EARTH SCIENCES
SIMON FRASER UNIVERSITY

HYDROGEOLOGICAL ASSESSMENT OF THE BELCARRA AQUIFER, BRITISH COLUMBIA

Final Report

Prepared by:

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Prepared for:

Environmental Affairs Committee
Village of Belcarra, BC

February 2005

EXECUTIVE SUMMARY

The Village of Belcarra is remotely located within the GVRD making importing of municipal water cost prohibitive. The majority of residents obtain their domestic water supply from wells drilled into the Belcarra Aquifer and limited surface water sources. The main purpose of this study was to develop a conceptual model of the Belcarra Aquifer. The geology of the Belcarra region, based on geological maps and drilled well records, consists of fractured granitic bedrock overlain by glacial sediments and topsoil. Groundwater generally recharges at elevations above 30-60m, and discharges at lower elevations. Overall, the groundwater quality (based on dissolved metals and anions) of Belcarra aquifer is good. The groundwater can be generally classified as a bicarbonate to bicarbonate-chloride-sulfate type water based on anions, and a calcium-magnesuim to a sodium-calcium type water based on cations. Climate data (precipitation) were described using the Cumulative Precipitation Departure method to illustrate that recharge is direct from precipitation. Two methods were used to estimate recharge to the aquifer. The observation well data were analyzed using the Hydrograph method a water balance program called HELP provided another estimate of recharge. In consideration of both methods, the most representative range of recharge estimate is 114 mm/yr. This value is based on the hydrograph method using a porosity of 0.01. Higher recharge may occur in areas that are more intensely fractured. With an annual precipitation of 2331 mm/yr, this estimate corresponds to a minimum of 4.8% of annual precipitation that is recharging the aquifer.

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1. INTRODUCTION

1.1. BACKGROUND

The Village of Belcarra is situated on the peninsula between Indian Arm and the south arm of Burrard Inlet in the Greater Vancouver Regional District (GVRD), southwest British Columbia (Figure 1.1). Currently, all the developable land in the Village of Belcarra is subdivided or is located in the Belcarra Regional Park. Present development consists of approximately 250 single family homes and cottages, of which approximately 225 homes are occupied year round; the population is approximately 600. Belcarra has approximately 320 single family lots and the ultimate service population is anticipated to be 800 people.

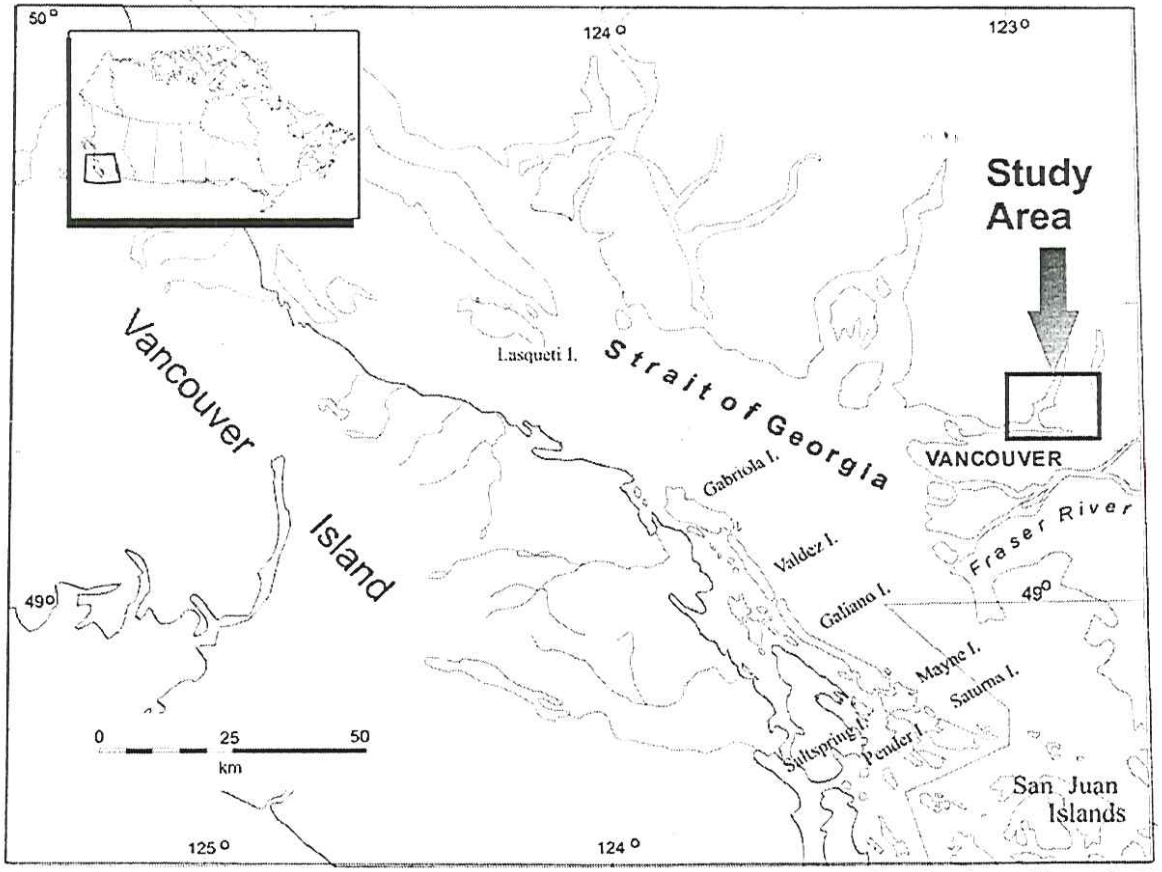
Due to its remote location within the GVRD, importing municipal water is cost prohibitive, thus, the majority of residents of Belcarra currently rely primarily on individual wells drilled into the Belcarra Aquifer and limited surface water sources for domestic water supply. The following information, concerning the current status of water supply for Belcarra, is summarized from a local water supply study undertaken by Dayton and Knight (1990). The study determined that possible water sources for the Village include:

- neighbourhood creeks
- groundwater wells
- Sasamat Lake
- Buntzen Lake
- Port Moody
- North Vancouver

The surface water sources in the area consist of small streams and watersheds of limited area, including the Sasamat Lake and Ray Creek watersheds. These surface water sources are very susceptible to summer drought conditions and cannot be relied upon for year round water supply. Surface water supplies are often contaminated by total coliform and fecal coliform contamination as a result of unrestricted public access to watershed areas, on-site in ground sewage disposal systems, and road access through watershed areas. The Ray Creek watershed is protected through the Village-GVRD Agreement Package by prohibiting the construction of trails and minimizing environmental impacts from construction in the Ray Creek catchment area, which lies within the village. The watershed is identified as a potential primary source for both the Village and the Regional Park. Sasamat Lake is licensed for water supply for 1,950,000 gallons per day (gpd), and Windmere Creek, which flows from the lake, is licensed for 3,000 gpd. The source quantity, in this case, is suitable for additional licensing, as the present storage is estimated to be four times less than the estimated 10 year drought watershed yield. Buntzen Lake supplies the hydro generating station on Indian Arm, and also provides cooling water for the Thermo Generating Plant west of Ioco. The quality of water from Buntzen Lake is reported to be good and could also be a source for development of a new water system.

Groundwater supplies are derived from wells completed in bedrock that comprises the Belcarra Aquifer. The Belcarra Aquifer is an unconfined, fractured bedrock aquifer overlain by unweathered glacial till and soil (Pacific Hydrology, 1994). Due to the fractured nature of the bedrock, the performance of the aquifer is unpredictable and large drawdowns may occur due to overuse and reaction to drought conditions. There is also the problem of saltwater intrusion into this coastal aquifer.

The British Columbia Ministry of Water, Land and Air Protection (BCWLAP) developed a classification system for aquifers based on level of groundwater development (Table 1.1) and vulnerability to potential contamination (Table 1.2) (BC WLAP, undated).



(Modified from: Mustard, 1994)

Figure 1.1: Study location map.

Table 1.1: Interpretation of the levels of development.

Level of Development	**Interpretation**
Heavy I	• Demand for water is high relative to water availability • Additional development of this aquifer should be carefully assessed
Moderate II	• Demand is moderate relative to water availability • Additional development of this aquifer should be given careful consideration
Light III	• Demand is light relative to water availability • Additional development should not be a problem, provided productivity can meet the demand

Table 1. 2: Interpretation of the different levels of vulnerability

Vulnerability	Interpretation
High A	• Highly vulnerable to contamination from surface sources, **A** aquifers have little natural protection against contamination introduced at the surface • Existing land uses or future additional developments, which may introduce a contaminant to the land surface, should initiate measures to protect against introducing contaminants. • **A** aquifers should be given first priority for the implementation of quality protection measures.
Moderate B	• Moderately vulnerable to contamination from surface sources, **B** aquifers have limited natural protection against contamination introduced at the ground surface. Degree of natural protection may vary across an aquifer. • Existing land uses or future additional developments, that could introduce a contaminant to the land surface, should initiate measures to protect against introducing contaminants. • **B** aquifers should be given priority over **C** aquifers when it comes to implementing quality protection measures.
Low C	• Generally not considered very vulnerable to contamination from surface sources, **C** aquifers are more protected against contamination introduces at the ground surface. • **C** aquifers have the lowest vulnerability rating and are the least likely to become contaminated. • A rating of **C** does not imply that all **C** aquifers are immune to contamination. All aquifers are vulnerable to contamination to a certain degree, especially if there are "windows' exposing the underlying aquifer or if the land-use activity breaks through the overlying confining layer.

The Belcarra Aquifer is classified as a "Type 1A" aquifer by BCWLAP, based on its high usage and vulnerability to potential contamination. There are approximately 200 deep-drilled wells in Belcarra, 90% of which are drilled into bedrock. It is also estimated that approximately 90% of residents use septic systems for disposal of household waste, many of which are located in close proximity to their wells (personal communications, Don Reid). Most of these wells also likely do not have a surface seal to prevent contaminated surface water and shallow groundwater from entering the well. Thus, because of the fractured nature of the bedrock, there is potentially a high risk of these wells becoming contaminated by septic system effluent. Furthermore, due to the proximity of the ocean, many of the wells drilled near the coast may be more highly susceptible to contamination by seawater.

1.2. PREVIOUS STUDIES

Previous studies done on water supply planning for the Village of Belcarra include:

- Bedwell Bay-Belcarra Waterworks Survey (Dayton, 1964)
- A Feasibility Study for Water Supply to North Shore, Port Moody, Bedwell Bay and Anmore (Dillon, 1968)
- Belcarra Water Supply Study (Halverson, 1980)

These studies were reviewed and excerpts included in a comprehensive report of water supply in the Village of Belcarra (Dayton & Knight Ltd. Consulting Engineers, 1990). The water supply study reviews the general characteristics of the area, existing water systems, water demands, future water supply options, and annual costs of a new water distribution system.

A biophysical inventory of Belcarra Regional Park was completed as Phase One of a Master Plan Study for the GVRD (Sigma Resource Consultants, 1977). The report describes the hydrogeological environment in terms of topography, geology, and vegetation as well as the groundwater characteristics of the area and use.

Halverson (1980) compiled information from previous reports into a study on Village Planning Water Sources for the Village Advisory Planning Commission, and divided the Village into seven groundwater areas; each with its own characteristics and production prospects. Present use, yields, and problems in each of these areas were discussed.

Pacific Hydrology (1994) prepared a report for the greater Vancouver Regional District Parks Department on the Pre-design of Belcarra Picnic Area Site Expansion and Admiralty Drive. The report provides descriptions of water supplies in the area and the groundwater regime of Woodhaven Swamp, and comments on the use and protection of groundwater in the study area and the effects of development on groundwater.

A small assessment of Groundwater Supply for Belcarra Water Users' Society was carried out by Piteau Associated Engineering Ltd. (2003). This assessment reviewed the operational history of the wells, examined hydrogeological features, such as soil and rock types, and potential sources of groundwater recharge and contamination, measured depths to water table in all accessible wells, and installed data loggers in three wells to monitor water levels from September 18th to 23rd, 2003.

1.3. PURPOSE

In April 2002, the Environmental Affairs Committee hosted the first Belcarra Aquifer Forum to raise awareness within the community about groundwater. The Environmental Affairs Committee later met with Dr. Allen of SFU in April 2004 to discuss undertaking a hydrogeological assessment of the Belcarra Aquifer. The main purpose of the assessment is to develop a conceptual model of the Belcarra Aquifer. The research described in this report constitutes a preliminary assessment of the Belcarra Aquifer. It will also act as a benchmark for future studies, allowing future changes in water quality and quantity to be appropriately referenced. The work is considered to be Phase 1 of a multi-stage assessment that ultimately will consider other aspects of the hydrogeology of the Belcarra Aquifer, including the physical properties of the aquifer, groundwater use and long term sustainability of the aquifer.

1.4. OBJECTIVES

The objectives of this study are:

1) To delineate and characterize the Belcarra aquifer, including its spatial extent and geology;
2) To describe the chemical composition of groundwater in the area and interpret the chemical data within the context of the local geology and hydrogeology;
3) To determine the catchment area, recharge rates to the aquifer and an estimate of the potential yield of the aquifer.

1.5. SCOPE OF RESEARCH

- Review existing reports, aerial photographs, surface and geological maps and BCWLAP observation well data.
- Compile all available water well information into a single comprehensive database that shows well completion details, geology, etc.
- Prepare a well location map coverage in ARC GIS.
- Create cross-sections showing the subsurface geology and anticipated groundwater regimes.
- Delineate any aquifers in the area, and define groundwater flow directions.
- Analyze climate data for the Lower Mainland and compare with Belcarra Observation well hydrograph to determine both the timing of recharge and an estimate of recharge to the aquifer.
- Determine the catchment area for the aquifer(s).

- Conduct an exploratory groundwater chemistry sampling program and interpret the chemical results.
- Assess the potential source of groundwater to the aquifer(s) based on the chemistry and the presence of contamination from seawater.

1.6. LIST OF AVAILABLE INFORMATION

The following information was received from the Village of Belcarra:

- Various reports described in the Previous Studies section.
- Chemistry data from previous well water testing (some incomplete)
- Shapefiles for the cadastral map of the Village

The remaining information was obtained online and through various government ministries:

- Well drillers logs online from the Ministry of Water, Land and Air Protection website at http://wlapwww.gov.bc.ca/wat/aquifers/index.html.
- Climate data from Environment Canada for stations:
  - 1101138 Buntzen Bay
  - 1101140 Buntzen Lake
  - 1101889 Como Lake Ave
  - 1103660 Ioco Refinery
  - 1106CL2 Port Moody Glenayre
- DEMs and TRIM data from LandData BC for mapsheets 092G.026 and 092G.036.
- Airphotos from the Government of BC
  - 30BCC96081 87-94,
  - 30BCC96081 124-130,
  - 30BCC96082 92-97

1.7. OUTLINE OF REPORT

This report was derived almost entirely from an unpublished B.Sc. honours thesis prepared by Melissa Holt in the Department of Earth Sciences at Simon Fraser University. Dr. Diana Allen acted as her senior supervisor, coordinated the research activities undertaken as part of this study, and oversaw the analysis of results.

The report is organised into 6 sections to provide a general overview of the regional setting, the local geology and hydrogeology, the groundwater chemistry, recharge to the aquifer, and an integrated discussion with conclusions. The respective methodologies and data collection information are provided within each section.

Section 1 provides background and defines the purpose and objectives of the study. The regional geology as well as the local geology and hydrogeology are discussed in Section 2. Section 3 describes the results of the chemical sampling program and the analysis of groundwater chemistry, and interprets these results within the context of the local hydrogeology. Section 4 uses climate data and the observation well hydrograph to obtain a range of estimates of recharge for the aquifer. Section 5 provides a discussion of the quality of the groundwater and impacts on environmental ecosystems. Section 6 provides conclusions and recommendations for further work.

2. GEOLOGIC AND HYDROGEOLOGIC SETTING

2.1. REGIONAL GEOLOGY

The Vancouver region, situated on the southwest coast of British Columbia, Canada, lies within the active Cascadia Subduction Zone, in which the Juan de Fuca plate moves beneath the North American plate (Armstrong, 1990). This tectonic setting has resulted in a complex geological environment, which consists of older bedrock belonging to the Coast Plutonic Complex, the Cascade Mountains and the Georgia Basin, and younger unconsolidated glacial sediments and more recent Fraser River delta sediments.

Bedrock throughout the region is composed of Coast Plutonic Complex rocks, Georgia Basin sedimentary rocks and Cascade volcanic rocks. The Coast Plutonic Complex is a belt of granodiorite or quartz diorite containing roof pendants of metamorphosed sedimentary and volcanic rocks. It is 60-200 km wide and extends from the Fraser River up to the Yukon-Alaska border (Armstrong, 1990). The Coast Intrusions consist of mainly granodiorite with hornblende or biotite, or quartz diorite with hornblende or diorite. The pendants are composed of the Gambier Group and the Bowen Island Group. Gambier Group rocks include andesite, dacite and rhyolite flows, pyroclastics, argillite, metasiltstone, minor limestone and conglomerate. Bowen Island Group rocks include andesite and dacite flows and pyroclastics, chert, sandstone, siltstone, gneiss, schist and amphibolite (Armstrong, 1990).

The Georgia Basin began to form around 70Ma through the erosion of the Coast Plutonic rocks. The Georgia Basin was a depression that housed a lake, and it provided center for deposition of gravel, sand, mud and plant debris. The combination of tectonic uplift and subsidence due to accumulation of sediment allowed the sequence of shallow, fresh-water sedimentation to grow up to 4400m thick (Armstrong, 1990). These sediments were deposited as horizontal beds and later became lithified, but younger tectonic activity (~40Ma) has tilted these rocks 8-12° to the south.

The Cascade volcanic chain extends from California to southern British Columbia. The Lower Mainland exhibits intrusive andesite dykes and sills, layers of basalt, as well as thin volcanic ash layers. The oldest of these rocks date back approximately 50Ma (Armstrong, 1990).

The dominant forces controlling the surficial geology of the area are glaciers and the Fraser River. There have been three major glaciations in the last 65,000 years, which have resulted in the carving out of U-shaped valleys and the deposition of glacial sediments in many areas. These sediments include glaciomarine silts and sands with dropstones, river deposits of clay, silt, sand and gravel, as well as moraine and kame deposits, and lodgement tills containing mostly sands and gravels. The Fraser River developed around 8,000-10,000 years ago, and it currently discharges approximately 18 million tonnes of sand, silt and mud annually (Armstrong, 1990). The Fraser Delta is prograding into the Strait of Georgia with younger deposits continually covering older deposits. It is composed of shoreline sand and clayey silt; river gravel, sand, silt and clay; and peat bogs and swamps.

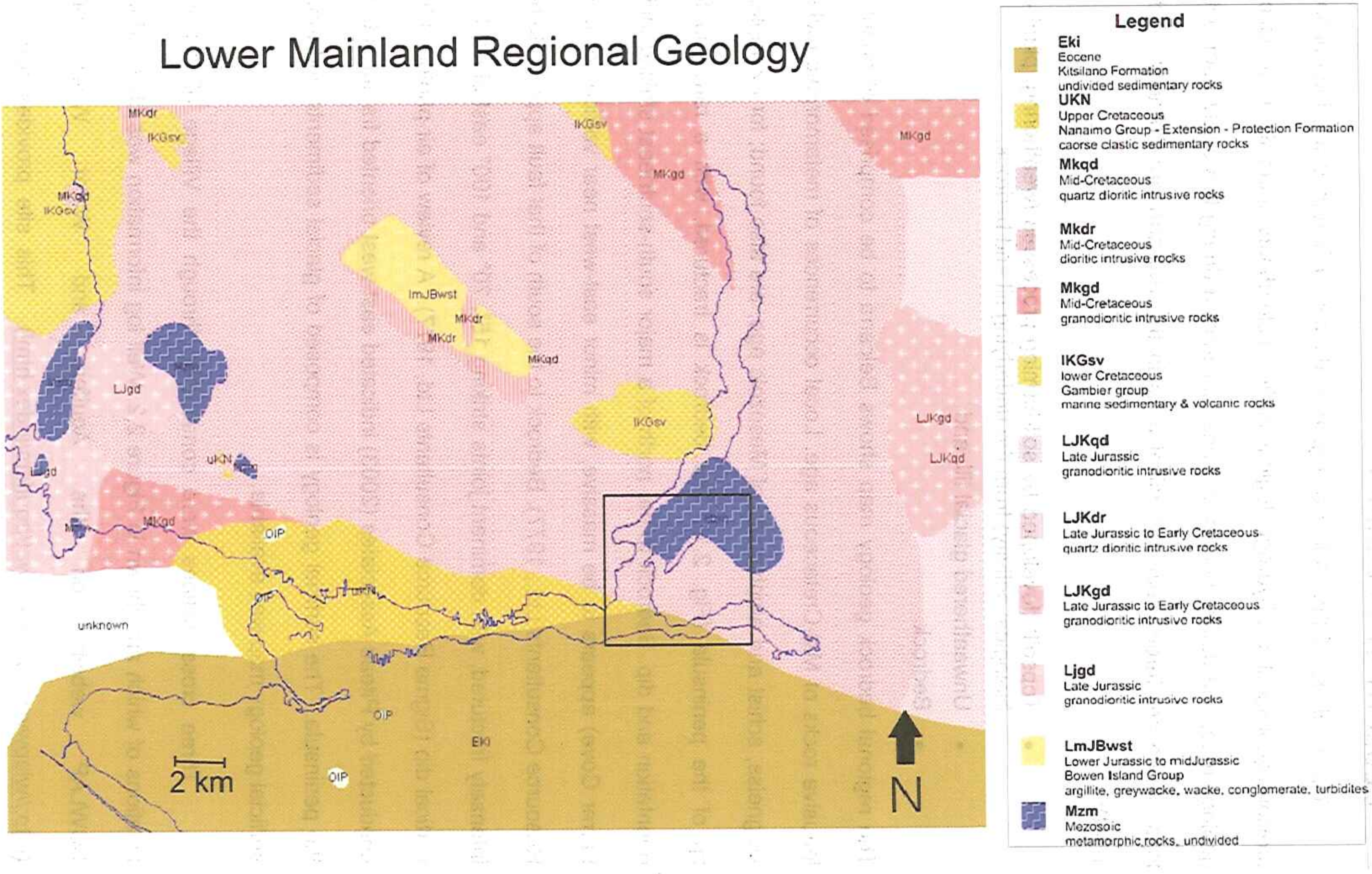


Figure 2.1: Regional geology of the lower mainland

2.2. GEOLOGY OF BELCARRA

The geology of the Belcarra region is described herein using information from previous geological and hydrogeological studies, field observations, the regional bedrock geology map, and detailed cross-sections constructed during this study from water well logs. There are three main geological units in the Belcarra area (Pacific Hydrology, 1994):

- Topsoil: developed by soil-forming processes (weathering, plant growth, biological activity) from the underlying till and bedrock;
- Unweathered glacial till; and
- Bedrock.

