Chapter 2 RESEARCH APPROACH AND METHODS

2.1 Introduction

This chapter presents an overview of the research approach utilized. The research questions and objectives are presented; the literature review methods are outlined; and the data acquisition methods are discussed.

The research centred on a case study conducted on North and South Pender Islands, British Columbia. The case study required review of climatic data, geologic mapping, geophysical investigations, and review of existing water well records to enable a groundwater resource assessment and an estimation of the groundwater storage capacity on the islands. The findings from the case study led to development of an approach to conducting groundwater assessments and a conceptual model for groundwater management on small islands.

2.2 Research Questions

Clear, concise research questions provide a basis for the development of a conceptual model to estimate the groundwater resources on small islands, with North and South Pender Islands as a case study. The research questions addressed in this dissertation are summarized as follows:

- What are the groundwater resources of North and South Pender Islands?
- Where do the groundwater resources occur?
- How can the groundwater resources of the islands be determined in a cost-effective manner?
- Who controls the groundwater resources?
- How can knowledge of groundwater resources be incorporated into community plans?

2.3 Methods for Literature Review and Analysis

The literature was reviewed and analysed for three purposes: 1) to provide a context within which the research should be conducted; 2) to identify and indicate shortcomings in the previous research; and 3) to define areas of water management requiring future research. In the literature review, the science of groundwater was investigated to determine the best approaches for undertaking a groundwater resource assessment. The information so gathered could then be utilized in groundwater management. Groundwater resource assessment and management were integrated in an interdisciplinary approach.

In view of the wide range of subject areas that impact groundwater management strategies, the following literature was examined:

- Water resource management
    - Water supply
    - Water demand
    - Integrated water resource management
- Water resource assessment
    - Geology
    - Geophysics
    - Hydrogeology
    - Climate
- Groundwater modeling
    - Conceptual models
    - Finite element models/analysis
    - Finite difference models
    - Stoichastic models

- Community planning
    - Institutional framework
    - Legal framework
    - Socio-political framework
    - Socio-economic framework
    - Decision-making procedures
    - Risk assessment and risk management
- Small island environments
- Securities commission requirements for other commodities

The literature review was conducted with the aid of library catalogues, abstract databases, and Internet search engines. The University of Calgary library catalogue was examined for textbook and journal references on a wide range of topics. The information was categorized in three ways: subject area; whether it had been peer reviewed; and whether it is relevant to small island groundwater issues.

The following databases were used: Georef, ProQuest, Engineering Abstracts, Earth Science Abstracts, Environmental Abstracts, and Science and Technology Abstracts. The most relevant of the specific journals were noted and regularly monitored to ensure that the most recent findings were referred to during the research process.

Internet searches were restricted to government websites (federal, provincial/state, and municipal), corporate websites for software modeling programs, electronic journals and websites providing copies of peer reviewed articles. The Internet searches played an integral role in identifying current water modeling software packages.

The literature review provided information on the legal and institutional frameworks of North and South Pender Islands, as well as on other small islands. This information provided insight into water supply, water demand and integrated water resource management options. The review of current management practices enabled the development of alternative groundwater resource management approaches. The literature review also provided the basis for developing conceptual models for small island groundwater resource assessments.

2.4 Research Strategy

The research strategy was partially based on the premise put forward by Miloradov and Marjanovic (1998) that an understanding of physical groundwater resources ultimately provides the basis for defining management options (Figure 2.1). The research involved collection or review of climatic data, geological mapping, review of existing water well records, and geophysical investigations, with the aim of assessing groundwater resources and developing management approaches. This water management approach does not take into account the social, economic and political aspects required for implementation of any management options, so the Miloradov and Marjanovic approach was combined with the groundwater management model of Burke and Moench (2000) (Figure 2.2). The basis for each model is a reliance on natural science to provide the resource assessment; however, Burke and Moench (2000) explicitly treat the social, economic and institutional frameworks as being equal to the natural sciences in importance. The two models are complementary; the Burke and Moench (2000) model represents a generalized model while the Miloradov and Marjanovic (1998) model represents a detailed approach to the physical basis of groundwater management.

