Hydrogeologic characterization of Nova Scotia's groundwater regions

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ABSTRACT
Nova Scotia's aquifers have been broadly divided into five bedrock and five surficial groundwater regions based on existing mapping of the dominant bedrock types and sediment deposits. Hydrogeologic characterization of the groundwater regions was carried out by classifying over 70,000 water well records, over 900 pumping test records and over 1000 inorganic groundwater chemistry records into the major groundwater regions, and conducting statistical analyses for various hydrogeologic properties. The statistical summaries provide a general guide to expected hydrogeological properties, and the mapping and associated databases developed during this study provide a useful framework for more detailed assessment activities.

RÉSUMÉ
Les aquifères de la Nouvelle-Écosse ont été divisées en cinq régions d'eaux souterraines surficielles et de roche selon la cartographie existante des lithologies dominantes de roche et des dépôts de sédiment. La caractérisation hydrogéologique des régions d'eaux souterraines a été effectuée par la classification de plus de 70000 notations de puits d'eau, plus de 900 notations de pompage d'essai et de plus de 1000 données d'échantillon d'eaux dans les régions d'eaux souterraines, et les analyses statistiques on était conduite pour différentes propriétés hydrogéologiques. Les résumés statistiques fournissent un guide général des propriétés hydrogéologiques, et la cartographie et les bases de données developer durant cette étude fournissent un cadre utile pour des activités plus détaillées d'évaluation.

1 INTRODUCTION

In April 2007, the Province of Nova Scotia passed the *Environmental Goals and Sustainable Prosperity Act*. One of the targets set out in the act is the development of a comprehensive water resource management strategy by 2010, which will help the government make decisions about Nova Scotia's water resources.

Historically, provincial agencies had a key role in assessing and mapping groundwater resources in the Nova Scotia, and published a series of regional groundwater assessment reports between the late 1960s and mid-1980s. These regional assessments covered less than a third of the province, and with the exception of the recently completed Annapolis-Cornwallis Valley Aquifer Study, led by the Geological Society of Canada (GSC) (Rivard et al. 2007), the province's aquifers have not been subject to regional scale hydrogeological investigation in several decades.

Planning for the water resource strategy has highlighted the need for strengthened knowledge about Nova Scotia's water resources. To advance the current understanding of groundwater quality and quantity in the province, a program to generate scientifically based assessment and mapping of Nova Scotia's aquifers was initiated at the Nova Scotia Department of Natural Resources (DNR) in September 2007. Initial groundwater mapping and aquifer characterization efforts have focused on the compilation and development of spatial groundwater databases and provincial scale hydrogeologic characterization. The objective of this paper is to present revised mapping of Nova Scotia's major groundwater regions, and to assess and compare, using statistical and GIS methods, the hydrogeological properties of these groundwater regions.

2 MAPS OF NOVA SCOTIA'S GROUNDWATER REGIONS

Maps of Nova Scotia's groundwater regions were originally published by the Nova Scotia Department of the Environment and Environment Canada (1985), dividing the province into five bedrock groundwater regions and three surficial groundwater regions. Revised maps of bedrock and surficial groundwater regions were recently compiled by DNR, using the latest provincial scale bedrock and surficial geology mapping.

The Bedrock Groundwater Regions Map (Kennedy and Drage, 2008) broadly classifies the bedrock groundwater regions of Nova Scotia into five major categories based on the dominant rock types interpreted from Keppie (2000) for Hopper et al. (2002). For example, the boundaries of the carbonate/evaporite groundwater region generally correspond to the boundaries of the Windsor Group, although the Windsor Group also includes siliclastic sedimentary bedrock units (e.g. shales). Similarly, the Surficial Groundwater Regions Map (Kennedy in prep.) broadly classifies the surficial groundwater regions of Nova Scotia into five major categories based on mapping by Stea et al. (1992). Table 1 shows the general classification scheme of major bedrock groups and surficial deposits into groundwater regions, and Figures 1 and 2 show the bedrock and surficial groundwater regions of Nova Scotia.

