sedimentary Rocks (Second Edition); Prentice-Hall Inc., Englewood Cliffs, New Jersey, 782 p.

Boisvert, V.

2004: Hydrogéologie des formations quaternaires et influence sur la recharge de la région de Moncton, Nouveau-Brunswick; M.Sc. thesis, Université du Québec, Institut national de la recherche scientifique (INRS), Centre Eau, Terre et Environnement, 96 p.

Boisvert, V., Parent, M., Michaud, Y., Lefebvre, R.,

Butler, K.E., and Deblonde, C.

2002: The hydrostratigraphic context of Quaternary units in the Moncton region, New Brunswick — a preliminary assessment; in *Ground and Water: Theory to Practice*; Proceedings of 55th Canadian Geotechnical Conference and 3rd Joint Groundwater Speciality Conference of the International Association of Hydrogeologists—Canadian National Chapter (IAH-CNC) and Canadian Geotechnical Society (CGS), Niagara Falls, Ontario, October 20–23, 2002, p. 235–240.

Bouwer, H. and Rice, R.C.

1976: A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells; *Water Resources Research*, v. 12, no. 3, p. 423–428.

Boyle, D.R.

1991: Groundwater investigations in the Maritime Carboniferous Basin of Canada; Geological Survey of Canada, unpublished poster presented at New Brunswick Department of Natural Resources Annual Review.

Bray, D.I., Demarchant, D.P., and Sullivan, D.L.

1982: Some hydrotechnical problems related to the construction of a causeway in the estuary of the Petitcodiac River, New Brunswick; *Canadian Journal of Civil Engineering*, v. 9, p. 296–307.

Brown, D.D.

1971: Hydrogeology of Taylor Island, New Brunswick; Ph.D. thesis, University of Western Ontario, London, Ontario, 160 p.

Brown, I.C.

1967: Groundwater in Canada; Geological Survey of Canada, Economic Geology Report 24, 219 p.

Butler, J.J., Jr. and Garnett, E.J.

2000: Simple procedures for analysis of slug tests in formations of high hydraulic conductivity using spreadsheet and scientific graphics software; Kansas Geological Survey, Open-File Report 2000-40, 23 p.

Butler, K.E., Parrott, R., Hughes-Clarke, J.E., and Daigle, A.

2002: Delineating river-bottom recharge to the Fredericton aquifer by seismic and electrical imaging; *Atlantic Geology*, v. 38, no. 1, p. 77.

Carr, P.A.

1964: Geology and hydrogeology of the Moncton map-area, New Brunswick, Canada; Ph.D. thesis, University of Illinois, Urbana-Champaign, Illinois, 104 p.

1969: Salt-water intrusion in Prince Edward Island; *Canadian Journal of Earth Sciences*, v. 6, no. 1, p. 63–74.

Carrier, C.

2003: Étude de l'interaction entre le système d'écoulement local d'une tourbière ombrotrophe et le système d'écoulement des eaux souterraines régionales dans le sud-est du Nouveau-Brunswick: caractérisation et modélisation hydrogéologiques; M.Sc. thesis, Université Laval, Québec, Québec, 121 p.

Chalifoux, S., Michaud, Y., Rivard, C., Chiasson, R.,

Deblonde, C., and Boudreau, S.

2003: RADARSAT-1 and Landsat-7 contribution for the sustainable management of groundwater resources (poster and abstract); Geological Society of America, Northeastern Section, 38th Annual Meeting, March 27–29, 2003, Halifax, Nova Scotia; Geological Society of America, Abstracts with Programs, vol. 35, no. 3, p. 3.

Chapman, T.G.

1991: Comment on 'Evaluation of automated techniques for base flow and recession analyses' by R.J. Nathan and T.A. McMahon; *Water Resources Research*, v. 27, no. 7, p. 1783–1784.

- Chi, G., Giles, P.S., Williamson, M.A., Lavoie, D., and Bertrand, R.**
2003: Diagenetic history and porosity evolution of Upper Carboniferous sandstones from the Spring Valley #1 well, Maritimes Basin, Canada — implications for reservoir development; *Journal of Geochemical Exploration*, v. 80, p. 171–191.
- Chow, V.T., Maidment, D.R., and Mays, L.W.**
1988: *Applied Hydrology*; McGraw-Hill Science/Engineering/Math, Singapore, 572 p.
- Conohan, D.**
2002: A compilation and preliminary assessment of groundwater hydrogeochemical data from Carboniferous bedrock aquifers within the province of New Brunswick; B.Sc. thesis, University of New Brunswick, Fredericton, New Brunswick, 22 p.
- Cooper, H.H. and Jacob, C.E.**
1946: A generalized graphical method for evaluating formation constants and summarizing well-field history; *Transactions of the American Geophysical Union*, v. 27, p. 526–534.
- Cooper, H.H., Bredehoeft, J.D., and Papadopoulos, S.S.**
1967: Response of a finite-diameter well to an instantaneous charge of water; *Water Resources Research*, v. 3, no. 1, p. 263–269.
- Coutagne, A.**
1954: Quelques considérations sur le pouvoir évaporant de l'atmosphère, le déficit d'écoulement effectif et le déficit d'écoulement maximum; *La Houille Blanche*, p. 360–374.
- Dyck, W., Garrison, E.W., Godoi, H.O., and Wells, G.S.**
1976: Minor and trace element contents of well waters, Carboniferous Basin, eastern Canada; *Geological Survey of Canada, Open File 340*, 22 maps.
- Elrick, D.E., Reynolds, W.D., and Tan, K.A.**
1989: Hydraulic conductivity measurements in the unsaturated zone using improved well analyses; *Ground Water Monitoring Review*, v. 9, p. 184–193.
- Environment Canada**
2002: Canadian climate normals or averages; Environment Canada, <http://www.climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html>, [accessed January 22, 2007].
2004: The Green Lane: percentage of population reliant on groundwater (municipal, domestic, and rural only); <<http://www.ec.gc.ca/water/images/nature/grdwtr/a5f6e.htm>>, [accessed June 27, 2006].
- Fetter, C.W.**
1980: *Applied Hydrogeology*; Charles E. Merrill and Co., Columbus, Ohio, 488 p.
- Francis, R.M.**
1989: Hydrogeology of the Winter River basin, Prince Edward Island; Prince Edward Island Department of Environment, Water Resources Branch, 118 p.
- Francis, R.M. and Gale, J.E.**
1988: Permeability distribution in a fractured sedimentary aquifer system; *International Association of Hydrogeologists–Canadian National Chapter (IAH-CNC) Proceedings, Atlantic Region, Halifax, Nova Scotia, May 1988*, p. 72–79.
- Furey, P.R. and Gupta, V.K.**
2001: A physically based filter for separating base flow from streamflow time series; *Water Resources Research*, v. 37, no. 1, p. 2709–2722.
- Gemtec Ltd.**
1991: Peatland hydrology, bog 569, Pigeon Hill, New Brunswick; New Brunswick Ministry of Natural Resources and Energy, Mineral Resources Division, Open File Report 91-10, 91 p.
- Gemtec Ltd. and FGA Ltd.**
1994: South Fredericton aquifer protection study; technical report prepared by Gemtec Ltd. and FGA Ltd., File 213.41.
- GEO-SLOPE International Ltd.**
1997: SEEP/W®, version 4 user's guide; GEO-SLOPE International Ltd., <<http://www.geo-slope.com/products/seepw.asp>>, [accessed January 22, 2007].
- Gussow, W.C.**
1953: Carboniferous stratigraphy and structural geology of New Brunswick, Canada; *American Association of Petroleum Geologists Bulletin*, v. 37, p. 1713–1816.
- Hacquebard, P.A. and Barss, M.S.**
1970: Palaeogeography and facies aspects of the Minto coal seam, New Brunswick, Canada; *Sixth International Congress on Carboniferous Stratigraphy and Geology*, 1967, Sheffield, United Kingdom, v. III, p. 861–872.
- Hamel, A.**
2002: Détermination de la recharge des aquifères de roc fracturé du sud-ouest du Québec; *Mémoire de maîtrise, Université Laval, Québec, Québec*, 288 p.
- Hamel, A., Therrien, R., and Gélinas, P.J.**
2001: Groundwater recharge of fractured rock aquifers in south-western Quebec; *Proceedings of 54th Canadian Geotechnical Conference and 2nd Joint Groundwater Speciality Conference of the International Association of Hydrogeologists–Canadian National Chapter (IAH-CNC) and Canadian Geotechnical Society (CGS)*, September 16–19, Calgary, Alberta, p. 1078–1084.
- Health Canada**
2003: Guidelines for Canadian drinking water quality — summary table; <http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/doc_sup-appui/sum_guide-res_recom/index_e.html>, [accessed January 22, 2007].
- Healy, R.W. and Cook, P.G.**
2002: Using groundwater levels to estimate recharge; *Hydrogeology Journal*, v. 10, p. 91–109.
- Hobson, G.D. and Carr, P.A.**
1967: Hammer seismic survey, Moncton map-area, New Brunswick; *Geological Survey of Canada, Paper 65-43*, 9 p.
- Jacques Whitford and Associates Limited**
1990a: Water supply and wastewater treatment for industrial development in Prince Edward Island; unpublished technical report prepared by Jacques Whitford and Associates Limited, Project 5520, v. 1 of 2, 137 p.
1990b: Salt water well study; unpublished technical report prepared by Jacques Whitford and Associates Limited for Prince Edward Island Department of Environment, Project 5424, 52 p.
- Jacques Whitford Environment Ltd.**
1992: Final report on town of Amherst wellfield development, Amherst, Nova Scotia; technical report prepared by Jacques Whitford Environment Ltd., Project 6805, v. 1, 36 p.
1995: Sussex well field protection plan, Sussex, New Brunswick; technical report prepared by Jacques Whitford Environment Ltd., Project 51258, 49 p.