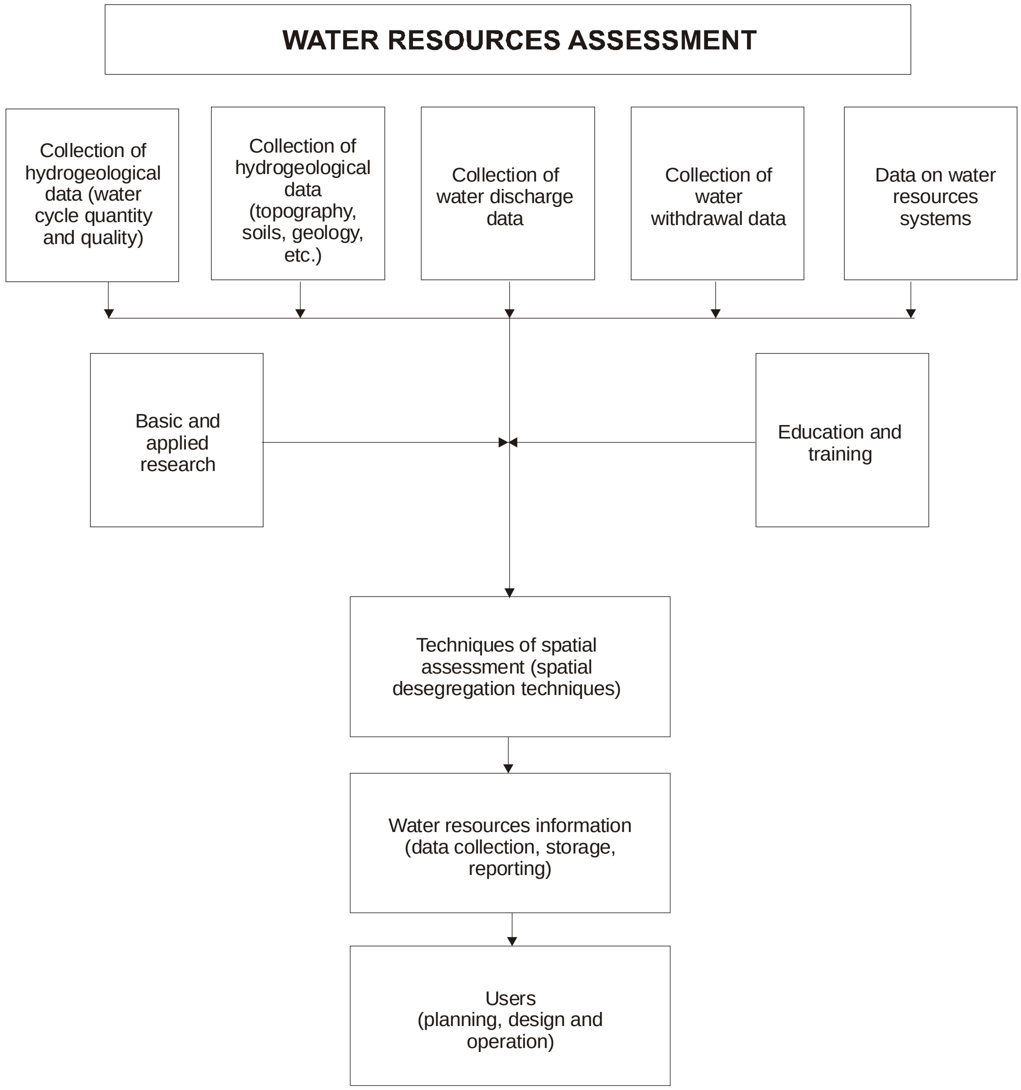

Figure 2.1: Outline of water resource assessment process (after Miloradov and Marjanovic, 1998).

Groundwater resource management is complex and interdisciplinary, as can be seen by the wide range of topics listed in the literature review section, the research objectives and the research questions. It was necessary to have a strategy for dealing with the interdisciplinary nature of groundwater management. Tashakkori and Teddlie (1998) refer to the methodological mixes put forward by Patton (1990), which include the following simple three-component approach:

1) Design 2) Measurement 3) Analysis

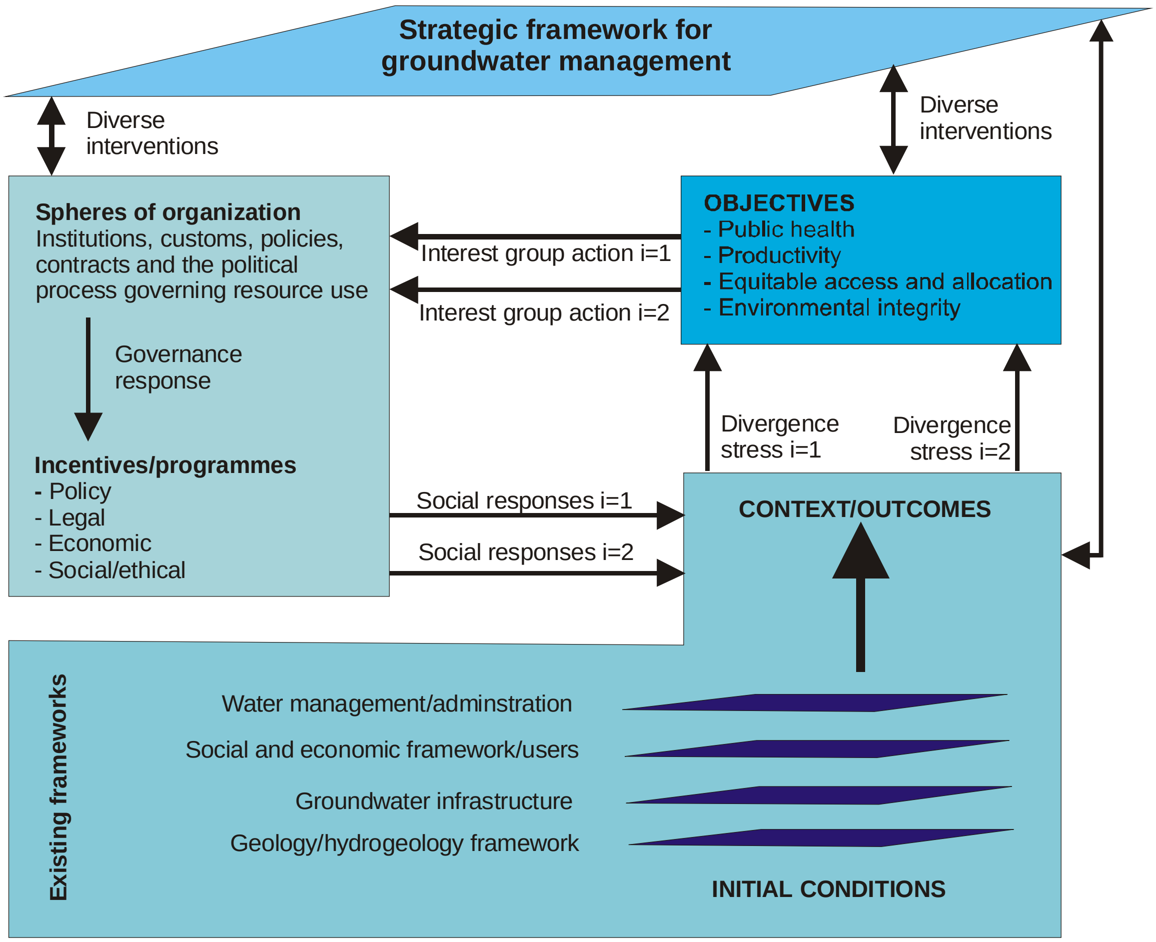

Figure 2.2: Descriptive model change process in groundwater management (Burke and Moench, 2000).

This approach incorporates both quantitative and qualitative data and lends itself to the use of both deductive and inductive reasoning, as illustrated by the research cycle in Figure 2.3. On the inductive reasoning side of the ledger, the field observations were used to develop conceptual models; on the deductive side, theory and hypothesis preceded observations.

The field work and resulting interpretation provide a physical basis for groundwater assessment on North and South Pender Island. There is a misconception that science-based research is value-free (Hoekstra, 1998). The actual data may be value-free but in order to apply any of the results, researchers must consider social norms and values. A number of researchers have discussed the need to incorporate social and economic perspectives into the physical assessment (Vincent, 2003; Wolfe and Brooks, 2003; Postel, 2003). Water was recognized by Cleaver and Franks (2000) to possess environmental, economic and social values. An integrated management approach factors these values into the decision-making process (Government of Canada, 2003).