Table 1. Classification of bedrock and surficial geology.

	Groundwater Region	Major Bedrock Groups/ Surficial Deposits
Bedrock	Sedimentary (mostly siliciclastic units)	Cumberland, Fundy, Horton, Mabou, Morien, and Pictou groups
	Carbonate/Evaporite	Windsor Group
	Volcanic	Stirling and Fourchu groups, and North Mountain Formation of Fundy Group
	Plutonic	All granitic bedrock types
	Metamorphic	Meguma Supergroup, Georgeville Group
Surficial	Alluvial/Glaciofluvial	Outwash, kame fields, eskers, alluvial deposits
	Marine/Glaciomarine	Marine and glaciomarine deposits
	Drumlins/Hummocky Till	Silty and stony drumlins, and hummocky ground moraine deposits
	Cretaceous Sediments	Silica sand deposits of Cretaceous age
	Other	Colluvial, glaciolacustrine, and silty/stony till deposits

3 SPATIAL DATABASE DEVELOPMENT AND ANALYSES

To generate statistical summaries of the hydrogeologic properties of the identified groundwater regions, two key provincial groundwater databases were enhanced; the Nova Scotia well logs database (NSDNR 2009a) and the Nova Scotia pumping test database (NSDNR 2009b). Inorganic groundwater chemistry data were compiled from various databases and also analyzed as part of the hydrogeological characterization work. The use of these databases required georeferencing of the datasets, and the development of filters to ensure that the most reliable data were used.

3.1 Well Logs

The 2008 version of the Nova Scotia well logs database contains 107,205 records of mostly residential wells (>95%) constructed between 1940 and February 2008. Information recorded by the driller on the log includes the well depth, casing depth, depth to static water level, stratigraphy, and estimated well yield. Although the quality of this dataset can vary, the well logs database is a valuable source of groundwater information in the province due the wide coverage and large number of available records. Georeferencing of well locations was required prior to conducting spatial analyses of the data.

The majority of wells drilled after 2004 did not require georeferencing because each well's UTM coordinates were recorded by the driller using a handheld GPS unit. Older well logs in the database were plotted using various methods according to the best available location information. In most cases the location was determined to be the centroid of the grid cell originally used by the driller to reference the well location (three different grid systems have been employed since well logs were maintained by the province). Alternatively, where a property ID number was available on the well log, the well location was determined using the centroid of the property polygon, or the approximate building location on the property (SNSMR 2009). The accuracy of the UTM coordinates assigned to each well record in the database was estimated based on the method used to locate the wells (refer to NSDNR 2009a for details).

Following the assignment of UTM coordinates to the well logs the database was filtered to include only wells where the location was accurate to a minimum of 1500 m. A groundwater region was assigned to each well log by overlying the well location on the groundwater region maps using GIS software. Dug wells, and wells that appeared to have incompatible stratigraphy compared to the known underlying geology, or multiple rock types identified in the record (e.g. granite and sandstone), were excluded from the analysis. Approximately 70% of the total records in the database were retained following the application of these data filters (Appendix 1). The distribution of well log data is shown in Figures 1 and 2.

The median well yield was calculated for each of the ten groundwater regions based on the driller's yield estimate upon completion of drilling. The driller's yield test typically involves placement of the drill stem toward the bottom of the borehole, injecting air, and measuring the rate of displaced water as return flow over one hour. The median specific capacity of each groundwater region was estimated as another measure of hydraulic capacity. Specific capacity (Cs) is defined as Q/s, where Q is the yield estimate and s is the drawdown. Drawdown was estimated as the static water level subtracted from the well depth, since drillers infrequently record drawdown during the short-term yield test.