Jacques Whitford Environment Ltd. (cont.)

- 1998: Phase II report: salt water well exploration program, Borden-Carleton, Prince Edward Island; technical report prepared by Jacques Whitford Environment Ltd., Project 90153/12289, 15 p.

Johnson, M.

- 2002: Withdrawal water use in New Brunswick; unpublished technical report, New Brunswick Department of Environment and Local Government, Sciences and Reporting Branch, 73 p.

Johnson, S.C.

- 1995a: A preliminary report on the stratigraphy of Late Namurian to Stephanian fluvial strata in southeastern New Brunswick; *in* Current Research 1995-E, Geological Survey of Canada, p. 313–320.
- 1995b: Carboniferous geology of the Cape Tormentine area (NTS 11 L/04), Westmorland County, New Brunswick; New Brunswick Department of Natural Resources and Energy, Minerals and Energy Division. Map Plate 95-8 (revised March 2002).
- 1995c: Carboniferous geology of the Port Elgin area (NTS 21 I/01), Westmorland County, New Brunswick; New Brunswick Department of Natural Resources and Energy, Minerals and Energy Division, Map Plate 95-9 (revised March 2002).
- 1997: Carboniferous geology of the Amherst area (NTS 21 H/16 and part of 21H/09), Westmorland County, New Brunswick; New Brunswick Department of Natural Resources and Energy, Minerals and Energy Division, Map Plate 97-9 (revised March 2002).

Johnson, S.C. and St. Peter, C.

- 1997: Carboniferous geology of the Moncton map area (NTS 21 I/02), Westmorland and Albert counties, New Brunswick; New Brunswick Department of Natural Resources and Energy, Minerals and Energy Division, MP 97-7 (revised March 2002).

Keys, D. and Henderson, R.E.

- 1987: An investigation of the peat resources of New Brunswick; New Brunswick Department of Natural Resources and Energy, Minerals and Energy Division, Open File Report 83-10, 228 p.

Kruseman, G.P. and de Ridder, N.A.

- 2000: Analysis and Evaluation of Pumping Test Data (Second Edition); International Institute for Land Reclamation and Improvement, Netherlands, 377 p.

Lohman, S.W.

- 1979: Ground-water hydraulics; United States Geological Survey, Professional Paper 708, 70 p.

Lynch, G., Giles, P.S., Deblonde, C., Barr, S.M., Piper, D.J.W., St. Peter, C., Hetu, R.J., Johnson, S.C., Pe-Piper, G., St. Jean, R., Murphy, J.B., Chandler, F.W., and Boehner, R.C.

- 1998: Magdalen Basin NATMAP onshore geological database; Geological Survey of Canada, Open File 3564, CD-ROM.

MacDougall, J.I., Veer, C., and Wilson, F.

- 1988: Soils of Prince Edward Island; Agriculture Canada, Research Branch, Publication 83-54, 210 p.

McCutcheon, S.R. and Robinson, P.T.

- 1987: Geological constraints on the genesis of the Maritimes Basin, Atlantic Canada; *in* Sedimentary Basins and Basin-Forming Mechanisms, (ed.) C. Beaumont and A.J. Tankard, Canadian Society of Petroleum Geologists, Memoir 12, p. 287–297.

McIntosh, J.R.

- 1984: Groundwater hydrographs in Nova Scotia, 1965–1981; Nova Scotia Department of Environment, ISBN 0-88871-045-3, 185 p.

McLeod, M.J. and Johnson, S.C.

- 1999a: Bedrock geological compilation of the Petitcodiac area (NTS 21 H/14), Kings, Westmorland, and Queens counties, New Brunswick; New Brunswick Department of Natural Resources and Energy, Minerals and Energy Division, Map Plate 99-23.
- 1999b: Bedrock geological compilation of the Hillsborough area (NTS 21 H/15), Albert and Westmorland counties, New Brunswick; New Brunswick Department of Natural Resources and Energy, Minerals and Energy Division, Map Plate 99-26.

Meteorological Service of Canada

- 2002: Historical adjusted climate database for Canada, version December 2002: rehabilitated precipitation and homogenized temperature data sets; Meteorological Service of Canada, Climate Research Branch, Climate Monitoring and Data Interpretation Division, Adjusted Historical Canadian Climate Data (AHCCD), <<http://www.cccma.bc.ec.gc.ca/hccd/>>, [accessed June 28, 2006].

Michaud Y., Lefebvre R., and McCormack R.

- 2004: Guide méthodologique pour la cartographie hydrogéologique régionale des aquifères granulaires de surface; report submitted to the Ministère de l'Environnement du Québec.

Molz, F.J., Morin, R.H., Hess, A.E., Melville, J.G., and Guven, O.

- 1989: The impeller meter for measuring aquifer permeability variations: evaluation and comparison with other tests; Water Resources Research, v. 25, no. 7, p. 1677–1683.

Morin, R.H., Calvert, T.R., Rivard, C., and Michaud, Y.

- 2003: Integrating surface and borehole geophysics with pumping tests to investigate the hydrostratigraphy of the Maritimes Carboniferous Basin: case study from Sackville, New Brunswick (abstract); Geological Society of America, Northeastern Section, 38th Annual Meeting, March 27–29, 2003, Halifax, Nova Scotia; Geological Society of America, Abstracts with Programs, vol. 35, no. 3, p. 31.

Morin, R.H., Hess, A.E., and Paillet, F.L.

- 1988: Determining the distribution of hydraulic conductivity in a fractured limestone aquifer by simultaneous injection and geophysical logging; Ground Water, v. 26, no. 5, p. 587–595.

Morin, R.H., Thériault, T., Therrien, R., and Michaud, Y.

- 2002: Generalized hydrogeologic properties of the Maritimes Carboniferous Basin from downhole measurements in selected wells, eastern Canada; *in* Ground and Water: Theory to Practice, Proceedings of 55th Canadian Geotechnical Conference and 3rd Joint Groundwater Speciality Conference of the International Association of Hydrogeologists–Canadian National Chapter (IAH-CNC) and Canadian Geotechnical Society (CGS), Niagara Falls, Ontario, October 20–23, 2002, p. 247–254.

Mutch, J.P., Jackson, R.E., Priddle, M.W., and Bray, D.I.

- 1992: The fate and simulation of aldicarb in the soil and groundwater of Prince Edward Island; Environment Canada, Scientific Series, No. 194, 96 p.