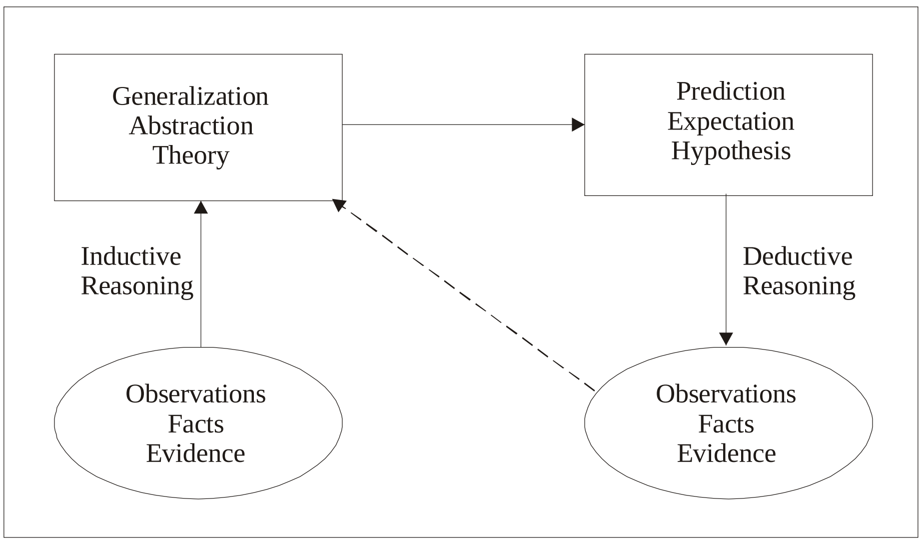

Figure 2.3: Comparison of inductive and deductive reasoning (Tashakkori and Teddlie, 1998)

A small island environment, defined by Falkland (1991) as having an area of 2,000 km^2 or less, was selected for the following reasons:

- the hydrogeological setting may be more easily defined on small land masses than on large ones
- they can also be viewed as a natural social science laboratory
- on a small island, some of the social, political and economic boundary conditions of larger geographic areas are non-existent or simpler (Bellamy *et al.*, 2001)

Salvati (2002) draws an analogy between small islands and natural hydrogeological laboratories.

The general research goal was to conduct a field-based groundwater resource assessment by combining airphoto interpretation, geologic mapping and complementary surface geophysical methods to extrapolate subsurface geologic conditions. The results of these combined techniques would yield an estimate of the groundwater storage capacity of the sediments and bedrock. A conceptual groundwater storage and management model for North and South Pender Islands would be developed through integration of the field results and the literature findings.

The idea of integrating geology and geophysics in resource assessment is not new; this approach was recommended by Halstead and Treichel (1966) for groundwater assessment on the Gulf Islands but was never undertaken. The approach is routinely utilized in oil and gas and mineral exploration and development (Henderson *et al.*, 2004a). It is, however, rarely used in groundwater resource assessments. Berardinucci and Ronneseth (2002) do not mention it in their aquifer classification guidelines for British Columbia, relying instead on interpolation of subsurface conditions between widely spaced drill holes. This dissertation emphasizes that a groundwater resource estimate for a small island is critical information in managing the island's water supply and in eventually developing community plans.

2.5 Climatic Data

The basis for all water resource investigations is the hydrologic cycle (ASCE, 1996), and groundwater is an integral part of the hydrologic cycle. Climatic data are a key component of the background information required for water resource evaluation on small islands, since precipitation is often the only source of groundwater replenishment (Falkland, 1991; Stoddart, 1992). Burke *et al.* (2000) state that natural variations in climate exert a major influence on groundwater management options. Precipitation and temperature information came from several sources on North Pender Island, including J. Crawford and M. Armstrong who acquired data for Environment Canada, and J. Roberts who acquired data for the Municipal District of Trincomali. Precipitation records have been kept since 1925, with only small gaps; during the years 1938, 1943, 1964, and 1982. At present, precipitation is recorded in both Trincomali and Port Washington on North Pender Island. There are no climatic data available for South Pender Island, but because of its proximity to North Pender Island, it is assumed that the climatic conditions are the same.

The precipitation data were processed statistically to determine average annual and monthly rainfall, median rainfall, standard deviation, and the coefficient of variability. There is no information relating to the intensity of a precipitation event. Precipitation intensity influences surface runoff and infiltration, both of which influence groundwater recharge and storage (ASCE, 1996).

Temperature data were analyzed statistically to determine average monthly and annual temperatures. Temperature data have not been recorded for almost a decade on the islands. The existing data were used to determine evapotranspiration estimates.

2.6 Geology

The establishment of a management strategy for groundwater resources requires an understanding of aquifers (Spinks and Wilson, 1990). This understanding can be best achieved through knowledge of the local geology. Ozoray (1973) states that there cannot be effective management without a reasonable estimation of the resource in question. According to Davis and DeWiest (1966), geologic mapping is the most cost-effective means of groundwater resource assessment and involves mapping the pattern and surface extent of lithologic units and identifying structural features such as faults.

Geological mapping should be undertaken in a logical manner using a phased approach. A review of the existing literature provides information on the anticipated soil and rock types to be mapped as well as insights into the geological history of the area under investigation. Air photo interpretation or other forms of remote sensing can be utilised prior to field mapping to identify geomorphological features, bedrock outcrops, and major structural features. Field mapping entails examination of road cuts, coastlines, and other bedrock exposures. Road cuts and coastlines also provide information on the soils overlying the bedrock.

From a groundwater resource perspective, the most important characteristics of subsurface materials are porosity and permeability. Porosity is a measure of the pore spaces available for groundwater storage, and permeability is a measure of the interconnectedness of the pore spaces. Porosity is defined as the ratio of the volume of the interstices, whether connected or isolated, to the total volume of the soil or rock (ASCE, 1996). Permeability is a function of the size and connections of the voids in soil or rock (Roscoe Moss, 1990) and relates to the ease with which a fluid can move through the material. Porosity and permeability ultimately control the storage and flow of groundwater.

Porosity and permeability have primary and secondary components. Primary porosity is intergranular pore space, whereas secondary porosity is the openings or voids created after the rock formed including joints, fractures, and faults (Weight and Sonderegger, 2001). Effective porosity refers to the volume of interconnected pore space in an aquifer divided by the total volume of the aquifer and represent, from a water perspective, the mobile fraction of the stored water (Mays, 1996; Hudak, 2000).

Permeability is often confused with hydraulic conductivity. Hydraulic conductivity takes into consideration permeability, viscosity and density of the fluid being transmitted (Hudak, 2000). They are equivalent terms when the viscosity and density are constant, which is generally the case for potable groundwater. Geology controls both primary and secondary porosity and permeability, which in turn constitute the major limits to groundwater storage capacity (Falkland, 1991).

Airphotos can be examined to identify faults and fractures. The increased secondary porosity and permeability associated with such structures are important in estimating groundwater resources (Domenico and Schwartz, 1998).