3.2 Pumping Tests

The Nova Scotia pumping test database contains an inventory of pumping tests submitted to the province, typically in support of a water withdrawal approval application, and/or as a regulatory requirement for non-domestic use of the well. Records contained in the database are, therefore, more representative of high capacity groundwater supplies than residential supplies. Information recorded in the database includes details about the well construction and pumping test, and the interpreted apparent transmissivity (T), specific capacity

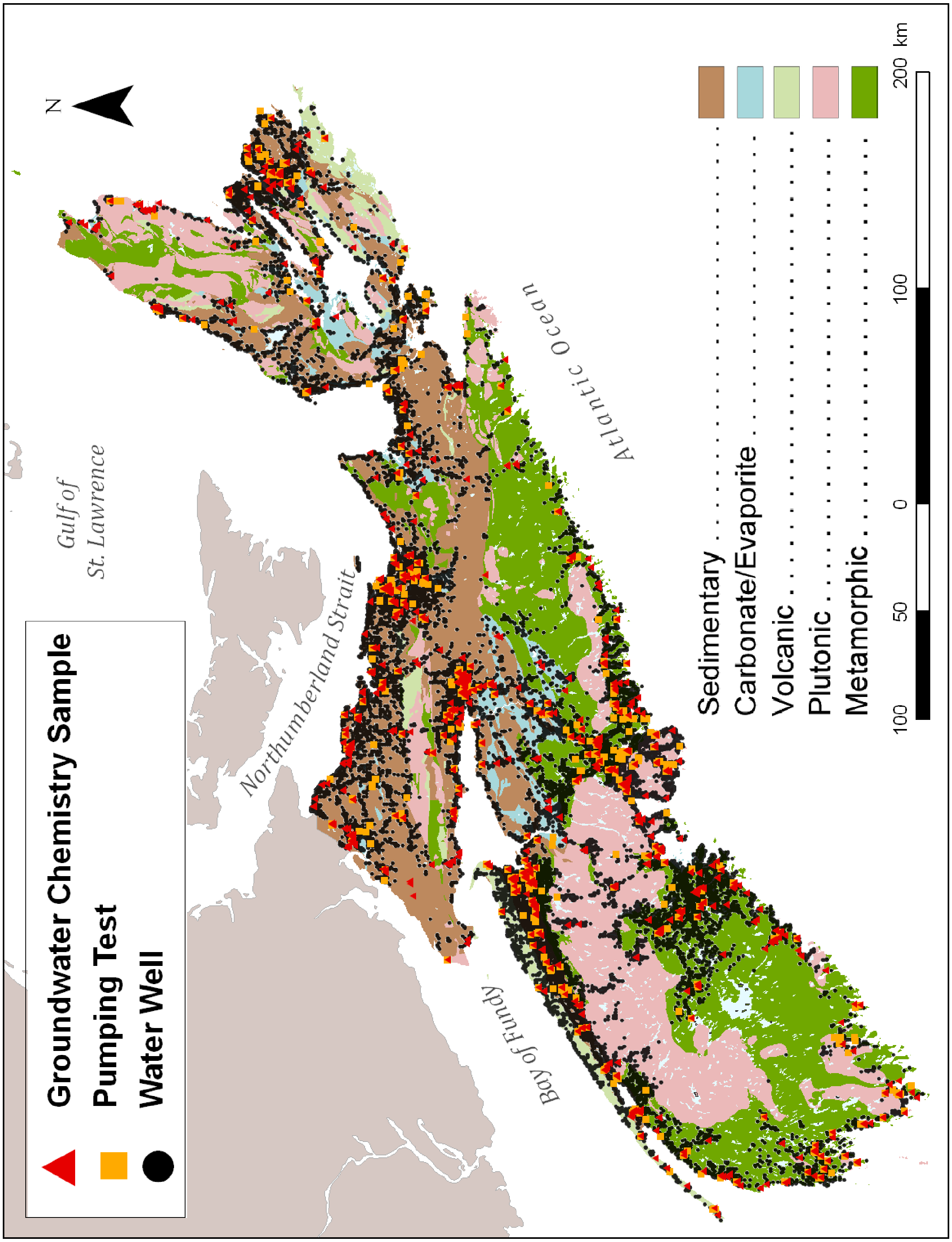

Figure 1. Bedrock groundwater regions of Nova Scotia and distribution of groundwater data.