- Nastev, M., Lefebvre, R., Rivera, A., and Martel, R.**
2006a: Quantitative assessment of regional rock aquifers, south-western Quebec, Canada; *Water Resources Management*, v. 20, p. 1–18.
- Nastev, M., Rivera, A., Lefebvre, R., Martel, R., and Savard, M.M.**
2006b: Numerical simulation of groundwater flow in regional rock aquifers, southwestern Quebec, Canada; *Hydrogeology Journal*, v. 13, p. 835–848.
- New Brunswick Department of Environment**
1992: Summary of 1991 groundwater levels from observation wells of the groundwater level monitoring network in New Brunswick; New Brunswick Department of Environment, Environmental Planning and Sciences Branch, Water Resource Monitoring Section, 48 p.
- New Brunswick Department of Environment and Local Government**
2001: Groundwater in New Brunswick; New Brunswick Department of Environment and Local Government, unpublished technical sheet.
- Nickerson, W.A.**
1994: Geophysical constraints on the stratigraphy, structure and tectonic evolution of the Late Devonian/Carboniferous Moncton Subbasin, New Brunswick; Ph.D. thesis, Memorial University, St. John's, Newfoundland and Labrador, 393 p.
- Nyvall, J.**
2002: Soil water storage capacity and available soil moisture; British Columbia Ministry of Agriculture, Food, and Fisheries, Water Conservation Factsheet 619000-1, 4 p.
- Peters, L.P.**
1981: Summary of work to date on the hydrochemistry of the Carboniferous Basin of New Brunswick; New Brunswick Department of Environment and Local Government, unpublished internal report, 29 p.
- Plumb, R.A. and Luthi, S.M.**
1989: Analysis of borehole images and their application to geologic modelling of an eolian reservoir; *Society of Petroleum Engineers Formation Evaluation*, v. 4, p. 505.
- Rampton, V.N., Gauthier, R.C., Thibault, J., and Seaman, A.A.**
1984: Quaternary geology of New Brunswick; Geological Survey of Canada, Memoir 416, 77 p.
- Rivera, A., Crowe, A., Kohut, A., Rudolph, D., Baker, C., Pupek, D., Shaheen, N., Lewis, M., and Parks, K.**
2003a: Canadian Framework for Collaboration on Groundwater (CFCG); Geological Survey of Canada, Report M40-62/2003, 60 p., <<http://www.nwri.ca/publications/pub2004/04-160-e.html>>, [accessed January 22, 2007].
- Rivera, A., Grasby, S. Sharpe, D., and Tóth J.**
2003b: Towards an inventory of the groundwater resources of Canada; Geological Survey of Canada, unpublished internal report, v. 4, March 31, 2003.
- Rivard, C., Deblonde, C., Michaud, Y., Boisvert, V., Carrier, C., Castonguay, S., and Lefebvre, R.**
2005a: Hydrogeological atlas of the south-central area of the Maritimes Carboniferous Basin; Geological Survey of Canada, Open File 4884, 54 p. and CD-ROM.
- Rivard, C., Marion, J., Michaud, Y., Benhammane, S., Morin, A., Lefebvre, R., and Rivera, A.**
2003: Étude de l'impact potentiel des changements climatiques sur les ressources en eau souterraine dans l'Est du Canada; Geological Survey of Canada, Open File 1577, 39 p.
- Rivard, C., Michaud, Y., Boisvert, V., Calvert, T., Morin, R.H., Deblonde, C., Lefebvre, R., and Pupek, D.A.**
2005b: Hydrogeological data from the south-central area of the Maritimes Carboniferous Basin (MGWI project); Geological Survey of Canada, Open File 4942, 143 p.
- Ross, M., Parent, M., Michaud, Y., Boisvert, E., and Girard, F.**
2001: On the construction of 3-D geological models for applications in regional hydrogeology in complex Quaternary terrains of eastern Canada (extended abstract); *in* Geological Models for Groundwater Flow Modelling Workshop, Geological Society of America, North-Central Section, 35th Annual Meeting, April 22, 2001; Illinois State Geological Survey, Open File 2001-1, p. 34–37.
- Savard, M., Simpson, S., Smirnoff, A., Paradis, D., Somers, G., Van Bochove, É., and Thériault, G.**
2004: A study of the nitrogen cycle in the Wilmot River watershed, Prince Edward Island: initial results; *Proceedings of the International Association of Hydrogeologists Conference*, October 24–27, 2004, Québec, Québec, Session 4A (Water Quality), p. 20–27.
- Scanlon, B.R., Healy, R.W., and Cook, P.G.**
2002: Choosing appropriate techniques for quantifying groundwater recharge; *Hydrogeology Journal*, v. 10, p. 18–39.
- Sloto R.A. and Crouse, M.Y.**
1996: HYSEP: a computer program for streamflow hydrograph separation and analysis; United States Geological Survey, Water-Resources Investigations, Report 96-4040, 46 p.
- St. Peter, C.**
1993: Maritimes Basin evolution: key geologic and seismic evidence from the Moncton Subbasin of New Brunswick; *Atlantic Geology*, v. 29, p. 233–270.
1995a: Bedrock geology of North River/Salisbury area (21 I/03a), New Brunswick; New Brunswick Department of Natural Resources and Energy, Minerals and Energy Division, Map Plate 95-22F (revised August 2001).
1995b: Bedrock geology of Killams Mills/Nevers Brook area, (21 I/03b), New Brunswick; New Brunswick Department of Natural Resources and Energy, Minerals and Energy Division, Map Plate 95-22G (revised August 2001).
1995c: Bedrock geology of Ridge Brook/Havelock area, (21 I/03c), New Brunswick; New Brunswick Department of Natural Resources and Energy, Minerals and Energy Division, Map Plate 95-22H (revised August 2001).
1995d: Bedrock geology of Canaan/Gallagher Ridge area, (21 I/03h), New Brunswick; New Brunswick Department of Natural Resources and Energy, Minerals and Energy Division, Map Plate 95-22J (revised August 2001).
2000: Geology and hydrology descriptions of bedrock field trip stops in the Moncton Subbasin, New Brunswick; Maritimes Groundwater Initiative Field Trip, September 16–17, 2000, unpublished internal report prepared for the New Brunswick Department of Natural Resources, 10 p.
- Steenhuis, T.S., Winchell, M., Rossing, J., Zollweg, J.A., and Walter, M.F.**
1995: SCS runoff equation revisited for variable-source runoff areas; *Journal of Irrigation and Drainage Engineering*, v. 121, no. 3, p. 234–238.
- Tecsult Inc.**
2003: Apport des images RADARSAT-1 et Landsat pour une gestion durable des ressources en eau souterraine; Tecsult Inc., Rapport exécutif, 9 p.

Terzaghi, R.

1965: Sources of error in joint surveys; *Geotechnique*, v. 15, p. 287–304.

Thériault, T.

2001: Détermination de la transmissivité des différentes lithologies composant le bassin du Carbonifère dans les Maritimes; B.Sc. thesis, Université Laval, Québec, Québec, 24 p.

Todd, D.K.

1980: *Groundwater Hydrology* (Second Edition); John Wiley and Sons, Inc., New York, New York, 535 p.

Turc, L.

1954: Le bilan d'eau des sols: relations entre les précipitations, l'évapotranspiration et l'écoulement; *Annales agronomiques*, Série A, p. 491–595.

United States Soil Conservation Service

1972: *National Engineering Handbook: Section 4 — Hydrology*; United States Department of Agriculture, Natural Resources Conservation Service, available from United States Government Printing Office, Washington, DC, <<http://www.hydrocad.net/neh-4.htm>>, [accessed January 22, 2007].

Valsangkar, H.M. and Gregory, A.

2001: New Brunswick groundwater level monitoring network — data summary, 1978–1992; New Brunswick Department of Environment and Local Government, Sciences and Planning Division, 168 p.

van de Poll, H.W., Gibling, M.R., and Hyde, R.S.

1995: Upper Paleozoic rocks; *in* Chapter 5 of *Geology of the Appalachian-Caledonian Orogen in Canada and Greenland*, (ed.) H. Williams; Geological Survey of Canada, *Geology of Canada*, no. 6, p. 449–566 (*also* Geological Society of America, *Geology of North America*, v. F-1).

van der Kamp, G.

1981: Salt water intrusion in a layered coastal aquifer at York Point, Prince Edward Island; National Hydrology Research Institute, Inland Waters Directorate, Scientific Series No. 121, Paper 14.

Vaughan, J.G. and Somers, G.H.

1980: Regional water resources, Cumberland County, Nova Scotia; Nova Scotia Department of Environment, 81 p.

WASY GmbH

1998: FEFLOW® reference manual; WASY GmbH, Institute of Water Resources Planning and System Research Ltd., Berlin, <<http://www.wasy.de/english/produkte/feflow/index.html>>, [accessed January 22, 2007].

Wheeler, J., Arun, J.V., and Belyea, P.S.

1985: Geotechnical investigation collector sewer tunnel, Petlocodiac River crossing, City of Moncton, New Brunswick; technical report prepared by Jacques Whitford and Associates Limited for Boyd A. Touchie Engineering Ltd., 110 p.

Williams, H. (ed.)

1995: Geology of the Appalachian-Caledonian Orogen in Canada and Greenland; Geological Survey of Canada, *Geology of Canada*, no. 6, 944 p. (*also* Geological Society of America, *Geology of North America*, v. F-1).

Young, J.J., Somers, G.H., and Raymond, B.G.

2002: Distribution and trends for nitrate in Prince Edward Island groundwater and surface waters; *in* Proceedings of the National Conference on Agricultural Nutrients and their Impact on Rural Water Quality, April 29–30, 2002; Agricultural Institute of Canada Foundation.