The regional bedrock geology map shows Belcarra to be comprised of quartz diorite intrusive rocks of Mid-Cretaceous age. Local occurrences of metamorphic rocks, such as gneiss, schist and amphibolite of Mesozoic age, are also found; for example, at the tip of the peninsula (Fig. 2.1). The bedrock is fractured, with a range in fracture orientation and dip. Bedrock to the north of a major south-southeast striking fault (near Farrer Cove) appears to be massive, with minor east-west near vertical joints (Sigma Resource Consultants Ltd., 1977). Bedrock to the south of that fault appears to be more intensely fractured, with dominant joints striking 15°, 70° and 100° east of north at near vertical dip (Sigma Resource Consultants Ltd, 1977). A review of air-photos of the area conducted by Piteau Associates (2003) indicated east-west oriented fractures traversing the peninsula. The surficial geology is composed of glacial sediments and topsoil. No surficial geology map was available.

Three cross-sections were constructed through the Village of Belcarra, the locations of which are shown in Figure 2.2. Well log information was obtained from the BCWLAP website on the Aquifers and Water Wells of BC (http://wlapwww.gov.bc.ca/wat/aquifers/index.html). This site provides access to the water well records that are housed in the WELL database, which contains information such as well tag number (a unique well identifier), the date of drilling, static depth of water at the end of drilling, and a description of the lithologies encountered at specific depths during drilling. A complete set of well logs for the Belcarra area is given in Appendix A. Note that there may be numerous wells not represented in the database because the submission of well records is currently voluntary in the province.

The first step was to compile the well log information into an MS Excel spreadsheet (Appendix B) and attempt to verify the locations of the wells. The WELL database is incomplete in many respects as either lithology records are missing for a particular well or the locational information is not available despite the fact that a record exists. Considerable effort was made as part of this study to collect and verify well information for Belcarra with the assistance of the Environmental Committee. Thus, a set of updated well locations is available.

Once the database had been assembled, the lithologic information had to be verified and interpreted before the cross-sections could be constructed. This was necessary not only because the quality of the logs varies considerably, but also because there can be several descriptions for what is likely the same type of rock. To simplify this process, an in-house computer program, LD Builder (Lithologic Database Builder), developed by Drs. Schuurman and Allen at Simon Fraser University, was used to fix errors in the database (e.g., spelling) and then standardize the lithologic units. The program searches for geologic keywords in the "lithology description field" and then classifies the rock or sediment type according to a standard set of geological terms. The majority of the interpretations were fairly straightforward to make, as the main three units (topsoil, till and bedrock) had the same general descriptors in the well logs. There was only one case in which the interpretation of a well log had to be modified. In that particular case the driller had recorded the rock as basalt, but according to the regional geology map, there is no basalt. Rather, the rock unit was interpreted as amphibolite (roof pendant) because this type of metamorphic rock has been mapped near that well location and because, to the unknowing eye, basalt and amphibolite (both black in colour) would look similar, especially rock chips collected during drilling. The well is situated in the northern section of the peninsula (along cross-section 2).

Three cross-sections were created in areas with most dense well information (Fig. 2.2). The updated well locations were plotted in ArcGIS, and EZ Profiler was used to create elevation profiles. Cross-section 1 is located along Bedwell Bay Road; cross-section 2 is located along Belcarra Bay Road; and cross-section 3 is perpendicular to the southern tip of cross-section 2. Some wells were projected onto a line of section; thus, the cross-sections contain wells from higher and lower elevations than are actually present at that particular profile elevation. The complete lithologic descriptions from the well logs were recorded on the cross-sections in Corel Draw (Fig. 2.3, 2.4, 2.5), and interpreted geologic cross-sections were then constructed based on the results of standardization (Fig. 2.6, 2.7, 2.8). Thus, a pair of cross-sections is provided for each line; one that shows the detailed lithologic descriptions and one that shows the interpretation.

The cross-sections confirm what is anticipated based on the regional bedrock geology map. The Village of Belcarra is located on top of fractured quartz diorite with minor amphibolite of uncertain spatial extent. The density of fracturing is uncertain based on drillers' logs, as this information was generally not consistently reported. Bedrock is overlain by 5-20m of glacial till variably composed of silt, sand, clay and gravel, and 0-5m of topsoil.

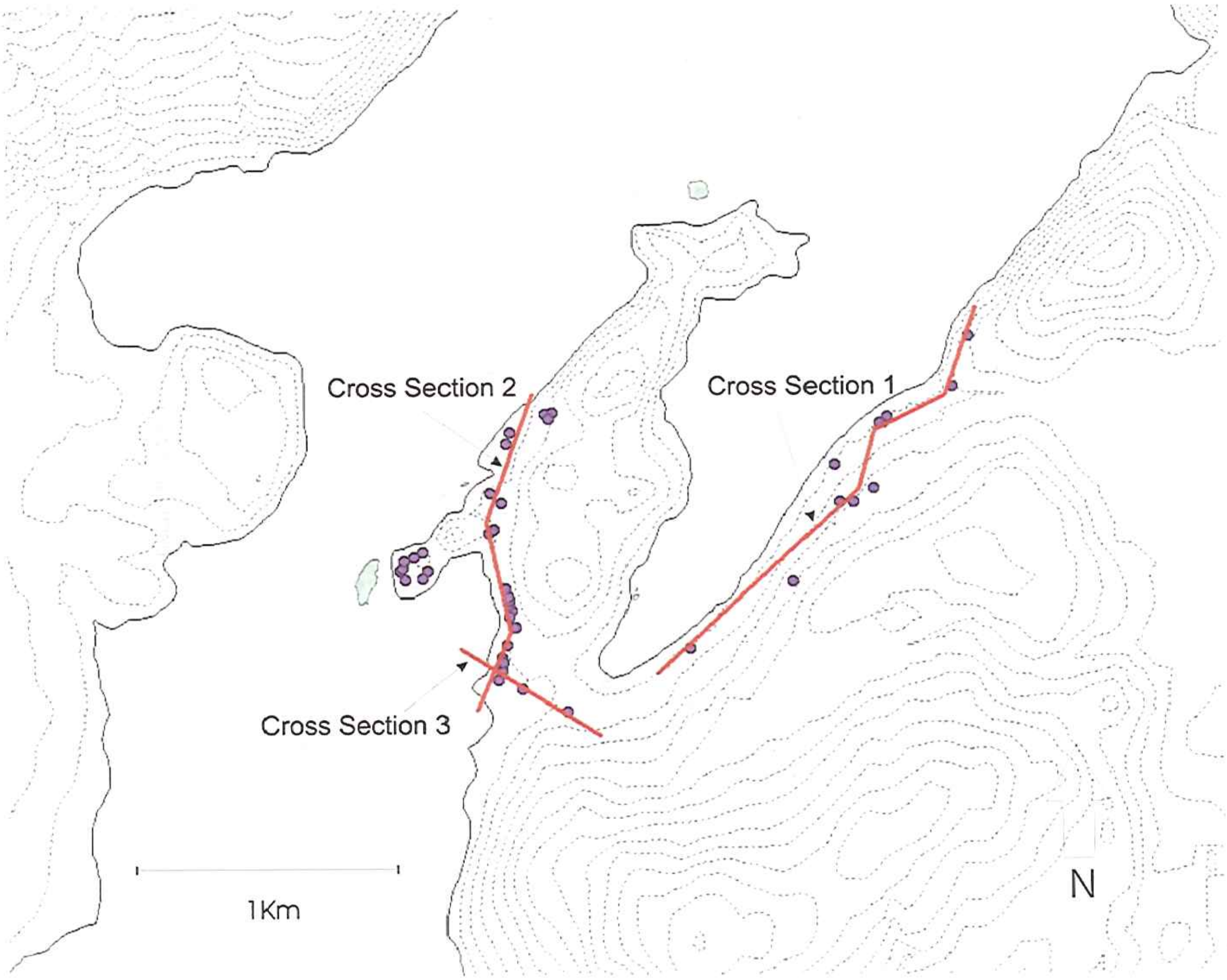


Figure 2.2: Location of cross-sections

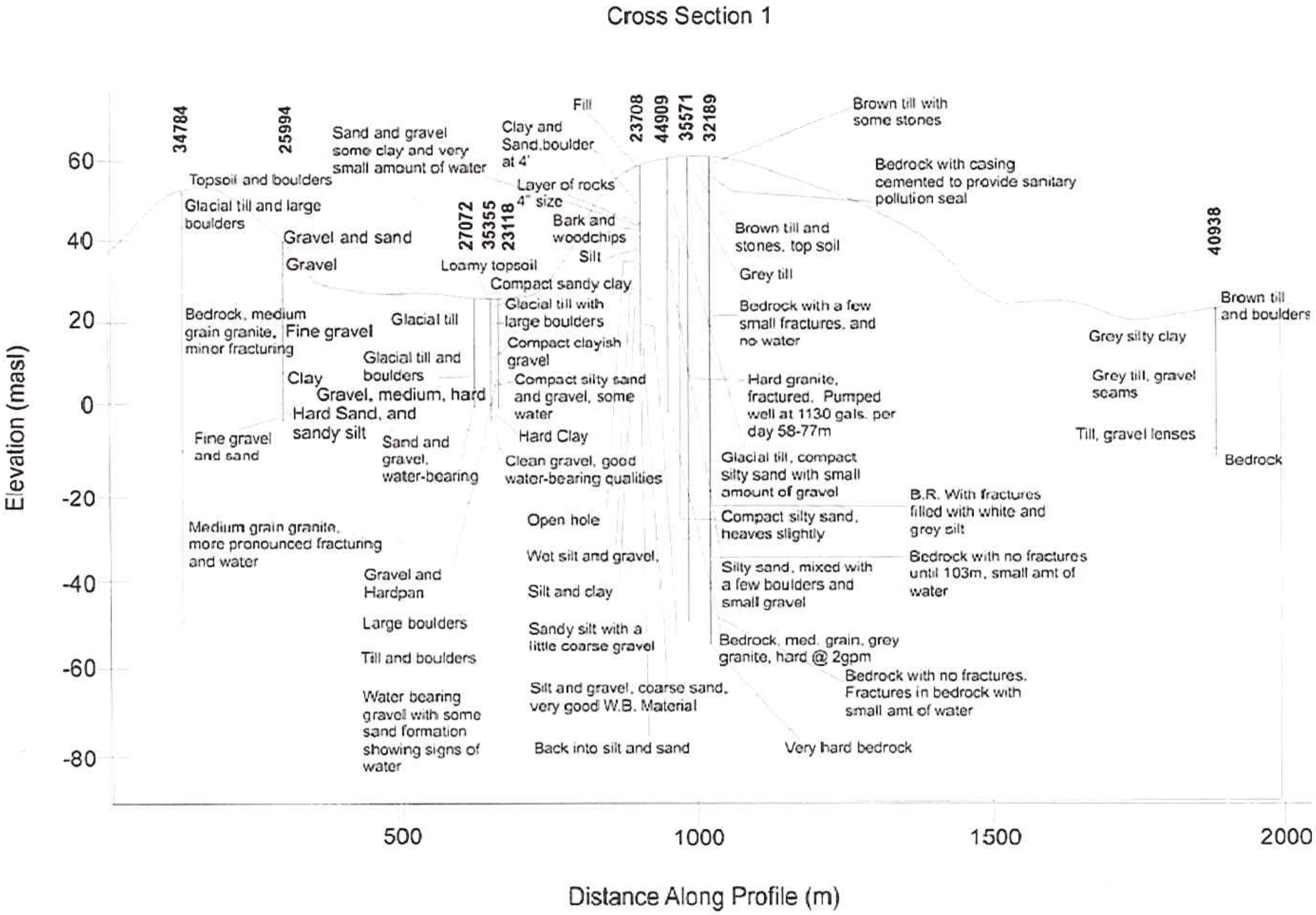


Figure 2.3: Well log information cross-section 1.

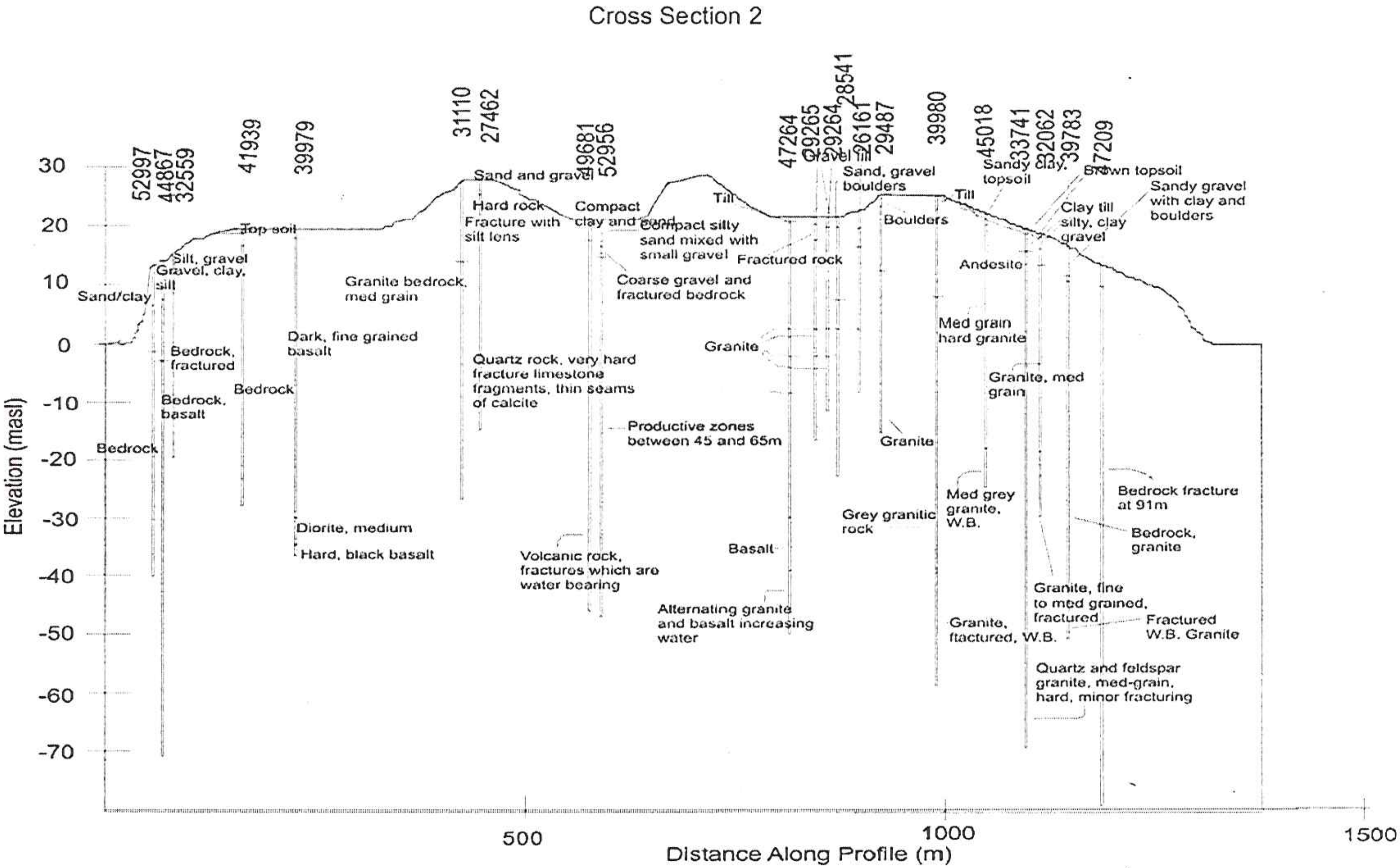


Figure 2.4: Well log information cross-section 2.

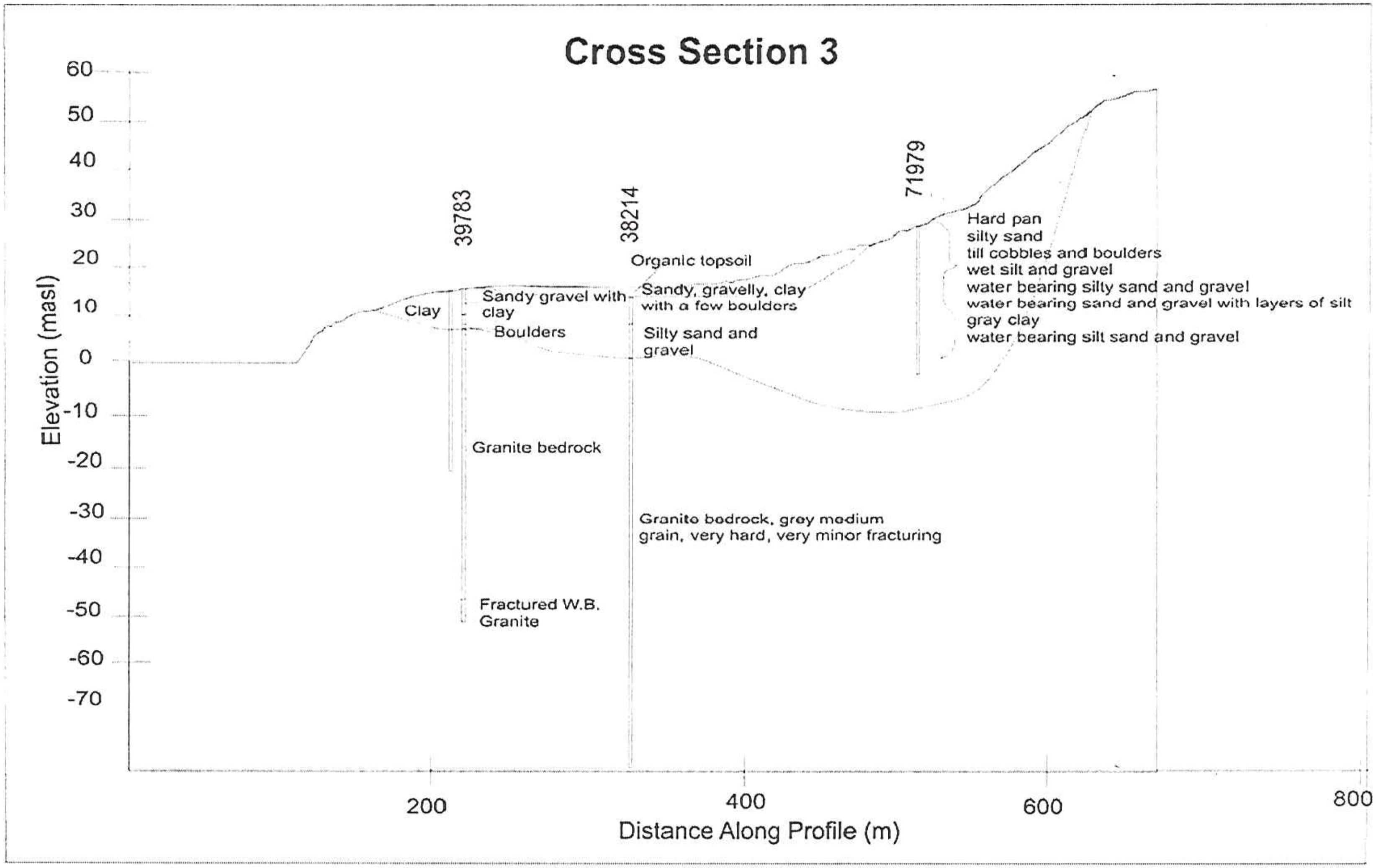


Figure 2.5: Well log information cross-section 3.

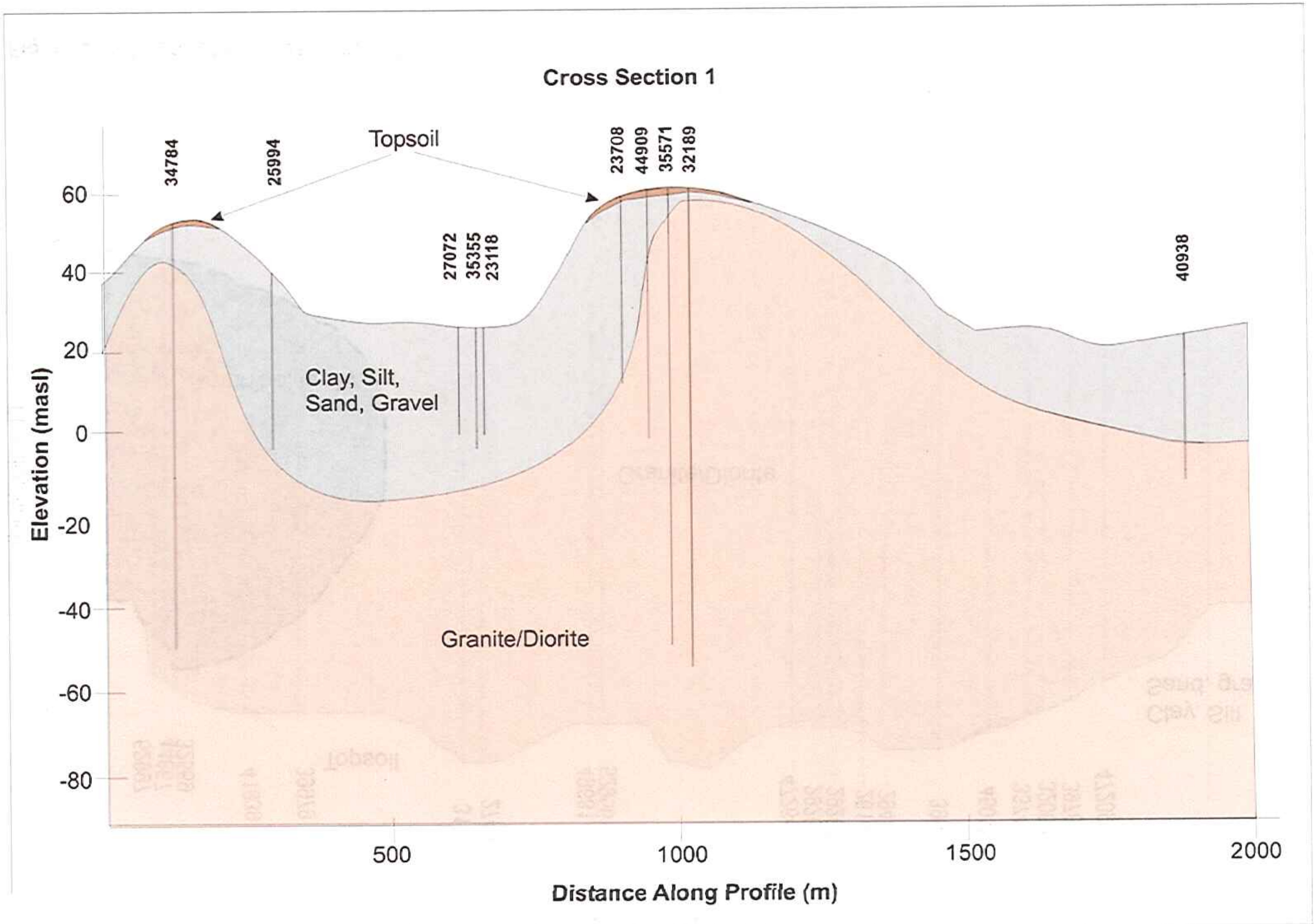


Figure 2.6: Interpreted cross-section 1.