2.7 Geophysical Methods

No single exploration technique can directly detect the presence of exploitable groundwater in the subsurface (Mandel and Shifton, 1981). Drill holes yield very detailed geological and hydrogeological information for a small area, whereas geophysical surveys provide an indirect means of mapping aquifer characteristics over a significantly larger area. Mandel and Shifton (1981) and Weight and Sonderegger (2001) state that there are no geophysical techniques that can directly determine groundwater potential in the subsurface, but that geophysical approaches do provide an indirect means of assessing groundwater conditions.

With an understanding of the underlying physical basis and the limitations of geophysical methods, researchers can reduce the ambiguities involved in interpretation. The geophysicist must have access to all available information from a site (CCME, 1994, and Weight and Sonderegger, 2001) to assist in the selection of techniques, plan the investigation, and process the results. With sufficient information, including borehole logs, geologic maps, and geologic cross-sections, it is possible to determine whether a particular geophysical investigation will meet the objectives of the study acquisition parameters that are optimal for the geophysical investigation. For example, in oil sands exploration, it is common to use a combination of borehole geophysical logs, geologic maps and lithologic logs (Henderson *et al.*, 2004a).

For geophysical methods to be applicable, there must be a mappable contrast in the physical properties of the stratigraphic units (Henderson and Bowman, 1994). The key term is “mappable”. The contrast will vary with the thickness of the horizon of interest, its depth of occurrence, and the difference in the physical properties of adjacent geological horizons.

The major properties of earth materials that are utilized in geophysical exploration are electrical, spontaneous potential, density, magnetic, acoustic velocity, temperature, dielectric permittivity, and radioactivity (Sharma, 1997). Geophysical techniques utilized to map differences in these properties are borehole, surface, and airborne (Mandel and Shifton, 1981). These categories can be further sub-divided on the basis of the individual geophysical methods.

In this research, investigations were restricted to use of surface geophysical methods and a review of available airborne geophysical data. This limitation is partly a result of the lack of access to water wells for logging with geophysical tools and partly due to a lack of access to borehole geophysical tools. Plans had been made with British Columbia Land Water and Air to geophysically log two observation wells on North Pender Island with a borehole radar system but had to be abandoned due to liability/insurance concerns.

Table 2.1 presents the range of physical properties for common earth materials relevant to this dissertation. The table combines results published in the literature and on the author's three decades of experience measuring these properties.

Table 2.1: Physical properties of common earth materials (based on Kearey and Brooks, 1984; Telford *et al.*, 1990; Kelly *et al.*, 1993; CCME 1994; Sharma 1997; Weight and Sonderegger, 2001).

Material Type	Density	P-Wave Velocity (m/sec)	Resistivity (ohm-m)
Clay	1.1-2.4	1000-2600	1-100
Sand, gravel (dry)	1.3-2.2	200-1000	100-10,000
Sand, gravel (wet)	1.3-2.2	1500-2000	50-3,000
Shale	2.1-2.75	2000-4000	5-40
Siltstone	2.2-2.75	2000-4000	30-100
Sandstone	2.15-2.65	2050-6000	50-10000
Limestone	2.44-2.71	2600-6000	100-100000
Granite	2.52-2.81	3650-6000	1-300000
Volcanic	2.5-3.5	5500-8500	500-300000
Metamorphic	2.4-3.5	3500-7250	5-300000
Water (fresh)	1.0	1400-1500	3-100
Water (saline)	1.01-1.05	1400-1500	0.2-1

Since it is generally not possible to directly determine physical properties of subsurface rocks and soils, geophysicists rely on surface geophysical methods, to estimate their physical properties (Mandel and Shifton, 1981; CCME, 1994). Table 2.2 presents surface geophysical methods and the physical properties of earth materials that can be inferred from each. In each instance, the physical property measured relates to hydrogeological properties – porosity and permeability/hydraulic conductivity through variations in soil or bedrock type, degree of fracturing and weathering (Kelly and Mares, 1993).

Table 2.2: Surface geophysical methods and related physical properties being delineated

Geophysical Method	Physical Property
Seismic refraction (P and S-wave)	Density, acoustic velocity
Seismic reflection (P and S-wave)	Density, acoustic velocity
Gravity	Density
Magnetic	Magnetism
Electrical	Resistivity/conductivity
Nuclear Magnetic Resonance	Magnetism
Electromagnetic - Fixed Frequency Time-Domain Horizontal Loop	Resistivity/conductivity
Ground Penetrating Radar	Dielectric permittivity
Magnetotellurics	Resistivity/conductivity
Self-potential	Spontaneous potential
Induced Polarization	Resistivity/conductivity

A significant range of values is possible for the physical properties as evidenced in Table 2.1. This overlap can result in ambiguity in the interpretation of results. Figure 2.4, for example illustrates the ranges of electrical properties for soils in the Unified Soil Classification system. The electrical properties for a particular site may represent a composite of a number of factors. For example, the electrical properties of earth materials are controlled by clay content, degree of saturation, porosity, total dissolved solids, and temperature (Henderson and Bowman, 1994; Scanlon *et al.*, 1999). Without additional information, it may be difficult to distinguish an increase in clay content from a slight increase in total dissolved solids in the groundwater. Similar overlap occurs with other physical properties.

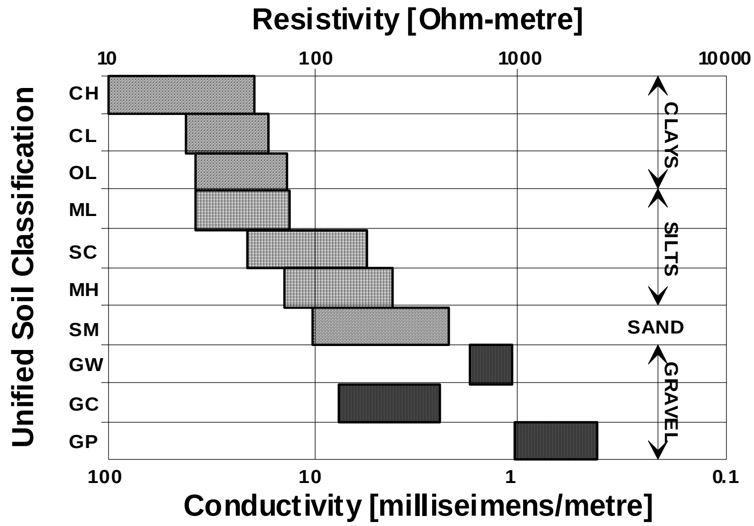

Figure 2.4: Resistivity versus soil types of the Unified Soil Classification system. (Kaufman and Hoekstra, 2001).

