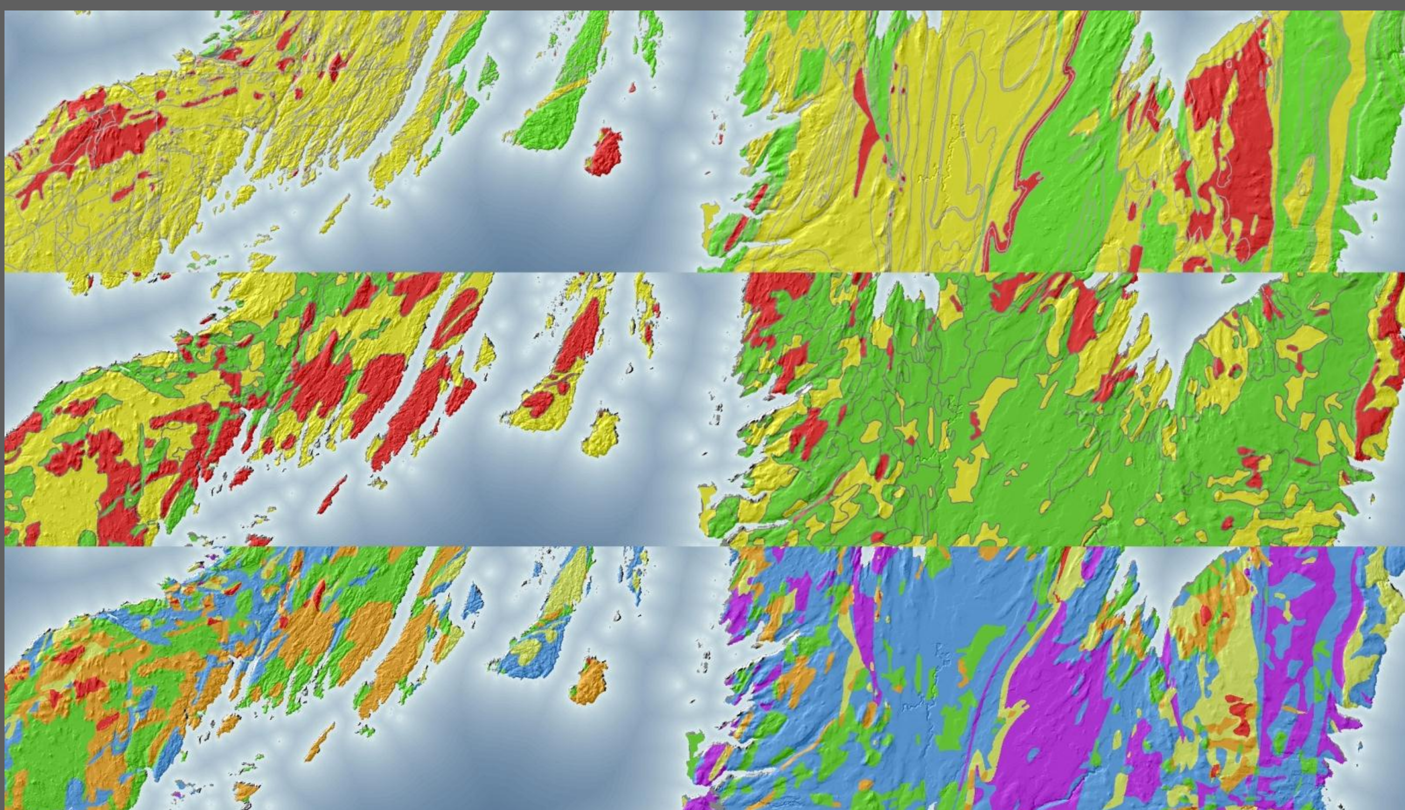
Groundwater Vulnerability Mapping
Eastern Newfoundland

Task 2: Study Area Hydrogeology



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Prepared for:

Water Resources Management Division
Department of Environment and Conservation
Government of Newfoundland and Labrador

Prepared by:

CBCL LIMITED
Consulting Engineers

Final Report	M. Bishop	October 2013	C. Walker
Draft Report	M. Bishop	August 2013	C. Walker
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October 23, 2013

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Dear Ms. Hanchar:

RE: Groundwater Vulnerability Mapping - Final Report # 1- Data Compilation

On behalf of CBCL Limited, I am pleased to submit the Final Report for the above noted project. If you have any questions or concerns, please contact the undersigned.

Yours very truly,

CBCL Limited

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CHAPTER 1 INTRODUCTION

1.1 Background

CBCL Limited (CBCL) was retained by the Water Resources Management Division of the Department of Environment and Conservation (ENVC) to complete a Groundwater Vulnerability Delineation and Mapping study for Eastern Newfoundland. Groundwater is an essential resource for the island of Newfoundland. According to ENVC, approximately 29% of people in Newfoundland rely on groundwater as a source of potable water. ENVC has recognized the value of Newfoundland's groundwater resources and has implemented this study to provide a basis for the protection of the province's groundwater resources.

Groundwater vulnerability is a measure of the likelihood for contaminants to enter an aquifer, and the influence of transport and attenuation along a groundwater flow path. Groundwater vulnerability is a function of the hydrogeologic setting, and some definitions are extended to include the influence of land use on the likelihood of contaminant release. For the purposes of this report, "aquifer vulnerability" will be used to describe the physical factors governing groundwater contamination by anthropogenic sources, and "land use-vulnerability" will be used to incorporate land use information.

Aquifer vulnerability is determined primarily by the rate of transport of contaminants through confining layers and the rate of transport through an aquifer. The thickness and grain size distribution of unconsolidated materials control the former, and the aquifer and contaminant properties control the latter. These and other factors can be further subdivided to provide a means of quantifying aquifer vulnerability. Methods to determine aquifer vulnerability have been the subject of study and application in other jurisdictions for over forty years.

1.2 Scope of Work

This report forms the second of three components of aquifer vulnerability mapping. The first task entailed collation, formatting, and trimming of data from the province and topographic survey of Canada to the Eastern Newfoundland study area. This report presents the results of Task 2, a hydrogeological analysis of these data, including a synthesis and comparison to existing studies on the hydrogeology of Eastern Newfoundland. This analysis provides a discussion on the parameters and indices that are used to complete Task 3: mapping and geospatial analysis of aquifer vulnerability – land use-vulnerability.

CHAPTER 2 LITERATURE REVIEW

2.1 Government of Newfoundland and Labrador Water Resources Reports

A series of government reports on water resources of the study area were completed between 1981 and 1985, subdivided into the following geographic regions:

- Avalon Peninsula;
- Bonavista Bay;
- Trinity Bay; and
- Burin Peninsula.

Each report provided an overview of the hydrogeology of the study area, summarizing data from the province's drilled well database and available pumping test data. Drilled well records were georeferenced by associating each well with the community listed for each well. Data on the well yield were then associated with the mapped geologic unit underlying these communities. Reporting on bedrock aquifers focussed on the potential effects of faulting and structural features on groundwater flow. Each report also provided an inventory of major river basins and surficial aquifers in the study area, and a limited summary of groundwater quality data.

The well yield and geologic data presented in the four studies is summarized in Table 2.1. The data in Table 2.1 represent the first attempts to group bedrock formations in the study area into larger hydrostratigraphic units (HUs) using well yields. The variety of bedrock types and variability within each group and formation make this a complex task. The groups in Table 2.1 represent data grouped primarily by well yield and mapped bedrock unit. The groupings do not account for vertical data, groundwater flow features, aquifer-aquitard interaction, or groundwater recharge and discharge zones. In this sense they do not represent true HUs.

Owing to the relatively high degree of chemical cementation in the sedimentary rocks of Eastern Newfoundland, the primary permeability (matrix permeability) of bedrock formations is limited. The hydraulic conductivity of bedrock formations in the study area is thus determined by secondary permeability (faults, contacts, fractures and joints). One report suggested that the more extensively fractured zones of bedrock have been preferentially weathered, forming depressions in the bedrock surface, and that these depressions were then in-filled by glacial material (FracFlow Consultants Inc., 1984).

The data in Table 2.1 indicate that the rock type is not a determining factor in well yield. For example, granitic and volcanic formations exhibit higher well yields than many sandstone units in the study area.

The data also show variability within Formations and Groups. In the Trinity Bay area, for example, the Bonavista, Brigus, and Smith Point Formations exhibit both low and moderate to high yield zones. The Conception Group and Musgravetown Groups were also grouped differently between the Avalon, Trinity Bay, and Bonavista Bay areas. The well yield data shown in Table 2.1 were not normalized against the well depth.

Hydrostratigraphic mapping generally distinguished between low permeability till and higher permeability deposits of sand and gravel, including eskers, kames, outwash plains and beach deposits. Quaternary mapping was used to identify major surficial aquifers in each of the four sub-study areas, summarized below.

Avalon Peninsula

- Outwash most extensive in the broad sandur between Topsail Cove and Seal Cove (over 15 metres thick at Seal Cove);
- Largest esker is over 8 km long, running toward Chance Cove;
- 5 km long esker north of Cappahayden;
- 5 km long esker between St. Bride's and Branch;
- Kame terrace/esker at Cuslett Brook;
- Kame terrace/esker along Southeast River; and
- Fluvial deposits in the Peter's River, Crossing Place River, Salmonier River, Branch River, and Lance Brook valleys.

Bonavista Bay

- Till varies from clayey to gravelly according to underlying bedrock parent material;
- Eskers are present immediately west of an end moraine that traverses the study area from northwest to southeast;
- An 8 metre high kame terrace 1.6 km to the north of Terra Nova;
- Kame terrace south of Gander Lake;
- Kame terrace west of Gambo;
- Outwash valleys:
  - From southeast end of Gander Lake to Freshwater Bay;
  - Stream channel of Northwest Brook and two smaller streams to Gambo Pond;
  - Valley of Terra Nova river;
  - Northeast arm to Eastport Area;
  - Valley west of Gloverstown;
  - Sultans Brook Valley;
  - Following Big Brook into the southwest corner of Newman Sound;
  - Near Port Blandford in Clode Sound;
  - Following Southwest Brook;
  - Within the valley leading into Smith Sound and Georges Brook; and
  - Within the valley leading into Bonavista Bay at Plate Cove.

Table 2.1. Summary of Well Yield Analyses from Provincial Reports

Study Area	Group of Geologic Units and Well Yields (Increasing Well Yield →)						
Avalon Peninsula	Group		B	A	D	C	E
	Rock Types		SNDST, SHL, SLTST, CNG, VOL	VOL, SED, PLU	SHL, SLTST, LMSN, QZT, CNG, SLTST	BRC, CNG, SNDST, SLTST, SHL	SNDST, SLTST
	Yield (L/min)		Low-Moderate (20)	Moderate (25)	Moderate (27)	Moderate-High (43)	High (73.5)
	Geologic Units		Conception Gr.	Harbour Main Gr.	St. John's Fm.	Signal Hill Gr.	Wabana Gr.
			Dildo Gr.	Holyrood Granite	Bonavista Fm.		Bell Island Gr.
					Smith Pt. Fm.		
					Brigus Fm.		
					Chamberlain's Br. Fm.		
					Manuel's R. Fm.		
					Elliot Cove Fm.		
Trinity Bay	Group	1		2	3	4	
	Rock Types	Meta-Sedimentary			Cambrian / Granite		
	Yield (L/min)	Low (10)		Moderate (23)	Moderate-High (29)	High (33)	
	Geologic Units	Bonavista Fm.		Conception Gr.	Bonavista Fm.	Hodgewater Fm.	
		Smith Pt. Fm.		Musgravetown Gr.	Smith Pt. Fm.		
		Brigus Fm.			Brigus Fm.		
		Random Fm.			Chamberlain's Br. Fm.		
		Connecting Pt. Fm.			Manuel's R. Fm.		
Bonavista Bay	Group	1	2	4	5	3	
	Rock Types	Meta-Volcanic, Sedimentary	Meta-Sedimentary and Sedimentary	Granitic-Mafic	Pebble Conglomerate and Sandstone	not in study area	
	Yield (L/min)	Low (5)	Low (10)	Moderate-High (26)	High (29)		
	Geologic Units	Love Cove Gr.	Connecting Pt. Fm.	Granite	Musgravetown Gr.		
		Adeyton Fm.	Davidsville Fm.				
		Harcourt Gr.					
Burin Peninsula	Group	3	2	1	6	4	5
	Rock Types	Ordovician Sedimentary	Hadrynian and Cambrian Sedimentary	Hadrynian Volcanic	Carbonate, St. Lawrence Granite	Devonian Carbonate, Sedimentary	Hadrynian-Devonian Granitic
		SHL, SLTST, SCHST,	SNDST, SLTST, SHL, SLTST			CNG, SNDST	
	Yield (L/min)	Low (10.5)	Low-Moderate (16.5)	Low-Moderate (18)	Moderate-High (32)	Moderate-High (38)	High (45)
	Geologic Units	Baie D'Espoir		Burin Gr.	St. Lawrence Granite		
				Love Cove Gr.	Grand Beach Complex		
				Marystown Gr.			
				Long Harbour Gr.			
				Connaigre Bay Gr.			

SNDST Sandstone
CNGL Conglomerate
SED Sedimentary
SLTST Siltstone
SHL Shale

VOL Volcanic
PLU Plutonic
LMSN Limestone
QZT Quartzite
BRC Breccia

Trinity Bay
- Till is generally coarse, granular and sandy;
- Rare eskers and kames, generally close to the coastlines;
- Clarkes beach comprises a large kame terrace;
- 3 km kame terrace in North River Valley;
- Large kame terrace in South River Valley;
- Outwash deposit at Swift Current; and
- Outwash deposit at head of South West Arm.

Burin Peninsula
- Outwash valley in Lamaline;
- Outwash valley in Grand Bank; and
- Outwash sand deposit near Winterland and Freshwater Pond.