Appendix A

Monitoring well locations and their fluctuations

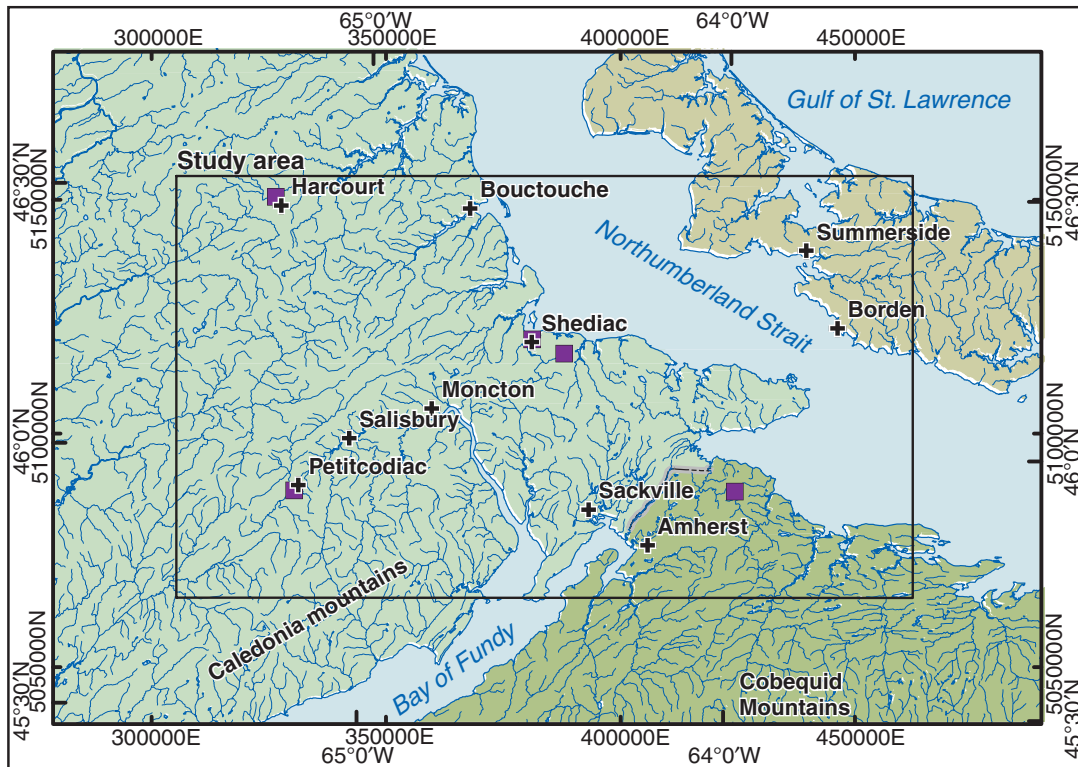


Figure A-1. Locations of the five monitoring wells, Maritimes Groundwater Initiative study area.

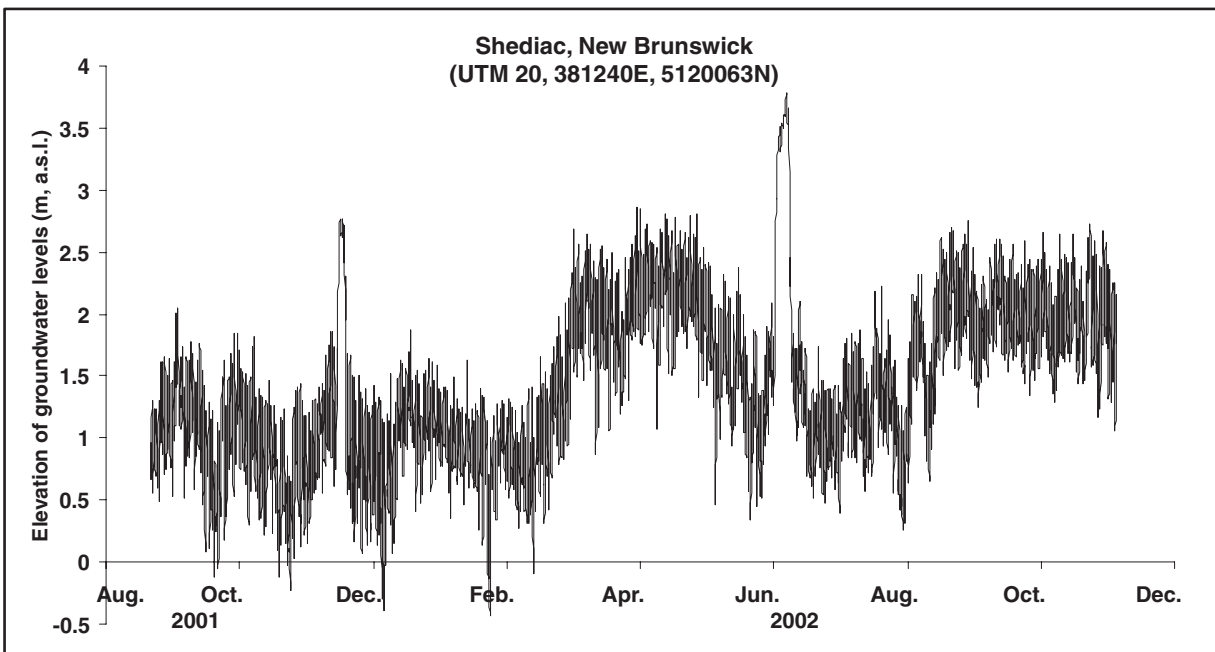


Figure A-2. Water-level fluctuations in the Shediac (New Brunswick) monitoring well, August 2001 to November 2002. This well is affected by tides.

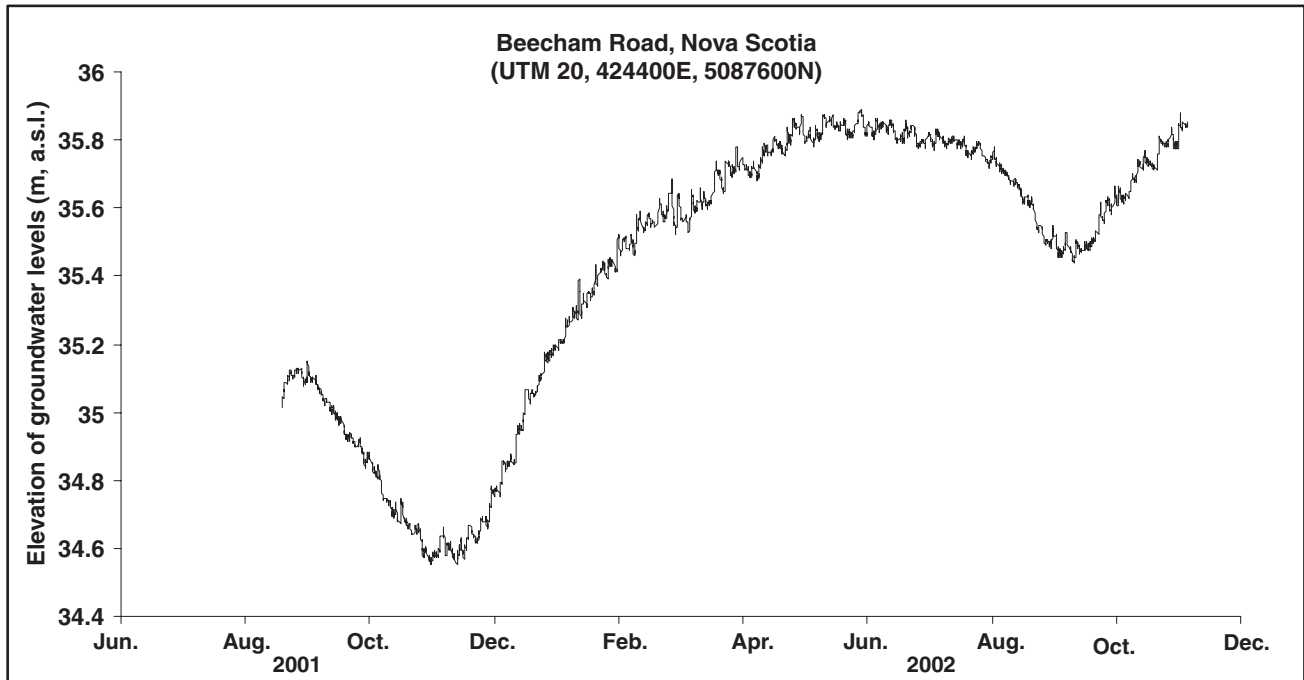


Figure A-3. Water-level fluctuations in the Beecham Road (Nova Scotia) monitoring well, June 2001 to November 2002.