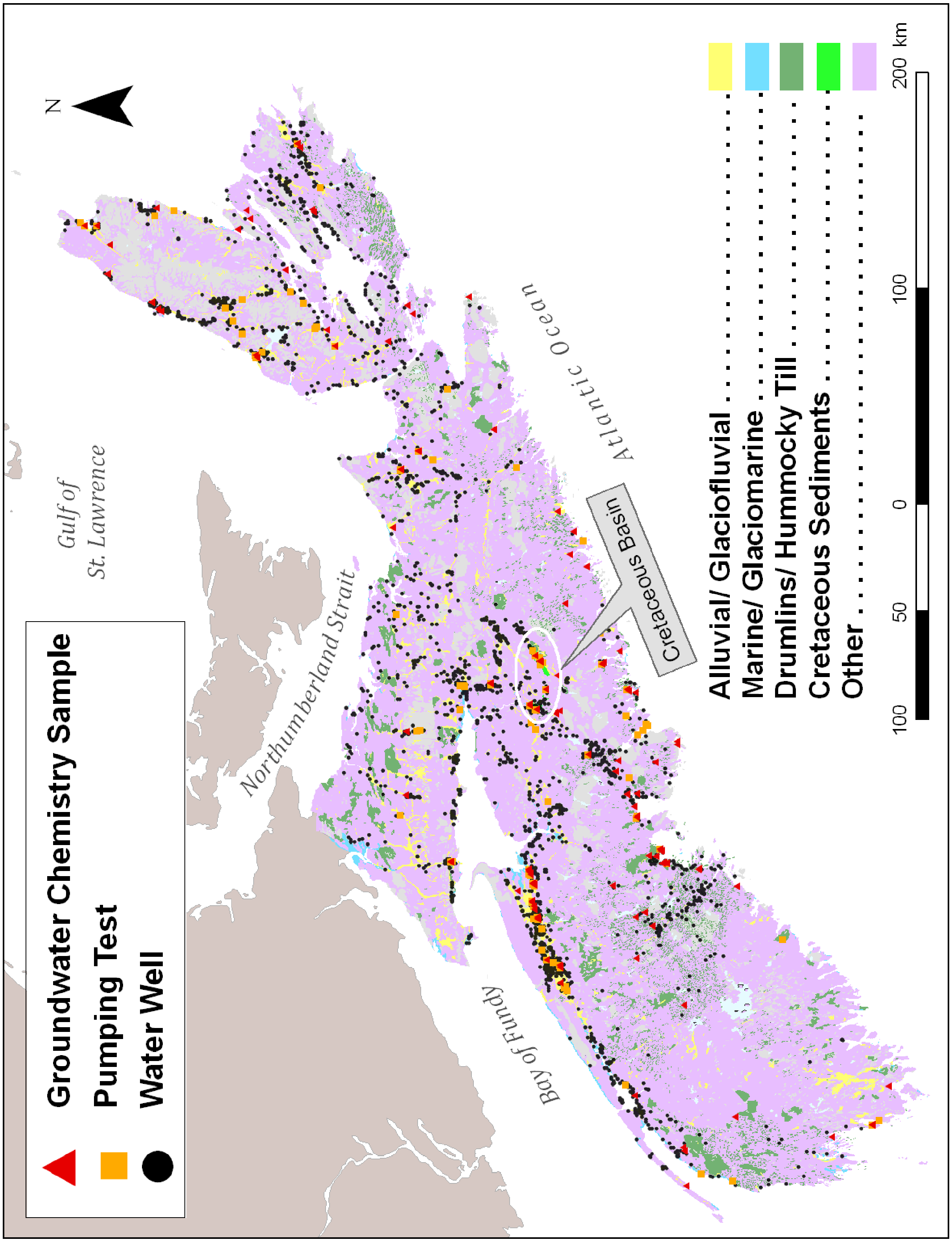

Figure 2. Surficial groundwater regions of Nova Scotia and distribution of groundwater data.