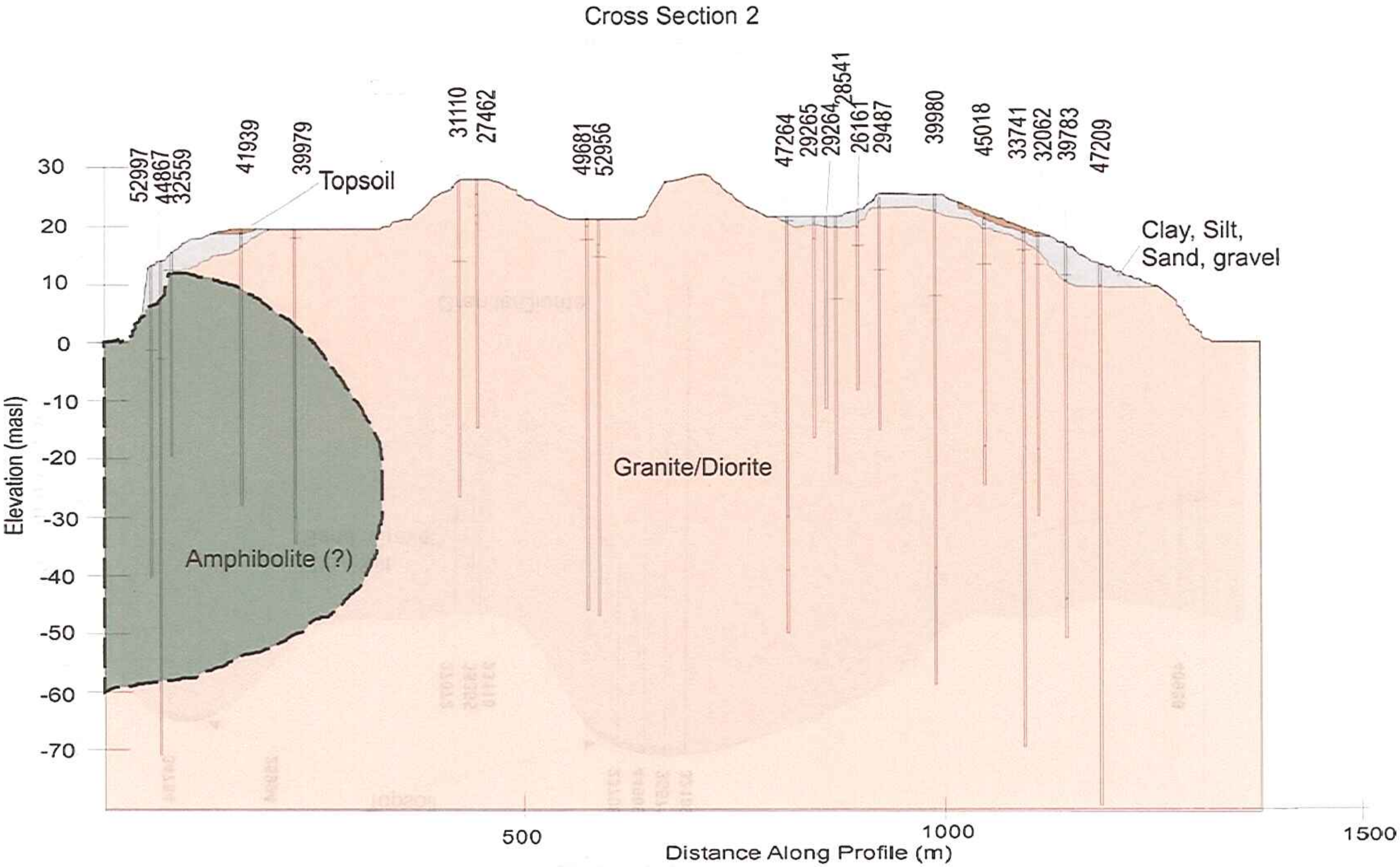


Figure 2.7: Interpreted cross-section 2.

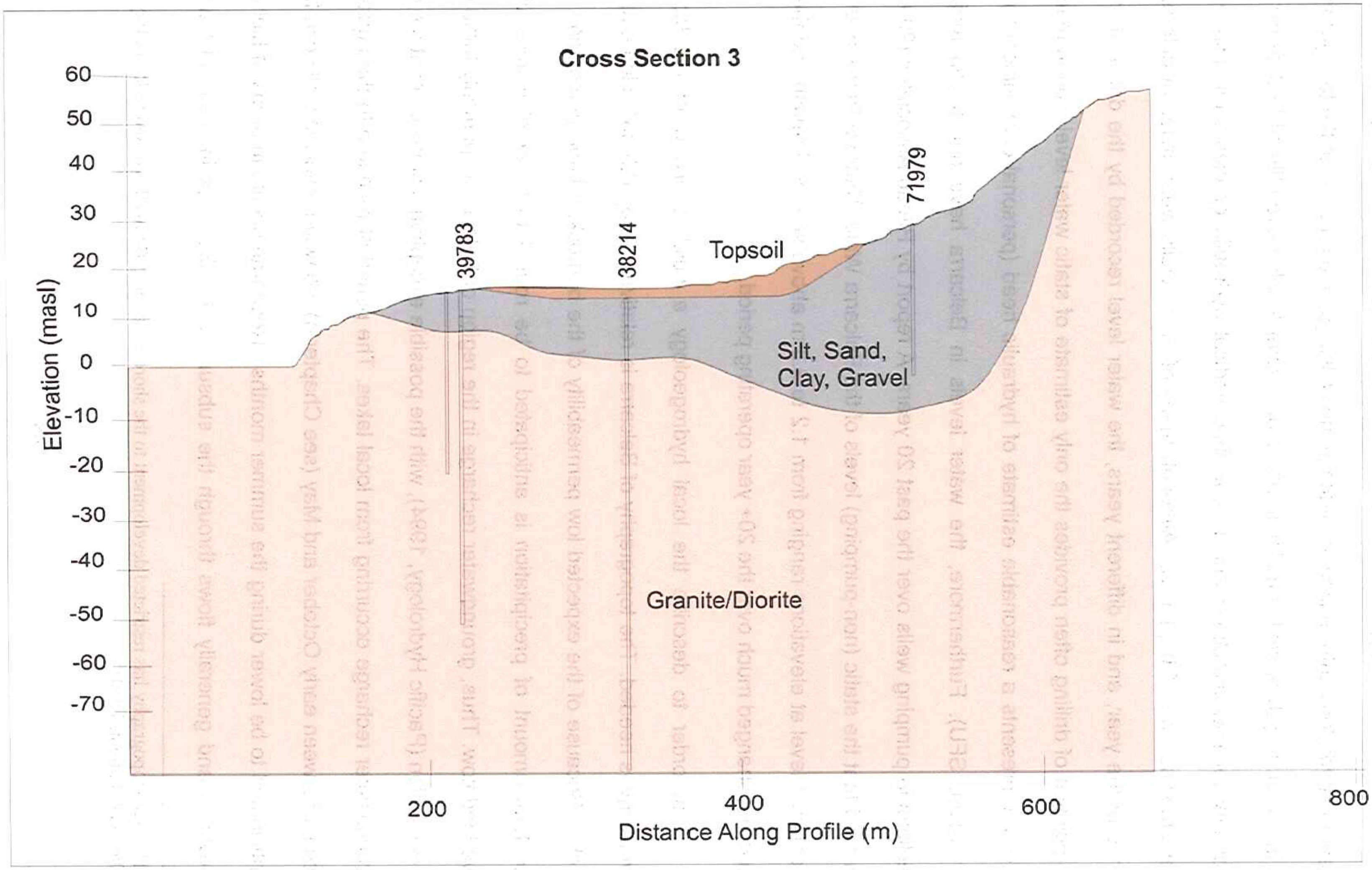


Figure 2.8: Interpreted cross-section 3.

2.3 HYDROGEOLOGY OF BELCARRA

The hydrogeology of Belcarra was defined according to both the geology of the area, the hydrologic information recorded in the well logs, and analysis of the topography of the area. Depth of well completion and static water levels were utilized to determine groundwater flow directions and to calculate vertical hydraulic gradients for adjacent wells (discussed in Chapter 4). Although many of these wells were drilled at different times of the year, and in different years, the water level recorded by the driller at the completion of drilling often provides the only estimate of static water level, and in many cases, represents a reasonable estimate of hydraulic head (personal communications, Dr. Allen, SFU). Furthermore, the water levels in Belcarra have not shown major declines in pumping wells over the past 20 years. A report by Piteau Associates (2003) showed that the static (non-pumping) levels of the Belcarra Water User Wells are above mean sea level at elevations ranging from 1.2 to 2.3 m above sea level (masl) and they have not changed much over the 20+ year operating period.

In order to describe the local hydrogeology a quick overview of the local hydrology is needed. The topography of Belcarra is relatively steep (25-35% slope) and rocky[1]. Because of the expected low permeability of the bedrock, a large percentage of the total amount of precipitation is anticipated to be routed to lower elevations via overland flow. Thus, groundwater recharge in the region of Belcarra is primarily through precipitation (Pacific Hydrology, 1994), with the possible exception a small percentage of groundwater recharge occurring from local lakes. The period of recharge to the aquifer occurs between early October and May (see Chapter 4), so water levels in wells can be anticipated to be lower during the summer months. Recharge occurs in areas of higher elevation and generally flows through the subsurface to discharge in areas of lower

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[1] The steep topography has restricted development to the shoreline around Bedwell Bay and Belcarra Bay (Dayton & Knight, 1990)

elevation. Fractures in the bedrock, being of higher permeability, add a greater level of complexity to the hydrogeologic regime, and due to limited information contained in the well logs, the influence of fractures on the local hydrogeology cannot be determined without a more exhaustive field mapping program.

Notwithstanding the role of fractures, this general hydrogeological description was used as the framework for constructing the hydrogeologic cross-sections. The first step was to draw on the static water level for each well. Once these were plotted correctly the static water table was interpolated. When interpreting the water table location it is important to keep in mind that some wells were projected onto the section, and also that the wells are all completed at different depth intervals. For the wells that were projected onto the section, their static water levels appeared not to correspond to adjacent wells. This is because the hydrologic regime is different for wells at different positions along the hydraulic gradient, and the position of the static water table in relation to the measured water level will vary accordingly. For example, wells that are located up-gradient of the cross-section are most likely in an area of recharge relative to a well down-gradient, and thus, these wells should have higher water levels compared to wells of similar depth on the cross-section. This relation is combined with the relation that if the depth of the up gradient well is shallower, then the head in that well will be higher than if it is a deeper well (recharge). The opposite is true of down-gradient wells. Heads at depth are greater than heads in the shallow subsurface (discharge).

After the static water levels were plotted for each well, representative flow lines were added by interpreting the individual well water levels and depth of completion of those wells and taking into consideration the local topography. Sizes of the vertically oriented flow lines on each flow diagram are indicative of the relative size of the hydraulic gradient at each well. Cross-section 1 shows that the groundwater flow is generally downwards, or is recharging, from regions of elevation above 60m. Flow of water is upwards, or discharging, in regions of lower elevation below 60m (Fig. 2.9). Cross-section 2 shows the flow of water from regions of higher elevation to regions of lower elevation along the peninsula (Fig. 2.10). From the static water elevations, one can infer that recharge occurs in areas of higher elevation and discharges in areas of lower elevation, but the transition appears to occur more between 30 m elevation as compared to 60m in the previous cross-section. Cross-section 3 shows the water flow perpendicular to cross-section two, and it can be seen that the flow probably transitions from recharging to discharging just below 30 m elevation.

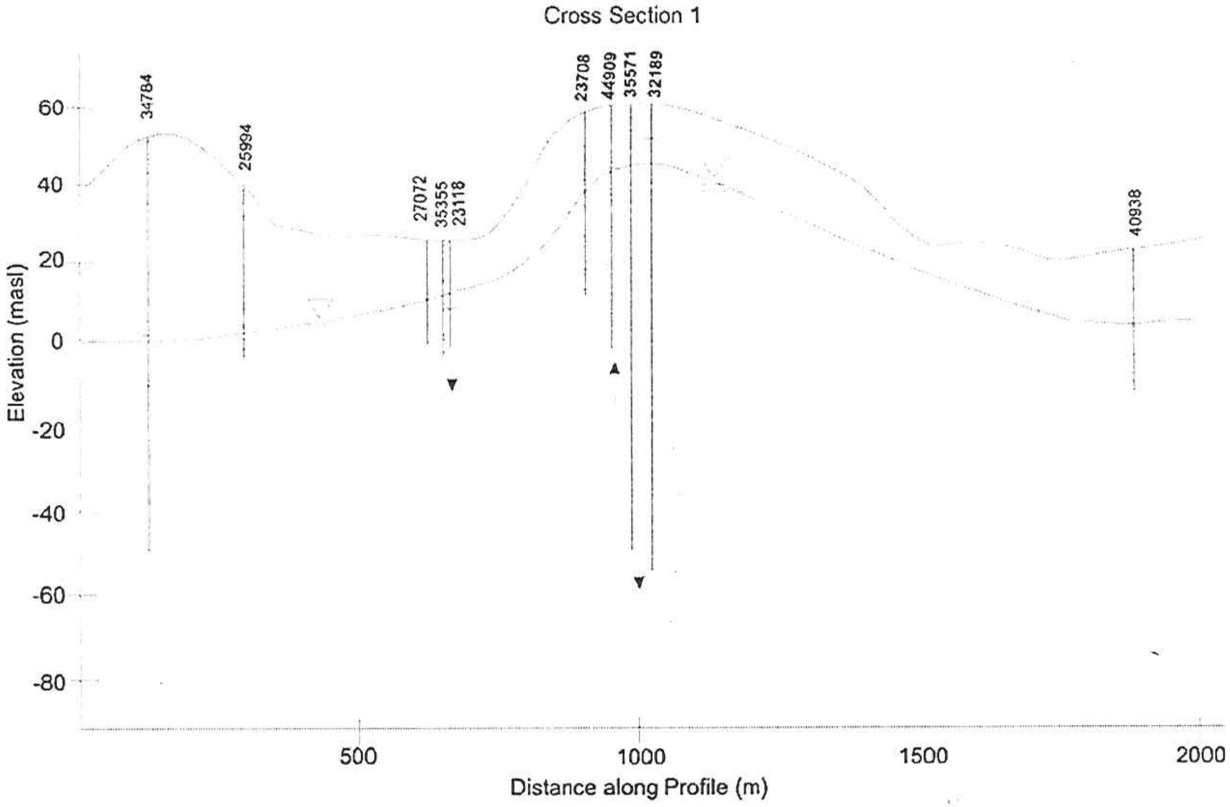

Figure 2.9: Location of water table for cross-section 1.

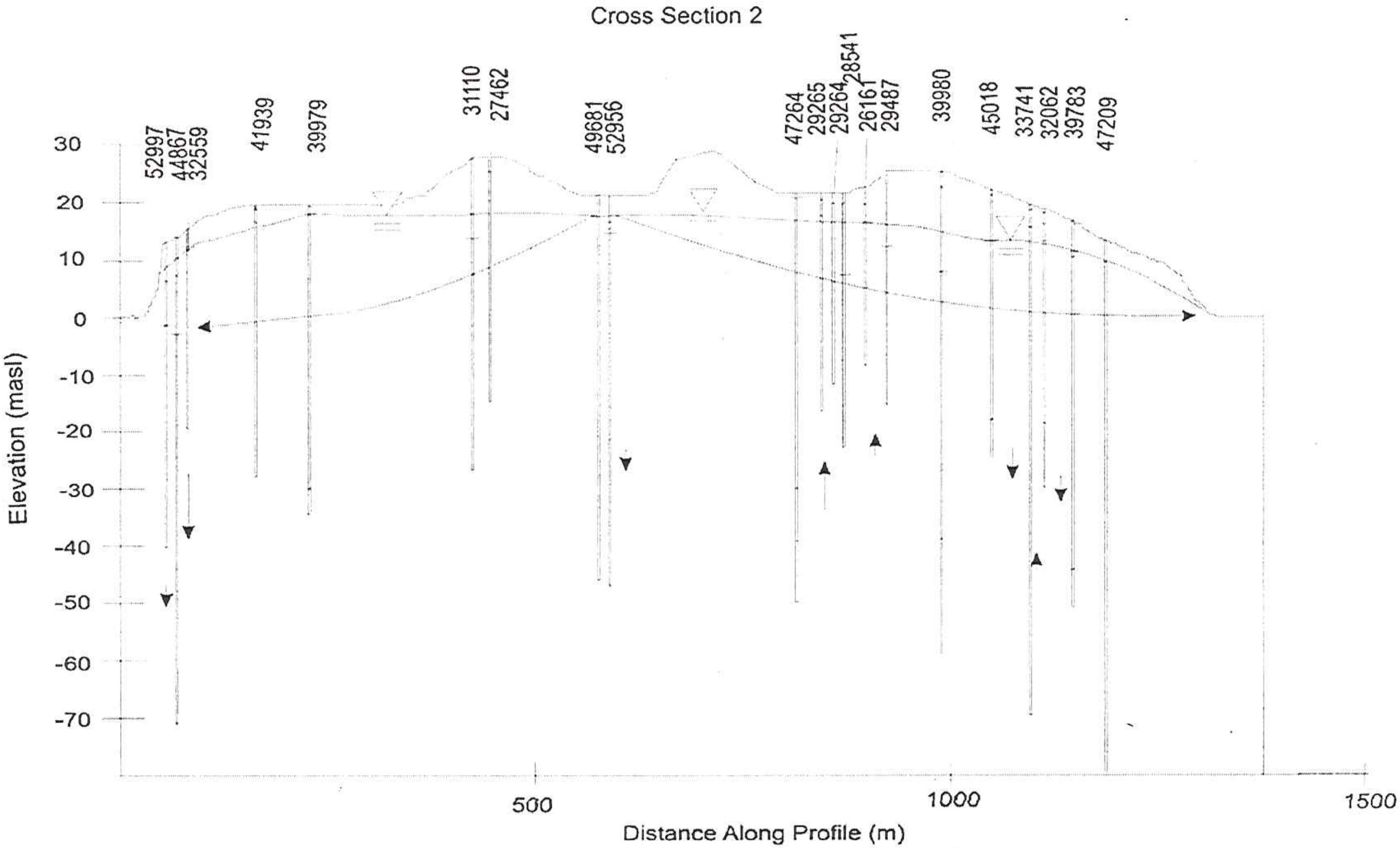

Figure 2.10: Location of water table for cross-section 2.

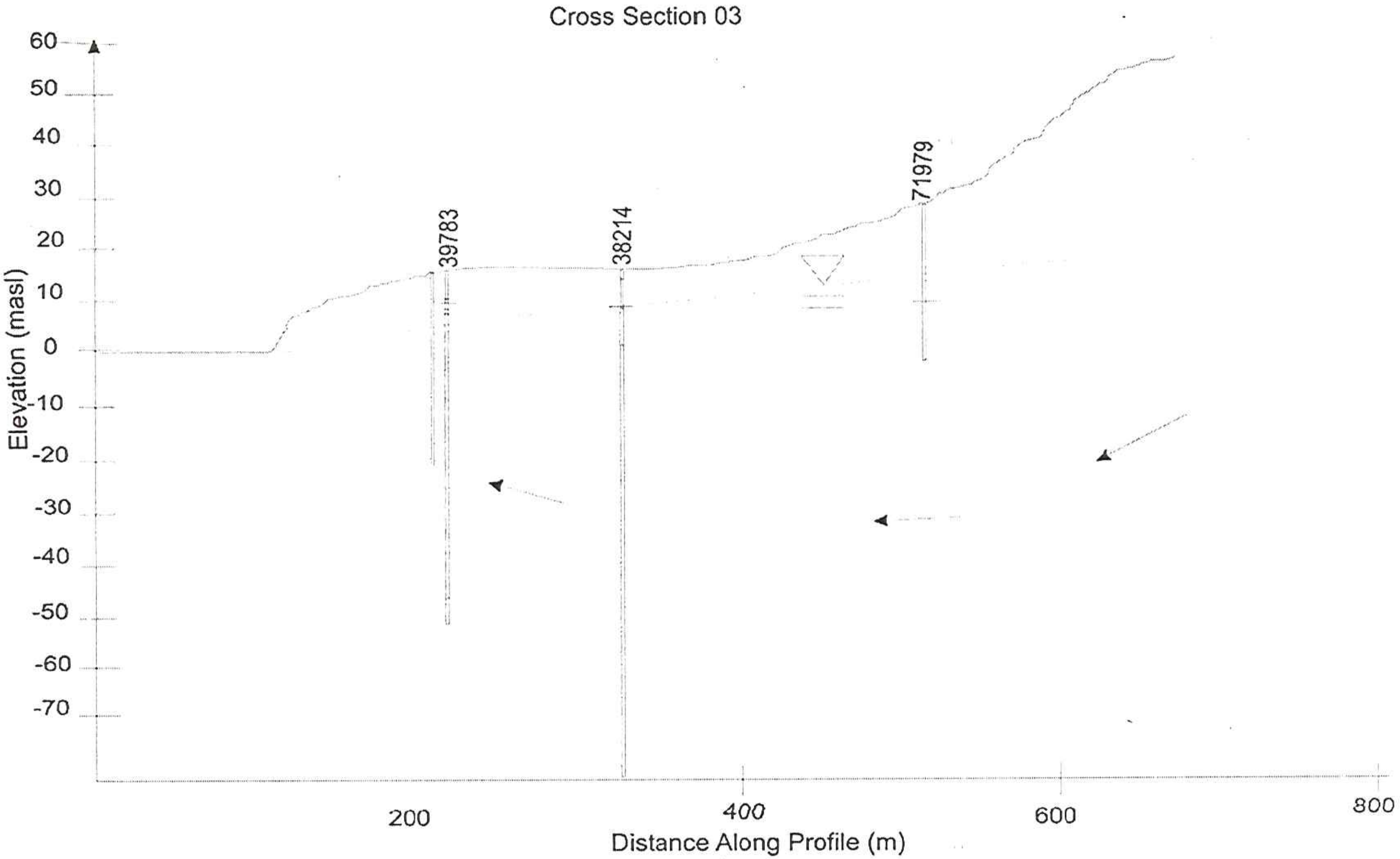

Figure 2.11: Location of water table for cross-section 3.