2.2 Hydrogeologic Atlas of Eastern Newfoundland

Mapping of HUs was recently updated and refined, including GIS layers to incorporate the updated HUs for the Eastern Newfoundland study area. Following the same methodology used in the provincial sub-region reports (Section 2.1), drilled well records were associated with the community listed in each drilled well record, and then associated with the underlying geologic unit. HUs were defined according to rock type, age, and well yield (well yields were not normalized against the well depths). This system of classification was ultimately used to group the varying geologic units into one of six bedrock HUs, shown in Table 2.2 (after AMEC, 2012) and displayed on Figure 2.1 (after AMEC, 2012).

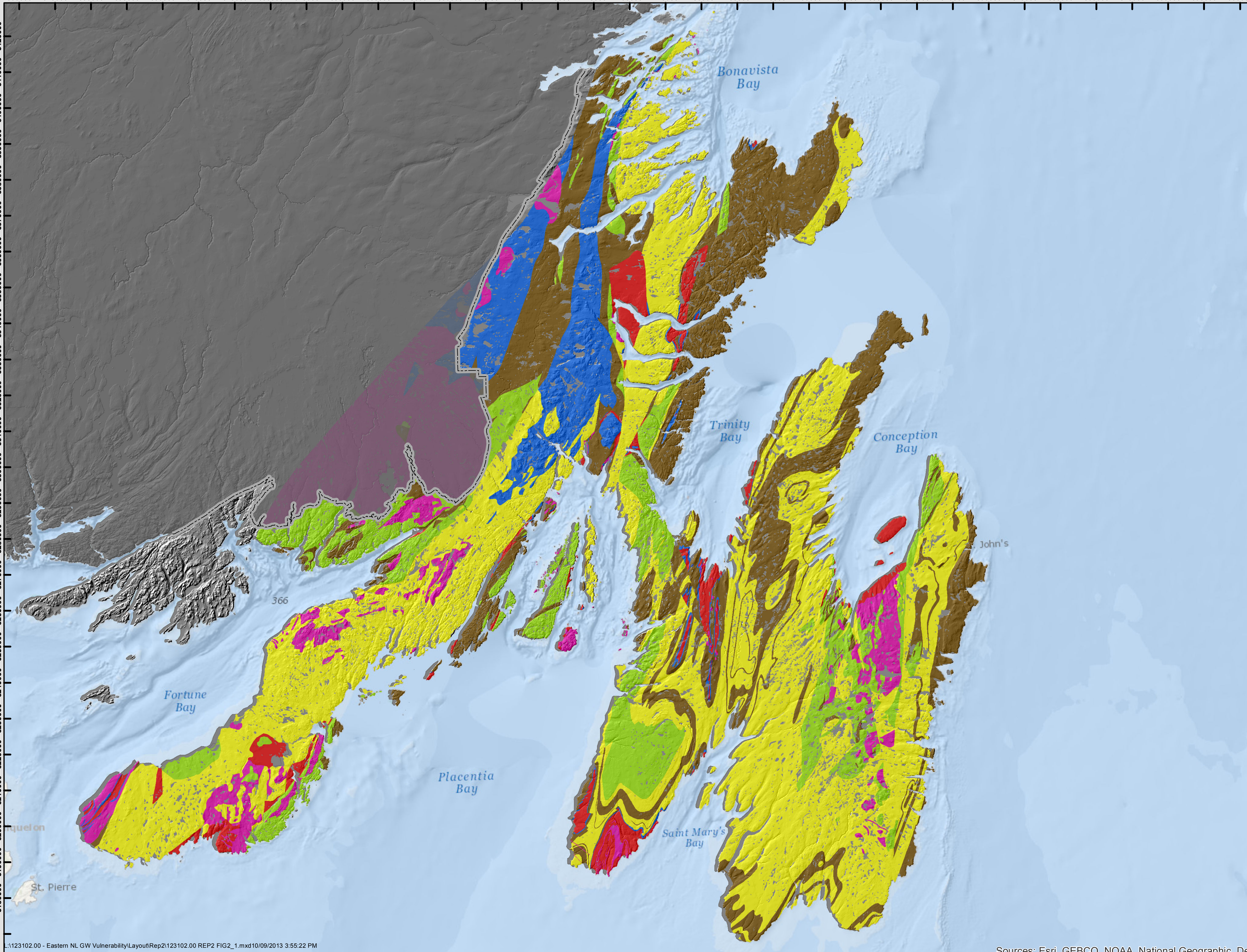
Mean well yields were relatively consistent across HUs 1 (siltstone and shale), 2 (sandstone and conglomerate), 4 (volcanic) and 6 (meta volcanic). Unit 5, representing a grouping of plutonic strata, showed the highest mean yield of 31 L/min. The younger Cambro-Ordovician strata showed a slightly higher mean yield than the older sedimentary units, at 29 L/min.

The major glaciofluvial deposits of the study area were listed as follows:
- Valleys draining into Clode Sound, Smith Sound and Northwest Arm (Bonavista Peninsula);
- Swift Current Valley (Burin Peninsula);
- South Brook and Shearstown Brook Valleys (Baie de Verde Peninsula); and
- Southern Avalon coastline including Holyrood Bay and O'Brien's Pond.

Hydrologic data were examined to provide an indication of groundwater recharge using baseflow separations at three hydrometric stations. Each station was selected to be representative of a hydrologic sub-region within the study area. The analysis indicated unusually high run-off rates, attributed to difficulties in measuring precipitation and evapotranspiration.

Table 2.2. Hydrostratigraphic Units, Hydrogeology of Eastern Newfoundland (after AMEC, 2012)

Hydrostratigraphic Unit	Lithology	Number of Wells	Average Yield (L/min)
Unit 1 Low to Moderate Yield Siltstone and Shale Strata	Silstone, shale, with minor volcanic flows and tuffs	5100	20
Unit 2 Low to Moderate Yield Sandstone and Conglomerate	Sandstone, conglomerate, breccia, greywacke, withi minor volcanic flows and tuff	2789	22
Unit 3 Moderate Yield Cambro-Ordovician Sedimentary Strata	Shale, siltstone, sandstone, with minor slate and limestone beds	1694	29
Unit 4 Low to Moderate Yield Volcanic Strata	Basic pillow lava, breccia and tuff, with minor sedimentary rocks	1819	25
Unit 5 Moderate Yield Plutonic Strata	Granite, granodiorite, diorite and gabbro	95	31
Unit 6 Low to Moderate Yield Meta Volcanic Strata	Sericite and chlorite schist derived from felsic and mafic volcanic and sedimentary rocks; minor gneiss and migmatite	168	18



LEGEND

Study Area Boundary

Hydrostatigraphic Unit

- Late Neoproterozoic Silstone and Shale
- Late Neoproterozoic Sandstone and Conglomerate
- Cambrian Sedimentary
- Volcanic
- Plutonic
- Metamorphic

Figure 2.1

Hydrostratigraphic Units
(after AMEC, 2012)

Eastern Newfoundland Groundwater Vulnerability Assessment

Coordinate System: NAD 1983 UTM Zone 21N
Projection: Transverse Mercator
Datum: North American 1983
Units: Meter

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0 5 10 20 30 40 km

1:1,000,000 @ 11 x 17

Elevated arsenic concentrations were noted in 11 communities within the study area, listed below. These communities provide a basis for more detailed mapping of groundwater suitability during Task 3.

- Avondale;
- Bellevue;
- Blaketown;
- Chapels Cove, Conception Bay;
- Chance Cove;
- Dunfield, Trinity Bay;
- Freshwater (Carbonear);
- Harbour Grace;
- Holyrood;
- Norman's Cove; and
- Small Point-Adam's Cove-Blackhead-Broad Cove.

CHAPTER 3 ANALYSIS OF HYDROGEOLOGICAL DATA

3.1 Baseflow and Groundwater Recharge

3.1.1 Methodology

Stream gauging data are available at 45 stations across the study area, maintained by Environment Canada. Daily stream flow and precipitation data were obtained from the Environment Canada database and subject to two forms of analysis to obtain estimates of baseflow for available watersheds. Stream flow stations are listed in Table A1 and shown on Figure 3.1.

Stream gauging data were analyzed using the following techniques:

1. Baseflow separation.
2. Baseflow minima.

Technique #1 entailed application of the BASEFLOW model, a recursive digital filter for the separation of long wave and short wave characteristics in stream flow data (Arnold et al., 1995). The output for this model was shown to provide a good fit to manual and other automated techniques for base flow separations. Daily baseflow data were averaged over periods of two to 58 years to obtain the average daily baseflow for each watershed. This average flow was converted to an average annual recharge rate over the total area of the watershed.

The latter technique was developed for worst case low-flow scenarios in stormwater modelling (EPA Storm Water Management Model). Daily flow data were used to determine the annual minima for periods of two to 58 years. Annual flow minima were fitted to various statistical models to provide a 1 in 2 year low-flow estimate of baseflow in the absence of run-off. This 1 in 2 year (average) flow was converted to a minimum annual recharge rate over the total area of the watershed.

3.1.2 Results

Results from the BASEFLOW model are shown on Figure 3.1, normalized over the watershed areas as millimetres of recharge. The data show relatively high rates of recharge, which suggests that baseflow separations incorporated flow that exceeded actual groundwater recharge, possibly in the form of interflow. The data nevertheless provide a point of comparison between available watersheds, and a means to assess the relative recharge in different parts of the province. Where sufficient data were

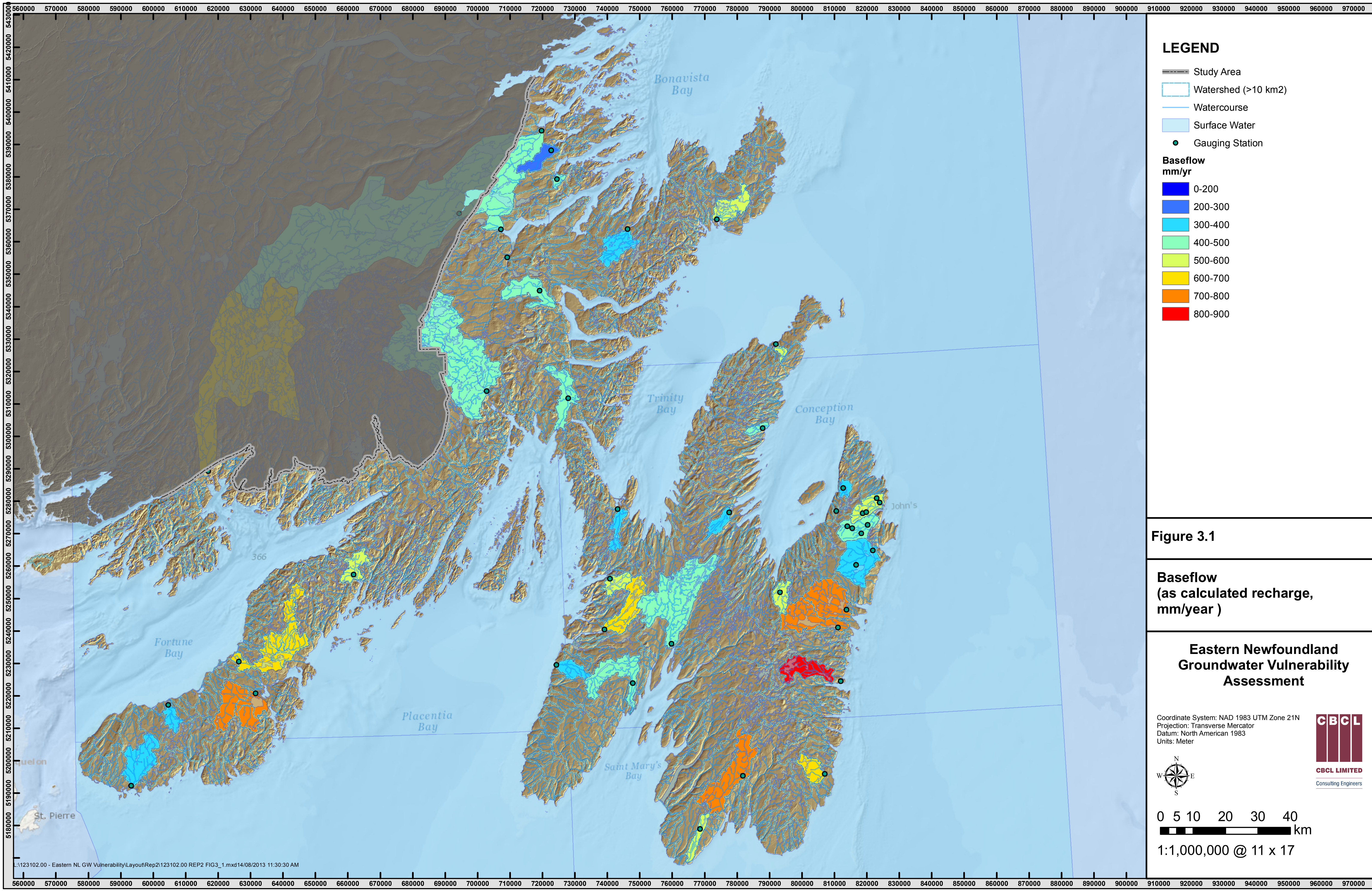


Figure 3.1

Baseflow (as calculated recharge, mm/year)

Eastern Newfoundland Groundwater Vulnerability Assessment

available, the recession constant (α) was calculated. The recession constant provides a means of comparing the recharge characteristics of each watershed.

Baseflow minima data are shown on Figure 3.2, normalized over the watershed areas as millimetres of recharge. Regression of the data for the two methods indicated good correlation. The magnitude of recharge values obtained using the method of baseflow minima are closer to expected recharge rates, but likely represent the minimum recharge observed during dry summer conditions. Actual rates of groundwater recharge are expected to fall in the range of the results of the two techniques.

Baseflow mapping provides a potential means to assign recharge indices for vulnerability mapping. The analysis did not however, provide a means to reliably assign recharge data to all watersheds on a regional basis. Factors such as slope, precipitation, roughness, soil type and ground cover, land use, and shape of the recession curve are needed for association of equivalent watersheds on a case by case basis. A more detailed assessment of individual target watersheds could allow for development of water budgets that account for factors affecting run-off and evapotranspiration. This data would provide better estimates of actual recharge to various parts of the basin.