Many researchers have identified a correlation between the properties of materials measured using geophysical methods and their hydrogeological properties (Kelly, 1977; Kosinski and Kelly, 1981; Mazac *et al.*, 1985; Engineering Geophysics Working Party, 1998; Triosi *et al.*, 2000; Seaton and Burby, 2002; Yang and Lee, 2002; Niwas and de Lima, 2003; Prasad, 2003). Resistivity/conductivity can provide an estimate of effective porosity for coarse-grained materials. Archie's law provides a correlation between resistivity and porosity (Frohlich and Parkes, 1989):

$$R_b = a.R_w.P^{-m}.S^{-n} \qquad (2.1)$$

where R_b=bulk layer resistivity, R_w=pore water resistivity, P=porosity, S=saturation, and m, n, and a are material constants.

Meju (2002) found that this equation was invalid where clay minerals are present and noted that clay content is often the determining factor for both hydraulic and electrical properties of groundwater aquifers. Kelly (1977) stated that the advantage of surface electrical/electromagnetic methods is that current flow is affected by the same averaging process as the flow of water making it an ideal approach for estimating hydraulic properties.

Acoustic velocity and density have also been used to estimate hydraulic properties. Sharma (1997) quotes Gardner *et al.* who presented an empirical relationship showing an increase in compression wave velocity with density for sedimentary rocks:

$$D = a.V^{1/4} \qquad (2.2)$$

where a is a constant (1670) and D is density (kg/m^3) and V is compression wave velocity (km/s).

In borehole surveys, Telford *et al.* (1990) determined porosity from an empirical time-average equation:

$$P = (\Delta t - \Delta t_m)/(\Delta t_f - t) \qquad (2.3)$$

where P = porosity, t = formation transit time, t_m = rock matrix time, and t_f = fluid transit time.

Prasad (2003) noted that seismic attenuation is strongly influenced by pore geometry. By combining complementary electrical and acoustical geophysical methods, it is possible to estimate hydraulic properties of aquifers and to reduce some of the ambiguity inherent in each method.

The use of geophysical measurements to determine these properties requires calibration generally provided by test pit data, drill hole data, or geological maps. Dassargues (1997) suggests that hydrogeologic properties can only be determined from geophysical data by understanding the local geology and developing a correlation from measured data.

The Geological Survey of Canada (1979a to d) has airborne magnetic data available for the survey area. These airborne geophysical data were reviewed but were not used because line spacing was too wide (1200 m) to be of more than general interest. A combination of airborne magnetic and electromagnetic surveys may yield information on regional geology and major structural features when a more detailed survey grid is utilized (Henderson *et al.*, 2004b). The Alberta Geological Survey has undertaken a test program to evaluate the applicability of airborne magnetic and electromagnetic methods for mapping regional aquifers (L. Andriashek, personal communication, 2007).

2.7.1 Geophysical Methods Utilized

2.7.1.1 Seismic Refraction

In engineering and environmental applications, seismic refraction methods are typically utilized to map depth to the water table, and depth to and rippability of bedrock (Henderson *et al.*, 2004a). An overview of seismic refraction methods and their applicability to hydrologic investigations was given by Haeni (1986). Variations in material acoustic velocity in the subsurface enable geophysicists to map geological horizons by recording refracted seismic waves with respect to a known geometry of the seismic wave path. Both density and acoustic velocity are related to porosity and water saturation (Prassad, 2003). Seismic refraction was utilized in the current research to map the presence of a perched water table, depth to competent bedrock, and variations in bedrock compression wave velocity.

Figure 2.5 illustrates the seismic refraction method. Seismic waves are produced by an acoustic source, usually activated at the surface, with resulting arrival times recorded at receiver sites (geophones) located at a known distance from the source (Kearey and Brooks, 1984). The acquisition geometry, including geophone separation, source interval, and energy source type, impacts the depth of exploration and the resolution of the results. For the investigations on North and South Pender Islands, recording geometry consisted of 24 geophones placed in a line (spread), generally at 5 m intervals, but occasionally, due to space constraints at 3 m intervals. The seismograph setup utilized is illustrated in Figure 2.6. Acoustic energy was imparted to the subsurface by means of a sledge-hammer impacting a metal plate placed on the ground surface (Figure 2.7). The source locations were offset at either end of the geophone array, at either end of the array and at several interior points along the array (Figure 2.7). The multiplicity of data collected enabled the researcher to use computer-based algorithms to interpret variations in acoustic impedance with depth.