(Cs) and long-term 'safe' yield, or Q_{20} of the well. The Q_{20} has been defined as 70% of the 20 year yield calculated for the pumping well (refer to Maathuis and van der Kamp 2006 for details). Although this dataset is considerably smaller than the well logs database, these data are considered more reliable because they are subject to interpretation by hydrogeologists based on the results of a long-term pumping test (i.e. 72 hours).

The version of the pumping test database, most recently compiled and analyzed using statistics by McDonald (2008), was revised. The location coordinates and groundwater regions of pumping tests were assigned or verified following a similar methodology as outlined for the well logs. Five number summaries (quartiles, median, maximum and minimum) were calculated for each of the groundwater regions for Q_{20}, specific capacity and transmissivity. Pumping tests of less than four hours duration, and pumping tests on dug wells and wells that intercept multiple groundwater regions (e.g. alluvial/glaciofluvial and sedimentary) were excluded from the analysis. The marine/glaciomarine and 'other' surficial groundwater regions were also excluded due to small sample populations. Over 85% of the total records in the database were retained following the application of these data filters (Appendix 2). The distribution of pumping test data is shown in Figures 1 and 2.

3.3 Groundwater Chemistry

The Nova Scotia inorganic groundwater chemistry database, most recently compiled and analyzed using statistics by Keddie (2006), was updated with new sources of groundwater chemistry data. Location coordinates were assigned to each groundwater sample in the database by cross-checking existing groundwater databases (e.g. well logs, pumping tests) with the groundwater chemistry database for common site or well references. Groundwater regions were then assigned to each groundwater source in the database by overlying the location of the source with the groundwater region maps using GIS software.

Median values were calculated for 16 water chemistry parameters, representing major ions, anions, and trace metals. Non-detects were considered in the statistical analysis by assigning a value equal to half of the detection limit (refer to USEPA 1998 for details). For a given source, only the most recent raw groundwater sample result was used. Groundwater chemistry samples could not be assigned to individual surficial groundwater regions due to a lack of available detail in the record, and hence they were combined into a single 'surficial' category. The distribution of groundwater chemistry data is shown in Figures 1 and 2.

4 RESULTS AND DISCUSSION

4.1 Groundwater Quantity

Figure 3 shows the statistical summaries of the pumping test data for yield, specific capacity and transmissivity. Wells located in the surficial groundwater regions tend to be the most productive (highest yield, Cs and T) because these deposits can more readily store and transmit groundwater compared to the bedrock groundwater regions. This tendency is especially evident with respect to the well-sorted materials of the alluvial/glaciofluvial groundwater region, where the median yield is more than an order of magnitude greater than the metamorphic and plutonic groundwater regions. Although these aquifers have the highest productivity, they are of limited areal extent compared to the 'other' surficial groundwater region, which covers the majority of the province and comprises mostly low permeability materials unsuitable for drilled well water supplies. Consequently, most drillers target underlying bedrock aquifers (>90% of wells drilled in Nova Scotia).

Wells located in the sedimentary and carbonate/ evaporite groundwater regions have higher yields, Cs and T compared to the three crystalline bedrock groundwater regions, because these rocks tend to be more fractured, and groundwater can flow both along fractures and through the rock itself. The metamorphic, plutonic and volcanic groundwater regions yield lower quantities of groundwater because groundwater can flow only along fractures within the rock, although yields are generally higher in the volcanic region due to the presence of well-developed columnar jointing (Trescott 1968).