3.2 Geospatial and Statistical Analysis of Drilled Well Yields

3.2.1 Methodology

Bedrock geology mapping and geospatial data from the province's updated Drilled Well database were combined to provide an updated analysis of bedrock yields. The purpose of this analysis was to provide a statistically significant estimate of the yield of each mapped bedrock component in the study area. The data are used primarily for the assignment of extrinsic aquifer vulnerability indices, but may also provide some indication of regional trends, yields by formation type and age, and hydrostratigraphic units.

Drilled well records were filtered to include only those records indicating a georeferencing method of "GPS" or "Map". Both of these methods are considered accurate enough to place drilled well locations within a given bedrock geology polygon from provincial mapping. Drilled well records were then intersected and associated with the underlying bedrock polygon unit. This methodology provides considerably increased resolution for the assignment of yield data compared to previous studies.

Depth Normalized Yield ($\bar{Q}$)
The airlift yield for each well record was divided by the well depth to provide a depth-normalized-yield, abbreviated in this report as "$\bar{Q}$". $\bar{Q}$ data are reported in units of m^2/day.

$\bar{Q}$ data were also used to provide a broad estimate of the aquifer transmissivity. If the depth of the well is set equal to the drawdown required to obtain the airlift yield, and the airlift yield is substituted as a proxy for a stable pumping rate, the $\bar{Q}$ represents a lower estimate of the specific capacity of the well. The specific capacity was multiplied by 1.3 to obtain a (low) rough estimate of the aquifer transmissivity (Neville, 2009). A statistical analysis of transmissivity data obtained by this method, compared to transmissivity data from the pumping test database is discussed below.

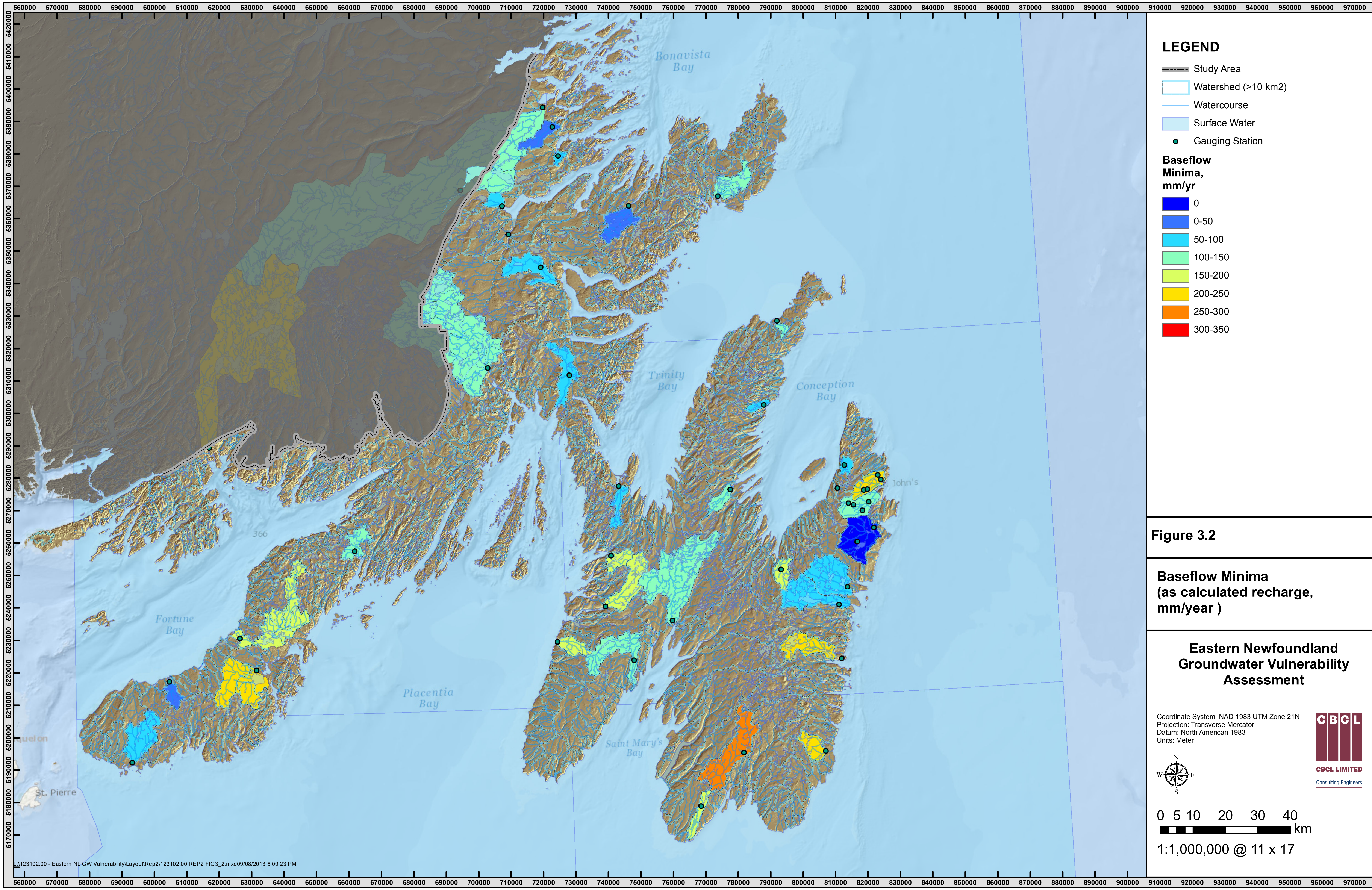


Figure 3.2

Baseflow Minima (as calculated recharge, mm/year)

Eastern Newfoundland Groundwater Vulnerability Assessment

As drilled well data for the study area were clustered and did not intersect with all bedrock geology polygons in the study area, direct assignment of well yield data to geology polygons was not possible. It was necessary to control for anomalously high or low yields for a given polygon and ensure that each polygon was assigned a statistically significant yield. An analysis of variance (ANOVA) was completed in order to assign appropriate $\bar{Q}$ data for each polygon in the study area. The methodology followed studies by the United States Geological Survey (USGS) and others (Moore et al., 2002; Belcher and Elliot, 2002; Banks, 1998; Daniel, 1989;). As well yield and hydraulic conductivity data are ln-normally distributed, the analysis was performed on the negative natural-log transformed value of $\bar{Q}$, or p$\bar{Q}$.

A master feature class was created by intersecting p$\bar{Q}$ data with bedrock geology polygons. Each polygon was associated with a unique "FID" which allowed for distinction between different zones / areas of a given geologic unit. A simplified rock type was assigned to each polygon based on provincial mapping. Simplified rock types included:

- Conglomerate (CNGL);
- Sandstone (SNDST);
- Siltstone (SLTST);
- Shale (SHLE);
- Metamorphic (META);
- Volcanic (VOL); and
- Plutonic (PLU).

Each bedrock polygon contained the following fields, forming the basis for ANOVA:

- p$\bar{Q}$;
- Rock Type;
- Formation or Group; and
- Polygon FID.

A series of 1-way ANOVAs were completed in order to determine which bedrock polygons exhibited a distinct mean p$\bar{Q}$, and to group those polygons which did not. For situations where only two sample means were available, a Student's T-Test was used in place of ANOVA. Each statistical test compared the variance of the mean p$\bar{Q}$ data across groups to the variance within each group. All analyses were completed at the 95% significance level. Figure 3.3 shows a schematic of the grouping process.

Polygons that contained at least three well records were tested against the Formation mean. If the mean p$\bar{Q}$ within a polygon was statistically distinct from the mean of the formation as a whole, the polygon was assigned that mean. Additional ANOVAs were used to develop groups of polygons exhibiting equal means, and these groupings were used in assignment of $\bar{Q}$ data. Any remaining polygons were grouped under the formation mean.

Formation means were also tested against the group mean for a given rock type. If the mean p$\bar{Q}$ within a formation was statistically distinct from the mean of the rock type group as a whole, the formation was assigned that mean. Additional ANOVAs were used to develop groups of formations exhibiting equal means, and these groupings were used in assignment of $\bar{Q}$ data. Any remaining formations were grouped under the rock type mean.

$\bar{Q}$ data were assigned according to the greatest level of spatial detail possible, subject to the results of the ANOVA. Polygons that contained no $\bar{Q}$ data were automatically grouped according to the formation. Polygons that contained no formation or group data were grouped according to Rock Type. Each Rock Type contained many different formations / groups, and some formations or groups contained many distinct polygons (FIDs). Table B1 provides a summary of the raw data used for ANOVA.

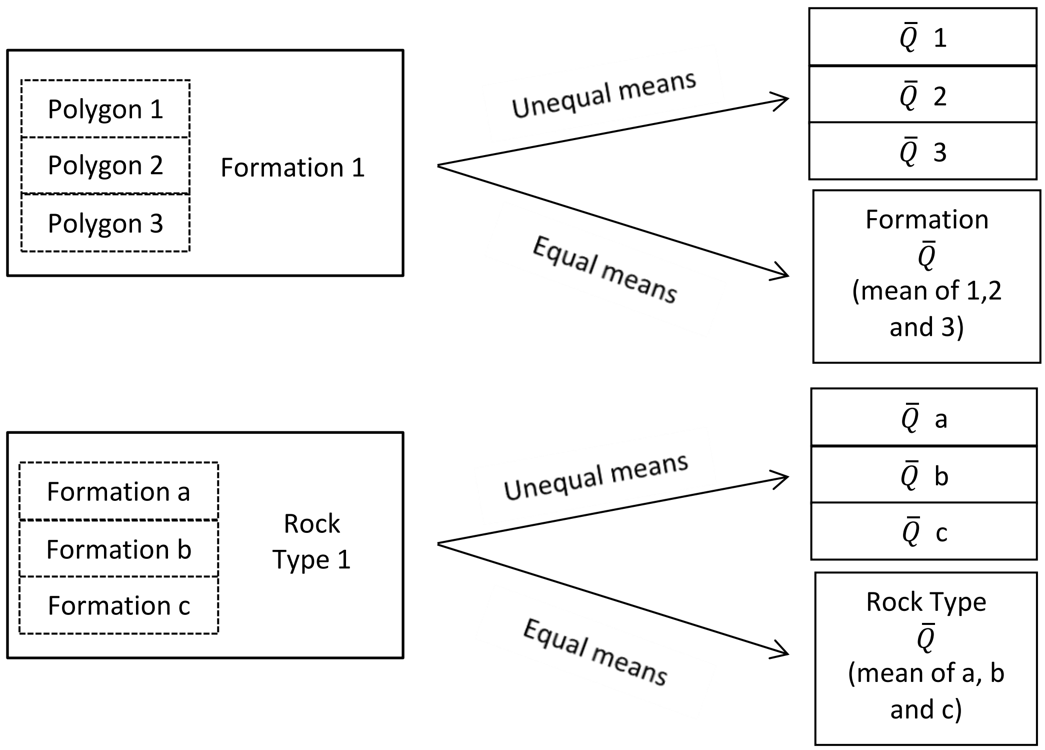


Figure 3.3: Schematic of ANOVA Grouping

The resulting feature class provided a $\bar{Q}$ for each polygon using the greatest level of detail possible while remaining statistically significant. A field was created to indicate the level of detail used to assign each polygon $\bar{Q}$ (i.e. Rock Type, Formation/Group, or FID), shown in Table B1.

Transmissivity estimates based on airlift yield data were compared to transmissivity estimates in the pumping test database compiled as part of Task 1. An ANOVA was completed for the data grouped by rock type, and a series of T-Tests was completed for pairs of means available for 14 Formations and Groups.

3.2.2 Results

3.2.2.1 Transmissivity data

Tables B1 shows the results of statistical testing using ANOVA. Transmissivity data obtained from the pumping test database were tested by rock type. The mean transmissivities for 60 observations varied from 0.7 to 9 m^2/day, but the ln-transformed data showed no statistical differences between rock types. The analysis suggests one of the following conclusions:

- All rock types in the data set exhibit similar transmissivities;

- There are insufficient data to represent the variability of the study area; or
- The assigned rock type categories are too broad or were not described in adequate detail in the borehole log.

Table B2 shows the results of t-tests. Transmissivity data from the pumping test database were compared to estimates of transmissivity using $\bar{Q}$ data. The data for sandstone and conglomerate rock types showed acceptable agreement, suggesting that use of the well depth to calculate specific capacity for these rock types introduced acceptable error. $\bar{Q}$ estimates of transmissivity for plutonic, shale, and siltstone rock types were not in agreement with pumping test data.

T-tests were also completed to compare transmissivity estimates within formations. Estimates for the Big Head, Fermeuse, Heart's Content, and Trepassey Formations showed adequate agreement. The Fermeuse and Heart's Content Formations were grouped as shale rock. The data indicate that groupings of these formations at a more local scale produced acceptable estimates of the rock transmissivity from $\bar{Q}$ data.

In general there was significant variation between transmissivity data obtained from pumping tests and estimates based on $\bar{Q}$ data. The variation was shown to be too large to apply this method to the study area as a whole. Aquifer test data (if available) was thus reserved for use only at local scales in vulnerability mapping (Task 3).

3.2.2.2 Well Yield Data

Table B1 shows a summary of ANOVA of p$\bar{Q}$ data. The mean p$\bar{Q}$ data showed differences between rock types and formations. Individual polygons within eight of the formations tested did not show significant variance, indicating that $\bar{Q}$ data for these formations should be lumped. Individual polygons within nine of the formations tested showed significant variance, indicating that means could be calculated and assigned for selected polygons within these formations. ANOVA tables were used to group polygons within each formation. T-tests were used to test the means for formations containing data within only two polygons (Table B2). Polygon $\bar{Q}$ data were lumped within the formation for an additional seven formations, and calculated separately for an additional five formations. Final Groupings are shown in Table B3.

Table B4 summarizes the groups and distinct mean $\bar{Q}$ s assigned to polygons in the study area, ranging from 0.03 to 4.05 m^2/day. A large part of the study area, comprising 836 polygons, was assigned the mean $\bar{Q}$ for all metamorphic, sandstone, shale, and volcanic units. Other groups that accounted for at least 100 polygons (out of 3156) included VOL1 (555), CNGL3 (525), PLU (514), PLU3 (281), VOL2 (275), SNDST1 (166), and SHLE1 (110). The formation groups "SLTST3", "SHLE2", and "SLTST1" were not assigned to any polygons, as all polygons within these groups were assigned individual mean $\bar{Q}$ s. Provincial mapping of detailed bedrock geology includes several polygons to represent granular quaternary material. These Quaternary Units were assigned a $\bar{Q}$ of 3.0 m^2/day. This value was close to the maximum mean $\bar{Q}$ in Table B4, and was assigned to represent the relatively high hydraulic conductivity of the granular deposits.