3. HYDROCHEMISTRY

3.1. METHODOLOGY

A total of 20 groundwater samples were collected and analyzed from representative wells in the village of Belcarra (Fig. 3.1). The wells were chosen based on a number of factors including, completeness of well log lithology descriptions, geographic location, depth of well completion, and whether or not a well was accessible during the sampling period[2]. The objective of the chemical sampling program was to describe the chemical composition of groundwater in the Belcarra area and interpret the chemical data within the context of the local geology and hydrogeology.

Well owners were contacted by obtaining civic addresses and phone numbers from the Village of Belcarra Hall. Prior to sampling, owners were asked a few simple questions such as; Would they like to participate in the SFU study by allowing their water to be sampled?, Where is the well located?, Where is the best place to get a sample?, and Does the water pass through a treatment system?.

3.2. FIELD SAMPLING

In order to limit degradation of the water sample caused by exposure of the sample, it is necessary to measure certain parameters in the field. A raw groundwater sample was collected directly from either an outdoor tap or kitchen sink, ensuring that the water had not passed through any water treatment system, such as a water softener.

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[2] Well selection was also limited on the basis that the sampling was conducted in July 2004 when many residents were on vacation.

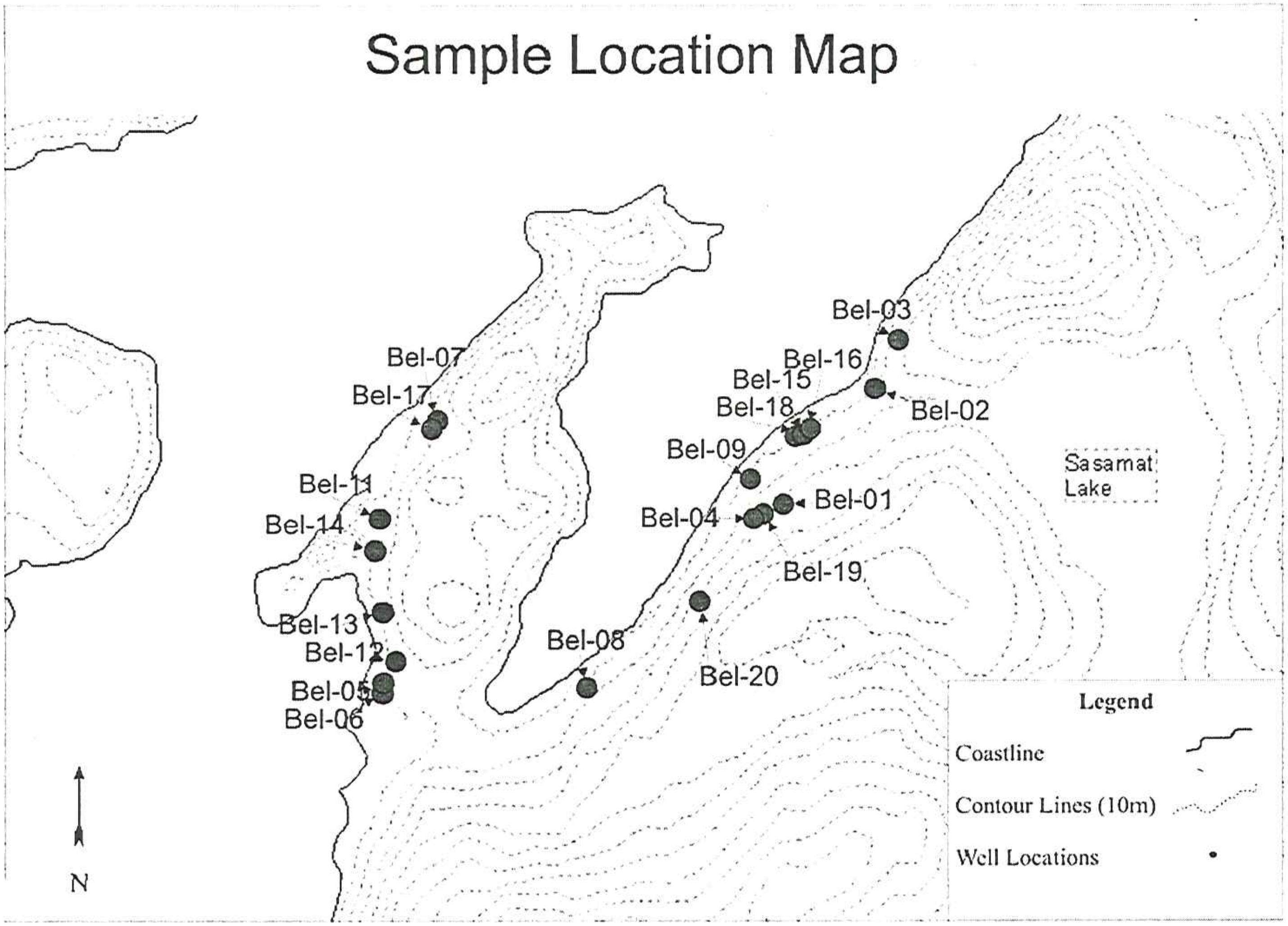

Figure 3.1: Location of water sampling

A flow through cell was used during field sampling to obtain accurate values of specific field parameters, including pH, temperature, electrical conductivity (EC) and oxidation-reduction (Redox) potential. Temperature and pH were tested using the Hanna Instruments portable pH meter (HI 9023). EC was measured with the Hanna Instruments portable conductivity meter (HI 9033). Redox potential was measured with the Oakton Instruments waterproof double junction ORPTestr. In a flow-through cell, groundwater flows directly from the well and through the flow through cell, thus it does not come in contact with the atmosphere and undergo chemical changes as a consequence (Fig. 3.2). The cell used consisted of a 1.4 L Rubbermaid "servin' saver" with five holes cut in the lid for the placement of probes. Before any sampling occurred the probes were calibrated using standard calibration solutions. Water was allowed to flow through the cell until it was full, and the readings on the meters were allowed to stabilize before they were recorded.

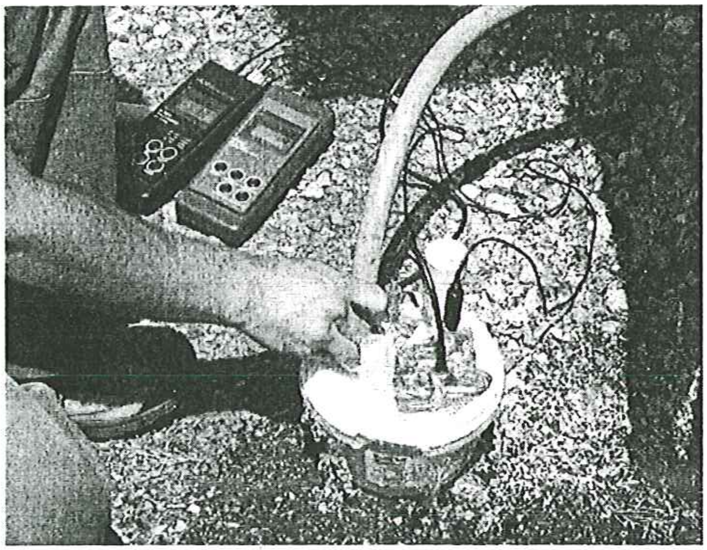

Figure 3.2: Flow through cell with various probes for measurement of field parameters

Chemical titrations were carried out in the field to test for chloride (Cl), total alkalinity and sulfate (SO_4) immediately following flow through cell measurements. Cl was tested on unfiltered water samples, while alkalinity and SO_4 were tested on filtered water samples. A Nalgene filter holder with funnel was used with 0.45 m Whatman Cellulose Nitrate Membrane Filters and a MityvacII hand pump to remove suspended particles that may interfere with the chemistry results.

Cl titrations were completed with a HACH test kit using a mercuric nitrate titrant. The concentration of acid used and the volume of sample needed to perform each titration were determined by looking at the relationship between conductivity and alkalinity with chloride from previous water chemistry results from other local study areas. All Cl titrations were completed with 100mL samples and 0.2256N Mercuric Nitrate. One packet of Diphenylcarbazone reagent was added to the 100mL sample in a 125mL Erlynmeyer flask and stirred. The mercuric nitrate was then added with a HACH digital titrator until the sample turned pink. The digits of titrant added were multiplied by a scaling factor of 0.1 to determine chloride concentration, based on the fact that 100mL of sample was used.

Alkalinity was measured using a Hanna Alkalinity test kit (HI 4811). Titrations were done using 5mL of filtered sample and adding 2 drops of bromcresol green indicator. The acid used was 0.02N HCl, and it was added drop by drop until the blue solution turned yellow. Bromcresol green has a transition endpoint of approximately pH 4.3, at which point it changes colour. The total alkalinity was calculated from volume of titrant added by the following equation:

Total Alkalinity (mg/L HCO_3) = Volume of 0.02N HCl used (mL) x 244 [3.1]

Two titrations were completed for all samples and the average of the two was used to calculate total alkalinity (reported as bicarbonate HCO_3).

SO_4 measurements were carried out with a Hanna Sulphate meter (HI 93751). The instrument was zeroed before each measurement with a 10mL filtered sample. Then a packet of sulphate reagent (HI 93751-0) was added, and the sample was shaken for 1 minute. Readings were taken after allowing the sample to sit for 5 min.

All containers and flasks used for sample collection and parameter measurements were rinsed twice with distilled water between samples. In addition, for quality control purposes, a sample of distilled water underwent all of the procedures for measurement of field parameters and was submitted to the analytical laboratory as a field blank.

3.3. LAB ANALYSIS

Water samples were collected in 250 mL bottles for laboratory analysis of dissolved metals. The water was filtered and acidified prior to analysis. Sample bottles were filled to overflowing to avoid headspace in the bottle and minimize the possibility of further reactions occurring with the atmosphere. The sample bottles were delivered to PSC Analytical Services in Burnaby, BC for analysis. Dissolved metals were measured using ICP-MS (Inductively Coupled Plasma – Mass Spectrometer).

3.4. RESULTS

Water chemistry data for all sampled wells are included in Appendix C. Field and lab analysis results were entered into the hydrochemical program Aquachem 4.0 (Waterloo Hydrogeologic Inc., 1997). Aquachem was used to create plots and to calculate the charge balance error (CBE) for each sample.

3.4.1. CHARGE BALANCE ERROR

The CBE is used to test the integrity of the results according to the following equation:

$$CBE = \frac{\left(\sum zm_{cations} - \sum zm_{anions}\right)}{\left(\sum zm_{cations} + \sum zm_{anions}\right)} \times 100 \leq 5\% \qquad [3.2]$$

where z is the ionic valence and m is molarity (in moles per litre). The product of z and m is reported as equivalents per litre. As water is electrically neutral, the discrepancy from zero is a measure of the accuracy of the analysis. Ideally, the CBE should be less than or equal to 5%.

CBE ranges from -1% to -29%, with the negative values indicating the presence of more anions (Table 3.1); the average CBE was 18%. The CBE for the blank was -100%, reflecting the fact that no metals were measured, but anions were. In a couple of cases the CBE was close to 30%. Overall, the CBE results are not very good. There are a number of possible explanations for this.

First, all anions were measured in the field using simple test kits, which typically give rise to error. It is not uncommon to over-estimate the concentrations of ions using test kits, because most rely on colorimetric methods, which are subjective. Often the operator adds slightly more reagent than is necessary to reach an endpoint, in order to confirm that the endpoint has, in fact, been reached. The metals, on the other hand, were measured in an analytical laboratory using a very high precision and accurate ICP-MS.

Second, precipitation of metals within the sample container prior to analysis can possibly account for loss of positive charges in solution, making the CBE negative. Samples were filtered and acidified at the analytical lab, leaving time for some precipitation to occur despite the fact that the samples were transported to the lab as quickly as possible following sampling.

Third, the presence of a constituent in the water that was not analysed for can result in a high CBE. This is a possible source of error for this study given that nitrate was not analyzed and there is a potential for contamination from septic systems; however, it was not anticipated that nitrate would be present in high concentrations. Similarly, other less common anions, including bromide and iodide, which were also expected to be low in concentration, were not included in the analysis. Nonetheless, as all of metals were analyzed, the results would show a positive CBE if anions had not been analyzed. According to the results (Table 3.1), this is probably not the case as all of the CBE values are negative. Finally, it is possible that the source of error is the lab itself; however, this is unlikely.

Regardless of the source of error, the most likely explanation for a large CBEs is a low concentration of total dissolved solids in many samples (the average TDS value for all samples is 98.6 mg/L). At low total dissolved solids concentrations, small analytical errors tend to be accentuated. Particular samples that might fall into this category include Bel-2, Bel-12, and Bel-20. These all have relatively low TDS values (38.6, 63.7, and 38.7 mg/L, respectively), and CBE values that are among the highest. Notwithstanding the high CBEs calculated for this dataset, there is good consistency among the sample chemistries, suggesting that the data are reasonably representative of site conditions.

Table 3.1: Charge balance errors for all samples.

	Charge Balance (from Aquachem)		
	cations (meq/L)	anions (meq/L)	Charge Balance Error (%)
BEL-1	5.31	5.77	-4.2
BEL-2	0.72	1.26	-27.3
BEL-3	2.53	3.91	-21.4
BEL-4	3.63	3.7	-1.0
BEL-5	1.7	2.31	-15.2
BEL-6	1.47	1.82	-10.6
BEL-7	1.7	2.32	-15.4
BEL-8	0.91	1.5	-24.5
BEL-9	1.98	2.99	-20.3
BEL-10	2.16	3.49	-23.5
BEL-11	2.11	3.34	-22.6
BEL-12	1.14	1.71	-20.0
BEL-13	3.36	4.57	-15.3
BEL-14	1.64	2.1	-12.3
BEL-15	2.27	3.13	-15.9
BEL-16	2.38	3.59	-20.3
BEL-17	1.44	2.12	-19.1
BEL-18	2.02	2.98	-19.2
BEL-19	1.44	2.26	-22.2
BEL-20	0.98	1.78	-29.0
BEL-21 (Blank)	0	0.12	-100.0
Average	2.0445	2.8325	-18.0

3.4.2. DISSOLVED CONSTITUENTS

Bicarbonate (HCO_3 - calculated from total alkalinity) and electrical conductivity (EC) show the greatest variability among samples (Fig. 3.3). HCO_3 is the major control on EC, and ranges from 50 to >200 mg/L. EC ranges from 125 to 725 S/cm. Cl typically ranges from 5 to 45 mg/L range; however, Bel-1 and Bel-13 have higher values (70 and 104 mg/L, respectively). SO_4 concentrations are low and do not show much variability, ranging from 10 to 40 mg/L.

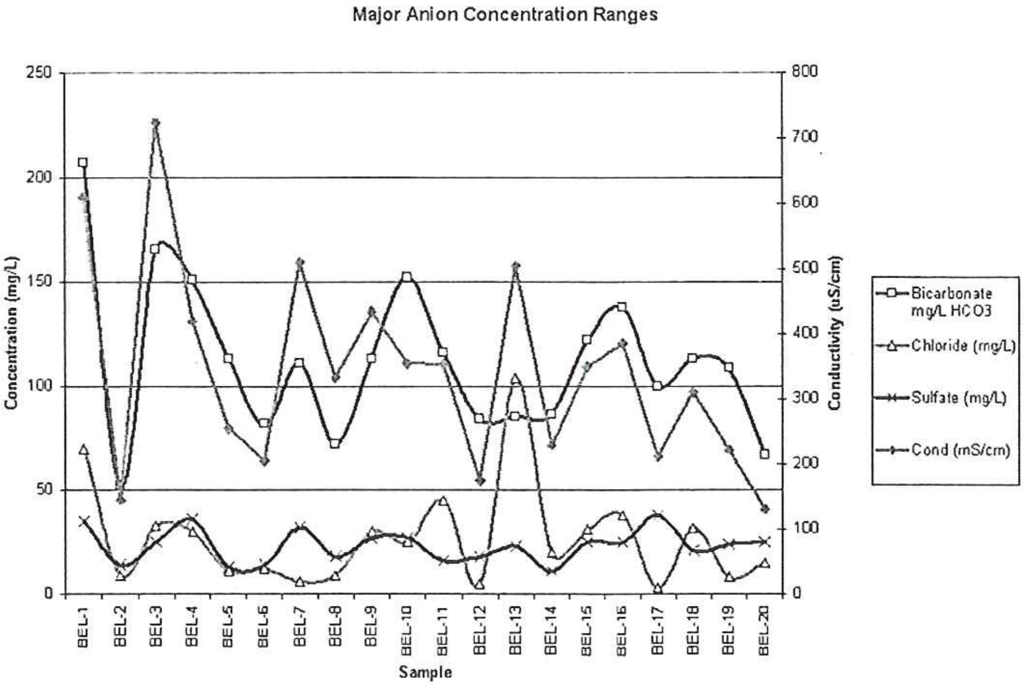

Figure 3.3: Range in dissolved anion concentrations. Samples are plotted in numerical order.

Selected dissolved metals (Ca, Mg, Na, K and S) are plotted in Figure 3.4. Calcium (Ca) and sodium (Na) are the dominant metals and range from 10 to 75 mg/L, and 7 to >100 mg/L, respectively. Magnesium (Mg) and sulphur (S) are present at concentrations less than 17 mg/L, and show minor variation. Potassium (K) is only present (greater than the detection limit of 1 mg/L) in 8 of the 20 samples, and has concentrations <5 mg/L. Other metals present in most of the samples are barium (Ba), boron (B), copper (Cu), manganese (Mn), molybdenum (Mo), strontium (Sr) and zinc (Zn) (Appendix C). These metals have such small concentrations that they do not affect the quality of the water.

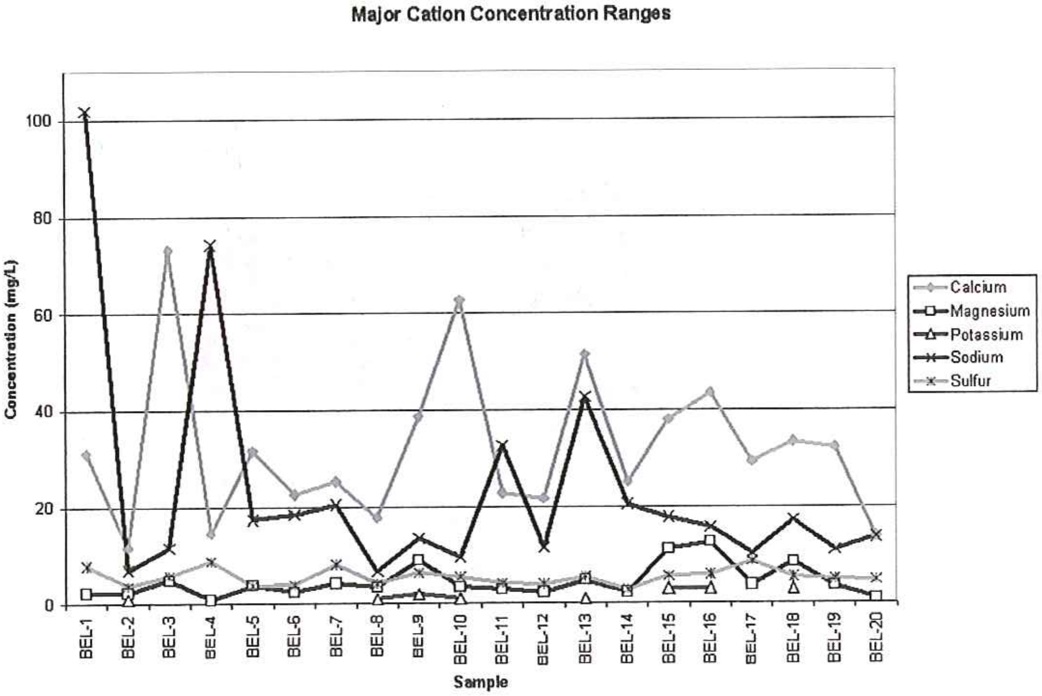

Figure 3.4: Range in dissolved metal concentrations. Samples are plotted in numerical order.

3.5. GENERAL OBSERVATIONS AND TRENDS

3.5.1. GROUNDWATER COMPOSITION

The average chemical composition of the groundwaters sampled in the Belcarra area is plotted on a pie chart (Fig. 3.5) in order to draw some broad generalizations concerning the hydrochemical character of the groundwater. Averages were computed by considering all samples, as many had charge balance errors greater than 15%. The average concentrations represent well the observed individual concentrations reported separately above. Overall, the groundwater quality (based on dissolved chemistry) of Belcarra aquifer is good.