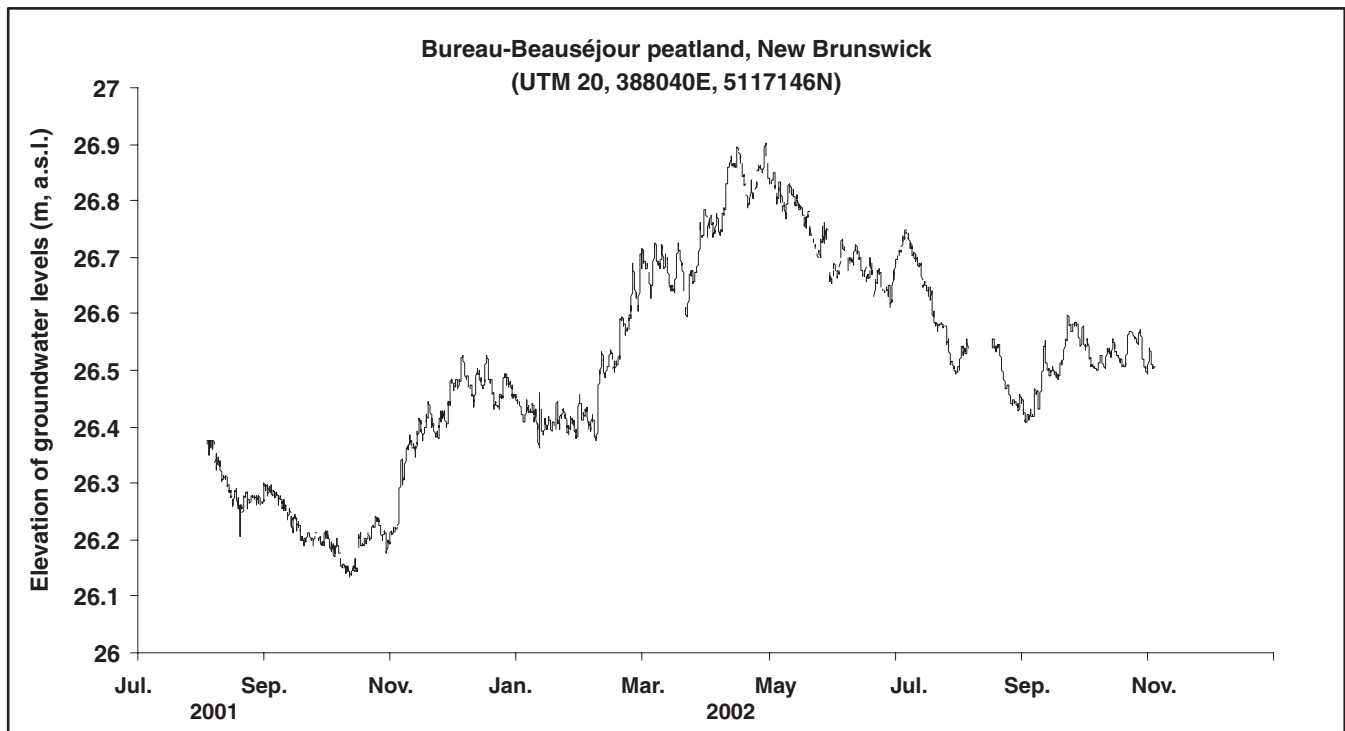


Figure A-4. Water-level fluctuations in the Bureau-Beauséjour peatland (New Brunswick) monitoring well, July 2001 to November 2002.

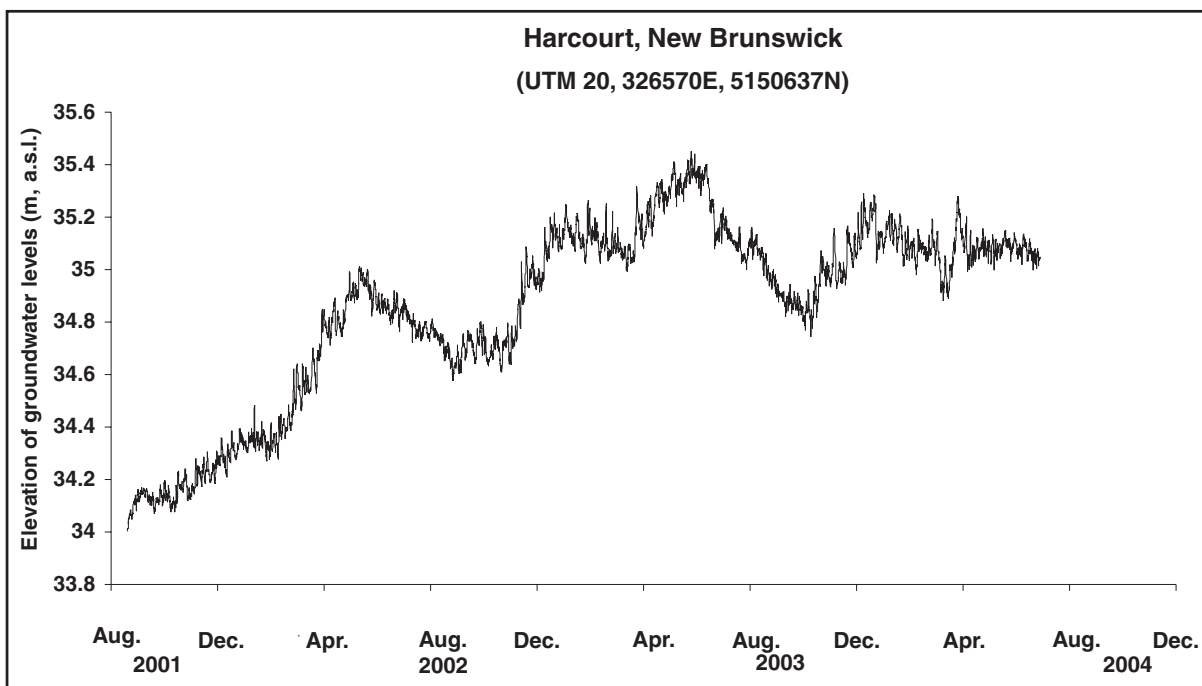


Figure A-5. Water-level fluctuations in the Harcourt (New Brunswick) monitoring well, August 2001 to August 2004.

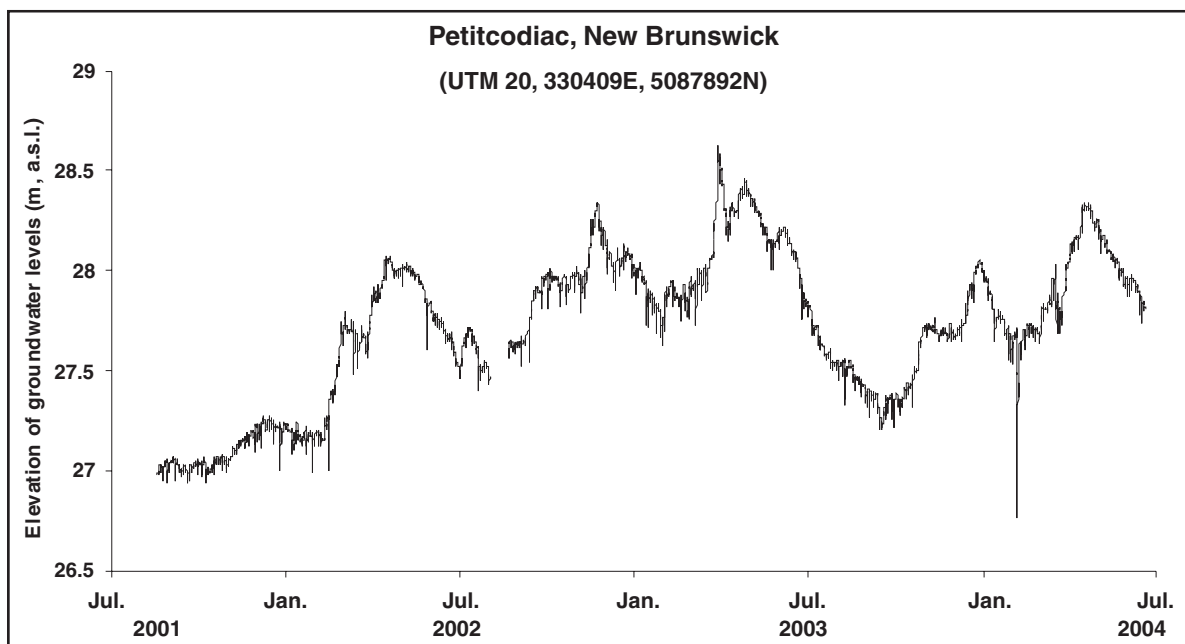


Figure A-6. Natural water-level fluctuations in the Petitcodiac (New Brunswick) monitoring well, July 2001 to July 2004.

Appendix B

Results obtained from packer tests

The following abbreviations apply to all tables in this appendix: b_i , length of interval i ; K , hydraulic conductivity; K_H , horizontal hydraulic conductivity; K_i , hydraulic conductivity of interval i ; K_v , vertical hydraulic conductivity; T , transmissivity.

Table B-1. Hydraulic conductivity obtained using packer test at each interval of the Shediac, New Brunswick well (section 3.9 m).

Depth 1 (m)	Depth 2 (m)	Middle depth (m)	T (m ² /s)	K (m/s)	Type of rock	Interval (m)	$K_i \cdot b_i$	b_i / K_i
42.81	46.71	44.76	9.73×10^{-5}	2.49×10^{-5}	Sandstone	3.90	9.73×10^{-5}	1.56×10^{-5}
						2.00	1.00×10^{-7}	4.00×10^{-7}
48.71	52.61	50.66	3.10×10^{-6}	7.95×10^{-7}	Sandstone	3.90	3.10×10^{-6}	4.91×10^{-6}
						0.90	4.50×10^{-8}	1.80×10^{-7}
53.51	57.41	55.46	2.47×10^{-7}	6.35×10^{-8}	Siltstone	3.90	2.47×10^{-7}	6.15×10^{-7}
						14.60		
$K_{\text{matrix}} = 5 \times 10^{-8}$ m/s $K_H = \Sigma K_i \cdot b_i / \Sigma b_i = 6.90 \times 10^{-6}$ $K_v = \Sigma b_i / \Sigma (b_i / K_i) = 1.17 \times 10^{-7}$ $K_H / K_v = 58.9$								

Table B-2. Hydraulic conductivity obtained using packer test at each interval of the Fort Lawrence, Nova Scotia well (section 2.34 m).