The median yield and Cs calculated from the well logs database are shown in Figure 3 for comparison. Median values from the well logs database follow the general trend observed for the pumping test data. A comparison of the median values also reveals some of the inherent biases associated with the two databases. The well logs median yield and Cs are generally lower than the values calculated from the pumping test data, which is likely attributed to the large number of residential wells present in the well logs database compared to the pumping test database. Well drillers typically suspend drilling once they have met the minimum water requirements for residential use of the water well (20 to 50 Lpm; litres per minute), which also explains the lower amount of variability between groundwater regions for median yield in the well logs data compared to the pumping test data. The largest differences in median yield and Cs calculated from the two source databases are associated with the surficial and sedimentary groundwater regions, because properly designed, constructed and developed wells installed in these aquifers have the greatest production potential, which is captured in the pumping test data.

4.2 Groundwater Quality

A summary of the statistics for selected parameters is presented in Tables 2 and 3. With the exception of manganese, the median values are all less than 50% of the Canadian Drinking Water Quality Guidelines (Health Canada 2008).

The groundwater chemistry of the surficial groundwater regions is variable, but can be generally characterized as having low alkalinity and hardness and moderate concentrations of dissolved solids (TDS). Wells located in the sedimentary or carbonate/evaporite groundwater regions typically have groundwater with moderate to high TDS and hardness compared to groundwater from the metamorphic, plutonic or volcanic groundwater regions. Sulphate (SO_4) and salt concentrations may also be elevated in the carbonate/ evaporite groundwater region, often rendering non-potable the well water supplies intercepting these aquifers. Naturally occurring trace metals, such as arsenic, iron, manganese, uranium and occasionally fluoride, may be present in all groundwater regions, although they are most often associated with the metamorphic and plutonic groundwater regions. Approximately 13% of the arsenic samples in the database from the metamorphic and plutonic groundwater regions exceed the Health Canada maximum acceptable concentration (MAC) of 10 µg/L, and approximately 15% of the uranium samples from the plutonic groundwater region exceed the MAC of 20 µg/L (Health Canada 2008).

5 CONCLUSIONS AND RESEARCH DIRECTIONS

The broad classification scheme, mapping and georeferenced datasets developed during this study provide a useful framework for more detailed, watershed scale hydrogeologic assessment activities in the province. Refinement of the hydrogeologic characterization of Nova Scotia's groundwater regions is needed, characterizing its component hydrostratigraphic units. Field investigations (e.g. test drilling, pump testing) will be required to address data gaps and to generate detailed information on these hydrostratigraphic units, especially for the surficial groundwater regions, where the assignment of groundwater regions was considered less reliable due to the complexity of the province's surficial geology.

The statistical summaries provide a general guide to expected groundwater quantity and quality in the province, and will be updated as new information becomes available. The summaries can be accessed as part of an online interactive map service (NSDNR 2009b). Based on the synoptic evaluation of groundwater quantity and quality characteristics, the most favourable hydrogeological conditions for groundwater supply development are associated with alluvial/glaciofluvial, marine/glaciomarine, and drumlin/ hummocky till surficial groundwater regions, and the sedimentary and volcanic bedrock groundwater regions. Biases and limitations of the databases, identified through comparison of the well logs and pumping test data, can help qualify interpretations made from these datasets.

Table 2. General chemistry – median of selected parameters.