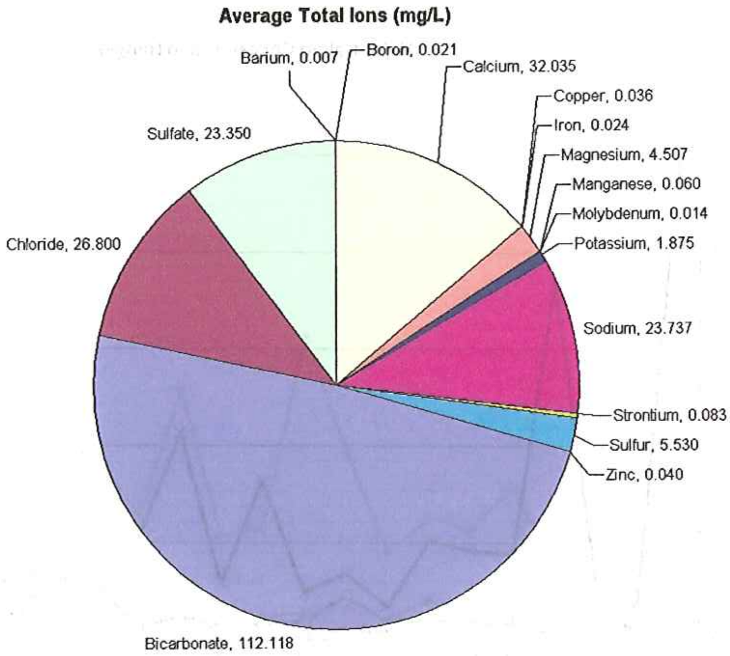

Figure 3. 5: Average ion concentration for Belcarra groundwaters

The results of the chemical analyses are also plotted on a Piper plot (Fig. 3.6). A Piper plot shows graphically the relation between anion chemistry and dissolved metal (cation) chemistry, plotted in each of the two lower triangles, respectively. The points represent the relative fractions of anions (HCO_3, SO_4 and Cl) and the cations (Na+K, Ca and Mg), assuming that these constituents represent 100% of the total cations and anions, respectively. This is a reasonable approximation given that other constituents are relatively minor.

The Piper diagram shows that the anion chemistry trends from HCO_3 to Cl in composition, and that cation chemistry trends from Ca to Na(+K) in composition. According to Figure 3.7, which shows the various types of water classifications, groundwater can be generally classified as a bicarbonate to bicarbonate-chloride-sulfate type water in terms of its anion chemistry, and as a calcium-magnesium to a sodium-calcium type water in terms of its cation chemistry.

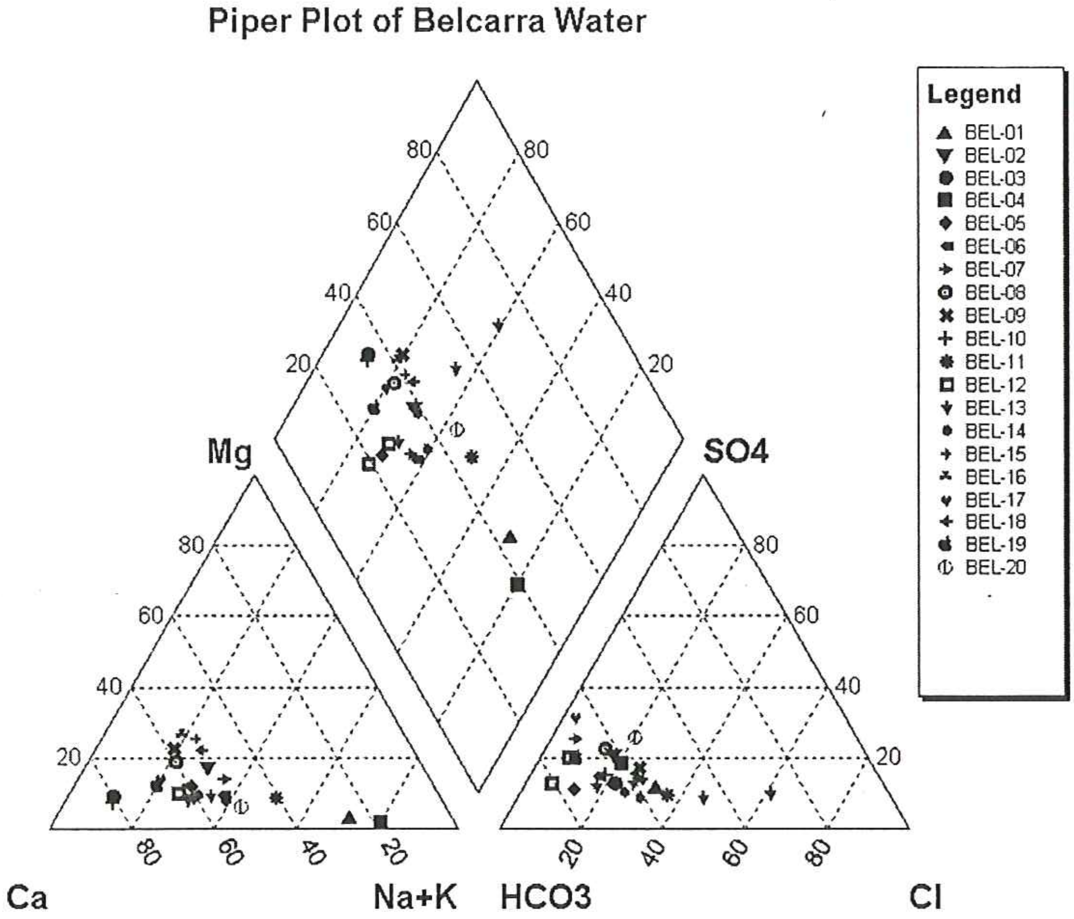

Figure 3.6: Piper plot of Belcarra water samples. Sample points shown in black are for the current study and in red are for previous studies.

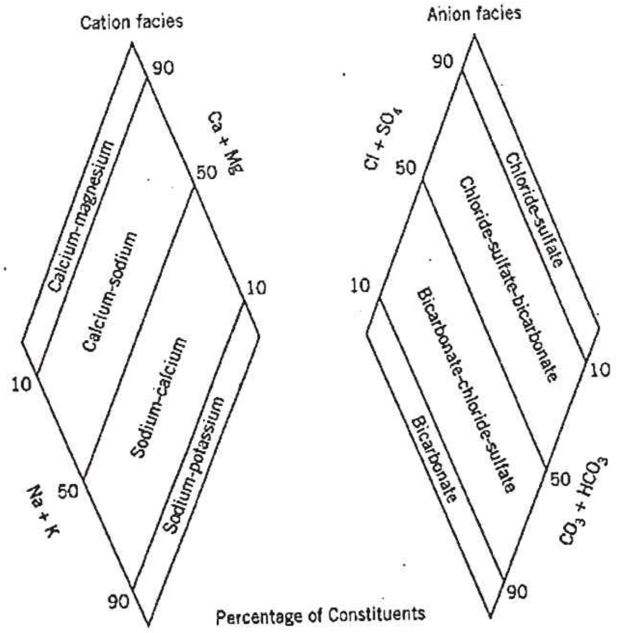

Figure 3.7: Piper plot divisions for classification of water types (from Domenico and Schwartz, 1990).

3.5.2. NA CONCENTRATIONS

Na concentrations were analyzed individually to see if there are any relations between its concentration and either well depth (Fig. 3.8) or distance inland from the coast (Fig. 3.9). In Figure 3.8, which shows Na concentration versus well depth, there is a slight positive trend (i.e., Na increases with depth) with a low R^2 value (R^2=0.0541). The low R^2 value is a consequence of four errant points lying above the trend line, which tends to reduce the degree of correlation. Three of these four high Na concentration points (Bel-1, Bel-11 and Bel-13) also have high Cl concentrations, indicating that these wells likely represent mixing with seawater. The position of the fourth point, Bel-4, likely represents cation exchange. In this well, the Na concentration is 74.2 mg/L and the Cl concentration is lower at 30 mg/L. The Cl value measured in this well is much lower than that measured in the other wells, suggesting that the source of sodium is not seawater, which would result in a similarly high value of Cl. The increase in Na (and K) tends to occur at the expense of Ca (or Mg), and is therefore, interpreted to be the result of cation exchange, in which Ca and Mg ions in the water exchange with the Na and K sorbed onto clay particles of weathered rocks in the subsurface. This type of chemical reaction has been observed in other coastal regions in the province (Allen and Suchy, 2001). When the three points representing seawater mixing and the fourth cation exchange point are ignored, the result is the dashed line and there is no trend (horizontal line), suggesting that Na concentrations do not increase with depth.

In Figure 3.9, which shows Na concentration versus distance inland from shore, the three points representing seawater mixing and the fourth cation exchange point, as described above, are indicated. These points are not included in the overall trend of the dashed line for reasons described above, and once again, there is no trend indicating that Na concentration does not increase with distance from shore.

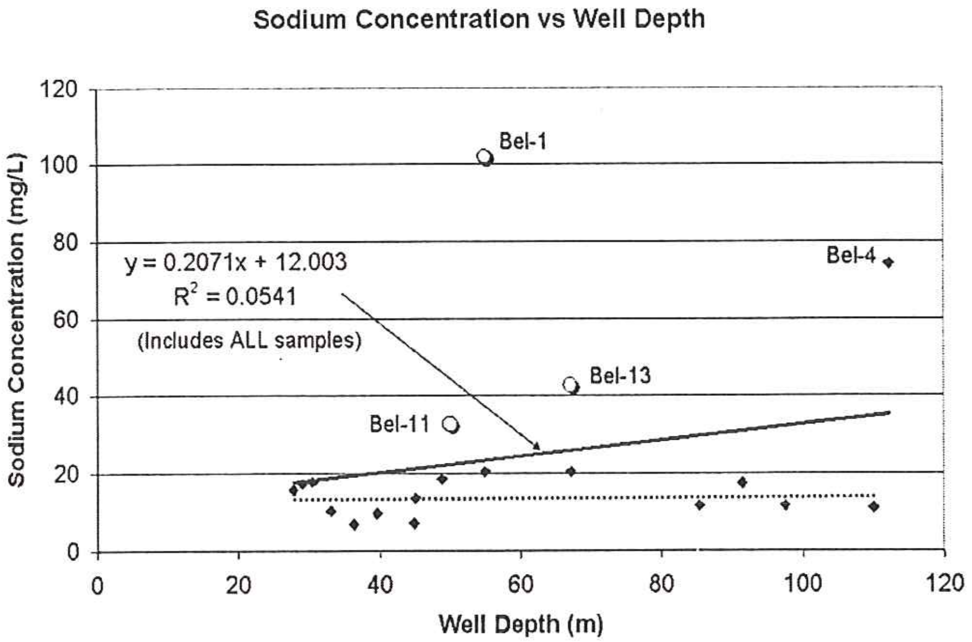

Figure 3.8: Sodium concentration as a function of well depth.

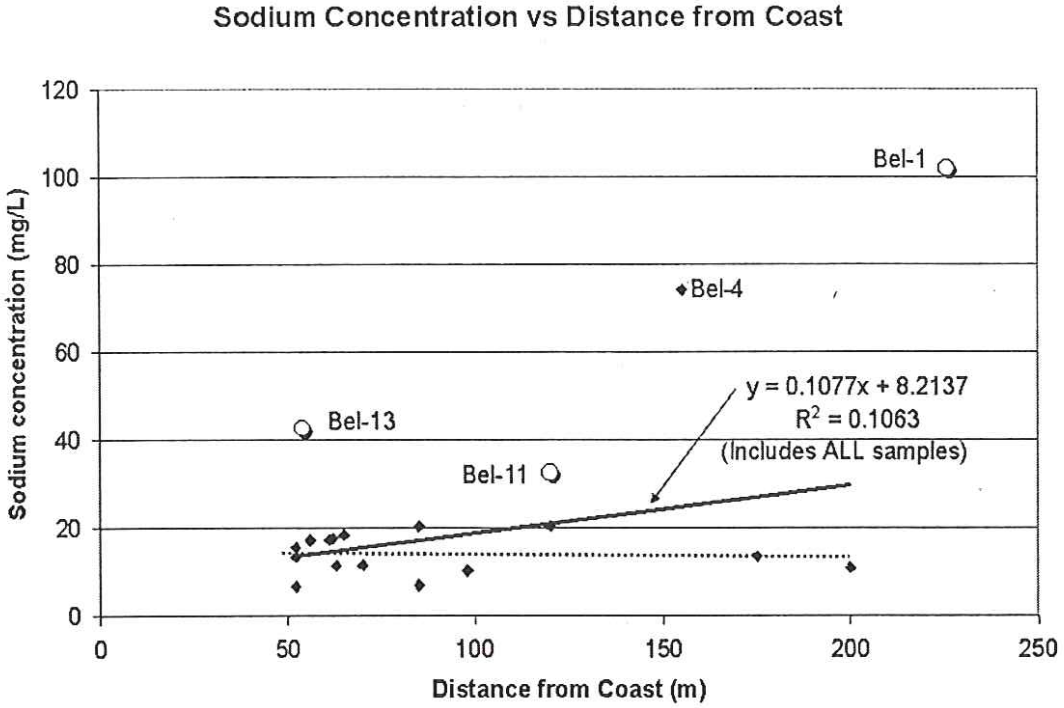

Figure 3.9: Sodium concentration as a function of distance from the coast.

3.5.3. COMPARISON WITH OLDER CHEMISTRY DATA

Data were compiled of previous chemistry results for samples Bel-12, 13, & 14. These samples were analyzed by ALS in Feb/01 and Apr/02, and by PSC Analytical Services in Oct/03 and again in Mar/04. These results were input into Aquachem, and are plotted on the Piper plot in Figure 3.6 (shown in red) along with the more recent results from this study (shown in black). The older samples plot in the same general area as the more recent samples, indicating that the overall relative concentrations have not changed appreciably over time in these wells.

3.5.4. TEMPORAL VARIATIONS IN CL CONCENTRATIONS

Chloride concentrations are also of particular interest as they serve as an indication of seawater mixing in coastal settings. Cl concentrations (mg/L) were plotted against time using previously reported data for Bel-12, Bel-13 and Bel-14, located along

Belcarra Bay Road near Turtle Head (data in Appendix C). This comparison was done to see if there is any observable temporal trend. The chart shown in Figure 3.10 shows there is an overall increase in chloride concentration in these wells. However, the relation is not linear. The Cl concentrations in Bel-12 do not appear to have changed over the period of record; however, only two data points are available. Well Bel-13 shows a general increase in chloride concentration, with considerable variability recently (R^2 value of 0.4813). Well Bel-14 may show a slight increase in Cl concentration, but the period of record is limited to the last year. Given the increase in concentration of Cl in Bel-13, and the location of this well close to the coast, it would be advisable to undertake regular sampling of this and nearby wells in order to monitor groundwater chemistry and look for warning signs of groundwater quality deterioration due to saltwater intrusion.

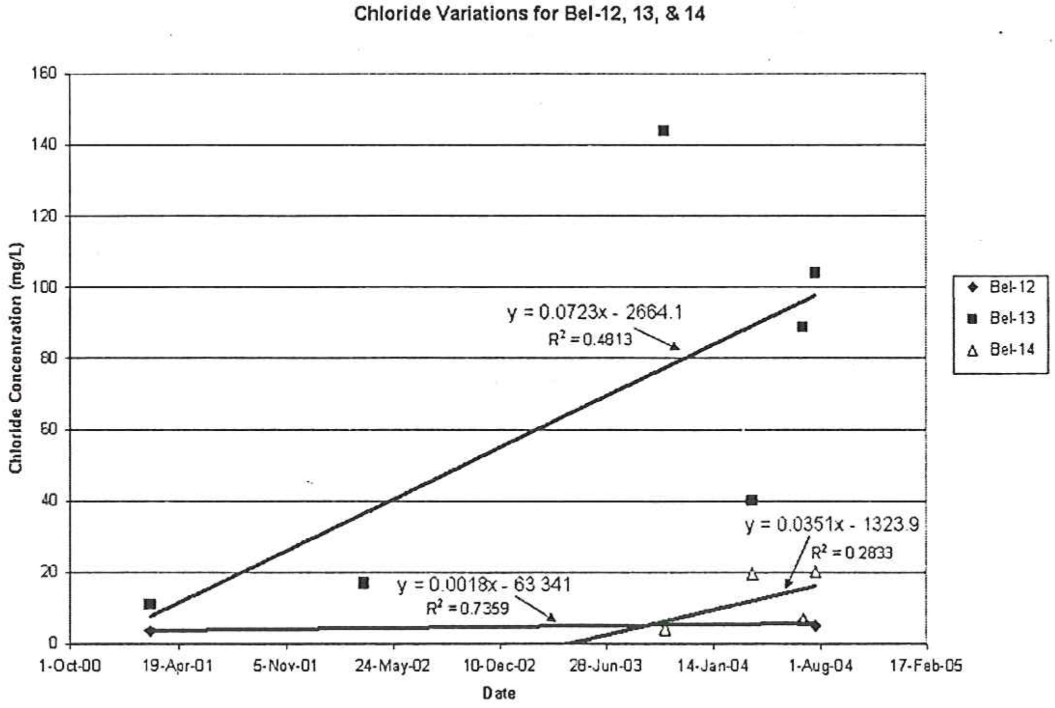

Figure 3.10: Chloride concentration variations for Bel-12, Bel-13 and Bel-14.

4. RECHARGE AND HYDROLOGY

4.1. CLIMATE STATIONS

Climate data were provided by Environment Canada for five climate stations around the Belcarra region, including Buntzen Bay (1101138), Buntzen Lake (1101140), Como Lake Ave (1101889), Ioco Refinery (1103660), and Port Moody Glenayre (1106CL2). The number in parentheses is a unique Environment Canada national station identifier (http://scitech.pyr.ec.gc.ca/climhydro). The data for these stations include station location, the period of record (POR), daily precipitation amounts, and some daily temperature information. A complete listing of station data can be found in Appendix D. The locations of these climate stations are shown in Figure 4.1. Table 4.1 shows the POR and information for each climate station.

4.1.1. PRECIPITATION

Daily precipitation data are shown in Figure 4.2 for the Buntzen Bay station (POR 1992 to 2002). There is considerable variability in precipitation, making it difficult to identify yearly or longer term trends, with the exception that summer precipitation is generally lower than winter precipitation. Graphs for the other stations are provided in Appendix D.

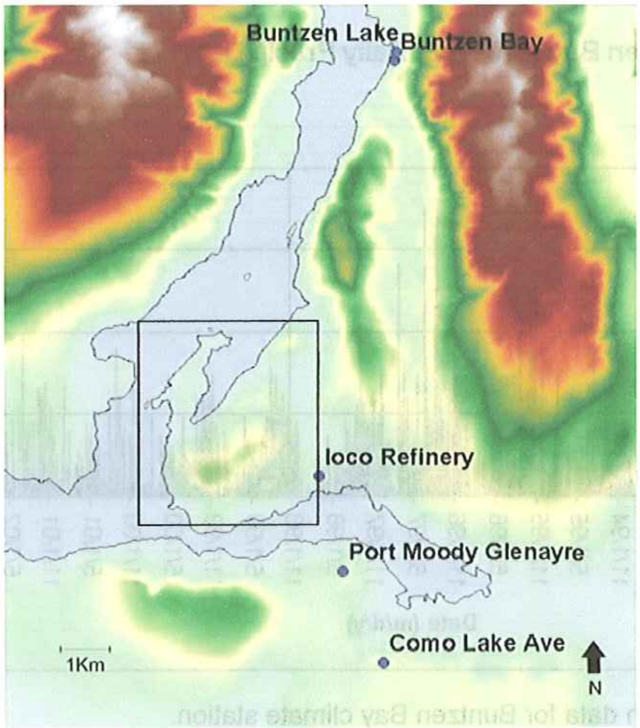

Figure 4.1: Climate station locations.

Table 4. 1: Climate station periods of record (POR) and information available.

Station Name	ID Number	Period of Record	Information
Buntzen Bay	1101138	11/71-02/74 02/92-11/02	daily precip
Buntzen Lake	1101140	01/24-05/83	daily precip
Como Lake Ave	1101889	12/72-04/83 05/87-11/02	daily precip
Ioco Refinery	1103660	08/16-06/95	daily precip
Port Moody Glenayre	1106CL2	11/70-09/75	daily precip, max and min temp.

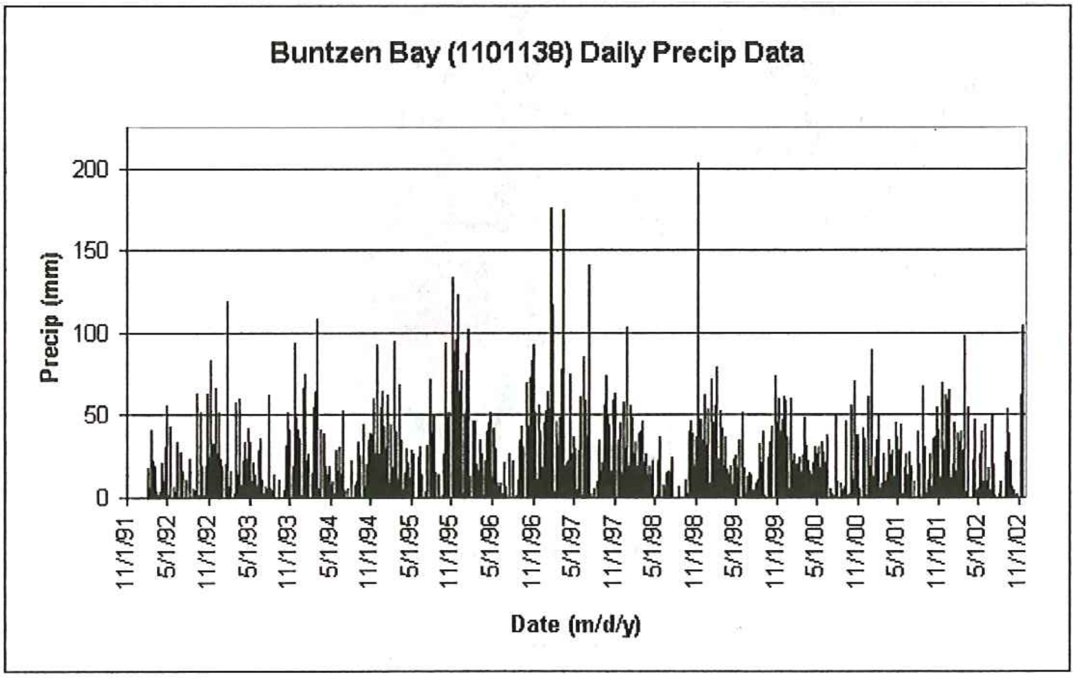

Figure 4.2: Daily precipitation data for Buntzen Bay climate station.

Average monthly precipitation was calculated for each station (Appendix D). The cyclical nature of the precipitation (Fig. 4.3), with higher amounts during the winter and spring months, and lower amounts during the summer and early fall months, is more apparent on the monthly graph compared to the daily graph. Figure 4.3 also compares monthly precipitation values for the Como Lake Avenue and Buntzen Bay Stations, revealing small differences in the amount of precipitation for different areas. For example, precipitation trends measured at these two stations are similar, but the Buntzen Bay station consistently shows higher amounts of precipitation in the winter months. This is consistent with the North Shore Mountains (Coast Mountains) receiving generally higher precipitation due to orographic effects. Comparisons between other stations were not possible due to lack of overlap in the PORs.