Depth 1 (m)	Depth 2 (m)	Middle depth (m)	T (m ² /s)	K (m/s)	Type of rock	Interval (m)	$K_i \cdot b_i$	b_i / K_i
7.51	9.85	8.68	3.36×10^{-4}	1.43×10^{-4}	Fine-grained sandstone	2.34	3.36×10^{-4}	1.63×10^{-4}
						3.66	1.83×10^{-7}	7.32×10^{-7}
13.51	15.85	14.68	7.27×10^{-5}	3.11×10^{-5}	Silt and shale	2.34	7.27×10^{-5}	7.53×10^{-4}
						4.16	2.08×10^{-7}	8.32×10^{-7}
20.01	22.35	21.18	3.54×10^{-5}	1.51×10^{-5}	Fine-grained sandstone	2.34	3.54×10^{-5}	1.55×10^{-5}
						2.16	1.08×10^{-7}	4.32×10^{-7}
24.51	26.85	25.68	8.54×10^{-8}	3.65×10^{-8}	Fine-grained sandstone	2.34	8.54×10^{-8}	6.41×10^{-7}
						5.16	2.58×10^{-7}	1.03×10^{-8}
32.01	34.35	33.18	6.66×10^{-5}	2.84×10^{-5}	Silt and shale	2.34	6.66×10^{-5}	8.23×10^{-4}
						11.91	5.96×10^{-7}	2.38×10^{-8}
46.26	48.60	47.43	6.38×10^{-7}	2.73×10^{-7}	Sandstone	2.34	6.38×10^{-7}	8.58×10^{-6}
						2.91	1.46×10^{-7}	5.82×10^{-7}
51.51	53.85	52.68	3.43×10^{-6}	1.47×10^{-6}	Siltstone	2.34	3.43×10^{-6}	1.60×10^{-6}
						3.72	1.86×10^{-7}	7.44×10^{-7}
57.57	59.91	58.74	5.87×10^{-7}	2.51×10^{-7}	Siltstone	2.34	5.87×10^{-7}	9.32×10^{-6}
						52.40		
$K_{\text{matrix}} = 5 \times 10^{-8}$ m/s $K_H = \Sigma K_i \cdot b_i / \Sigma b_i = 9.86 \times 10^{-6}$ $K_v = \Sigma b_i / \Sigma (b_i / K_i) = 6.92 \times 10^{-8}$ $K_H / K_v = 142.6$								

Table B-3. Hydraulic conductivity obtained using packer test at each interval of the Petitcodiac, New Brunswick well (section 2.34 m).

Depth 1 (m)	Depth 2 (m)	Middle depth (m)	T (m ² /s)	K (m/s)	Type of rock	Interval (m)	$K_i \cdot b_i$	b_i/K_i
15.21	17.55	16.38	2.23×10^{-7}	9.53×10^{-8}	Silt and shale	2.34	2.23×10^{-7}	2.46×10^{-7}
						8.36	4.18×10^{-7}	1.67×10^{-8}
25.91	28.25	27.08	9.24×10^{-7}	3.95×10^{-7}	Conglomerate and sandstone	2.34	9.24×10^{-7}	5.92×10^{-6}
						9.26	4.63×10^{-7}	1.85×10^{-8}
37.51	39.85	38.68	5.34×10^{-6}	2.28×10^{-6}	Silt and shale	2.34	5.34×10^{-6}	1.03×10^{-6}
						3.16	1.58×10^{-7}	6.32×10^{-7}
43.01	45.35	44.18	5.25×10^{-6}	2.24×10^{-6}	Conglomerate and sandstone	2.34	5.25×10^{-6}	1.04×10^{-6}
						3.16	1.58×10^{-7}	6.32×10^{-7}
48.51	50.85	49.68	4.29×10^{-6}	1.83×10^{-6}	Silt and shale	2.34	4.29×10^{-6}	1.28×10^{-6}
						1.16	5.80×10^{-8}	2.32×10^{-7}
52.01	54.35	53.18	9.12×10^{-8}	3.90×10^{-8}	Sandstone	2.34	9.12×10^{-8}	6.01×10^{-7}
						8.16	4.08×10^{-7}	1.63×10^{-8}
62.51	64.85	63.68	9.30×10^{-8}	3.97×10^{-8}	Conglomerate and sandstone	2.34	9.30×10^{-8}	5.89×10^{-7}
						6.66	3.33×10^{-7}	1.33×10^{-8}
71.51	73.85	72.68	1.09×10^{-7}	4.65×10^{-8}	Sandstone	2.34	1.09×10^{-7}	5.03×10^{-7}
						15.41	7.71×10^{-7}	3.08×10^{-8}
89.26	91.60	90.43	1.08×10^{-7}	4.61×10^{-8}	Conglomerate and sandstone	2.34	1.08×10^{-7}	5.08×10^{-7}
						9.91	4.96×10^{-7}	1.98×10^{-8}
101.51	103.85	102.68	3.04×10^{-8}	1.30×10^{-8}	Conglomerate and sandstone	2.34	3.04×10^{-8}	1.80×10^{-8}
						88.64		
$K_{\text{matrix}} = 5 \times 10^{-8}$ m/s $K_H = \Sigma K_i \cdot b_i / \Sigma b_i = 2.22 \times 10^{-7}$ $K_V = \Sigma b_i / \Sigma (b_i/K_i) = 5.10 \times 10^{-8}$ $K_H / K_V = 4.4$								

Table B-4. Hydraulic conductivity obtained using packer test at each interval of the Borden, Prince Edward Island well (section 2.34 m).

Depth 1 (m)	Depth 2 (m)	Middle depth (m)	T (m ² /s)	K (m/s)	Type of rock	Interval (m)	$K_i \cdot b_i$	b_i/K_i
15.51	17.85	16.68	6.15×10^{-6}	2.63×10^{-6}	Sandstone	2.34	6.15×10^{-6}	8.90×10^{-5}
						4.96	2.48×10^{-7}	9.92×10^{-7}
22.81	25.15	23.98	7.50×10^{-7}	3.21×10^{-7}	Sandstone	2.34	7.50×10^{-7}	7.30×10^{-6}
						24.86	1.24×10^{-6}	4.97×10^{-8}
50.01	52.35	51.18	1.04×10^{-4}	4.44×10^{-5}	Sandstone	2.34	1.04×10^{-4}	5.27×10^{-4}
						7.16	3.58×10^{-7}	1.43×10^{-8}
59.51	61.85	60.68	6.42×10^{-5}	2.74×10^{-5}	Sandstone	2.34	6.42×10^{-5}	8.53×10^{-4}
						3.66	1.83×10^{-7}	7.32×10^{-7}
65.51	67.85	66.68	8.65×10^{-6}	3.70×10^{-6}	Sandstone	2.34	8.65×10^{-6}	6.33×10^{-5}
						6.66	3.33×10^{-7}	1.33×10^{-8}
74.51	76.85	75.68	1.67×10^{-4}	7.12×10^{-5}	Sandstone	2.34	1.67×10^{-4}	3.29×10^{-4}
						8.16	4.08×10^{-7}	1.63×10^{-8}
85.01	87.35	86.18	1.80×10^{-5}	7.70×10^{-6}	Siltstone	2.34	1.80×10^{-5}	3.04×10^{-5}
						71.84		
$K_{\text{matrix}} = 5 \times 10^{-8}$ m/s $K_H = \Sigma K_i \cdot b_i / \Sigma b_i = 5.17 \times 10^{-6}$ $K_V = \Sigma b_i / \Sigma (b_i/K_i) = 3.04 \times 10^{-5}$ $K_H / K_V = 80.4$								

Table B-5. Hydraulic conductivity obtained using packer test at each interval of the Harcourt, New Brunswick well (section 2.34 m).