Groundwater Region	Alk. mg/L	Hard. mg/L	TDS mg/L	Ca mg/L	Mg mg/L	K mg/L	Na mg/L	pH mg/L	Cl mg/L	Fl mg/L	NO_3-NO_2 mg/L	SO_4 mg/L
Surficial (All)	30.0 (128)	68.7 (129)	131.8 (118)	20.0 (129)	3.1 (129)	1.5 (120)	13.8 (128)	7.0 (130)	22.8 (131)	0.05 (87)	0.32 (121)	11.0 (131)
Sedimentary	100.0 (407)	113.0 (436)	200.5 (408)	34.7 (442)	4.3 (438)	1.6 (409)	20.0 (440)	7.8 (438)	25.7 (438)	0.10 (324)	0.17 (374)	13.0 (441)
Carbonate/ Evaporite	142.5 (62)	219.5 (64)	433.0 (60)	64.3 (67)	11.0 (67)	2.2 (65)	37.5 (67)	7.9 (65)	33.9 (65)	0.25 (47)	0.03 (61)	75.0 (65)
Volcanic	45.0 (19)	39.3 (19)	147.0 (19)	13.0 (19)	2.9 (19)	0.3 (19)	22.7 (19)	7.7 (19)	35.0 (19)	0.08 (12)	0.55 (16)	8.0 (19)
Plutonic	56.0 (88)	55.2 (89)	135.0 (90)	17.0 (91)	2.6 (91)	1.3 (90)	17.2 (92)	7.1 (90)	25.0 (89)	0.22 (70)	0.08 (90)	7.0 (88)
Metamorphic	56.0 (211)	63.7 (204)	146.0 (202)	19.8 (205)	3.1 (203)	1.3 (202)	21.3 (209)	7.3 (212)	21.0 (211)	0.16 (145)	0.03 (196)	11.0 (210)

Sample population shown in brackets.

Table 3. Metals – median and geomean of selected parameters.

Groundwater Region	As (µg/L)		Fe (µg/L)		Mn (µg/L)		U (µg/L)	
	Median	Geomean	Median	Geomean	Median	Geomean	Median	Geomean
Surficial (All)	1.0 (115)	1.2	50.0 (129)	88.2	15.0 (130)	18.0	0.1 (105)	0.2
Sedimentary	1.0 (393)	1.6	30.0 (443)	57.5	7.0 (443)	13.2	0.6 (360)	0.6
Carbonate/ Evaporite	1.0 (61)	1.6	70.0 (67)	123.9	29.0 (67)	24.9	0.5 (58)	0.5
Volcanic	1.2 (17)	1.3	50.0 (19)	50.8	5.0 (19)	4.3	0.1 (9)	0.2
Plutonic	2.0 (87)	2.4	50.0 (93)	114.4	50.0 (93)	30.5	3.5 (82)	2.9
Metamorphic	1.0 (188)	1.9	91.0 (206)	143.2	43.0 (203)	37.4	0.2 (185)	0.3

Sample population shown in brackets.