Figure 3.4 shows $\bar{Q}$ values across the Eastern Newfoundland study area. The second highest $\bar{Q}$ was assigned to the quaternary deposits that are included in the province's bedrock mapping. Other localized high $\bar{Q}$ units (shown in darker orange and red) include:

- The Belleoram Granite on Fortune Bay;
- Sandstone of the Rocky Harbour Formation in the northwestern part of the study area;
- Terra Nova granite in the northwestern part of the study area;
- Volcanic rock of the Bull Arm Formation near Fox Harbour;
- Sandstone of the Maturin Ponds Formation near Long Harbour;
- A Ribbon of siltstone of the Mistaken Point Formation running from Conception Bay to Saint Mary's Bay;
- Sandstone of the Trepassey Formation near Carbonear; and
- Plutonic rocks of the Harbour Main Group on Conception Bay.

$\bar{Q}$ data were mapped as moderate to good (green to yellow) in the following locations:

- Throughout much of the Baie de Verde Peninsula (Baie de Verde, Big Head and Gibbett Hill Formations);
- In the volcanic and plutonic rocks south of Conception Bay;
- Rocks of the Fermeuse and Heart's Desire Formation on the western Avalon Peninsula;
- Over much of the Burin Peninsula (Saint Lawrence granite, Barasway Formation, Wandsworth Formation);
- Plutonic rocks in the western corner of the study area bear Seal Cove and Harbour Breton; and
- Plutonic rocks near and to the north of Come-By-Chance.

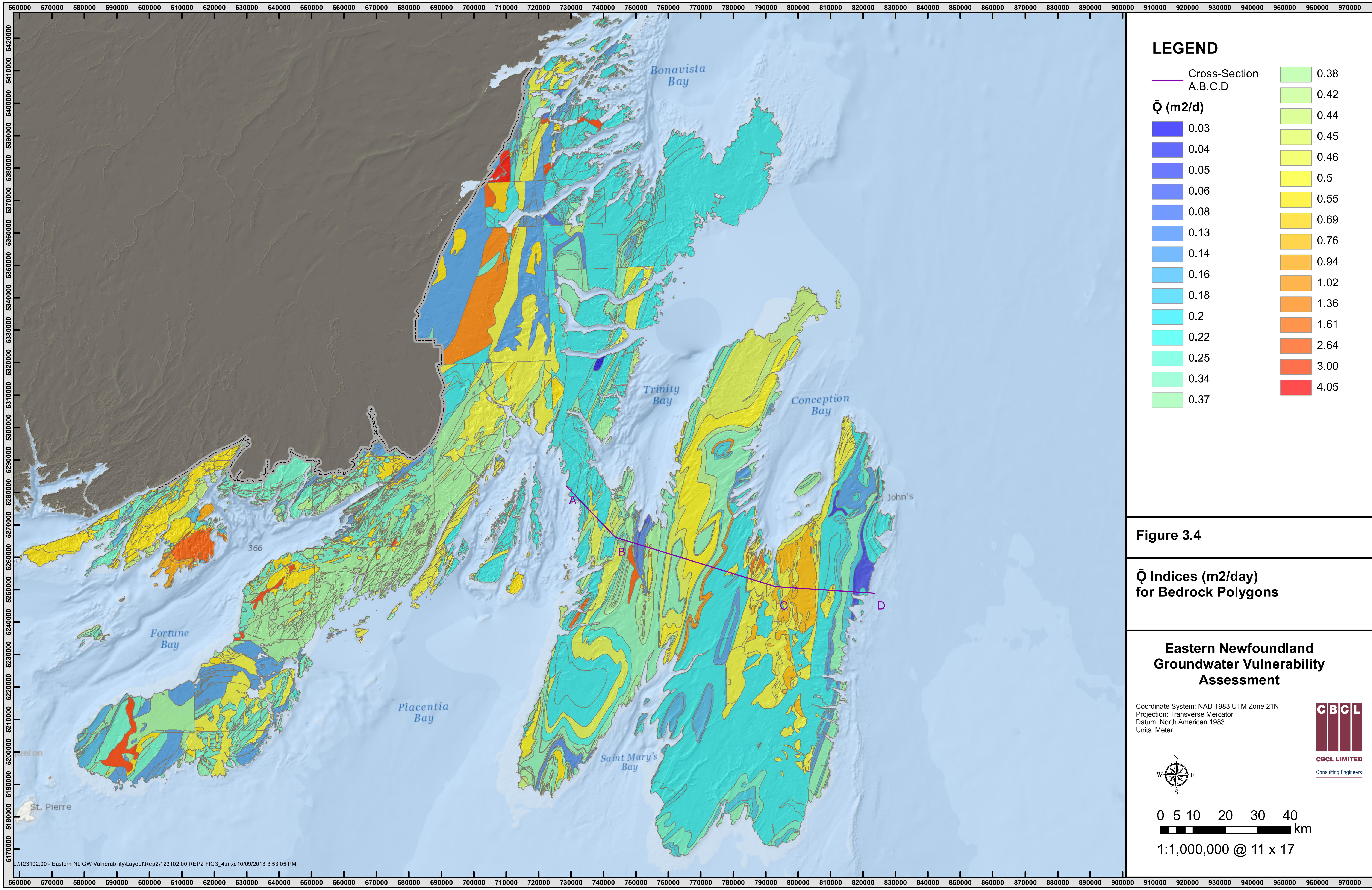
$\bar{Q}$ data were mapped as low to moderate (lighter blue):

- Over a large portions of the Avalon Peninsula (including the Drook Formation and Signal Hill Group);
- Rocks of the Mugravetown and Connecting Point groups from the southwest Avalon up to the Bonavista Peninsula; and
- The Connaigre Bay and Long Harbour groups on the north side of Fortune Bay.

The lowest $\bar{Q}$ (darker blue) areas were noted in the following locations:

- The Gibbet Hill Formation, Mistaken Point Formations, and Torbay Member of the Drook Formation near St. John's;
- The Elliott's Cove and Mistaken Point Formations south of Conception Harbour;
- The Mall Bay and Gaskier Formations near St. Mary's;
- The Bonavista Formation at Branch;
- The Big Head Formation on Southwest Arm;
- Rocks of the Love Cove group in the northwest part of the study area; and
- The Marystown Group rocks and Grand Beach Complex on the southern part of the Burin Peninsula.

The shaded units on Figure 3.3 generally correspond to the zones established in the Hydrogeologic Atlas of Eastern Newfoundland. The current data provide greater differentiation of well yields across mapped geologic units. The data on Figure 3.3 provide a means of indexing of the extrinsic vulnerability of each rock unit in the study area with as much detail as is currently available from geologic mapping and drilled well data. Indexing is discussed in Chapter 4.


LEGEND
Cross-Section A.B.C.D
Q̄ (m2/d)
0.03
0.04
0.05
0.06
0.08
0.13
0.14
0.16
0.18
0.2
0.22
0.25
0.34
0.37
0.38
0.42
0.44
0.45
0.46
0.5
0.55
0.69
0.76
0.94
1.02
1.36
1.61
2.64
3.00
4.05
Figure 3.4
Q̄ Indices (m2/day) for Bedrock Polygons
Eastern Newfoundland Groundwater Vulnerability Assessment
Coordinate System: NAD 1983 UTM Zone 21N
Projection: Transverse Mercator
Datum: North American 1983
Units: Meter
CBCL
CBCL LIMITED
Consulting Engineers
N
S
E
W
0 5 10 20 30 40
km
1:1,000,000 @ 11 x 17
Bonavista Bay
Trinity Bay
Conception Bay
Placentia Bay
Fortune Bay
Saint Mary's Bay
St. Pierre
366
A
B
C
D
..\123102.00 - Eastern NL GW Vulnerability\Layout\Rep2\123102.00 REP2 FIG3_4.mxd10/09/2013 3:53:05 PM

3.3 Geospatial and Statistical Analysis of Quaternary Material Thickness

3.3.1 Methodology

Quaternary geology mapping and geospatial data from the province's updated Drilled Well database were combined to provide an analysis of the thickness of potential confining units. The purpose of this analysis was to provide a statistically significant estimate of the thickness of each mapped quaternary unit, particularly till units with the potential to provide confinement to the underlying bedrock. The data will be used primarily for the assignment of an intrinsic aquifer vulnerability index.

Drilled well records were filtered to include only those records indicating a georeferencing method of "GPS" or "Map". Both of these methods are considered accurate enough to place drilled well locations within a given quaternary geology polygon from provincial mapping. Drilled well records were then intersected and associated with the underlying quaternary geology polygon unit.

As depth data for the study area were clustered, and did not intersect all quaternary geology polygons in the study area, direct assignment of depth-to-bedrock data to geology polygons was not possible. An analysis of variance (ANOVA) was completed in order to assign the best available depth data to each polygon in the study area. The methodology followed the process used in the analysis of well yield data (Section 3.2), but depth data were not ln-transformed.

A master feature class was created by intersecting depth to bedrock data with quaternary geology polygons. The material type was drawn from existing mapping, and included:

- Exposed Bedrock (EXBR);
- Glaciofluvial (GLFL);
- Drift Poor (DFTP);
- Glaciomarine and marine (GLMN);
- Bog (BOG);
- Alluvium (ALVM);
- Ablation Drift (ABLD);
- Till Blanket (TLBL);
- Till, Undifferentiated (TLUN); and
- Rogen Moraine (RGMN).

Each quaternary polygon contained the following fields, forming the basis for ANOVA:

- Depth;
- Material Type; and
- Polygon FID.

A series of 1-way ANOVAs were completed in order to determine which quaternary polygons exhibited a distinct mean depth, and to group those polygons which did not. Each statistical test compared the variance of the mean bedrock depth across groups to the variance within each group. All analyses were completed at the 95% significance level.

Polygons that contained at least three well records were tested against the material type mean. If the mean depth within a polygon was statistically distinct from the mean of the material type as a whole, the individual polygon was assigned that mean. Additional ANOVAs were used to develop groups of

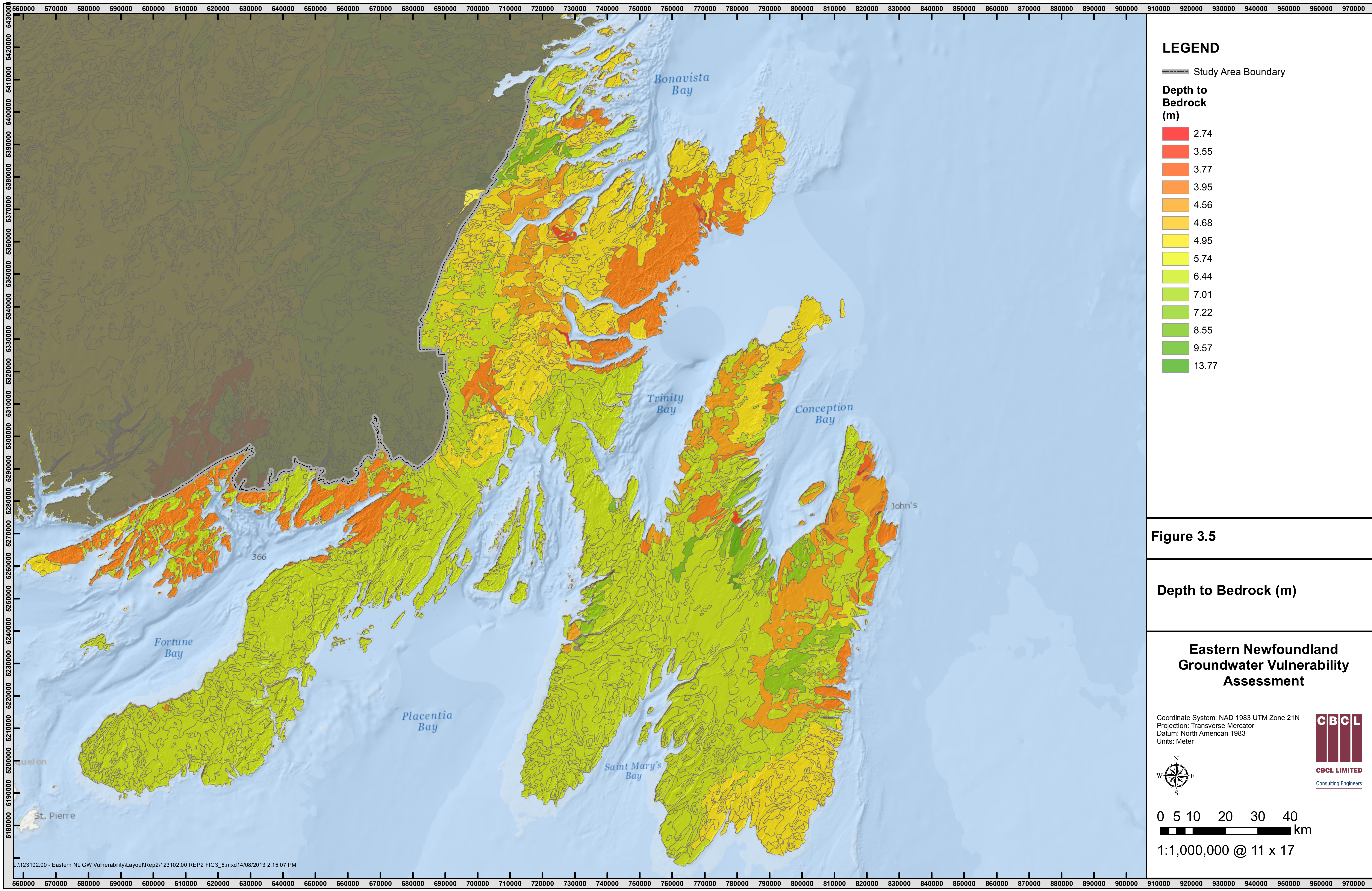


Figure 3.5

Depth to Bedrock (m)

polygons exhibiting equal means, and these groupings were used in assignment of depth data. Any remaining polygons were grouped under the material mean.