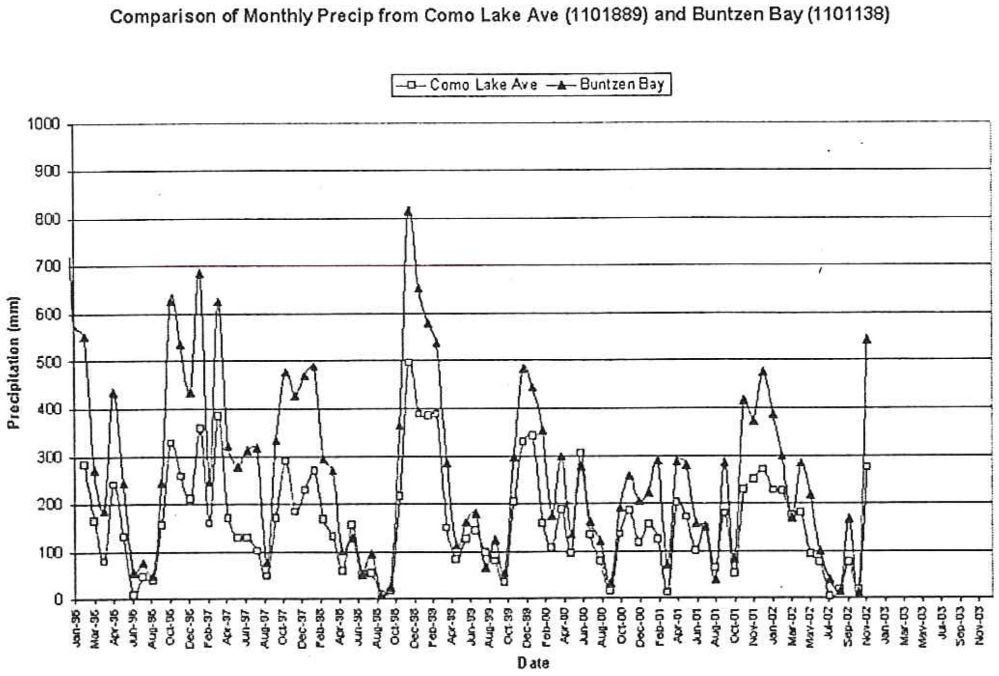

Figure 4.3: Comparison of monthly precipitation trends between Como Lake Avenue and Buntzen Bay stations.

4.1.2. TEMPERATURE

Temperature data (as maximum and minimum daily temperatures) were only available for the Port Moody Glenayre station. These values were plotted on the same graph as the precipitation normals[3] (Fig. 4.4), and show maximum, minimum, and mean temperatures (referenced to left axis), and precipitation, shown as bars (referenced to right axis). Average temperatures for the Port Moody Glenayre station range between 2.9°C and 17.7°C. These values are very similar to the Vancouver International Airport station average temperatures, which range between 3.3°C and 17.6°C (Fig. 4.5).

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[3] A Climate Normal is a 30 year average for the Station.

Temperature also acts as a reflection of potential evapotranspiration. Higher average temperatures generally relate to greater evapotranspiration rates, and thus potential recharge water is intercepted before it reaches the aquifer. When the temperature is plotted on the same graph as precipitation, the trend can be seen that precipitation is lowest in the summer months and temperatures are higher, both of which result in much lower recharge rates to the aquifer in the summer.

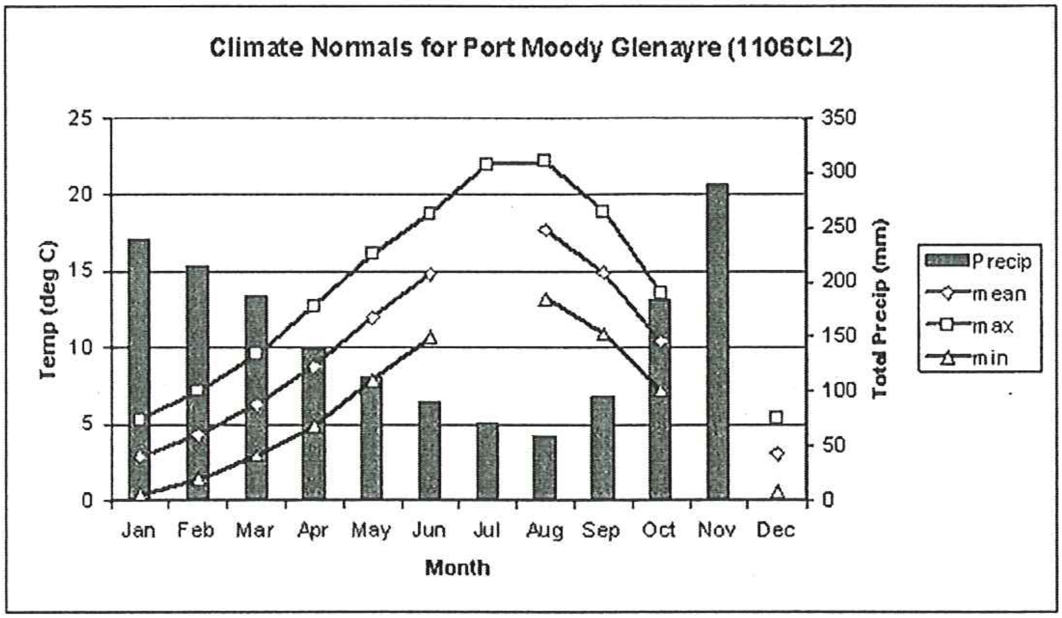

Figure 4.4: Temperature and total precipitation normals for the Port Moody Glenayre climate station.

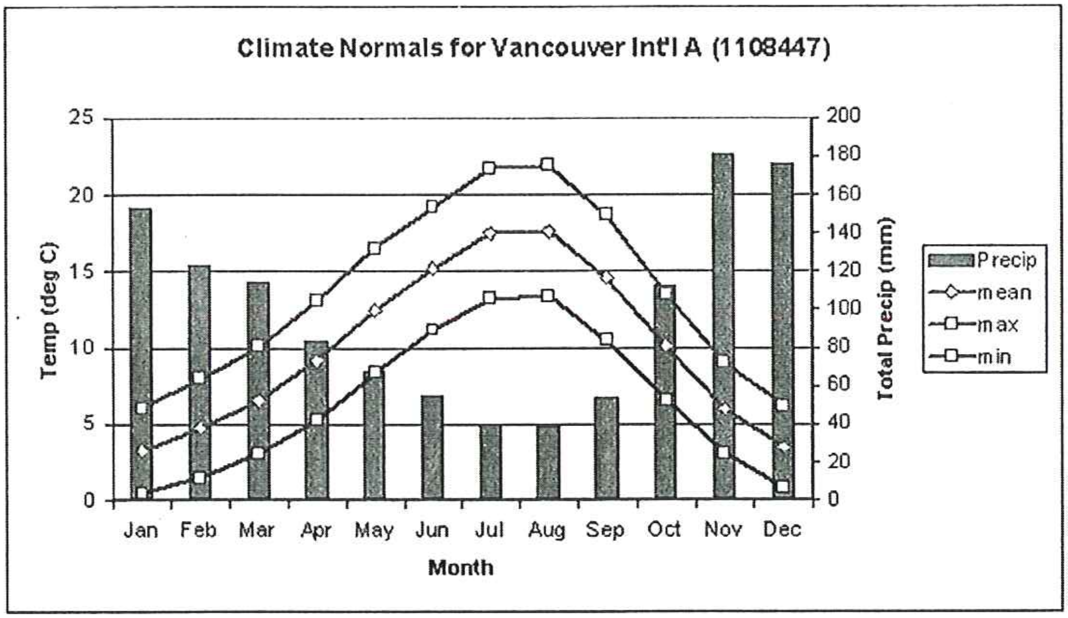

Figure 4.5: Temperature and total precipitation normals for the Vancouver International Airport station.

4.1.3. CLIMATE NORMALS

Climate normals were used to compare the precipitation data between the different climate stations in the Vancouver region (Fig. 4.6). There was no precipitation normal information available for the Buntzen Bay Climate station, so a climate "normal" was created for Buntzen Bay from the climate data available - only a 10 year period between 1992-2002. The Vancouver International Airport climate station was included to determine if it can be considered representative of the Village of Belcarra, because this particular station has a complete set of climate data (not just precipitation and temperature, but also humidity, wind speed, solar radiation, etc.).

Climate normals are very useful for comparing trends between stations. Representative climate data can also be used for modelling recharge to an aquifer (as will be discussed later in this chapter). The precipitation normals for all climate stations consistently show higher amounts of precipitation than the Vancouver International

Airport. Differences are due to the fact that the Airport is away from the mountains (i.e., it is located close to the ocean and at a lower elevation), and therefore, does not feel orographic effects as much as the stations located inland closer to the Coast Mountains. In fact, as the station location nears the mountains, the recorded about of precipitation increases.

To obtain a representative set of climate data for the Village of Belcarra, it was necessary to use the precipitation normals for the Como Lake Ave and Buntzen Bay climate stations, as these are the two closest climate stations with useful data. It was not possible to solely use the Buntzen Bay station data, because the POR was limited to 10 years. Representative monthly precipitation values for Belcarra were thus determined by taking the average of those calculated from the 10 year period of record (1992-2002) from the Buntzen Bay climate station and the Como Lake Ave precipitation normals from the Environment Canada website. These values are on average about 100 mm higher each month than those for the Vancouver International Airport climate normal (Fig. 4.6).

Ultimately, the climate data for the Village of Belcarra is a combination of the precipitation normal created with the Buntzen Bay and Como Lake Ave data, and the temperature normal from the Vancouver Int'l Airport station. Figures 4.4 and 4.5 show the similarities between the temperature normals for the Airport and the closest climate station to Belcarra with relevant data, which is Port Moody Glenayare. These graphs indicate that the Vancouver Int'l Airport temperature normal is indeed representative of Belcarra, and has a complete data set. The final representative climate data for Belcarra is shown in graph format in Fig 4.7. The total annual precipitation for Belcarra is 2331 mm.

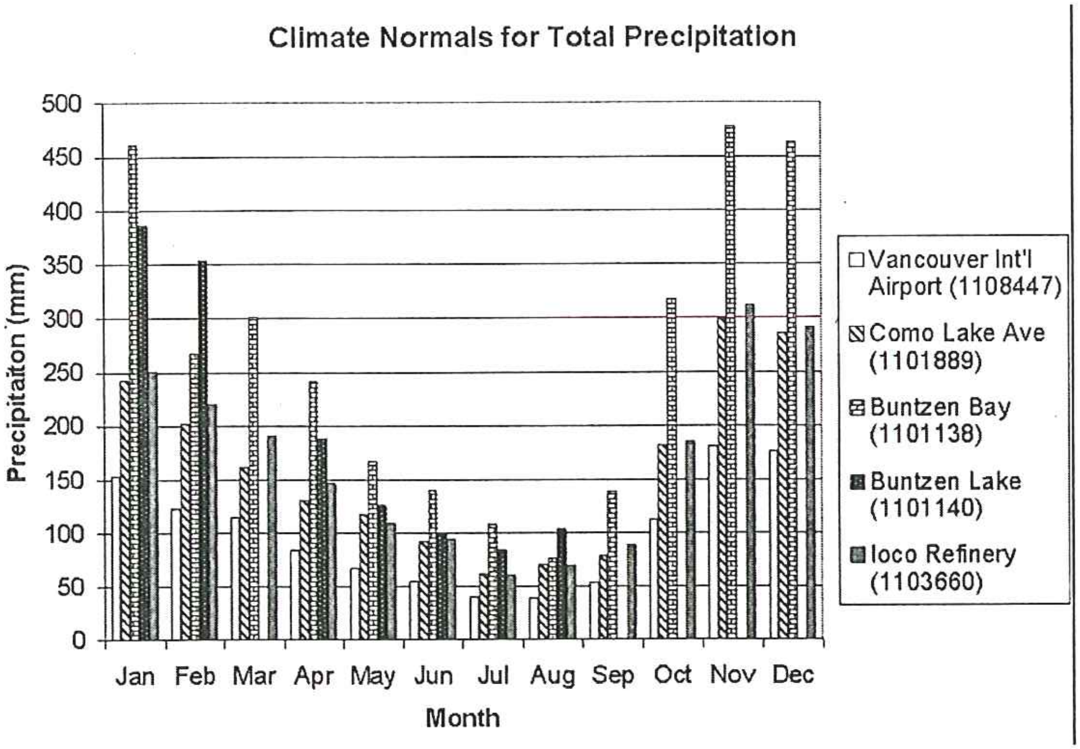

Figure 4.6: Climate normals for total precipitation for five climate stations in the Vancouver area (climate normals from Environment Canada).

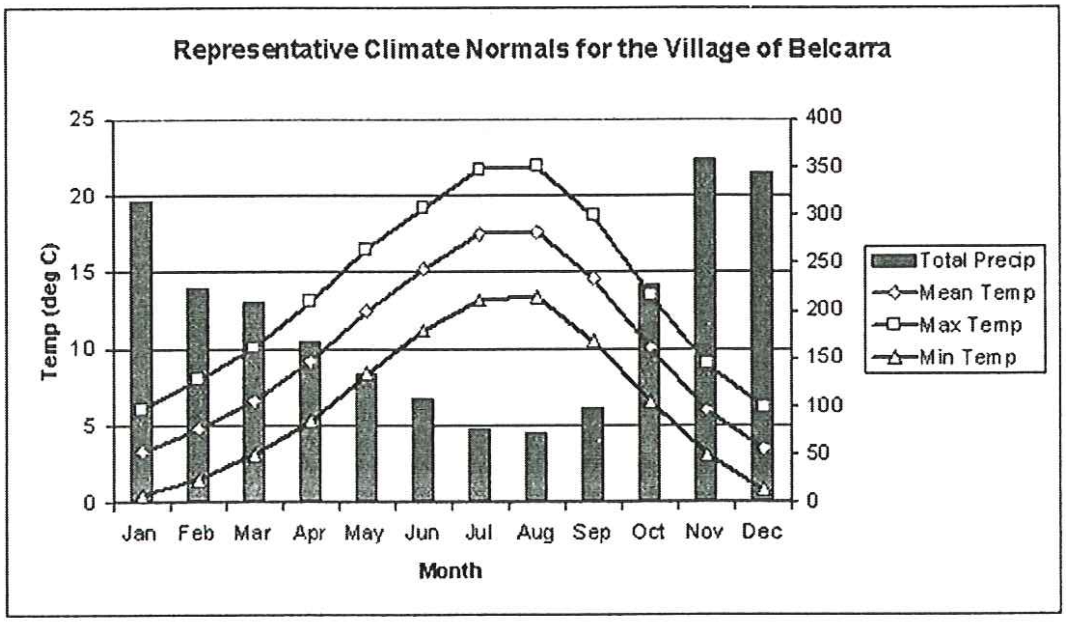

Figure 4.7: Final representative climate normals for the Village of Belcarra.

4.2. RECHARGE ESTIMATION FOR BELCARRA

One of the key components of a hydrogeological study is to arrive at an estimate of recharge to the aquifer. Because the Belcarra aquifer is fractured, recharge estimation is difficult owing to the fact that many recharge estimation methods require an estimate of the porosity and overall storage capacity[4] of the aquifer. Because this information is not yet available for the Belcarra aquifer, several methods for recharge estimation were used.

4.2.1. CATCHMENT AREA

A catchment area is the surface area of aquifer that likely contributes to groundwater recharge. The catchment area for Belcarra was delineated with the use of the hydrogeology cross-sections created in Chapter 3 and the topographic map. The main characteristic used to outline the recharge area was the decrease in head with increased depth below ground level (Domenico and Schwartz, 1998). The approximate transition between recharge and discharge was drawn on the map of the Village of Belcarra, and thus, defined the catchment area boundary (Fig. 4.8). The area of recharge was calculated within the Geographic Information System (GIS).

There appears to be two areas of recharge within the village; a smaller area on the peninsula, which is separated by a narrow zone of discharge from a second larger recharge area (Fig. 4.8). The catchment area on the peninsula is the area above approximately 40m elevation and is approximately 0.78 km^2 in area. The larger main catchment area corresponds to elevations above 60m and is approximately 8.01 km^2 in area. This results in a total area of recharge for Belcarra of roughly 8.79 km^2.

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[4] Pumping tests with multiple observation wells should be undertaken to derive estimates of aquifer storage

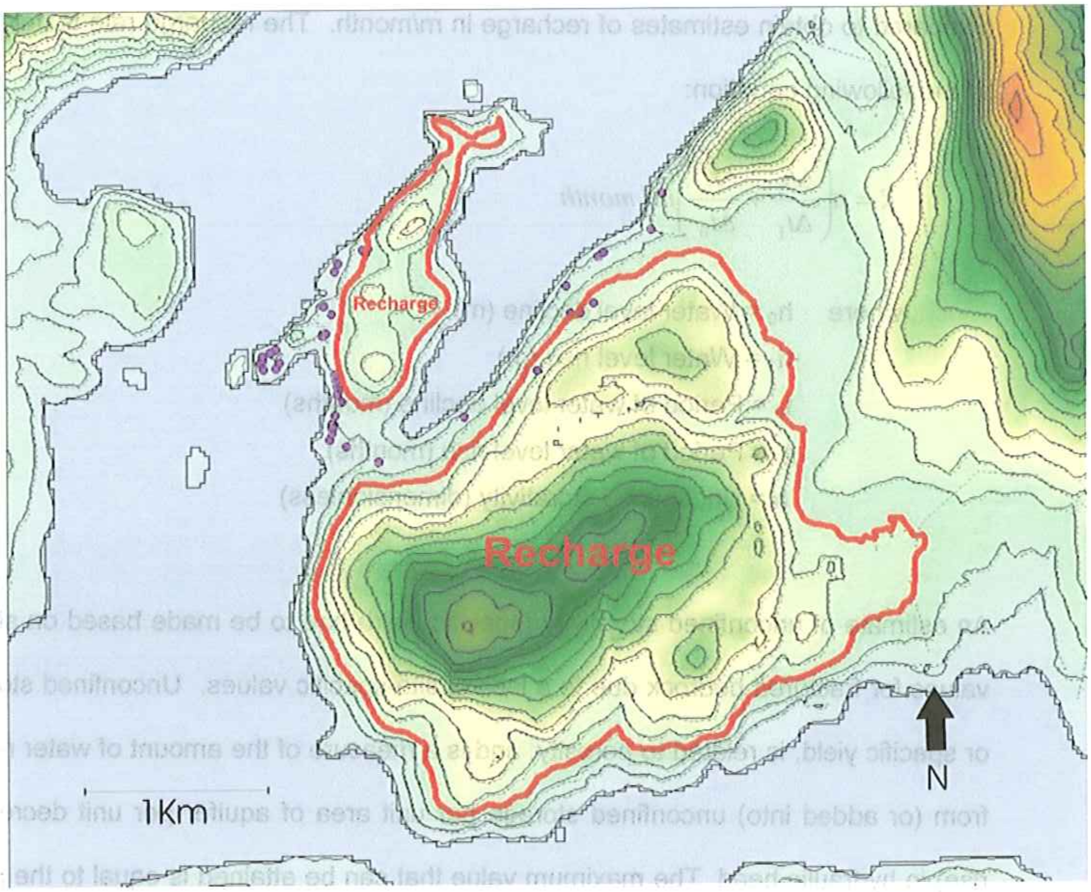

Figure 4.8: Approximate catchment area for groundwater recharge

4.2.2. HYDROGRAPH METHOD FOR ESTIMATING RECHARGE

The Water Management Branch of BCWLAP proposed to install a provincial observation well to monitor groundwater level fluctuations of the Belcarra Aquifer in fall 2000 as part of the provincial aquifer monitoring program. The observation well was drilled in the spring of 2001, and the data collected from it show the cyclic water level fluctuations reflecting the seasonal variations in climate (Fig. 4.9).

The hydrograph method for estimating recharge is done on aquifers that are recharged by precipitation. The recharge and discharge curves for each cycle are compared to obtain estimates of recharge in m/month. The recharge rate is determined by the following equation:

$$R = n\left(\frac{\Delta h_1}{\Delta t_1} + \frac{\Delta h_0}{\Delta t_0}\right) m/month \qquad [4.1]$$

where h_0 = Water level decline (m)
h_1 = Water level rise (m)
t_0 = Period of water level decline (months)
t_1 = Period of water level rise (months)
n = Unconfined storativity (dimensionless)

An estimate of unconfined storativity (specific yield) had to be made based on standard values for fractured bedrock due to a lack of site-specific values. Unconfined storativity, or specific yield, is related to porosity, and is a measure of the amount of water released from (or added into) unconfined storage per unit area of aquifer per unit decrease (or rise) in hydraulic head. The maximum value that can be attained is equal to the porosity of the aquifer. In contrast to values for confined storativity, which are significantly less (1E-6 to 1E-4), unconfined storativity values account for dewatering of the aquifer and typically range from 0.01 to 0.2 (or roughly 1% to 20% porosity).