Depth 1 (m)	Depth 2 (m)	Middle depth (m)	T (m ² /s)	K (m/s)	Type of rock	Interval (m)	$K_i \cdot b_i$	b_i/K_i
15.01	17.35	16.18	2.28×10^{-5}	9.74×10^{-6}	Sandstone	2.34	2.28×10^{-5}	2.40×10^{-5}
15.01	17.35	16.18	2.72×10^{-5}	1.16×10^{-5}	Sandstone	2.34	2.72×10^{-5}	4.68×10^{-7}
						3.66	1.83×10^{-7}	7.32×10^{-7}
21.01	23.35	22.18	2.55×10^{-5}	1.09×10^{-5}	Siltstone	2.34	2.55×10^{-5}	4.68×10^{-7}
						13.16	6.58×10^{-7}	2.63×10^{-8}
36.51	38.85	37.68	1.32×10^{-5}	5.64×10^{-6}	Sandstone	2.34	1.32×10^{-5}	4.68×10^{-7}
						17.16	8.58×10^{-7}	3.43×10^{-8}
56.01	58.35	57.18	7.64×10^{-8}	3.27×10^{-8}	Sandstone	2.34	7.64×10^{-8}	4.68×10^{-7}
						19.16	9.58×10^{-7}	3.83×10^{-8}
77.51	79.85	78.68	2.28×10^{-4}	9.74×10^{-5}	Mix of sandstone, siltstone and shale	2.34	2.28×10^{-4}	4.68×10^{-7}
						7.16	3.58×10^{-7}	1.43×10^{-8}
87.01	89.35	88.18	1.36×10^{-7}	5.81×10^{-8}	Sandstone	2.34	1.36×10^{-7}	4.68×10^{-7}
						15.16	7.58×10^{-7}	3.03×10^{-8}
104.51	106.85	105.68	1.31×10^{-2}	5.60×10^{-3}	Sandstone	2.34	1.31×10^{-2}	4.68×10^{-7}
						1.66	8.30×10^{-8}	3.03×10^{-8}
108.51	110.85	109.68	1.88×10^{-4}	8.05×10^{-5}	Sandstone	2.34	1.88×10^{-4}	4.68×10^{-7}
						98.18		
$K_{\text{matrix}} = 5 \times 10^{-8} \text{ m/s}$ $K_H = \Sigma K_i \cdot b_i / \Sigma b_i = 1.39 \times 10^{-4}$ $K_V = \Sigma b_i / \Sigma (b_i/K_i) = 5.12 \times 10^{-8}$ $K_H / K_V = 2707.5$								

Table B-6. Hydraulic conductivity obtained using packer test at each interval of the Port Elgin, New Brunswick well (section 2.14 m).

Depth 1 (m)	Depth 2 (m)	Middle depth (m)	T (m ² /s)	K (m/s)	Type of rock	Interval (m)	$K_i \cdot b_i$	b_i/K_i
29.30	31.44	30.37	1.92×10^{-6}	9.00×10^{-7}	Sandstone	2.14	1.92×10^{-6}	2.37×10^{-6}
						1.87	9.32×10^{-8}	3.73×10^{-7}
33.30	35.44	34.37	2.02×10^{-4}	9.46×10^{-5}	Sandstone	2.14	2.02×10^{-4}	2.26×10^{-4}
						2.86	1.43×10^{-7}	5.73×10^{-7}
38.30	40.44	39.37	1.58×10^{-6}	7.40×10^{-7}	Sandstone	2.14	1.58×10^{-6}	2.89×10^{-6}
						11.14		
$K_{\text{matrix}} = 5 \times 10^{-8} \text{ m/s}$ $K_H = \Sigma K_i \cdot b_i / \Sigma b_i = 1.85 \times 10^{-5}$ $K_V = \Sigma b_i / \Sigma (b_i/K_i) = 1.11 \times 10^{-7}$ $K_H / K_V = 165.7$								

Appendix C

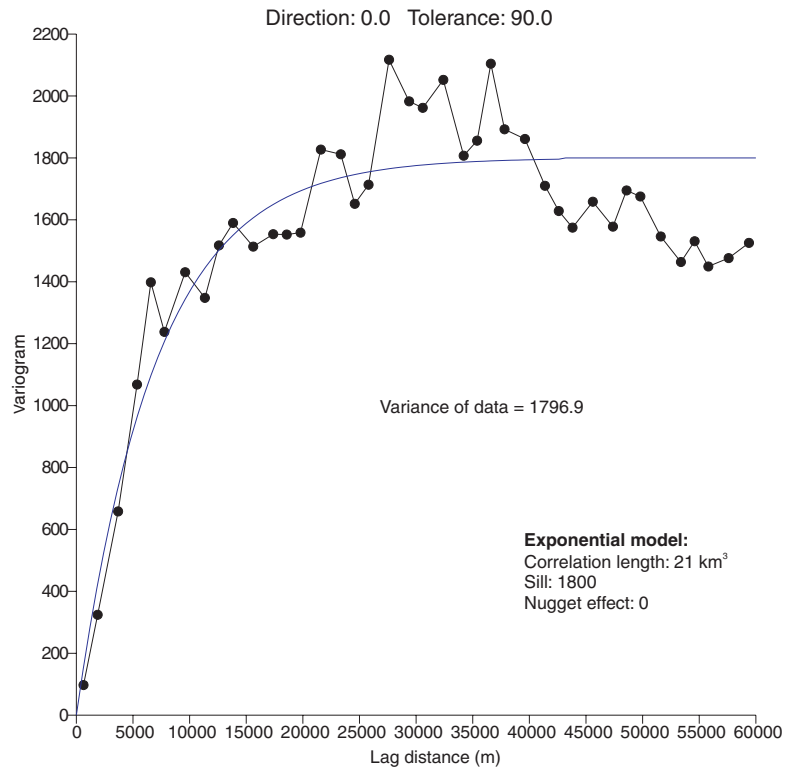


Figure C-1: Water-level measurement variogram

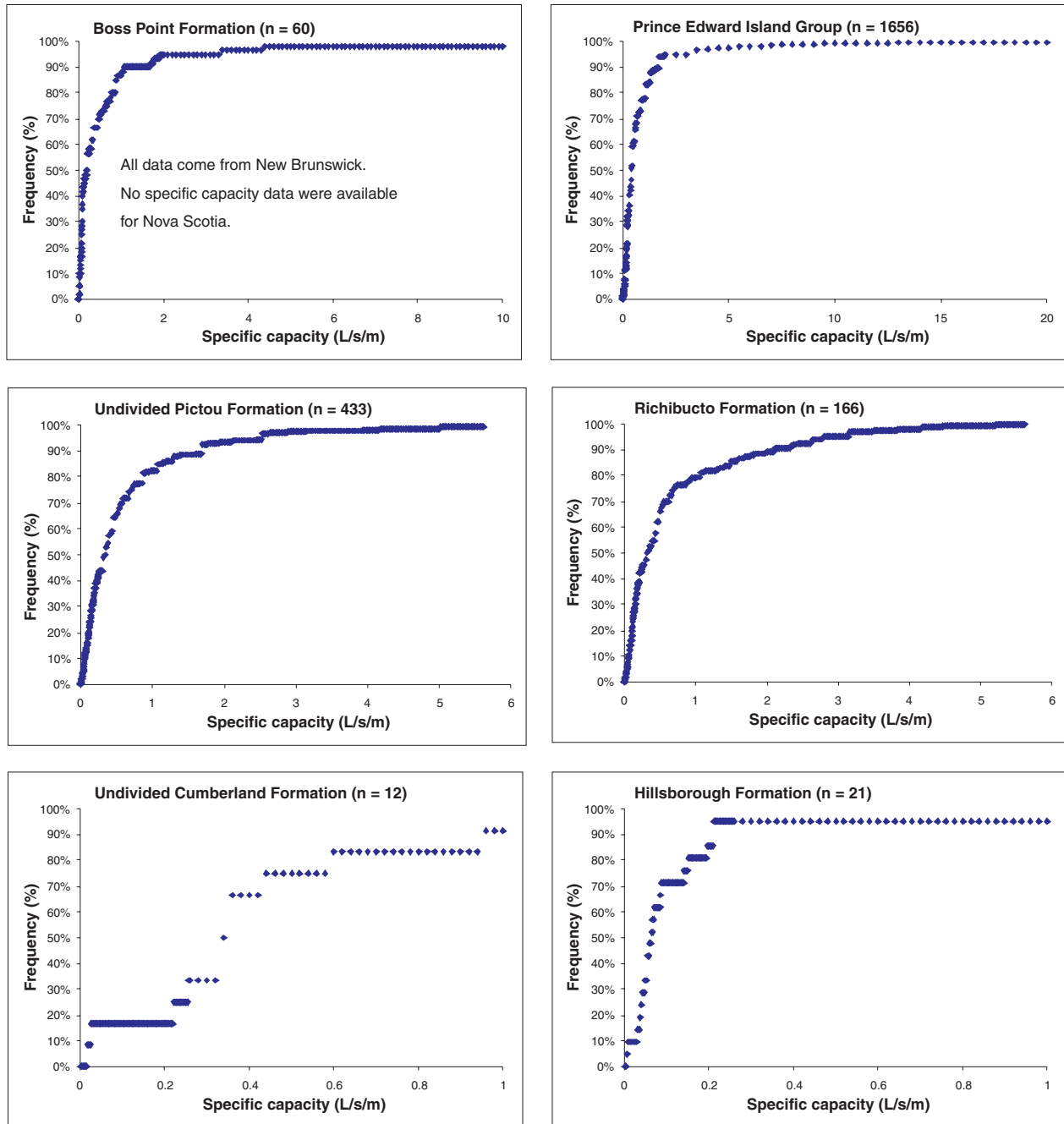
Appendix D

Table D-1: Estimated recharge for the New Brunswick portion of the Maritimes Groundwater Initiative

Formation or group	MGWI surface area (m ²)	Recharge rate (mm/a)	Recharge (m ³ /d)
Basement complex	442 246 571	33	40 105
Boss Point Formation	1 055 163 134	310	896 166
Horton, Mabou and Windsor groups	1 303 272 071	51	182 101
Richibucto Formation	4 202 447 218	192	2 210 602
Salisbury Formation	863 083 007	40	95 294
Sum:	7 866 212 002	Total : Minus 11% : Minus 29% :	3 424 268 3 047 599 2 431 230

Appendix E

Cumulative distributions of specific capacity



Undivided Cumberland Formation and Hillsborough Formation are two 'variable' aquifer units. Very few data are available, not representative of the aquifer potential in some areas.