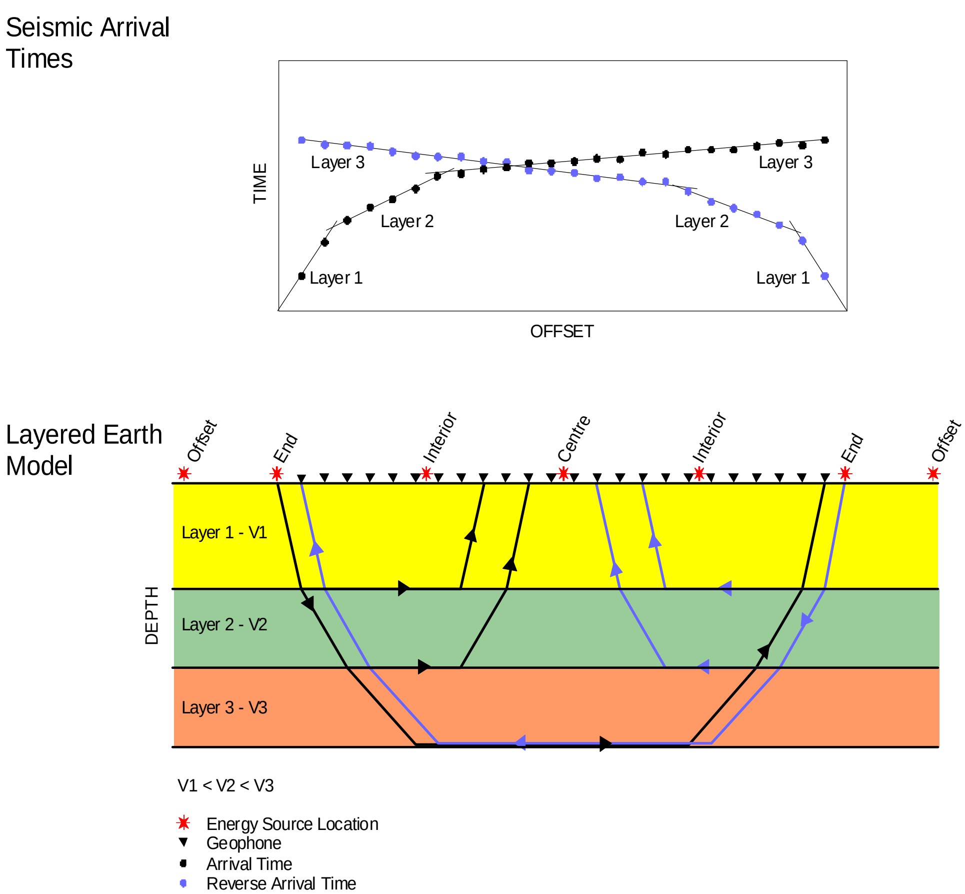

Figure 2.5: Schematic of seismic refraction method

Figure 2.6: Seismograph and power supply

Figure 2.7: Sledge-hammer as seismic energy source

The success of the method depends on the degree of contrast in acoustic impedance between the target and the host material. Typical acoustic velocities and densities for common geologic materials are presented in Table 2.1. The method requires that acoustic velocity increase with depth (Weight and Sonderegger, 2001); acoustic velocity reversals result in layers being hidden and therefore are undetectable by the seismic refraction method.

Seismic refraction data were acquired along 22 spreads located along roadways and in fields on both North and South Pender Islands (see Figures 5.1a and b). The data quality was very good, as illustrated in the sample shot record in Figure 2.8. The break in the slope of the bedrock refractor between geophones 8 and 9 in Figure 2.8 likely represents a fault. The seismic refraction data were interpreted with the use of a combination of software packages including GREMIX (Interprex, 1990), SIPQC (Rimrock Geophysics, 1995), and RAYFRAC (Intelligent Resources Inc, 2007). The interpretation was validated with hand calculations for both intercept-time and critical distance. The equations presented in Redpath (1973) were used, as were observed bedrock outcrops and a comparison with drillers' logs for water wells located close to the survey lines.

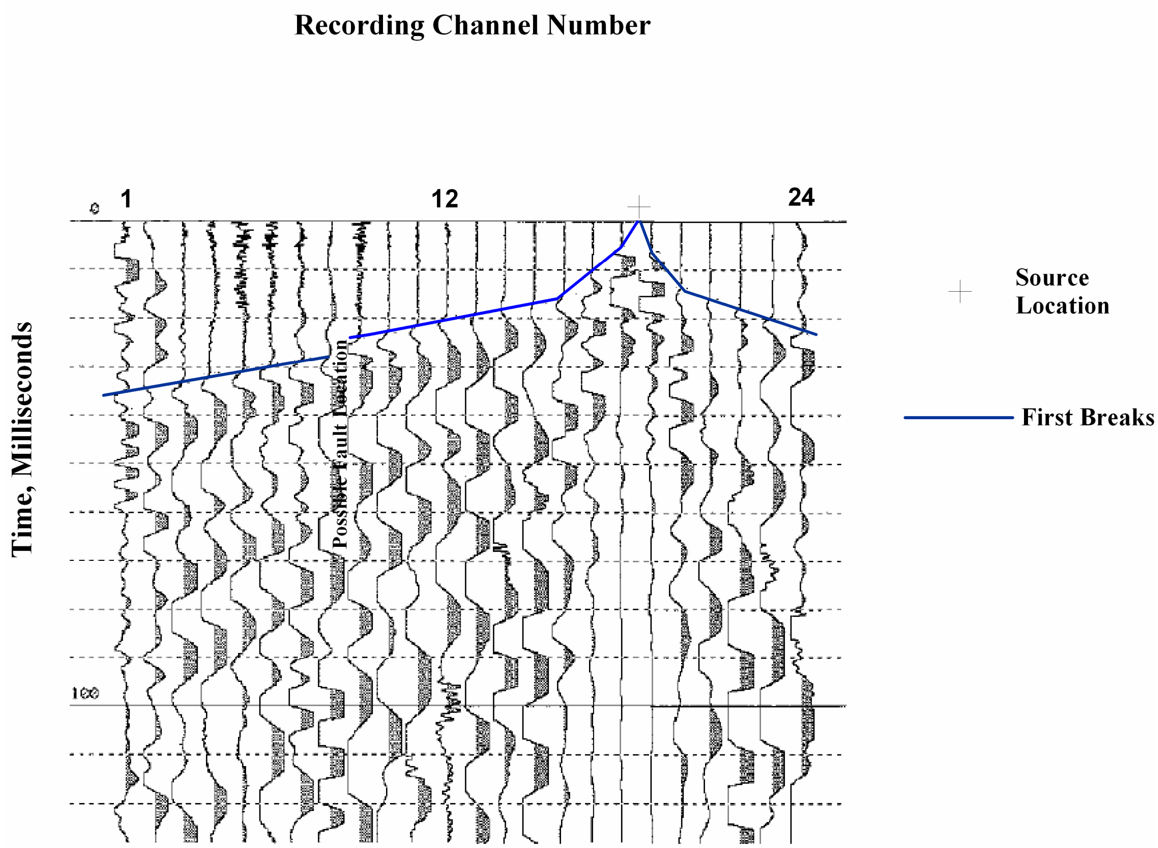

Figure 2.8: Typical seismic refraction record (Higgs Rd, South Pender Island)

2.7.1.2 Electrical Imaging

Electrical Imaging (EI) is an electrical resistivity technique used to determine resistivity variations with depth. A thorough overview of electrical resistivity techniques is provided by Koefoed (1979). When current is directly injected into the ground through a number of small electrodes, the resulting voltage gradients are measured across arrays of secondary electrodes (Fitts, 2002). A relationship, which includes initial current, measured potential difference, and the geometry of the electrode placement, enables analysis of the depth and thickness of geological horizons of contrasting electrical resistivity. A schematic of the basic principles of the method is presented in Figure 2.9.

The electrical properties of subsurface materials are related to grain size, porosity, permeability and the presence, quality and quantity of ground water (Scanlon *et al.*, 1999; Powers *et al.*, 1999). Electrical imaging was utilized in the current research to map variations in soil/bedrock type.