3.3.2 Results

Table C1 shows a summary of ANOVA of Depth to Bedrock data. The mean depths showed differences between quaternary material types. Individual polygons within two of the material types tested did not show significant variance, indicating that depth data for these formations should be lumped. Individual polygons within five of the material types tested showed significant variance, indicating that means could be calculated and assigned for selected polygons within these formations. ANOVA tables were used to group polygons within each formation, as shown in Table C2.

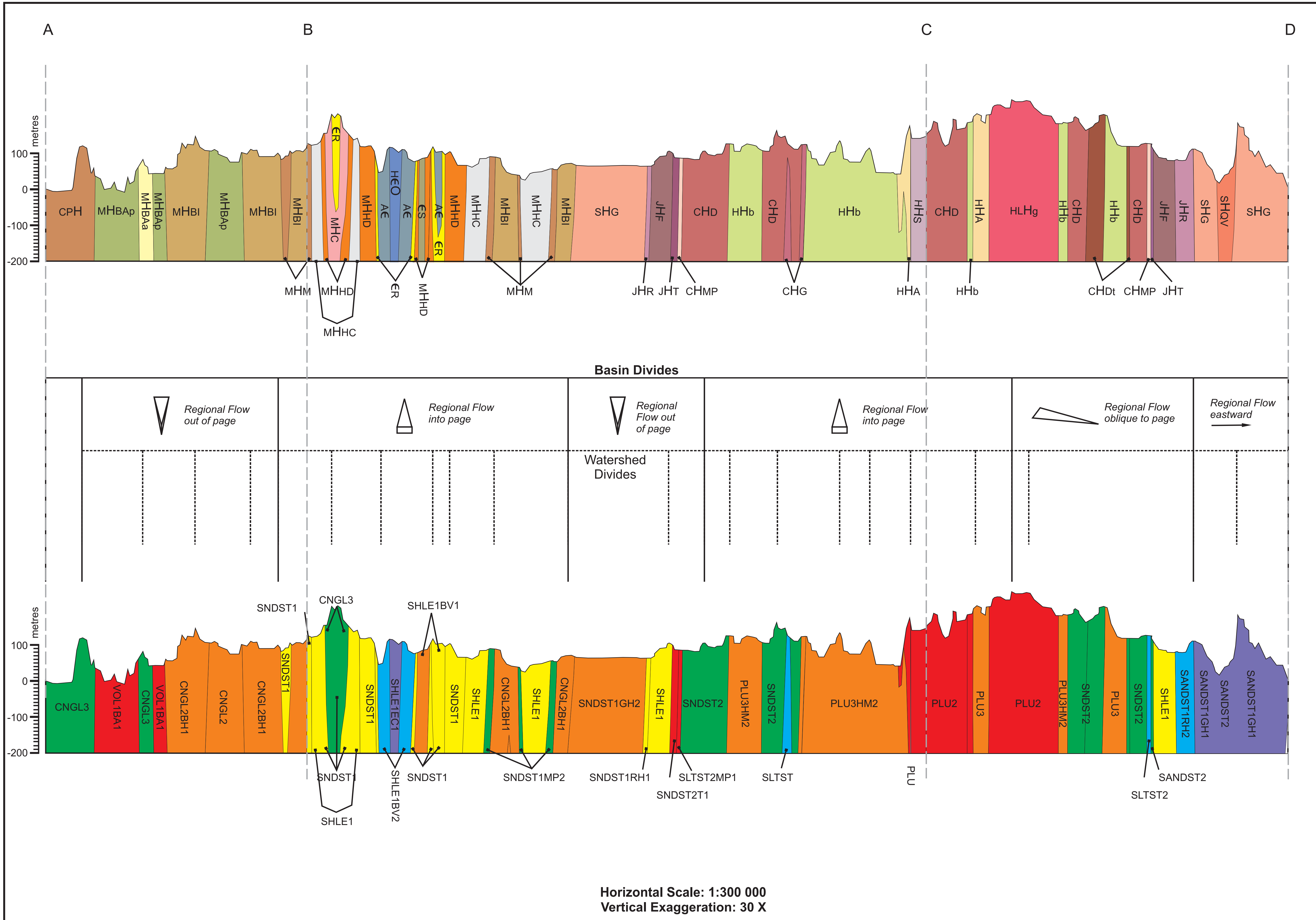
Table C3 summarizes the groups and distinct mean depths assigned to polygons in the study area, ranging from 2.74 to 13.77 metres. Much of the study area was assigned a mean based on the material groups QUAT1 and QUAT2. The DFTP1 and TLUN1 groups accounted for 19 and 16 polygons respectively. As only two data points were available for Alluvium material, alluvium was grouped under "QUAT1".

Figure 3.5 shows the depth to bedrock as mapped across the study area based on the ANOVA. Much of the study area, including the southwest Avalon and Burin Peninsulas were assigned an average depth to bedrock of 6.44 metres. Lesser thicknesses were assigned to the northern shore of Fortune Bay, the Bonavista Peninsula, the Baie de Verde Peninsula, and sections of the northeast Avalon Peninsula. Depths to bedrock in the Saint John's and Torbay areas were notably in the lower range of the study area, from 2.74 to 4.56 metres. The greatest thicknesses were noted in isolated parts of the Conception Bay area, Fox Harbour and Terra Nova-Glovertown.

3.4 Regional Groundwater Flow Data in Cross-Section

Data collected for vulnerability mapping were applied to an existing regional cross-section to determine how the data could be used to conceptualize typical flow fields. The geological cross-section was taken from provincial mapping (King, 1988), focussing on the upper 300 metres of the geologic profile, which accounts for most groundwater use. Figure 3.6 shows a reproduction of cross-section data over this depth interval. The geologic contacts viewed in this context are dipping but are primarily vertical, even when vertical exaggeration is accounted for.

Watershed groupings, watershed divides, and $\bar{Q}$ data were applied to the cross-section to demonstrate some regional groundwater flow features. Watershed mapping was used to determine likely regional flow systems within the units shown on Figure 3.6., shown to be generally parallel to the geologic contacts intersected by cross-section ABCD. Watershed mapping suggests that regional flow would be predominantly into and out of the plane of cross-section ABCD, and that little additional information on conceptual flow fields can be developed. Bedding planes transverse to the flow direction, such as those along the eastern-most part of the cross-section would affect groundwater flow patterns. If differences in $\bar{Q}$ data provide a reasonable index of the bulk hydraulic conductivity, the divisions shown could provide information on zones of predominantly vertical and horizontal flow at more local scales.



LEGEND

Hydrogeologic Unit and Well Yield Index

Hydrogeologic Unit	Well Yield Index
CNGL2BH2	0.03
SNDST1GH1	0.05
SHLE1EC1	0.06
SHLE1BV2	0.13
SLTST	0.16
SLTST2	0.17
SNDST1RH2	0.18
SNDST2	0.20
CNGL3	0.20
SNDST1MP2	0.22
SHLE1	0.33
SNDST1	0.37
SNDST1RH1	0.38
CNGL2	0.42
CNGL2BH1	0.45
PLU3	0.46
PLU3HM2	0.46
SNDST1GH2	0.48
SHLE1BV1	0.50
PLU	0.55
PLU2	0.76
SLST2MP1	1.0
SNDST2T1	1.0
VOL1BA1	2.6

FIGURE 3.6

CROSS- SECTION ABCD
(after King, 1988)
AND
REGIONAL YIELD DATA

Newfoundland and Labrador Department of Energy and Conservation

DATE: July 29, 2013

PROJECT NO.: 123102

CBCL LIMITED
Consulting Engineers

CHAPTER 4 AQUIFER VULNERABILITY PARAMETERS

4.1 Qualitative Mapping

4.1.1 Intrinsic Vulnerability Parameters

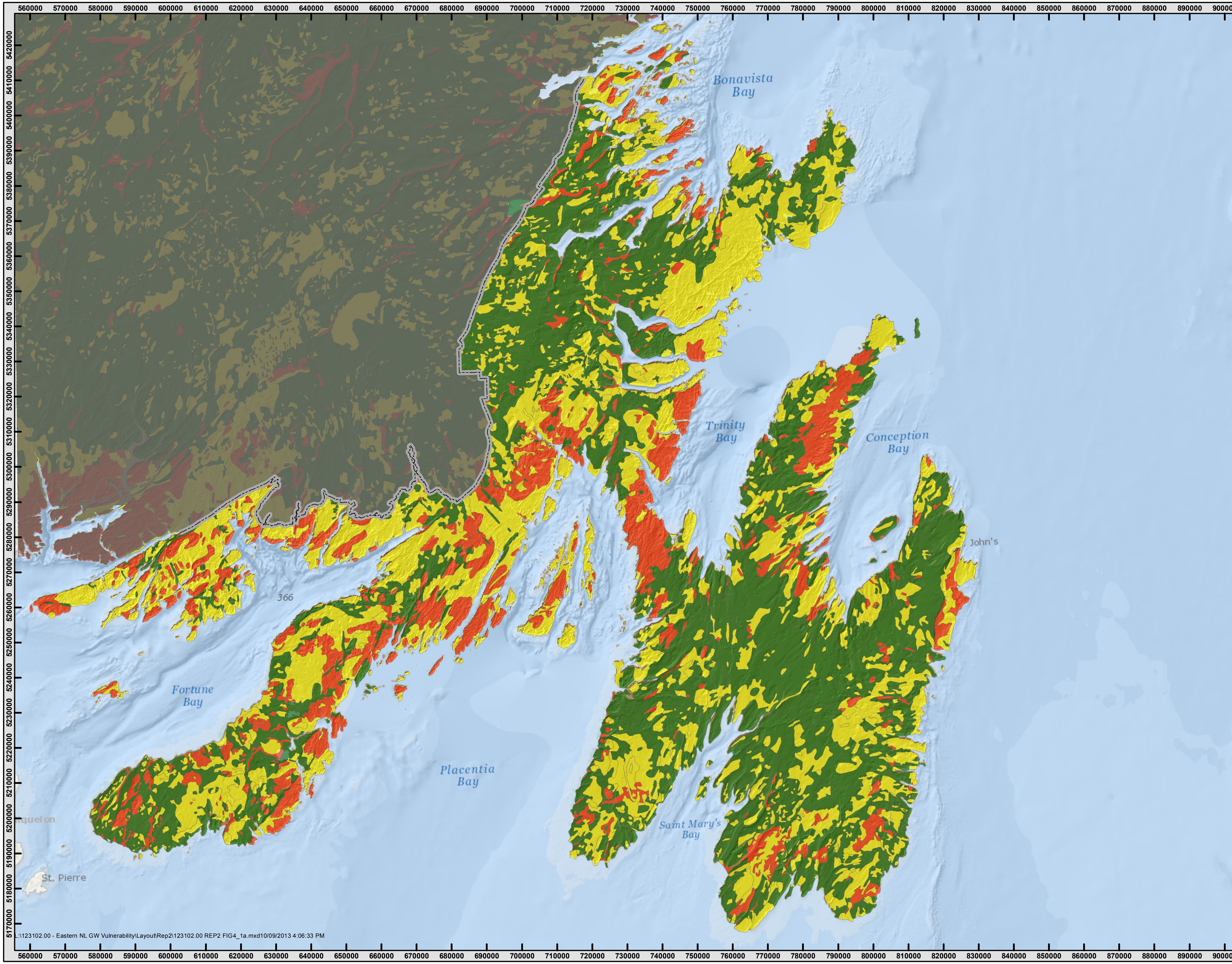
Intrinsic vulnerability scores represent the ease with which contaminants may enter the subsurface. Intrinsic vulnerability at the qualitative level is based on quaternary mapping. Quaternary map units are assigned a qualitative score as shown in Table 4.1 and on Figure 4.1.

Table 4.1: Qualitative Scores for Quaternary Mapping Units

Quaternary Unit	Rating
Glaciolacustrine	Low
Ablation Drift	Low
Till blanket	Low
Till, undifferentiated	Low
Rogen Moraine	Low
Drift poor	Moderate
Glaciomarine and marine	Moderate
Bog	Moderate
Alluvium	Moderate
Exposed Bedrock	High
Glaciofluvial	High

Ratings for quaternary units are based on the expected thickness and hydraulic conductivity of each unit. Eskers and glaciofluvial material are expected to consist primarily of sand and gravel, with relatively high hydraulic conductivity. Contaminants are expected to infiltrate readily through this material, resulting in a qualitative score of High. Exposed bedrock likewise exhibits a direct pathway to the subsurface, and is assigned a qualitative score of High.

Till and glaciolacustrine material are expected to consist of finer grained, poorly sorted material, resulting in a relatively low hydraulic conductivity and greater resistance to contaminants entering the subsurface. The qualitative score for these units is Low.



Legend

Study Area Boundary

Intrinsic Index

- Low
- Moderate
- High

Notes:
Intrinsic vulnerability scores represent the ease with which contaminants may enter the subsurface. Intrinsic vulnerability at the qualitative level was based on quaternary mapping. Ratings for quaternary units are based on the expected thickness and hydraulic conductivity of each unit.

Figure 4.1

Qualitative Indices for Intrinsic Aquifer Vulnerability

Eastern Newfoundland Groundwater Vulnerability Assessment

Coordinate System: NAD 1983 UTM Zone 21N
Projection: Transverse Mercator
Datum: North American 1983
Units: Meter

CBCL LIMITED
Consulting Engineers

0 5 10 20 30 40 km

1:1,000,000 @ 11 x 17

Drift poor, glaciomarine and marine, bog, and alluvium material are expected to exhibit variable thicknesses, grain sizes and degrees of sorting. These units are assigned an intermediate qualitative score of Moderate.

4.1.2 Extrinsic Vulnerability Parameters

Extrinsic vulnerability represents the ease with which contaminants are transported in the saturated zone. Extrinsic vulnerability at the qualitative level will be based the $\bar{Q}$ index of each bedrock polygon in the study area. $\bar{Q}$ indices will be assigned a qualitative score as shown in Table 4.2 and on Figure 4.2.