The hydrograph for the Village of Belcarra contains information for a period of three years, from 2001-2004. The hydrograph method for estimating recharge was applied to each of the three years (Fig. 4.9). Recharge was calculated with five different

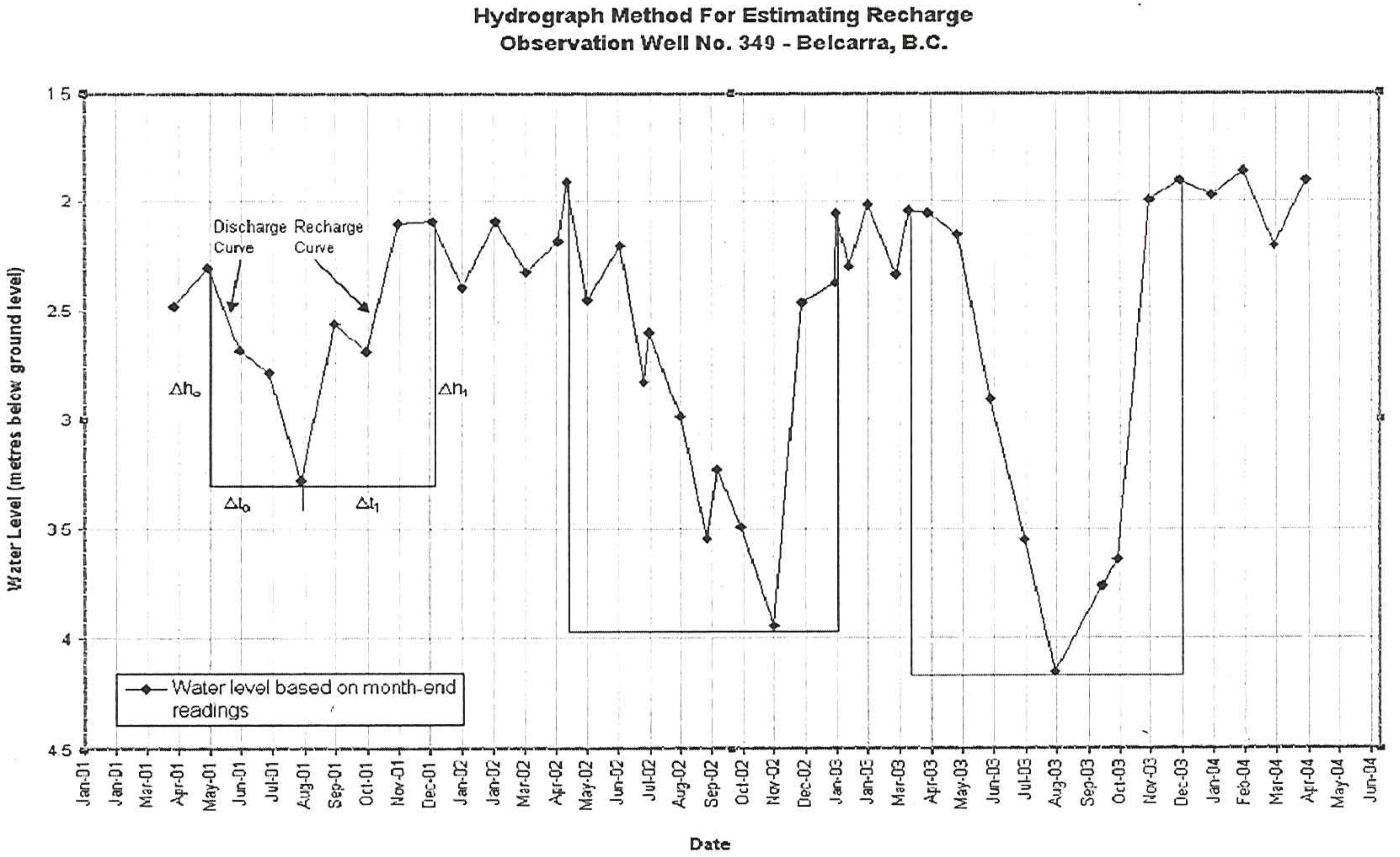

Figure 4.9: Hydrograph method of estimating recharge

values of storativity and the results are compiled in Table 4.2. Values range from 0.0061 to 0.2459 m/month. Given that the Belcarra aquifer is composed of crystalline rock, a conservative value of recharge, 0.0095 m/month, corresponds to an unconfined storativity of 0.01. This value relates to a porosity of 1%, and provides a total annual recharge to the aquifer on the order of 113 mm/year. The amount of recharge estimated from this method is approximately 4.9% of the total annual precipitation to Belcarra. If higher values of unconfined storativity are use, for example, 0.1 (or 10%), then recharge is on the order of 0.095 m/month (1140 mm/year or 48.9% of total annual precipitation). Higher recharge may occur in areas that are more intensely fractured, with higher porosity values, although without additional field studies, it is not possible to determine the spatial variability of recharge.

Table 4.2: Recharge estimates from the hydrograph method.

Recharge Period	h_o (m)	t_o (months)	h_1 (m)	t_1 (months)	n (unitless)	R (m/month)
2001-02	0.977	3	1.19	4.233	0.01	0.0061
					0.05	0.0303
					0.10	0.0607
					0.15	0.0910
					0.20	0.1214
2002-03	2.029	6.733	1.887	2.033	0.01	0.0123
					0.05	0.0615
					0.10	0.1229
					0.15	0.1844
					0.20	0.2459
2003-04	2.105	4.733	2.242	4.033	0.01	0.0100
					0.05	0.0500
					0.10	0.1001
					0.15	0.1501
					0.20	0.2001

Averages	0.01	0.0095
	0.05	0.0473
	0.10	0.0946
	0.15	0.1418
	0.20	0.1891

4.2.3. CUMULATIVE PRECIPITATION DEPARTURE METHOD

Cumulative precipitation departure (CPD) graphs are useful for assessing water level fluctuations in observation wells completed in shallow unconsolidated aquifers (Kohut et al., undated). Graphs are obtained by plotting the cumulative departures from the monthly precipitation mean for a given historic period of time. Although measures of recharge cannot be determined using this method, the utilization of the CPD data may be applicable to:

- Predicting groundwater level trends and the magnitude of the response to precipitation recharge of aquifers;
- Evaluating the significance of precipitation recharge versus other potential sources of aquifer recharge, such as rivers and lakes;
- Assessing whether aquifer depletion by over-withdrawal is occurring or whether regional water level declines may be primarily controlled by climatic factors.

It is advantageous to have long-term records of groundwater level fluctuations for management initiatives in developed aquifers, but where these are not available the CPD method can be used to generate theoretical historic hydrographs (Kohut et al., undated).

The climate data for Buntzen Bay were chosen as the most representative of precipitation for the Village of Belcarra as this station is the closest active climate station with the most comparable elevation. The monthly mean precipitation was calculated for the period of record, and the cumulative departure at any point was calculated as the sum of all the previous positive and/or negative departures from the mean. The CPD curve for a 10 year period of time is shown in Figure 4.10. Figure 4.11 shows the CPD curve plotted on the same chart as the limited hydrograph.

The long term trend of the CPD curve reflects larger order variations in climate above and below the mean. From 1997 to 2001, Belcarra received more than the average precipitation. This is evident by the curve being consistently above the zero level (zero departure). No data are available from 2002 to 2004 to confirm the trend of decreasing precipitation at this station. The CPD with hydrograph chart shows that the observation well hydrograph has a very similar trend to the CPD curve, confirming that the aquifer is recharged directly by precipitation. The hydrograph appears to respond slightly in advance of the CPD curve, which can be explained by the fact that the climate station is at some distance to the observation well, approximately 8.2 km. In reality, the observation well likely has a near instantaneous response or a slightly delayed response, which is due to the fact that groundwater in shallow unconsolidated aquifers is recharged directly by infiltration of precipitation, and the fluctuation in the water table is caused by the fluctuation of precipitation above and below the mean precipitation.

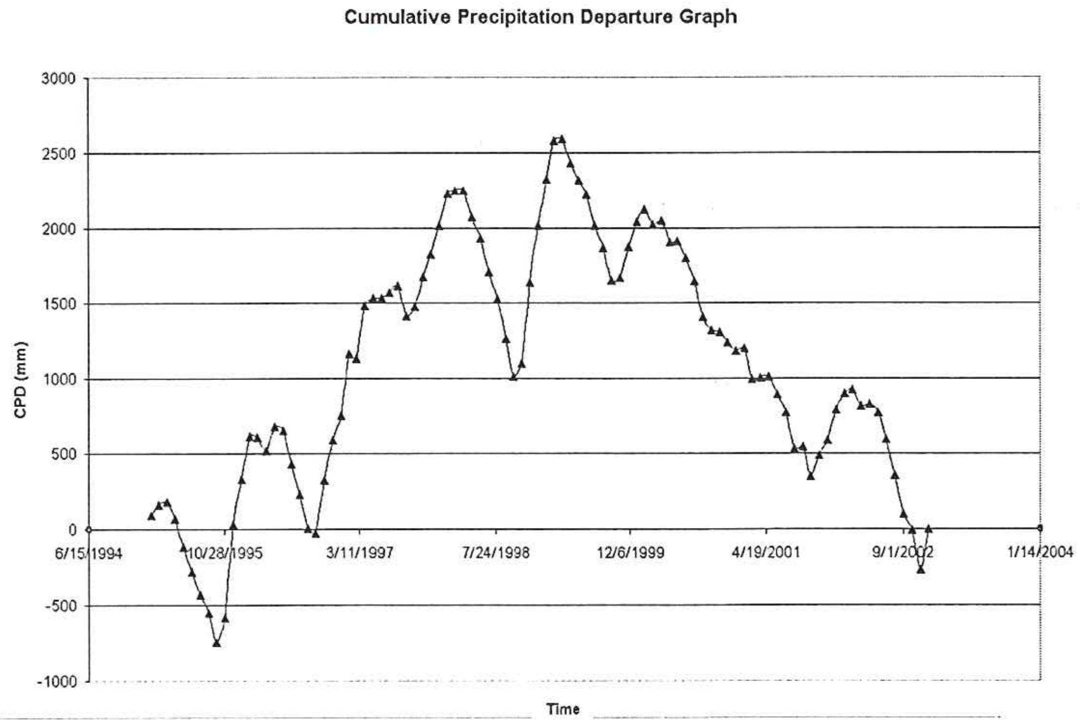

Figure 4.10: CPD curve for Buntzen Bay over a 10 year period.

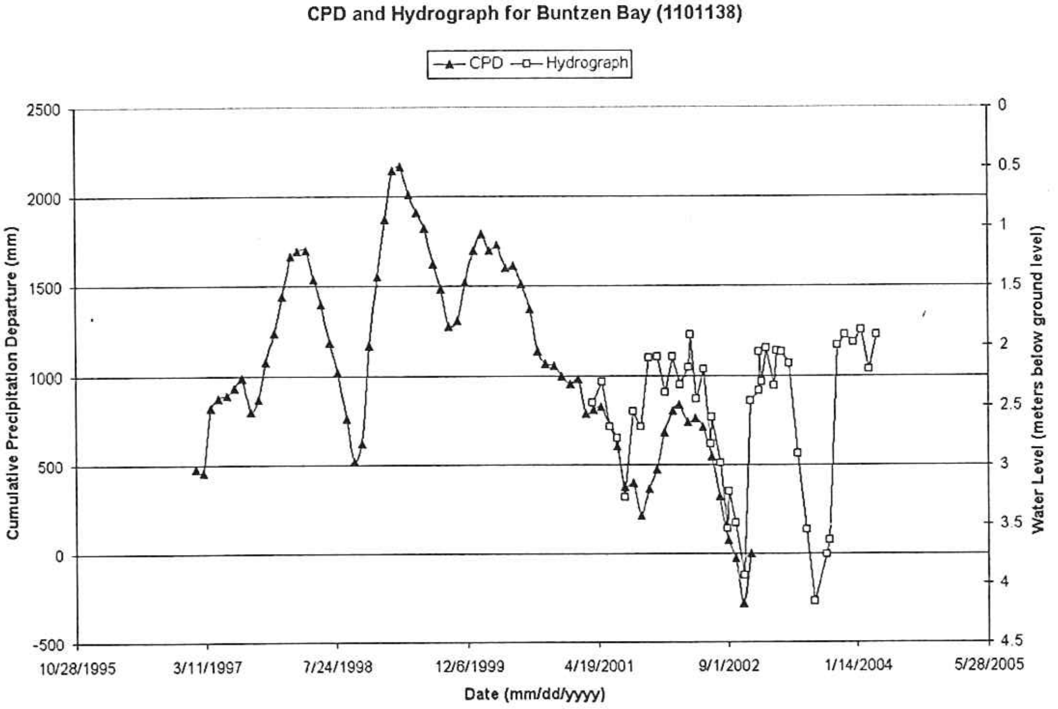

Figure 4.11: CPD curve for Buntzen Bay and observation well hydrograph.

4.2.4. HELP MODELLING

A program called HELP (Hydrologic Evaluation of Landfill Performance) (United State Environmental Projection Agency - USEPA) was used to obtain an estimate of recharge to the aquifer. The HELP program first runs a stochastic Weather Generator, which simulates 10 years of weather using known historic climate data. The weather data are then used to drive a water balance model for one or more representative geologic columns with prescribed surface conditions. The HELP weather station database includes the Vancouver International Airport (with full climate data); however, as indicated earlier, this climate station reports lower precipitation that the climate stations closer to Belcarra. Therefore, the database for Vancouver was adjusted manually within HELP to accommodate values of average monthly precipitation that are representative of Belcarra. As described in Section 4.1.3, representative monthly precipitation values were determined from the Como Lake Ave. and Buntzen Bay stations. All other climate parameters used in the simulations (i.e., temperature, probability of precipitation, radiation, wind speed, relative humidity) were for the Vancouver International climate station.

A representative geologic column consisting of three layers was created using information described in Chapter 2 (Fig. 4.12). Average thicknesses of geologic layers and the average depth to the water table were calculated from the well logs. Layer 1 is composed of loamy topsoil and is 1.4m thick, layer 2 is glacial and 18m thick, and layer 3 is fractured bedrock and is 5.6m thick. The base of the model corresponds to the average water table depth, which is around 25m below ground. Thus, percolation through the base of the model provides an estimate of aquifer recharge. The hydraulic properties of these layers were estimated from previous studies (for the Gulf Islands, Allen, personal communication) and text books, due to a lack of site-specific data for the aquifer. Other properties, related to the surface conditions, were estimated and entered into the program, including leaf area index, evapotranspiration, and vegetation class.

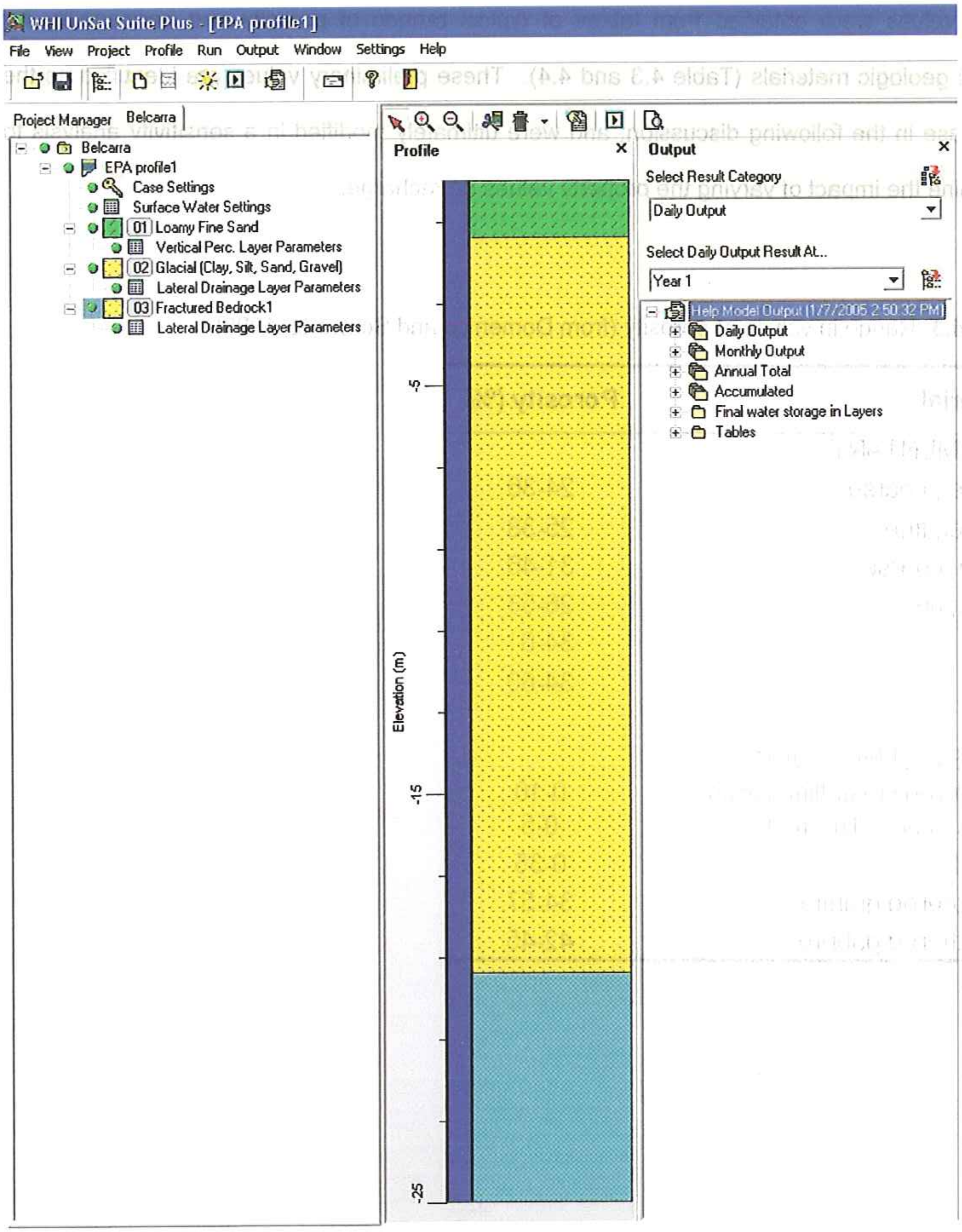

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Figure 4.12: Representative geologic column used in the HELP model.

Because of the high level of uncertainty in the aquifer properties, the various geologic units were assigned preliminary values based on the most likely properties of the subsurface layers.

These values were obtained from tables of typical ranges of porosity and permeability for various geologic materials (Table 4.3 and 4.4). These preliminary values are identified as the base case in the following discussion, and were ultimately modified in a sensitivity analysis to determine the impact of varying the property values on recharge.

Table 4.3: Range in values of porosity (from Domenico and Schwartz, 1998).

Material	Porosity (%)
SEDIMENTARY	
Gravel, coarse	24-36
Gravel, fine	25-38
Sand, coarse	31-46
Sand, fine	26-53
Silt	34-61
Clay	34-60
CRYSTALLINE ROCKS	
Fractured crystalline rocks	0-10
Dense crystalline rocks	0-5
Basalt	0-35
Weathered granite	34-57
Weathered gabbro	42-45

Table 4.4: Representative values of **hydraulic conductivity for various rock types (from Domenico and Schwartz, 1998).**

Material	Hydraulic Conductivity (m/s)
SEDIMENTARY	
Gravel	3×10^{-4} - 3×10^{-2}
Coarse sand	9×10^{-7} - 6×10^{-3}
Medium sand	9×10^{-7} - 5×10^{-4}
Fine sand	2×10^{-7} - 2×10^{-4}
Silt, loess	1×10^{-9} - 2×10^{-5}
Till	1×10^{-12} - 2×10^{-6}
Clay	1×10^{-11} - 4.7×10^{-9}
Unweathered marine clay	8×10^{-13} - 2×10^{-9}
CRYSTALLINE ROCKS	
Permeable basalt	4×10^{-7} - 2×10^{-2}
Fractured igneous and metamorphic rock	8×10^{-9} - 3×10^{-4}
Weathered granite	3.3×10^{-6} - 5.2×10^{-5}
Weathered gabbro	5.5×10^{-7} - 3.8×10^{-6}
Basalt	2×10^{-11} - 4.2×10^{-7}
Unfractured igneous and metamorphic rocks	3×10^{-14} - 2×10^{-10}

The results for the base case are shown in graphical form in the HELP Graphs (Figs. 4.13-4.15). HELP Graph 1 (Fig 4.13) shows all of the results over the full 10 year period for rates of precipitation, runoff, evapotranspiration, change in water storage, water budget balance, soil water, snow water, and percolation through layer 3 rate (or aquifer recharge). These values are all in feet per year and are fairly consistent throughout the 10 year period, with a slight decline in the rates of precipitation and percolation through layer 3. HELP Graph 2 (Fig 4.14) shows just the percolation through layer 3 for the last five years of the simulation. It is possible to see the seasonal variation in recharge through the year, with higher rates in the winter and spring months (0.7-1.4 ft/month), and lower rates (0.1-0.3 ft/month) in the summer. HELP Graph 3 (Fig 4.15) shows the results of percolation, precipitation, runoff and evapotranspiration for the 10th year only. The precipitation and percolation show similar trends as might be expected, as the aquifer is recharged directly by precipitation. Runoff is fairly consistent throughout the year at values below 0.1 ft/month showing a slight increase in the fall and winter months, and evapotranspiration is higher in the summer months (up to 0.3 ft/month).

HELP was run using a range of values for porosity and saturated hydraulic conductivity to test the sensitivity of the model, in terms of final recharge estimate, to changes in these variables. Table 4.6 shows the values of the layer properties (porosity and permeability) that were used in the sensitivity analysis. These correspond to the maximum (high) and minimum (low) values found in the literature. Table 4.5 shows the corresponding recharge results for each set of properties. The model was run with "model calculated" initial moisture settings. Table 4.5 indicates that the lowest value of recharge to the aquifer is 1609 mm/yr with the base values, and the highest recharge to the aquifer is 1971 mm/yr with high conductivity values. The small range in values for recharge indicates that the model is not extremely sensitive to changes in porosity and/or hydraulic conductivity.