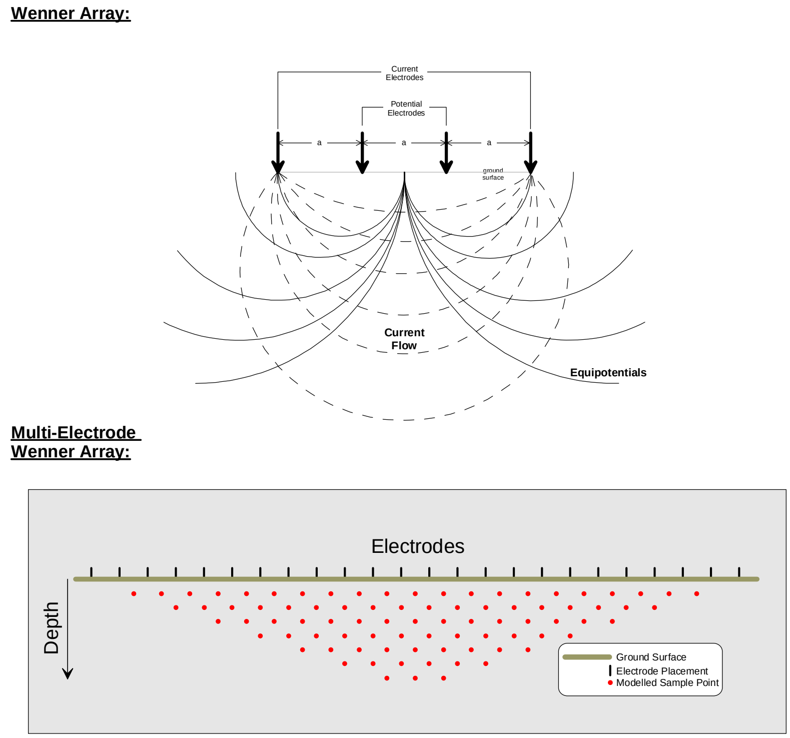

Figure 2.9: Schematic of multi-electrode resistivity (adapted from Fitts, 2002).

The IRIS Instruments Syscal R1 Plus multi-electrode instrument was used to acquire data and was configured with 48 electrodes positioned along a linear array. Electrode spacings of 1 m, 3 m, and 5 m were based on the line length. The individual line lengths chosen for the North and South Pender Islands investigations were selected on the basis of parameters such as presence of roads, changing bedrock types, variations in surficial geology and accessibility. A multiplexer system introduced current through a combination of electrode configurations while concurrently measuring the resulting potential difference across specified receiver electrodes (IRIS Instruments, 1999). Results were digitally recorded. The instrument set up is illustrated in Figure 2.10.

Figure 2.10: Electrical Imaging array, Medicine Beach, North Pender Island

Data processing utilized the RES2DINV software package (Loke and Barker, 1996) and incorporated the values of the initial current, measured potential difference, and geometric characteristics of the electrode array within a least squares inversion routine to generate a two-dimensional model of the subsurface resistivity. By adjusting the resistivity within the model for each iteration, the program optimally reduces the difference between the measured apparent resistivity and the resistivity calculated from the generated model. A measure of this difference is given by the root-mean-square (RMS) error. The model with the lowest possible RMS error can exhibit unrealistic variations in the model resistivity values and may not represent the best geologic model. The most prudent approach is to select the model at the iteration after which there is no significant change in the RMS error (Loke and Barker, 1996).

A limitation of the EI method is decreased vertical resolution with increased exploration depth (Henderson *et al.*, 2004c). In addition, lateral changes in electrical properties of the subsurface, by the Principle of Equivalency, may often be indistinguishable from variations in electrical properties with depth (Kaufman and Keller, 1983; Weight and Sonderegger, 2001). By the Principle of Equivalency, many different models may satisfy a given data set. Equivalency can be minimized by incorporating the results of other geophysical methods, drill hole data, test pit data, and geological mapping.

2.7.1.3 Time-domain Electromagnetic Soundings

The time-domain electromagnetic (TEM) sounding method was utilized to map variations in electrical properties to greater depths than could be achieved with the electrical imaging method. Results provided estimates of the thickness of the freshwater column on the islands and additional information on variations in bedrock stratigraphy.

TEM is a time domain technique that resolves the resistivity of the earth's subsurface at pre-determined time (depth) increments (McNeill, 1980). A detailed discussion on the time-domain electromagnetic method is presented in Kaufmann and Hoekstra (2001).

Instrumentation consists of a transmitter to impart current to a single turn loop of wire laid on the ground surface, and a receiver coil and module to measure and record the resulting magnetic field (Figure 2.11).

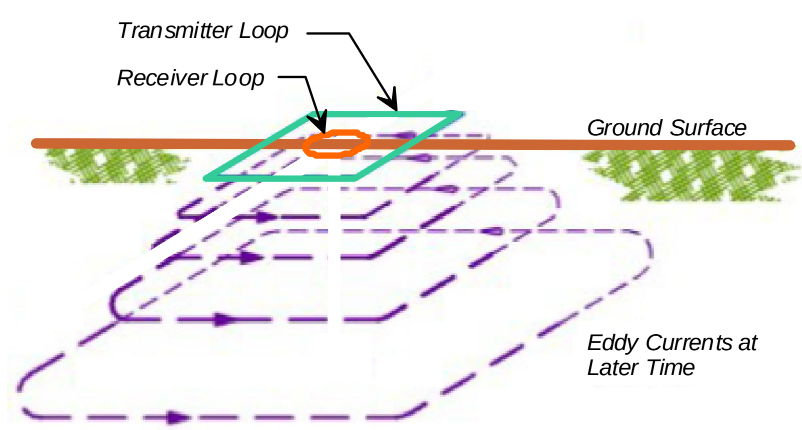

Figure 2.11: Time-domain electromagnetic sounding field set-up.

The transmitter is energized by successive current pulses. While the current is constant, magnetic field is invariant. The process of abruptly reducing the transmitter current to zero induces, in accordance with Faraday's law, a short duration pulse in the ground, causing a loop of current to flow in the immediate vicinity of the transmitter wire (Kaufmann and Hoekstra, 2001). Ground resistivity is such that the amplitude of the resulting current decays with time, thereby inducing a secondary magnetic field at an increasing depth from the source current (Figure 2.12) (McNeill, 1980). The secondary magnetic field, as measured at ground surface at incremental time gates, is dependent on the electrical properties of the subsurface. In this manner, variations in electrical properties may be resolved. One determines variations in lateral resistivity by moving the TEM instrument configuration along the ground surface and acquiring measurements at discrete intervals.