Table 4.2: Qualitative Scores for Bedrock Yield Indices

$\bar{Q}$	Rating
<0.2	Low
0.2 to 0.5	Moderate
>0.5	High

$\bar{Q}$ scores exceeding 0.5 m^2/d represent the highest yielding zones in the study area, but may not be representative of high hydraulic conductivities and high vulnerabilities as compared to other zones in North America.

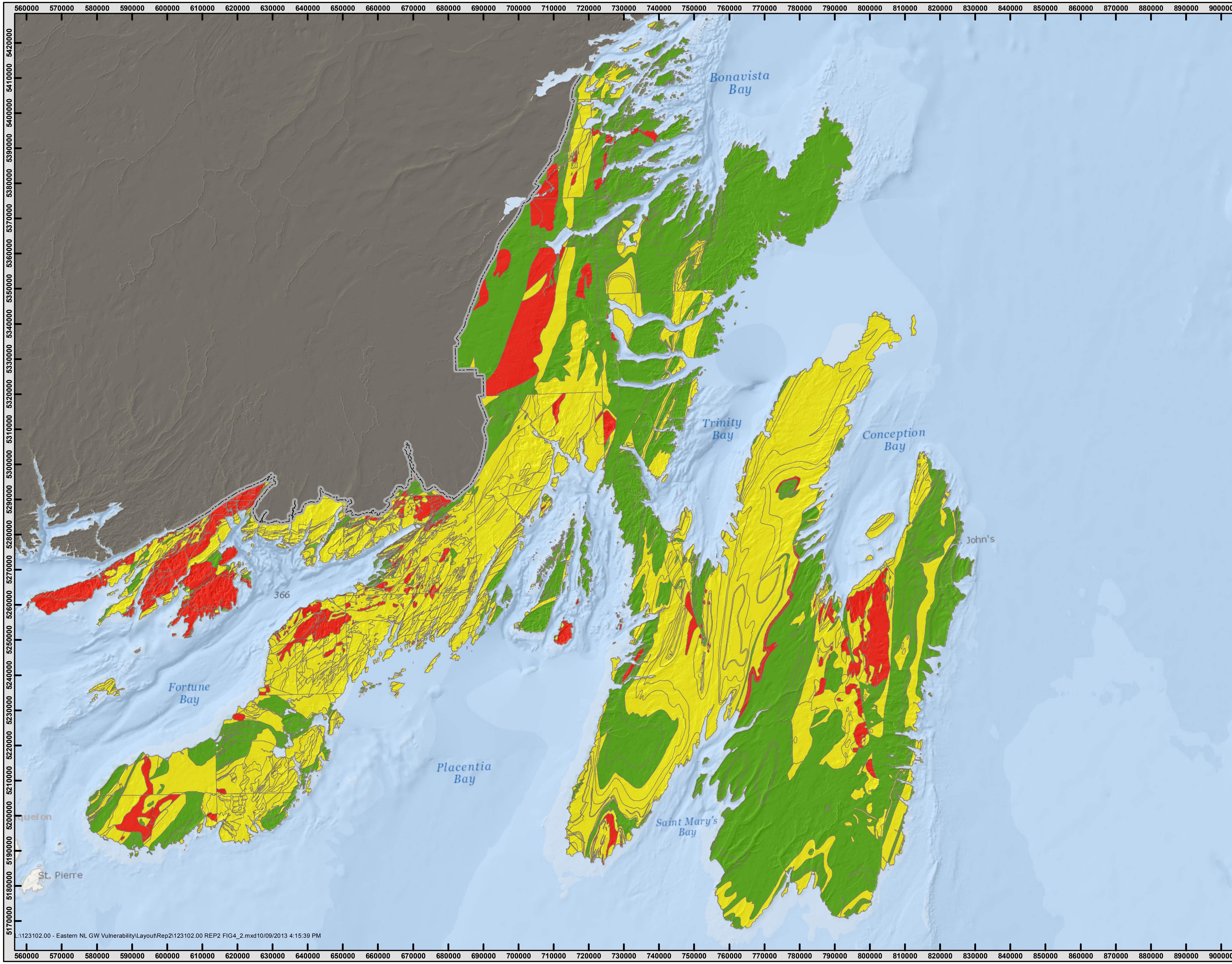
Preliminary results of qualitative mapping are on shown on Figure C1. Aquifer vulnerability mapping is discussed in Reporting for Task 3.

4.2 Soil Drainage

Soil drainage data are drawn from provincial mapping of soils data. Table 4.3 shows the vulnerability indices as determined by soil drainage categories. The indices in Table 4.3 were developed from the data available for the current work and DRASTIC soil media parameters presented in Table 7 of the EPA methodology (Aller et al., 1987).

Table 4.3: Soil Drainage Indices

Soil Drainage	Index
Water	1
Very Poor	2
Poor	3
Imperfect	5
Moderate	6
Well	8
Rock	8
Rapid	10



LEGEND

Study Area Boundary

Q̄ Index

- Low
- Moderate
- High

Notes:
Extrinsic vulnerability represents the ease with which contaminants are transported in the saturated zone. Extrinsic vulnerability at the qualitative level was based on the Q̄ index of each bedrock polygon in the study area.

Figure 4.2

Qualitative Indices for Extrinsic Aquifer Vulnerability

Eastern Newfoundland Groundwater Vulnerability Assessment

Coordinate System: NAD 1983 UTM Zone 21N
Projection: Transverse Mercator
Datum: North American 1983
Units: Meter

CBCL LIMITED
Consulting Engineers

0 5 10 20 30 40 km

1:1,000,000 @ 11 x 17

4.3 Quaternary Geology

Quaternary geology data are drawn from provincial mapping. Table 4.4 shows vulnerability indices as determined by material type and associated properties. The indices in Table 4.4 were developed from the data available for the current work and DRASTIC vadose zone parameters presented in Table 9 of the EPA methodology (Aller et al., 1987).

Table 4.4: Quaternary Mapping Indices

Quaternary Unit	Index
Rogen Moraine	1
Glaciolacustrine	3
Ablation Drift	3
Till blanket	3
Till, undifferentiated	3
Bog	5
Alluvium	5
Glaciomarine and marine	6
Drift poor	7
Glaciofluvial	8
Exposed Bedrock	9
Esker	10

4.4 Depth to Bedrock

Depth to bedrock data are drawn from the ANOVA of quaternary mapping and drilled well data as presented in Section 3.3. Table 4.5 shows the vulnerability indices as determined by the results of the ANOVA. The indices in Table 4.5 were adjusted using the DRASTIC depth to water parameters presented in Table 4 of the EPA methodology (Aller et al., 1987).

Table 4.5: Depth to Bedrock Indices

Depth to Bedrock (m)	Index
>24	1
24	2
21	3
18	4
15	5
12	6
9	7
6	8
3	9
<3	10

4.5 Slope

Slope data are drawn from the slope analysis presented under Task 1 of this study. Slope data were generated based on a DEM developed by CBCL for aquifer vulnerability mapping. Table 4.6 shows the vulnerability indices as determined by the slope analysis. The indices in Table 4.6 were adjusted based on the DRASTIC topography parameters presented in Table 8 of the EPA methodology (Aller et al., 1987).

Table 4.6: Slope Indices

% Slope	Index
>20	1
20	2
18	3
15	4
12	5
11	6
10	7
8	8
6	9
<2	10

4.6 Groundwater Recharge

Groundwater recharge data presented in Section 3.1 could be used for vulnerability mapping completed at local scales. Table 4.7 shows the vulnerability indices as determined by baseflow analyses. The indices in Table 4.7 were adjusted based on the DRASTIC recharge parameters presented in Table 5 of the EPA methodology (Aller et al., 1987).

Table 4.7: Recharge Indices

Recharge (mm)	Index
<70	1
70	2
100	3
130	4
160	5
190	6
220	7
250	8
280	9
>280	10

4.7 Bedrock Yield

Bedrock yield data are drawn from the ANOVA of bedrock unit mapping and drilled well data as presented in Section 3.2. Table 4.8 shows vulnerability indices as determined by the results of the

ANOVA. The indices were determined by pro-rating $\bar{Q}$ data on a ln-normal scale. Bedrock $\bar{Q}$ indices are used as a proxy for hydraulic conductivity indices. The DRASTIC aquifer media parameters in Table 6 and DRASTIC hydraulic conductivity parameters in Table 10 of the EPA methodology (Aller et al., 1987) were not directly comparable. The hydraulic conductivities used in Table 10 of the EPA methodology ranged from 4.7 x 10^{-5} m/s to 9.4 x 10^{-4} m/s, indexed from 1 to 10. These values are likely to be one to several orders of magnitude higher than those observed in the study area. A direct comparison of vulnerability indices produced in this study to established zones in the DRASTIC methodology would therefore require considerable adjustment and interpretation.

Table 4.8: $\bar{Q}$ Indices

$\bar{Q}$ (m^2/d)	Index
0.03	1
0.06	2
0.10	3
0.15	4
0.30	5
0.45	6
0.75	7
1.4	8
2.4	9
4.0	10

4.8 Weightings

Parameter weightings were based on the EPA methodology with a total weight from all categories of 23. Considering the differences in the parameters used in this study and those developed for DRASTIC, a direct comparison of scores was not considered to be practical. The weighting of parameters was, however, adjusted to be proportional to the closest corresponding DRASTIC parameter(s). Table 4.9 shows the proposed weightings.

Table 4.9: Parameter Weightings for Detailed Mapping Areas and DRASTIC

	Drastic Parameter	E. NFLD Parameter	Weighting	
D	Depth to Water	Depth to Bedrock	5	22%
R	Recharge	Baseflow	4	17%
A	Aquifer Media	Bedrock $\bar{Q}$	3	13%
S	Soil Media	Soil Drainage	2	9%
T	Topography	Slope	1	4%
I	Impact of Vadose Zone	Quaternary Geology	5	22%
C	Hydraulic Conductivity of Aquifer	Bedrock $\bar{Q}$	3	13%
Total			**23**	100%

Mapping at the regional is conducted to provide an initial screening and means of comparison to qualitative mapping. As baseflow data were not available for regional mapping, the Recharge/Baseflow parameter was redistributed to the Soil Drainage, Slope, and Quaternary Geology Parameters as shown in Table 4.10.

Table 4.10: Parameter Weightings for Study Area Screening and DRASTIC

	Drastic Parameter	E. NFLD Parameter	Weighting	
D	Depth to Water	Depth to Bedrock	5	22%
R	Recharge	N/A	0	
A	Aquifer Media	Bedrock $\bar{Q}$	3	13%
S	Soil Media	Soil Drainage	4	17%
T	Topography	Slope	2	9%
I	Impact of Vadose Zone	Quaternary Geology	6	26%
C	Hydraulic Conductivity of Aquifer	Bedrock $\bar{Q}$	3	13%
Total			**23**	100%

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APPENDIX A

Hydrometric Data

Table A1. Summary of Baseflow Separations and Baseflow Minima Calculations at Stream Gauging Stations