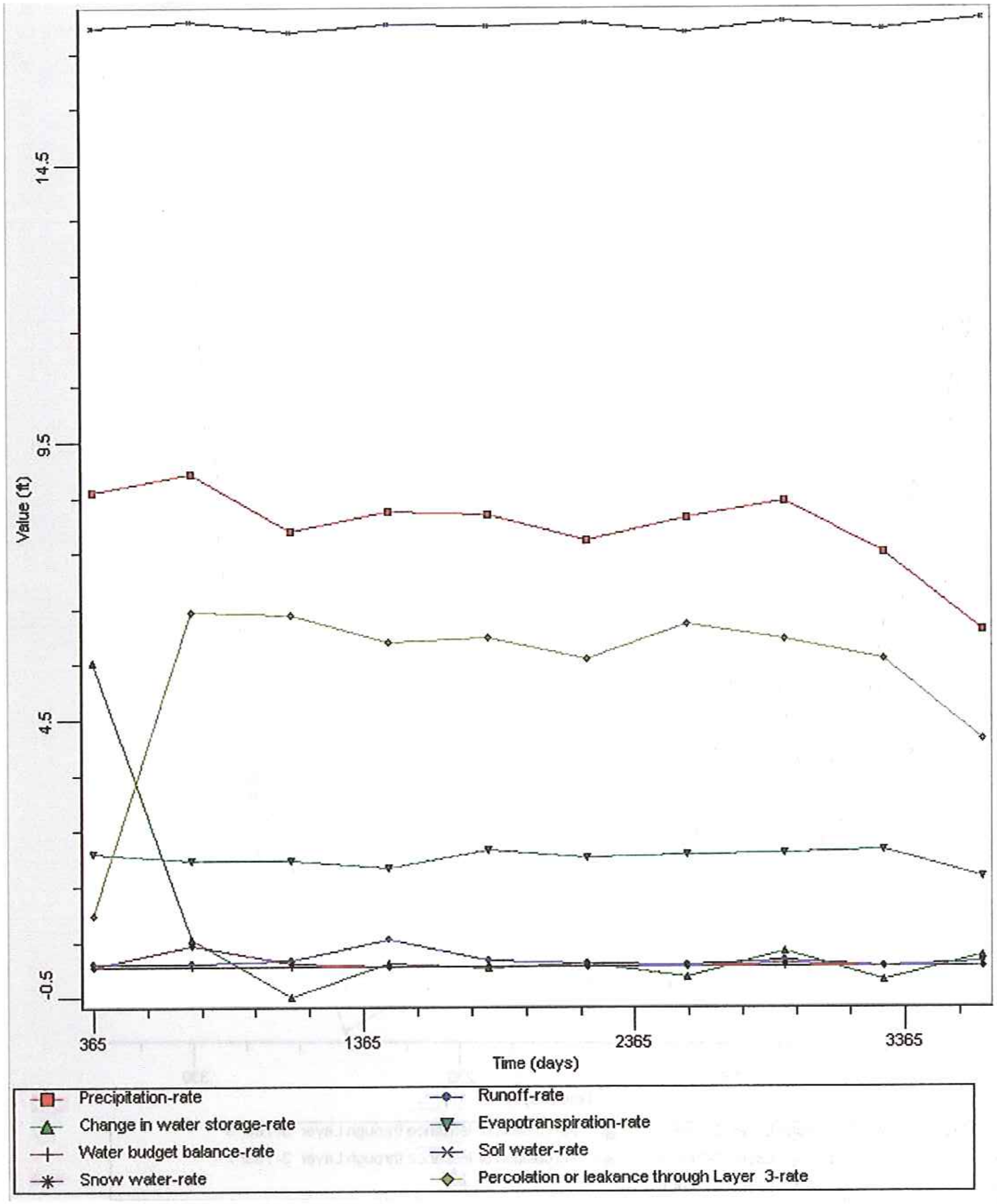

Figure 4.13: HELP Graph 1 - Full 10 years results for rates of precipitation , runoff, evapotranspiration, change in water storage, water budget balance, and soil water, snow water and percolation through layer 3.

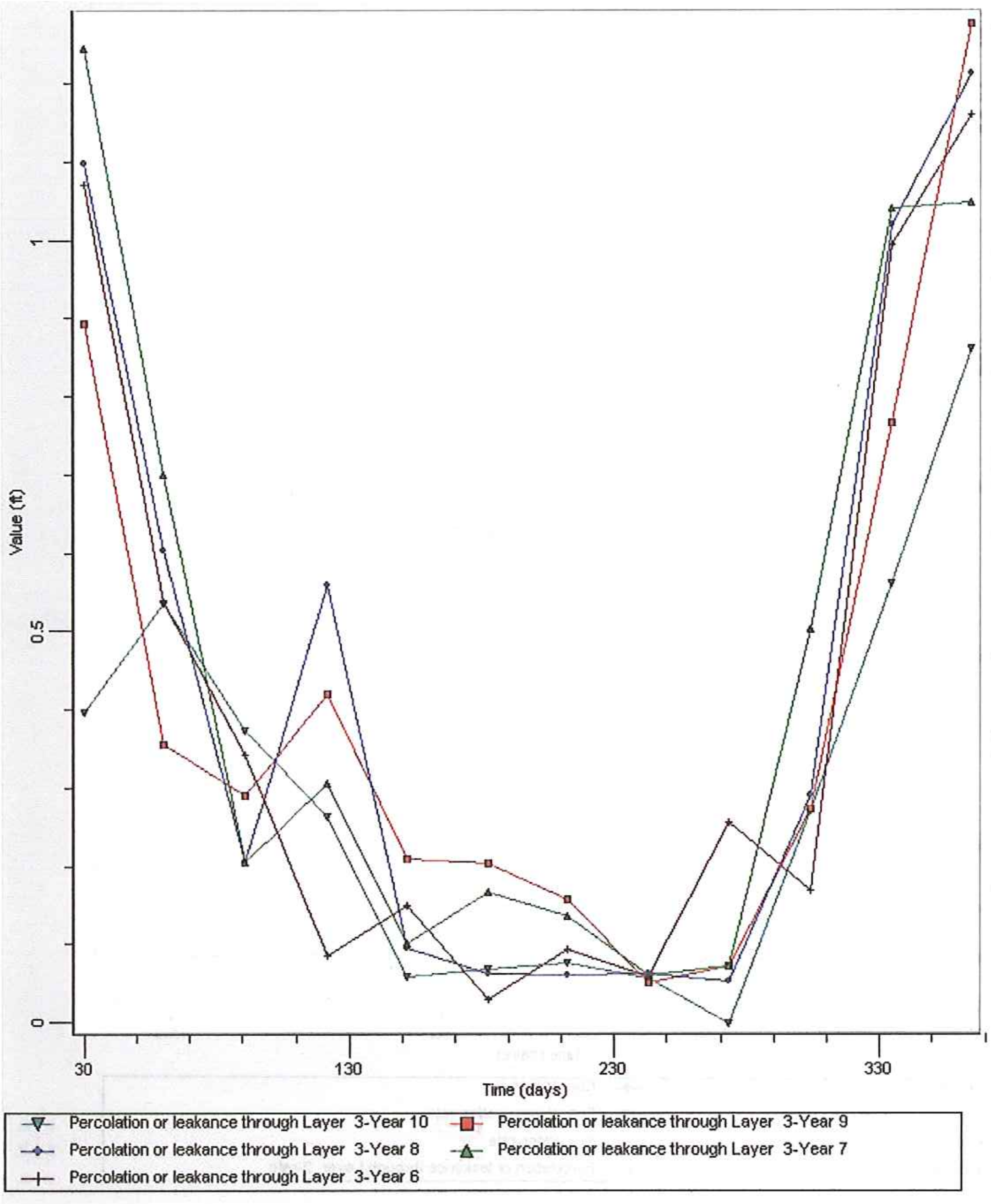

Figure 4.14: HELP Graph 2 - Percolation through layer 3 for last 5 years (range from0.01-1.4 ft/month).

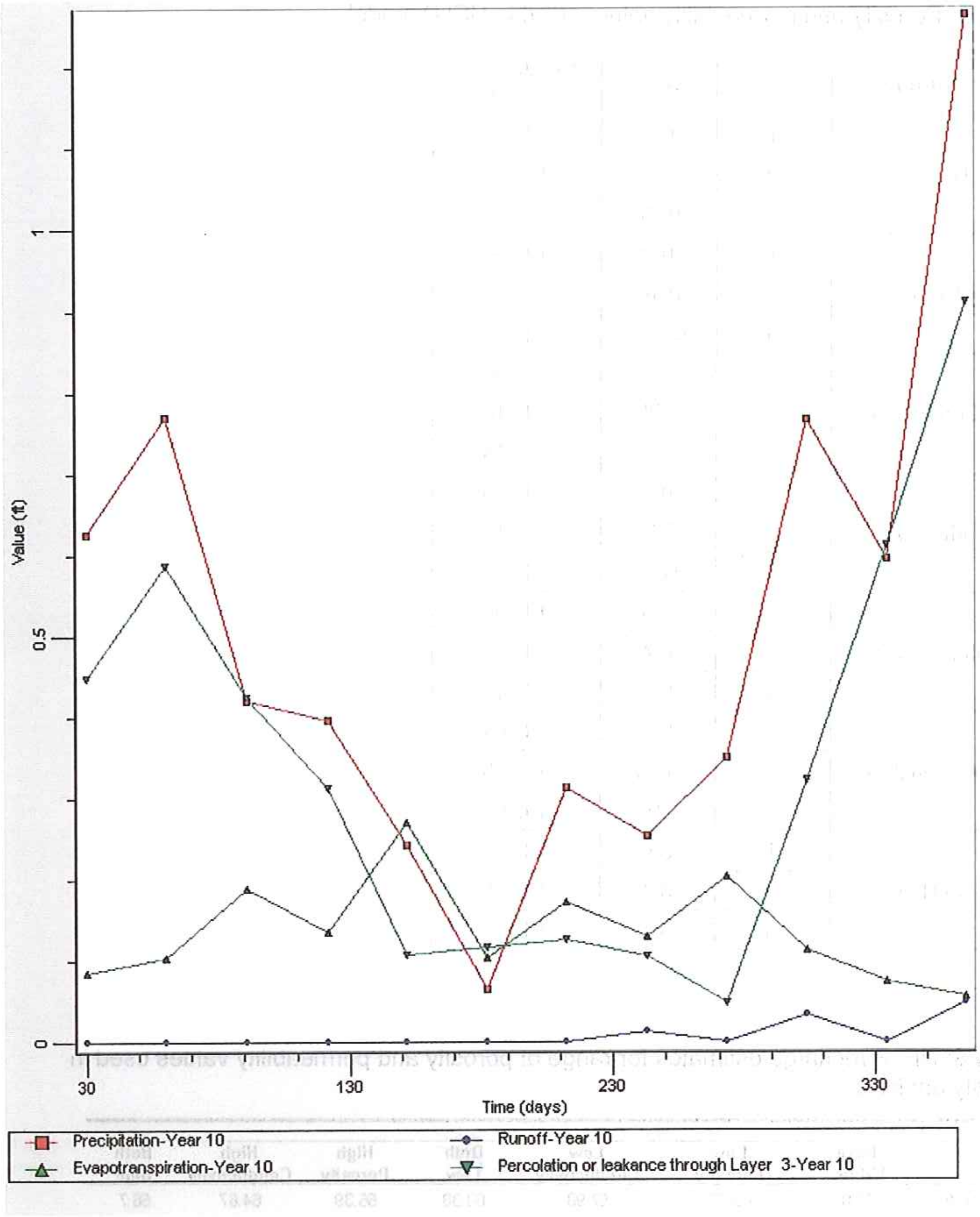

Figure 4.15: HELP Graph 3 - Percolation, precipitation, runoff and evapotranspiration for 10th year only.

Table 4.5: Porosity and permeability values used in HELP model.

Layer Properties	Layer	Porosity	Conductivity (m/s)
Base	1	0.3	1.E-07
	2	0.25	1.E-08
	3	0.01	1.E-11
Low Porosity	1	0.2	1.E-07
	2	0.15	1.E-08
	3	0.005	1.E-11
Low Conductivity	1	0.3	1.E-08
	2	0.25	1.E-10
	3	0.01	1.E-13
Both Low	1	0.2	1.E-08
	2	0.15	1.E-10
	3	0.005	1.E-13
High Porosity	1	0.5	1.E-07
	2	0.4	1.E-08
	3	0.1	1.E-11
High Conductivity	1	0.3	1.E-04
	2	0.25	1.E-05
	3	0.01	1.E-09
Both High	1	0.5	1.E-04
	2	0.4	1.E-05
	3	0.1	1.E-09

Table 4.6: HELP recharge estimates for range of porosity and permeability values used in sensitivity analysis.

	Base Values	**Low Porosity**	**Low Conductivity**	**Both Low**	**High Porosity**	**High Conductivity**	**Both High**
10 year total (ft)	52.8	62.25	57.98	60.38	55.39	64.67	56.7
annual avg (ft/yr)	5.28	6.225	5.798	6.038	5.539	6.467	5.67
mm/yr	1609	1897	1767	1840	1688	1971	1728

The model was run again with "user specified" initial moisture content values. The moisture content is defined as the volume of water present in the total volume of rock, and is usually reported as a decimal fraction or a percent (Freeze and Cherry, 1979). In situations where fluid flow is below the water table and all the pores are saturated, the moisture content is equal to the porosity, but above this zone (in the unsaturated zone), the moisture content is much less than the porosity. Varying initial moisture content values has an effect on the estimates for recharge rates to the aquifer. For lower initial moisture content values, the infiltrating water will begin to saturate the pores above the water table in the unsaturated zone before reaching the aquifer, and thus, will lower the recharge estimates. During the summer months the combination of evapotranspiration from vegetation and low precipitation results in a soil moisture deficiency which must be relieved before groundwater recharge can start. Most of the autumn precipitation is used to relieve the soil moisture deficiency so the period of aquifer recharge is winter and early spring (Pacific Hydrology, 1994). The model was run with the base case porosity and conductivity values as they yielded results that were the most consistent with the hydrograph method, and initial moisture content values of 75%, 50%, 25%, 10% and 5% were used. The results are shown in Table 4.7. The estimates range from 1399 mm/yr with an initial moisture content of 5%, up to 3136 mm/yr with a moisture content of 75%. These values are still quite high as 1399 mm/yr represents 60% of precipitation recharge to the aquifer.

Table 4.7: HELP recharge estimates with varying initial moisture content.

Moisture Content	**0.05**	**0.1**	**0.25**	**0.5**	**0.75**
10 year total	45.9	49.7	61.88	82.36	102.88
annual avg (ft/yr)	4.59	4.97	6.188	8.236	10.288
mm/yr	1399	1515	1886	2510	3136

4.3. SUSTAINABILITY OF THE BELCARRA AQUIFER

The two methods that have been used to estimate recharge to the Belcarra aquifer yielded results that ranged from 73mm/yr to 3136 mm/yr (Table 4.8). Recharge estimates with the hydrograph method were very highly dependent on specific yield, but tended to give more realistic values as the method is based on actual water level data. The HELP model gave higher values, but these were generally consistent with varying porosity values. The values of recharge estimated from the HELP model are quite high as they yield results for recharge to the aquifer of over 60%, which seem unrealistic. As well, a larger range of values was obtained with the HELP model when varying initial moisture contents. Despite the fact that parameters such as porosity, saturated hydraulic conductivity, and initial moisture content were changed, the values were all consistently above 50%, which may be a reflection of the limitation of using the HELP model for modelling recharge to fractured bedrock aquifers.

In consideration of both methods, the most representative range of recharge estimate is 114 mm/yr. This value is based on the hydrograph method using a porosity of 0.01. Higher recharge may occur in areas that are more intensely fractured. With an annual precipitation of 2331 mm/yr, this estimate corresponds to a minimum of 4.8% of annual precipitation that is recharging the aquifer (Table 4.8).

Table 4.8: Recharge estimates from hydrograph and HELP methods and percentage of annual precipitation.

Method	Max Recharge (mm/yr)	Min Recharge (mm/yr)	Most Representative (mm/yr)	Percentage of Annual Precipitation (%)
Hydrograph	2950	73	113	4.8
HELP (varying porosity and conductivity)	1971	1609	1609	69.0
HELP (varying moisture content)	3136	1399	1399	60.0

Per capita municipal water use in British Columbia is on par with the national average of 678 L/day, as reported by the BC WLAP. With the current population in Belcarra estimated to be 600 people year round, the current water consumption rate for the Village of Belcarra is around 148M L/yr, or 148,000 m^3/yr. By multiplying the area of recharge with the rate of recharge to the aquifer it is possible to obtain an estimate of the volume of water recharging the aquifer annually. The area of recharge estimated in section 1.2.1 is 8.794 km^2, and the recharge estimate from the hydrograph method is 114 mm/yr resulting in $10x10^5$ m^3/yr of recharge to the aquifer. These estimates indicate that Belcarra is using approximately 14.8% of the annual recharge to the aquifer, although use is not particularly well-distributed as most wells are situated near the coast.

5. DISCUSSION

5.1. CHEMISTRY

The average charge balance error for the chemistry testing was quite large (-18%) indicating inaccuracies in the chemistry testing. Since all the charge balance errors are negative, the anions were most likely overestimated. This is likely due to the fact that field kits, based on colorimetric methods, were used to measure anion concentrations, while dissolved metals were measured in an analytical lab. There is a tendency for people to overestimate anions in colorimetric methods whereas lab analyses are inherently more accurate. It is also possible that there was some metal precipitation in the samples due to not acidifying samples immediately in the field. This would result in the precipitates being filtered out before analysis, and not accounted for in the charge balance error calculations.

5.1.1. CANADIAN DRINKING WATER GUIDELINES

The results of the chemistry testing were compared with the recommended drinking water guidelines for inorganic compounds (Table 5.1). The ranges of values are for all the samples are generally below the recommended limits for the compounds indicating that Belcarra has good quality drinking water. The only samples that were above the guidelines were Bel-3 (hardness), Bel-9&4 (pH), and Bel-16 (manganese). All of these samples, except for Bel-4, have charge balance errors greater than 20%, so they probably represent erroneous ion measurement than actual poor water quality.

Table 5.1: Recommended drinking water guidelines for inorganic compounds. (Source: Environment Canada and U.S. Environmental Protection Agency). Concentrations in mg/L.

	Canada		United States	Range in Values
Alkalinity	30-500		-	52.46-207.4
Hardness	<120		-	38.6-203
pH	6.5-8.3 units		-	7.10-8.47
TDS	<1000			131-724
Fluoride	1.5		4.0	
Chloride	<=250.0		-	3.0-104
Nitrate	45.0		10.0	
Nitrite	3.2		1.0	
Sulphate	<=500.0		-	11.0-38.0
Aluminum		(10)	-	
Antimony		(10)	0.006	
Arsenic	0.025	(8)	0.05	
Barium	1.0		2	.001-.028
Beryllium		(10)	0.004	
Boron	5.0	(8)	-	0.01-0.083
Cadmium	0.005		0.005	
Calcium		(13)	-	11.7-73.1
Chromium	0.05		-	
Cobalt		(10)	-	
Copper	<=1.0		1.3	0.012-0.091
Iron	<=0.3		-	.005-0.061
Lead	0.01		0.015	
Manganese	<=0.05		-	.002-0.307
Nickel		(10)	-	
Selenium	0.01		0.05	
Silver		(13)	-	
Sodium	<=200		-	
Thallium	-		0.002	
Uranium	0.1	(10)	-	
Zinc	<=5.0		-	

Footnotes

8. Interim water guideline.
10. Guideline under review for addition to, or possible changes to, the current value.
13. Parameters identified as not requiring a numerical guideline.

5.2. RECHARGE AND AQUIFER YIELDS

The uncertainty for the recharge estimates is quite high. The two methods of recharge estimation include the hydrograph method and the HELP model. These methods gave very different estimates of 114 mm/yr and 1609 mm/yr, respectively. This is due to the fact that we just do not have enough data to get an accurate estimate of recharge to the aquifer. Considerably more research has to be done locally around Belcarra to determine the specific properties of the aquifer, as well as more research on fractured rock aquifers in general.

5.3. IMPACTS ON ENVIRONMENTAL ECOSYSTEMS

It is essential to keep in mind the uncertainty in the recharge estimate values, as well as to remember that the number estimated is the total amount of water recharging the system. In a steady state system, the infiltrating groundwater gets discharged into surface water systems, such as streams and lakes and into the ocean, as well as the amount that is removed by humans. There is no rule of thumb as to the amount of recharge that humans can take without harming the ecosystem. Any amount being taken out of the system for human consumption will result in lowering of base flow levels in streams, discharge to oceans or lakes. Good water stewardship relies heavily on people understanding that there is a balance between what people take and what ecosystems need to be supported. Due to the fact that our estimate does not take into account the amount of water that is discharging to the surrounding ecosystem it is not possible to say whether the aquifer is sustainable at present consumption rates.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. CONCLUSIONS

- Residents of Belcarra currently rely primarily on individual wells drilled into the Belcarra Aquifer and limited surface water sources for domestic water supply. There are approximately 200 deep drilled wells in Belcarra.
- The Belcarra Aquifer is an unconfined, fractured bedrock aquifer overlain by unweathered glacial till and soil. It is classified as a Type 1A aquifer by BCWLAP.
- There are three main geological units in the Belcarra area;

  1) Topsoil: developed by soil-forming processes (weathering, plant growth, biological activity) from the underlying till and bedrock;

  2) Unweathered glacial till; and
  3) Bedrock.

- Bedrock is overlain by 5-20m of glacial till variably composed of silt, sand, clay and gravel, and 0-5m of topsoil.
- Based on measured heads in wells, recharge generally occurs in areas of elevation above approx. 30-60m elevation. Discharge occurs in regions of elevation below 30-60m. Subsurface flow is radial from areas of recharge to areas of lower elevation.
- The fractured nature of the aquifer adds a greater level of complexity to the hydrogeologic regime, and the influence of fractures on the local hydrogeology cannot be determined without a more exhaustive field mapping program.
- The chemistry results yield CBE ranges from -1% to -29%; the average CBE was 18%. There are several possible explanations for the poor CBE results, the most likely of which is

related to the use of test kits for anion analysis and the overall low concentrations of total dissolved solids in many samples.

- Groundwater can be generally classified as a bicarbonate to bicarbonate-chloride-sulfate type water in terms of its anion chemistry, and as a calcium-magnesium to a sodium-calcium type water in terms of its cation chemistry.
- Comparison with older chemistry data shows that the overall relative concentrations have not changed appreciably over time in these wells.
- The total annual precipitation for Belcarra is calculated to be 2331 mm, and the total area of recharge for Belcarra is roughly 8.79 km^2.
- The hydrograph method of recharge estimates recharge to the aquifer on the order of 114 mm/year using an unconfined storativity of 0.01. The amount of recharge estimated from this method is approximately 4.9% of the total annual precipitation to Belcarra.
- The values of recharge estimated from the HELP model are quite high as they yield results for recharge to the aquifer of over 60%, which seems unrealistic. Despite the fact that parameters such as porosity, saturated hydraulic conductivity, and initial moisture content were changed, the values were all consistently above 50%, which shows the limitation of the HELP model for modelling fractured bedrock aquifers.
- Recharge to the aquifer is estimated at 10x10^5 m^3/yr. With estimates of consumption rates in the Village of Belcarra around 148,000 m^3/yr, the village is using approximately 14.8% of the annual recharge to the aquifer.

6.2. RECOMMENDATIONS

There is a big problem with the recharge estimate made in this report. It is desirable to have data over a very long period when doing this kind of estimate. It would be useful to do the hydrograph method later on when more data are available from the observation well with considerable overlap with recent climate data. It is recommended that the Village of Belcarra do pump tests on the aquifer to obtain K values and storage values that could eventually yield more accurate estimates of recharge to the aquifer. It would also be helpful to perform another survey of the residents to get a better idea of current water consumption from wells. Other aspects of the hydrogeology that were not covered in this study due to the limited scope would involve undertaking an analysis of nitrates and total coliform of all wells, and undertaking a study of septic tank locations and potential contamination pathways to the aquifer.

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