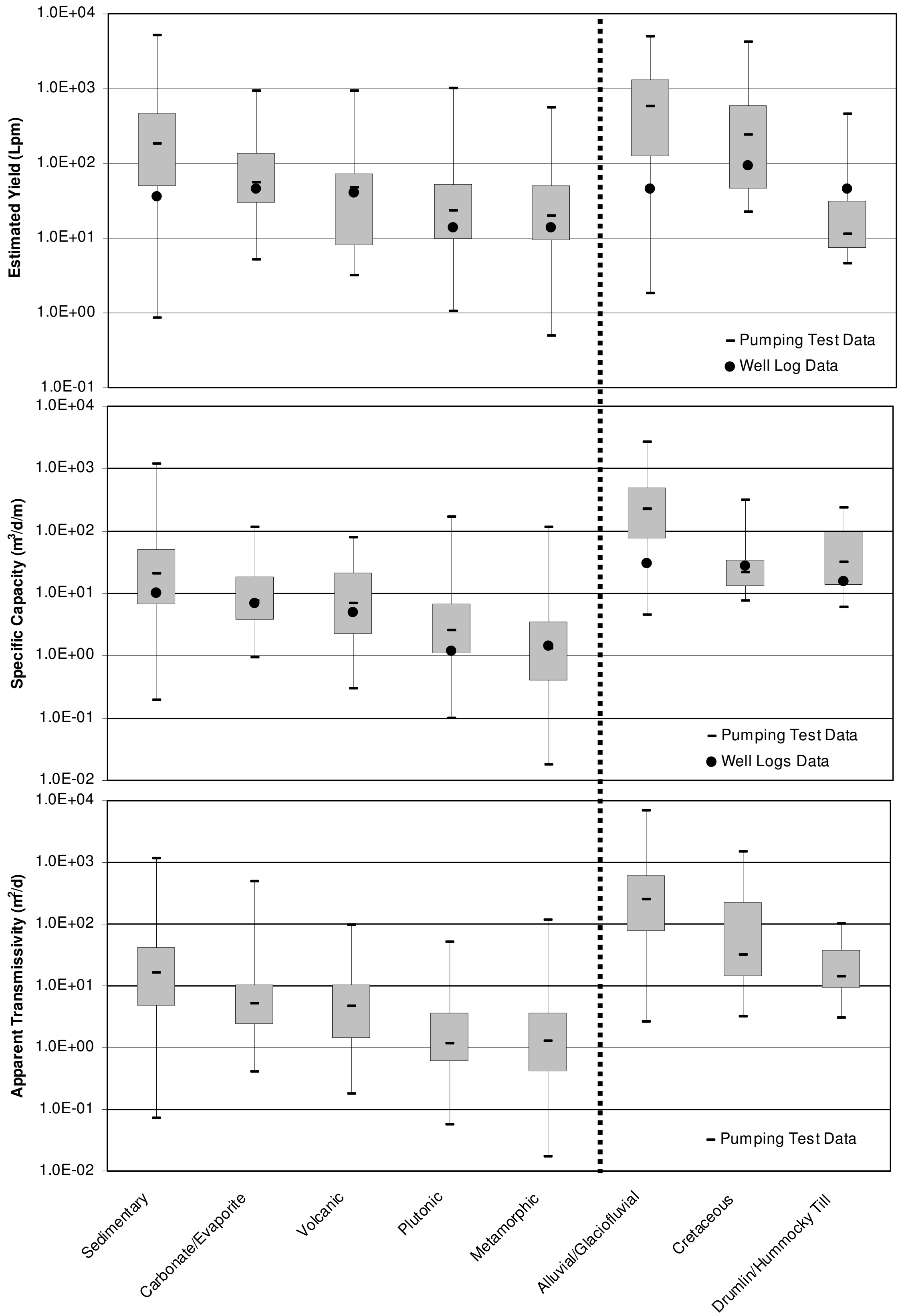

Figure 3. Five number summaries of pumping test data (max, min, median, Q_1, Q_3) for yield (A), Cs (B) and T (C) and median values of yield and Cs from well logs data. The box (Q_1 to Q_3) represents the middle fifty percent of the data.

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Appendix 1. Median values from well logs data.

Groundwater Region	Count (Drilled Wells)	Yield (Lpm)	Cs ($m^3/d/m$)
Sedimentary	35279	36.3	2.3
Carbonate/ Evaporite	2492	45.4	3.1
Volcanic	994	40.9	1.7
Plutonic	9279	13.6	0.5
Metamorphic	18878	13.6	0.6
Alluvial/ Glaciofluvial	3027	45.4	7.1
Cretaceous Sediments	41	90.8	7.9
Marine/ Glaciomarine	122	45.4	3.5
Drumlins/ Hummocky Till	402	45.4	4.5
Other	459	36.3	3.2

Appendix 2. Median values from pumping test data.

Groundwater Region	Count (Drilled Wells)	Yield (Lpm)	Cs ($m^3/d/m$)	T (m^2/d)
Sedimentary	398	181.8	20.4	16.0
Carbonate/ Evaporite	28	56.0	7.4	5.2
Volcanic	18	46.4	6.9	4.6
Plutonic	93	22.7	2.5	1.2
Metamorphic	191	20.0	2.1	1.3
Alluvial/ Glaciofluvial	80	570.5	220.0	249.8
Cretaceous Sediments	9	241.0	21.9	32.0
Drumlins/ Hummocky Till	9	11.4	30.8	14.3