CODE	STATION NAME	NORTHING	EASTING	WATERSHED AREA	alpha (recession constant)[1]	AVERAGE BASEFLOW[1]	ANNUAL RECHARGE	BASEFLOW MINIMUM	RECHARGE MINIMUM	N
				km2	min=7 days max=20 days	m3/s	mm/a	m3/s	mm/a	years
02YS001	TERRA NOVA RIVER AT EIGHT MILE BRIDGES	48°26'30.0¨ N	54°22'21.0¨ W	1290	0.035	22.86	559	4.306	105	34
02YS002	ROCKY POND BROOK AT ROCKY POND	48°31'37.0¨ N	53°57'32.0¨ W	2.31		0.03	426	0.005	68	4
02YS003	SOUTHWEST BROOK AT TERRA NOVA NATIONAL PARK	48°36'27.8¨ N	53°58'44.0¨ W	36.7	0.170	0.34	292	0.070	60	41
02YS004	PITTS BROOK NEAR PORT BLANDFORD	48°18'55.0¨ N	54°10'45.0¨ W	10.8		0.02	47	0.005	15	1
02YS005	TERRA NOVA RIVER AT GLOVERTOWN	48°39'45.9¨ N	54°0'54.9¨ W	2000	0.029	29.77	469	9.235	146	24
02YS006	NORTHWEST RIVER AT TERRA NOVA NATIONAL PARK	48°23'49.2¨ N	54°12'1.5¨ W	663	0.059	9.76	464	1.448	69	14
02ZF001	BAY DU NORD RIVER AT BIG FALLS	47°44'48.6¨ N	55°26'24.8¨ W	1170	0.038	24.50	660	8.703	235	58
02ZG001	GARNISH RIVER NEAR GARNISH	47°12'59.1¨ N	55°19'48.0¨ W	205	0.070	4.09	629	1.173	180	50
02ZG002	TIDES BROOK BELOW FRESHWATER POND	47°7'38.0¨ N	55°15'54.0¨ W	166	0.069	3.94	749	1.054	200	20
02ZG003	SALMONIER RIVER NEAR LAMALINE	46°52'40.1¨ N	55°46'34.3¨ W	115	0.100	1.44	395	0.269	74	29
02ZG004	RATTLE BROOK NEAR BOAT HARBOUR	47°27'0.1¨ N	54°51'10.9¨ W	42.7	0.118	0.70	518	0.136	100	28
02ZG005	LITTLE BARASWAY BROOK NEAR MOLLIERS	47°5'60.0¨ N	55°37'15.0¨ W	28.2	0.225	0.31	344	0.038	42	9
02ZH001	PIPERS HOLE RIVER AT MOTHERS BROOK	47°56'48.0¨ N	54°17'3.6¨ W	764	0.061	11.13	459	2.728	113	55
02ZH002	COME BY CHANCE RIVER NEAR GOOBIES	47°55'7.5¨ N	53°56'55.2¨ W	43.3	0.170	0.60	436	0.073	53	48
02ZJ001	SOUTHERN BAY RIVER NEAR SOUTHERN BAY	48°22'50.4¨ N	53°40'26.2¨ W	67.4	0.094	0.81	381	0.079	37	33
02ZJ002	SALMON COVE RIVER NEAR CHAMPNEYS	48°23'45.3¨ N	53°18'5.8¨ W	73.6	0.070	1.30	556	0.281	120	26
02ZJ003	SHOAL HARBOUR RIVER NEAR CLARENVILLE	48°13'12.6¨ N	54°2'58.7¨ W	106	0.083	1.40	415	0.195	58	23
02ZK001	ROCKY RIVER NEAR COLINET	47°13'37.6¨ N	53°34'7.0¨ W	301	0.068	4.57	479	0.985	103	55
02ZK002	NORTHEAST RIVER NEAR PLACENTIA	47°16'26.3¨ N	53°50'19.4¨ W	89.6	0.076	1.75	617	0.439	154	30
02ZK003	LITTLE BARACHOIS RIVER NEAR PLACENTIA	47°10'52.7¨ N	54°2'20.1¨ W	37.2	0.156	0.47	397	0.216	183.52	26
02ZK004	LITTLE SALMONIER RIVER NEAR NORTH HARBOUR	47°7'18.6¨ N	53°43'54.4¨ W	104	0.098	1.58	480	0.469	142	26
02ZK005	TROUT BROOK NEAR BELLEVUE	47°36'21.0¨ N	53°45'53.0¨ W	50.3	0.086	0.60	376	0.125	78	11
02ZK006	RATTLING BROOK BELOW BRIDGE	47°24'51.1¨ N	53°48'26.4¨ W	32.71	0.123	0.62	600	0.172	165	2
02ZL003	SPOUT COVE BROOK NEAR SPOUT COVE	47°48'43.0¨ N	53°9'15.0¨ W	10.8		0.17	499	0.027	79	18
02ZL004	SHEARSTOWN BROOK AT SHEARSTOWN	47°34'59.0¨ N	53°18'29.1¨ W	28.9	0.111	0.35	382	0.099	108	26
02ZL005	BIG BROOK AT LEAD COVE	48°2'34.0¨ N	53°4'55.6¨ W	11.2		0.18	517	0.037	104	26
02ZM001	PETTY HARBOUR RIVER AT SECOND POND	47°27'27.0¨ N	52°43'47.0¨ W	134	0.078	1.61	379	0.074	18	24
02ZM002	PIERRES BROOK AT GULL POND	47°17'50.0¨ N	52°50'60.0¨ W	117	0.011	2.83	764	0.337	90.78	26
02ZM003	MOBILE RIVER AT MOBILE FIRST POND	47°14'58.0¨ N	52°53'20.0¨ W	112		2.49	700	0.306	86.20	26
02ZM004	HORSE CHOPS RIVER NEAR CAPE BROYLE	47°5'60.0¨ N	52°55'60.0¨ W	88.1		2.38	852	0.637	228	1
02ZM006	NORTHEAST POND RIVER AT NORTHEAST POND	47°38'4.7¨ N	52°50'11.6¨ W	3.63		0.04	329	0.008	66	55
02ZM007	BROAD COVE BROOK NEAR ST. PHILLIPS	47°34'17.0¨ N	52°52'13.0¨ W	nm	0.114	0.34		0.042		15
02ZM008	WATERFORD RIVER AT KILBRIDE	47°31'44.6¨ N	52°44'42.2¨ W	52.7	0.091	0.85	511	0.271	162	35
02ZM009	SEAL COVE BROOK NEAR CAPPAHAYDEN	46°50'46.6¨ N	52°58'21.3¨ W	53.6	0.097	1.12	657	0.349	205	30
02ZM010	WATERFORD RIVER AT MOUNT PEARL	47°31'21.0¨ N	52°48'32.0¨ W	16.6	0.138	0.29	550	0.110	208	15
02ZM011	WATERFORD RIVER NEAR DONOVANS INDUSTRIAL PARK	47°31'41.0¨ N	52°49'42.0¨ W	11.4		0.18	489	0.070	194	4
02ZM016	SOUTH RIVER NEAR HOLYROOD	47°21'16.8¨ N	53°7'2.0¨ W	17.3	0.098	0.28	514	0.089	162	26
02ZM017	LEARY BROOK AT ST. JOHN'S	47°33'43.0¨ N	52°45'47.0¨ W	15.3	CRASHED			0.059	121	15
02ZM018	VIRGINIA RIVER AT PLEASANTVILLE	47°35'20.2¨ N	52°41'26.8¨ W	10.7	CRASHED			0.084	246	25
02ZM019	VIRGINIA RIVER AT CARTWRIGHT PLACE	47°36'6.0¨ N	52°42'6.0¨ W	5.55		0.10	574	0.035	201	13
02ZM020	LEARY BROOK AT PRINCE PHILIP DRIVE	47°33'51.3¨ N	52°44'54.5¨ W	17.8	0.098	0.32	562	0.116	206	24
02ZM021	SOUTH BROOK AT PEARL TOWN ROAD	47°30'24.0¨ N	52°46'24.0¨ W	9.21		0.13	459	0.031	105	12
02ZM022	RAYMOND BROOK AT OUTLET OF BAY BULLS BIG POND	47°25'12.6¨ N	52°48'2.3¨ W	nm	0.498	0.26		0.075		21
02ZN001	NORTHWEST BROOK AT NORTHWEST POND	46°51'8.0¨ N	53°18'11.0¨ W	53.3	0.086	1.22	723	0.474	280	30
02ZN002	ST. SHOTTS RIVER NEAR TREPASSEY	46°42'35.6¨ N	53°29'8.1¨ W	15.5	0.089	0.29	588	0.093	190	23

[1] As calculated using a digital recursive filter (Arnold et. al, 1995)

APPENDIX B

Geospatial ANOVA Results for Well Yields ($\bar{Q}$)

Table B1. ANOVA Summary for $\bar{Q}$ and Transmissivity Data

Test Group	Factor	F Statistic	F Critical	Variance
Population (pT)	Rock Type	2.30	2.37	EQUAL
Population (p$\bar{Q}$)		25.87	2.01	UNEQUAL
Conglomerate	Formation	4.57	1.91	UNEQUAL
Plutonic		2.46	1.77	UNEQUAL
Sandstone		2.34	1.62	UNEQUAL
Shale		5.81	2.02	UNEQUAL
Siltstone		5.18	2.40	UNEQUAL
Volcanic		1.76	1.74	UNEQUAL
Big Head Formation	Polygon	4.53	2.67	UNEQUAL
Bull Arm Formation (CNGL)		9.39	2.77	UNEQUAL
Bull Arm Formation (PLU)		2.29	2.35	EQUAL
Harbour Main Group		2.51	1.75	UNEQUAL
Heart's Desire Formation		0.75	2.55	EQUAL
Maturin Ponds Formation		5.65	2.39	UNEQUAL
Random Formation (SNDST)		1.00	3.59	EQUAL
Renews Head Formation		3.31	2.42	UNEQUAL
Trepassey Formation		5.11	2.37	UNEQUAL
Bonavista Formation		3.73	1.90	UNEQUAL
Drook Formation (SHLE)		1.13	2.12	EQUAL
Fermeuse Formation		1.82	2.41	EQUAL
Heart's Content Formation		1.89	2.67	EQUAL
Connecting Point Formation		1.60	2.34	EQUAL
Mistaken Point Formation		8.39	2.15	UNEQUAL
Bull Arm Formation (VOL)		9.26	2.37	UNEQUAL
Cashel Lookout Formation		1.42	2.48	EQUAL

Table B2. Summary of T-Tests

Test Group	Factor	t-Statistic	t-Critical	Means
CONGLOMERATE	ROCK T - T_Q̄	-1.03	1.97	EQUAL
PLUTONIC		-4.40	1.96	UNEQUAL
SANDSTONE		-1.78	1.96	EQUAL
SHALE		-4.25	1.96	UNEQUAL
SILTSTONE		-2.74	1.97	UNEQUAL
Big Head Formation	FM T - T_Q̄	-1.50	1.98	EQUAL
Drook Formation		-6.42	1.97	UNEQUAL
Fermeuse Formation		-1.58	1.97	EQUAL
Harbour Main Group		-4.21	1.97	UNEQUAL
Heart's Content Formation		1.31	1.98	EQUAL
Mistaken Point Formation		-2.44	1.97	UNEQUAL
Trepassey formation		-0.15	2.00	EQUAL
META: Love Cove Gr and Redmans Fm	Formation Q̄	1.31	2.13	EQUAL
Crown Hill Formation 10 & 273	POLYGON Q̄	-0.02	2.20	EQUAL
Great Bay de l'Eau Formation 979 & 1069		-0.16	2.01	EQUAL
Love Cove Group 1767 & 1885		0.08	2.23	EQUAL
Holyrood Intrusive Suite 1081 & 1243		0.01	1.99	EQUAL
Terra Nova Granite 1876 & 1955		2.90	2.09	UNEQUAL
Drook Formation 1460 & 1603		2.88	2.06	UNEQUAL
Gibbett Hill Formation 1557 & 1694		4.21	1.99	UNEQUAL
Rocky Harbour Formation 1741 & 2147		-3.31	2.31	UNEQUAL
Undivided Sedimentary rocks 1677 & 1734		-0.25	2.07	EQUAL
Elliotts Cove Formation 1302 & 1311		4.07	1.99	UNEQUAL
Andersons Cove Formation 2547 & 2560		-0.16	2.45	EQUAL
English Harbour East Formation 2663 & 2708		0.77	2.06	EQUAL

Table B3. Q̄ Groups, Codes and Data

LEVEL	ROCK	Formation	Polygon	FM CODE	pYPM	YPM
1	CNGL			CNGL	0.97	0.38
	PLU			PLU	0.59	0.55
	META			MTASEDVOL	1.37	0.25
	SNDST			MTASEDVOL	1.37	0.25
	SHLE			MTASEDVOL	1.37	0.25
	VOL			MTASEDVOL	1.37	0.25
	SLTST			SLTST	1.85	0.16
	QUAT			QUAT	-1.10	3.00
2	CNGL	Great Bay de l'Eau Formation		CNGL1	0.07	0.94
		Bay de Verde Formation		CNGL2	0.86	0.42
		Pools Cove Formation		CNGL2	0.86	0.42
		Big Head Formation		CNGL2	0.86	0.42
		Cannings Cove Formation		CNGL2	0.86	0.42
		Bull Arm Formation		CNGL3	1.62	0.20
		Cuckold Formation		CNGL3	1.62	0.20
		Connecting Point Group		CNGL3	1.62	0.20
		Crown Hill Formation		CNGL3	1.62	0.20
	PLU	Terra Nova Granite		PLU1	-0.88	2.42
		Belleoram Granite		PLU1	-0.88	2.42
		Holyrood Intrusive Suite		PLU2	0.28	0.76
		Harbour Main Group		PLU3	0.77	0.46
		St. Lawrence Granite		PLU3	0.77	0.46
		Swift Current Granite		PLU3	0.77	0.46
		Barasway Formation		PLU3	0.77	0.46
		Bull Arm Formation		PLU3	0.77	0.46
		Rocky Harbour Formation		PLU3	0.77	0.46
		Whalesback Gabbro		PLU3	0.77	0.46
		Anchor Drogue granodiorite		PLU3	0.77	0.46
		Wandsworth Formation		PLU3	0.77	0.46
	SNDST	Cinq Isles Formation		SNDST1	0.98	0.37
		Heart's Desire Formation		SNDST1	0.98	0.37
		Bay de Verde Formation		SNDST1	0.98	0.37
		Gibbett Hill Formation		SNDST1	0.98	0.37
		Connecting Point Group		SNDST1	0.98	0.37
		Random Formation		SNDST1	0.98	0.37
		Little Bell Island Formation		SNDST1	0.98	0.37
		Upper Rocky Harbour Formation		SNDST1	0.98	0.37
		Maturin Ponds Formation		SNDST1	0.98	0.37
		Blackhead Formation		SNDST2	1.62	0.20
		Rocky Harbour Formation		SNDST2	1.62	0.20
		Trepassey formation		SNDST2	1.62	0.20
		Renews Head Formation		SNDST2	1.62	0.20
		Quidi Vidi Formation		SNDST2	1.62	0.20
		Undivided Sedimentary rocks		SNDST2	1.62	0.20
		Drook Formation		SNDST2	1.62	0.20
		Musgravetown Group		SNDST2	1.62	0.20
		Trinny Cove Formation		SNDST2	1.62	0.20

Table B3. Q̄ Groups, Codes and Data

LEVEL	ROCK	Formation	Polygon	FM CODE	pYPM	YPM
2	SHLE	Elliotts Cove Formation		SHLE1	1.12	0.33
		Bonavista Formation		SHLE1	1.12	0.33
		Fermeuse Formation		SHLE1	1.12	0.33
		Heart's Content Formation		SHLE1	1.12	0.33
		(001M/04/0170a undivided Cambrian shales and limestones)		SHLE1	1.12	0.33
		Bay View Formation		SHLE1	1.12	0.33
		Drook Formation		SHLE2	1.67	0.19
	SLTST	Gibbett Hill Formation		SLTST1	0.35	0.71
		Bull Arm Formation		SLTST1	0.35	0.71
		Mistaken Point Formation		SLTST2	1.76	0.17
		Connecting Point Group		SLTST3	2.28	0.10
	VOL	English Harbour East Formation		VOL1	1.00	0.37
		Marystown Group		VOL1	1.00	0.37
		Bull Arm Formation		VOL1	1.00	0.37
		Garnish Formation		VOL1	1.00	0.37
		Cashel Lookout Formation		VOL1	1.00	0.37
		Creston Formation		VOL2	1.97	0.14
		Andersons Cove Formation		VOL2	1.97	0.14
		Unnamed Breccia		VOL2	1.97	0.14
		Taylors Bay Formation		VOL2	1.97	0.14
		Grand Beach Complex		VOL2	1.97	0.14
		Connecting Point Group		VOL2	1.97	0.14
		Port au Bras Formation		VOL2	1.97	0.14
		Love Cove Group		VOL2	1.97	0.14
		Path End Formation		VOL2	1.97	0.14
3	CNGL2	Big Head Formation	**1490**	CNGL2BH1	0.80	0.45
			1699	CNGL2BH1	0.80	0.45
			1679	CNGL2BH2	3.44	0.03
		Bull Arm Formation	**1820**	CNGL2BA1	1.07	0.34
			1792	CNGL2BA1	1.07	0.34
			1784	CNGL2BA2	2.61	0.07
	PLU3	Harbour Main Group	**1057**	PLU3HM1	-0.48	1.61
			1136	PLU3HM1	-0.48	1.61
			1052	PLU3HM1	-0.48	1.61
			1085	PLU3HM1	-0.48	1.61
			1065	PLU3HM2	0.77	0.46
			1654	PLU3HM2	0.77	0.46
			1068	PLU3HM2	0.77	0.46
			963	PLU3HM2	0.77	0.46
			1190	PLU3HM2	0.77	0.46
			1109	PLU3HM2	0.77	0.46
			1173	PLU3HM2	0.77	0.46
			954	PLU3HM2	0.77	0.46
			1271	PLU3HM2	0.77	0.46
		Terra Nova Granite	**1876**	PLU3TN1	0.37	0.69
			1955	PLU3TN2	-1.40	4.05