Figure E-1: Cumulative distributions of specific capacity for major aquifer units, Maritimes Groundwater Initiative area.

Specific capacity cumulative distributions of aquitard units

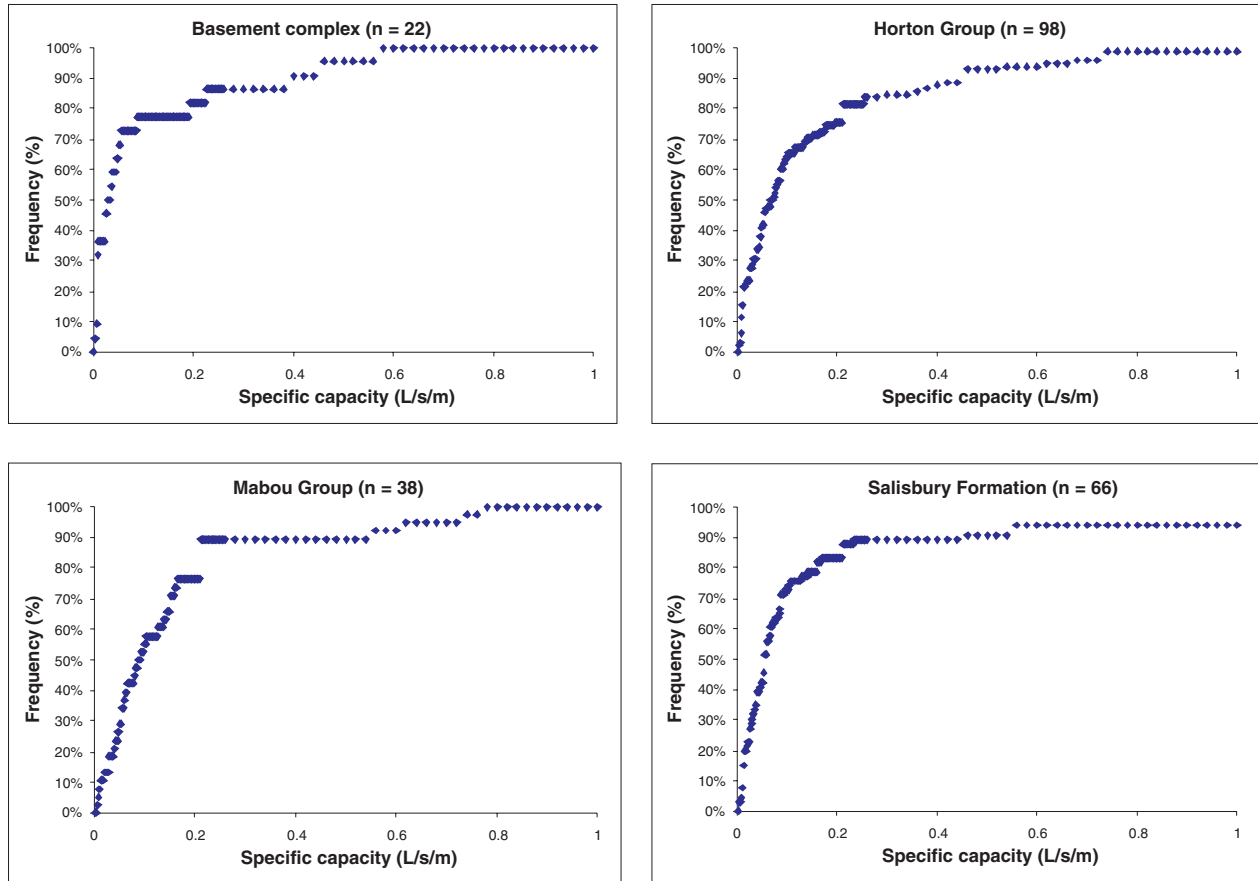


Figure E-2: Cumulative distributions of specific capacity for major aquitard units, Maritimes Groundwater Initiative area.

Appendix F

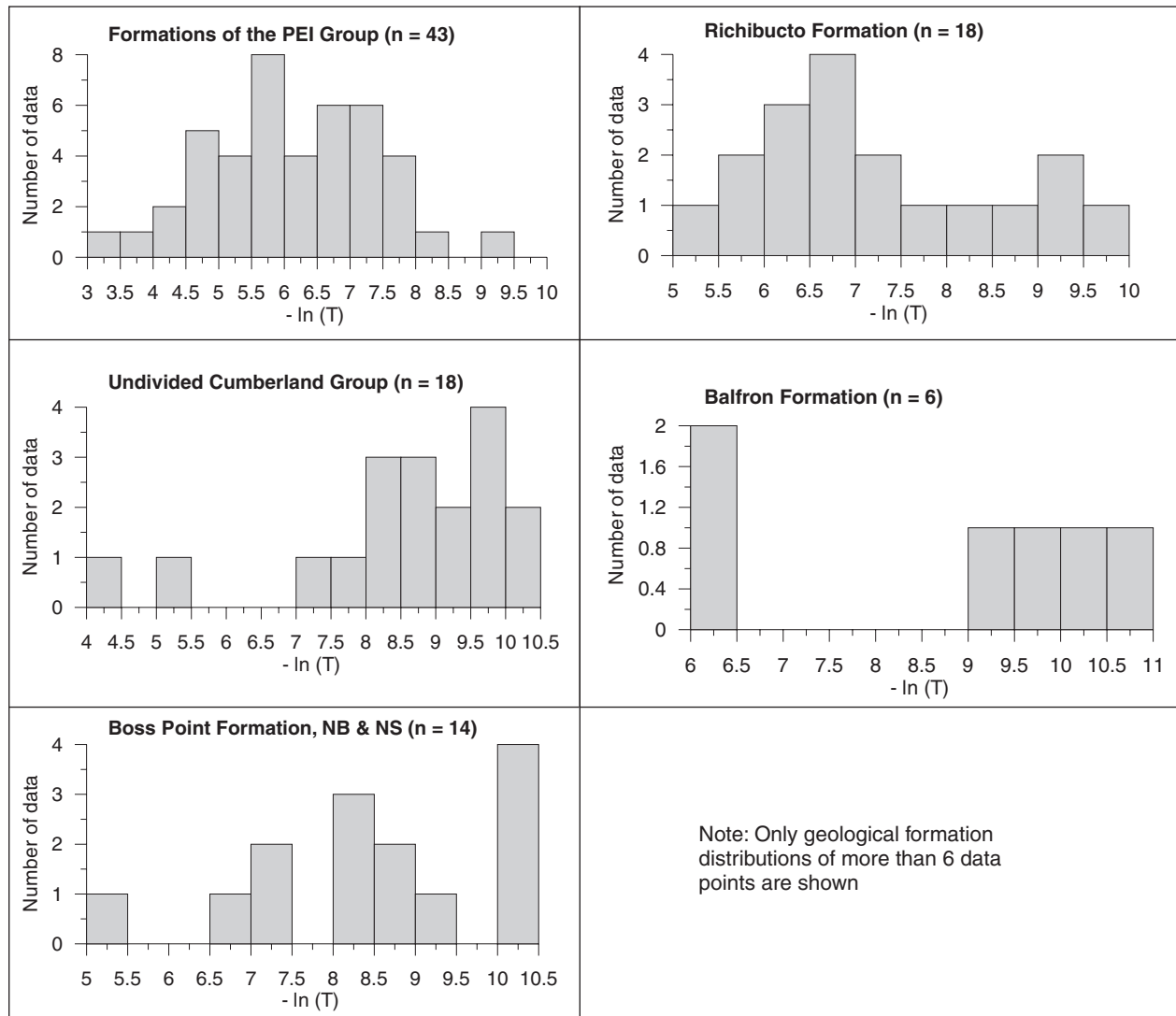


Figure F-1: Log distributions of transmissivity for various geological formations