Table B3. Q̄ Groups, Codes and Data

LEVEL	ROCK	Formation	Polygon	FM CODE	pYPM	YPM
3	SNDST1	Maturin Ponds Formation	**1163**	SNDST1MP1	-0.88	2.42
			1697	SNDST1MP2	1.51	0.22
			1185	SNDST1MP2	1.51	0.22
			1037	SNDST1MP2	1.51	0.22
			1684	SNDST1MP2	1.51	0.22
		Renews Head Formation	**1693**	SNDST1RH1	0.98	0.38
			1594	SNDST1RH2	1.71	0.18
			1550	SNDST1RH2	1.71	0.18
			1318	SNDST1RH2	1.71	0.18
		Gibbett Hill Formation	**1557**	SNDST1GH1	2.90	0.05
			1694	SNDST1GH2	0.74	0.48
	SNDST2	Trepassey formation	**1614**	SNDST2T1	-0.02	1.02
			1354	SNDST2T1	-0.02	1.02
			1662	SNDST2T2	1.99	0.14
			1559	SNDST2T2	1.99	0.14
			579	SNDST2T2	1.99	0.14
		Drook Formation	**1460**	SNDST2D1	3.13	0.04
			1603	SNDST2D2	1.40	0.25
		Rocky Harbour Formation	**1741**	SNDST2RH1	-0.31	1.36
			2147	SNDST2RH2	2.54	0.08
	SHLE1	Bonavista Formation	**1145**	SHLE1BV1	0.70	0.50
			328	SHLE1BV1	0.70	0.50
			1647	SHLE1BV1	0.70	0.50
			1315	SHLE1BV1	0.70	0.50
			1133	SHLE1BV1	0.70	0.50
			175	SHLE1BV2	2.03	0.13
			17	SHLE1BV2	2.03	0.13
			1725	SHLE1BV2	2.03	0.13
			1332	SHLE1BV2	2.03	0.13
			1188	SHLE1BV2	2.03	0.13
		Elliotts Cove Formation	**1302**	SHLE1EC1	2.87	0.06
			1311	SHLE1EC2	0.83	0.44
	SLTST2	Mistaken Point Formation	**1356**	SLTST2MP1	-0.01	1.01
			567	SLTST2MP2	1.94	0.14
			1660	SLTST2MP2	1.94	0.14
			750	SLTST2MP2	1.94	0.14
			1516	SLTST2MP2	1.94	0.14
			1623	SLTST2MP2	1.94	0.14
	VOL1	Bull Arm Formation	**1872**	VOL1BA1	-0.97	2.64
			669	VOL1BA1	-0.97	2.64
			1724	VOL1BA2	1.63	0.20
			1681	VOL1BA2	1.63	0.20
			1645	VOL1BA2	1.63	0.20

CNGL	Conglomerate
PLU	Plutonic
META	Metamorphic
SNDST	Sandstone
SHLE	Shale
VOL	Volcanic
SLTST	Silstone
QUAT	Quaternary

Table B4. Summary of Polygon, Formation, and Rock Type Group Means and Codes ($\bar{Q}$ Sample Size = 3160)

Code	$\bar{Q}$ (m2/d)	Sample Size	Polygons
CNGL2BH2	0.03	3	1
SNDST2D1	0.04	5	1
SNDST1GH1	0.05	9	1
SHLE1EC1	0.06	7	1
CNGL2BA2	0.07	17	1
SNDST2RH2	0.08	6	1
SLTST3	0.10	72	0
SHLE1BV2	0.13	42	5
SNDST2T2	0.14	43	3
VOL2	0.14	72	275
SLTST2MP2	0.14	170	5
SLTST	0.16	276	99
SLTST2	0.17	194	12
SNDST1RH2	0.18	144	3
SHLE2	0.19	429	0
VOL1BA2	0.20	45	3
SNDST2	0.20	478	68
CNGL3	0.20	93	525
SNDST1MP2	0.22	46	4
SNDST2D2	0.25	21	1
MTASEDVOL	0.25	2544	836
SHLE1	0.33	584	110
CNGL2BA1	0.34	39	2
VOL1	0.37	142	555
SNDST1	0.37	279	166
SNDST1RH1	0.38	47	1
CNGL	0.38	312	20
CNGL2	0.42	172	37
SHLE1EC2	0.44	68	1
CNGL2BH1	0.45	126	2
PLU3	0.46	416	281
PLU3HM2	0.46	245	9
SNDST1GH2	0.48	81	1
SHLE1BV1	0.50	92	5
PLU	0.55	20	514
PLU3TN1	0.69	4	1
SLTST1	0.71	266	0
PLU2	0.76	90	28
CNGL1	0.94	47	22
SLTST2MP1	1.01	18	1
SNDST2T1	1.02	17	2
SNDST2RH1	1.36	4	1
PLU3HM1	1.61	38	4
PLU1	2.42	31	21
SNDST1MP1	2.42	7	1
VOL1BA1	2.64	15	2
QUAT	3.00	0	23
PLU3TN2	4.05	17	1

APPENDIX C

Geospatial ANOVA Results for Depth to Bedrock

Table C1. ANOVA Summary for Depth to Bedrock

Test Group	Factor	F Statistic	F Critical	Variance
Quaternary Geology	Material Type	3.67	1.89	UNEQUAL
Ablation Drift	Polygon	1.22	1.90	EQUAL
Drift Poor	Polygon	2.01	1.56	UNEQUAL
Exposed Bedrock	Polygon	1.58	3.29	EQUAL
Glaciofluvial	Polygon	10.23	2.78	UNEQUAL
Rogen Moraine	Polygon	12.80	2.17	UNEQUAL
Till Blanket	Polygon	2.45	2.33	UNEQUAL
Till, Undifferentiated	Polygon	2.75	1.58	UNEQUAL

Table C2. Depth to Bedrock Groups, Codes and Data

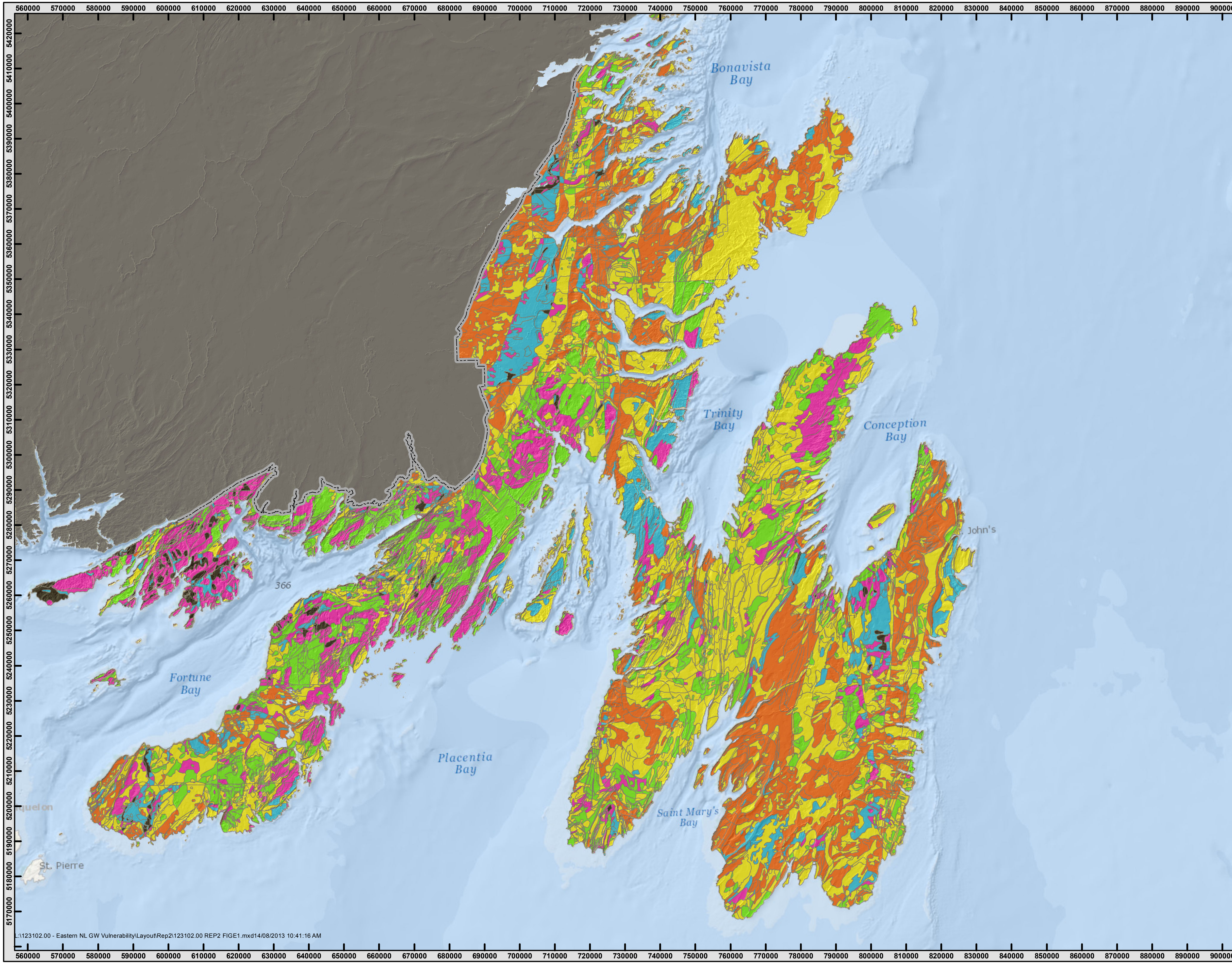
Level	Formation Group	Formation Type	Polygon ID	Mean Depth (m)
1	QUAT1	Exposed Bedrock (EXBR)		4.95
		Glaciomarine (GLMN)		4.95
		Till Blanket (TLBL)		4.95
		Till, Undivided (TLUN)		4.95
		Rogen Moraine (RGMN)		4.95
		Alluvium (ALVM)		4.95
		Drift Poor (DFTP)		4.95
	QUAT2	Ablation Drift (ABLD)		6.44
		Bog (BOG)		6.44
		Glaciofluvial (GLFL)		6.44
2	QUAT1	DFTP1	7	3.95
			2157	3.95
			1308	3.95
			1115	3.95
			2070	3.95
			2098	3.95
			1320	3.95
			891	3.95
			2076	3.95
			1471	3.95
			1140	3.95
			1135	3.95
			3329	3.95
			1221	3.95
			1170	3.95
			1360	3.95
			1174	3.95
			1224	3.95
			3791	3.95
		DFTP2	1513	7.22
			1432	7.22
			1163	7.22
			1611	7.22
			1492	7.22
			1147	7.22
		TLBL1	1139	3.55
			2075	3.55
			1146	3.55
			2150	3.55
		TLBL2	1375	7.01
			1643	7.01

Table C2. Depth to Bedrock Groups, Codes and Data

Level	Formation Group	Formation Type	Polygon ID	Mean Depth (m)
2	QUAT1	TLUN1	1396	4.56
			1319	4.56
			2063	4.56
			1494	4.56
			1363	4.56
			1184	4.56
			2	4.56
			5	4.56
			1120	4.56
			1116	4.56
			1967	4.56
			1483	4.56
			1313	4.56
			1964	4.56
			1198	4.56
			1219	4.56
		TLUN2	1273	8.55
			1216	8.55
			1222	8.55
			1491	8.55
			2686	8.55
		RGMN1	1117	3.77
			1331	3.77
			1129	3.77
		RGMN2	1354	5.74
			2052	5.74
		RGMN3	1511	13.77
	QUAT2	GLFL1	2033	2.74
			1126	2.74
		GLFL2	889	4.68
		GLFL3	1493	9.57

Table C3. Summary of Polygon and Quaternary Material Type Group Means and Codes (Sample Size = 1173)

Group	Depth to Bedrock (m)	Sample Size	Polygons
GLFL1	2.74	7	2
TLBL1	3.55	32	4
RGMN1	3.77	72	3
DFTP1	3.95	137	19
TLUN1	4.56	427	16
GLFL2	4.68	3	1
QUAT1	4.95	981	2609
RGMN2	5.74	51	2
QUAT2	6.44	190	2044
TLBL2	7.01	9	2
DFTP2	7.22	71	6
TLUN2	8.55	28	5
GLFL3	9.57	14	1
RGMN3	13.77	3	1



LEGEND

Study Area Boundary

Qualitative Groundwater Vulnerability Index

- 1 - (Low-Low)
- 2 - (Moderate-Low and Low-Moderate)
- 3 - (Moderate-Moderate)
- 4 - (High-Low and Low-High)
- 5 - (High-Moderate and Moderate-High)
- 6 - (High-High)

Figure C1

Qualitative Aquifer Vulnerability Indices

Eastern Newfoundland Groundwater Vulnerability Assessment

Coordinate System: NAD 1983 UTM Zone 21N
Projection: Transverse Mercator
Datum: North American 1983
Units: Meter

CBCL LIMITED
Consulting Engineers

0 5 10 20 30 40 km

1:1,000,000 @ 11 x 17