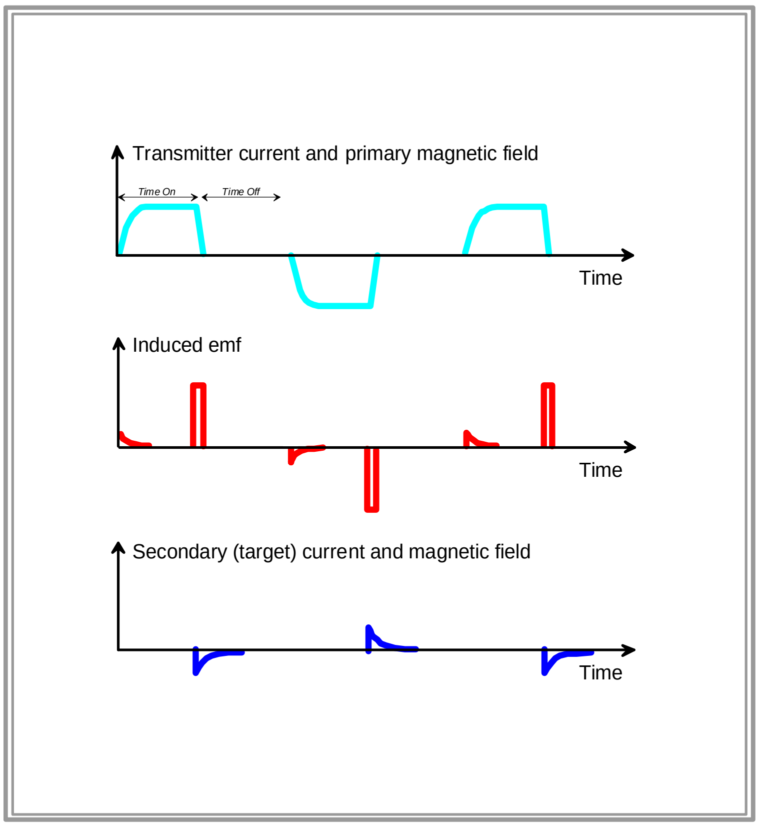

Figure 2.12: Time domain electromagnetic system waveforms for Geonics Protem systems. (McNeill, 1980).

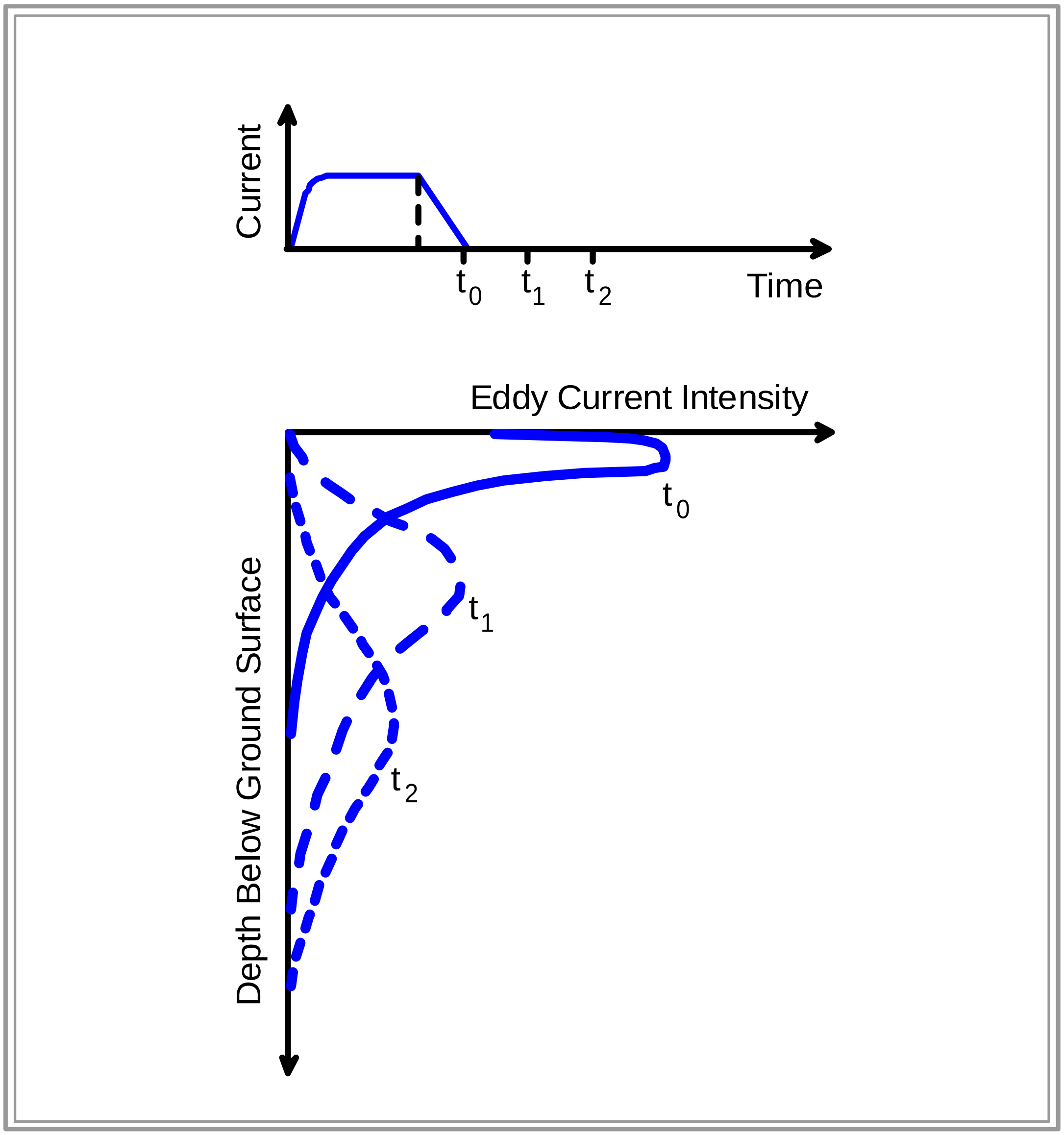

Figure 2.13: Variations in current intensity with time after current shut off. (McNeill, 1980).

The success of the TEM sounding method to delineate subsurface strata depends on the degree of contrast in electrical properties of successive lithologies, target thickness and depth of occurrence (Table 2.1 and Figure 2.4).

TEM data were acquired on North and South Pender Islands with the use of both the Geonics PROTEM 47 and 57 time domain electromagnetic systems. Transmitter loop dimensions varied from 20 m by 20 m to 80 m by 80 m. Receiver coil areas of 31.4 and 200 m squared were used. In total, 10 TEM sounding locations were occupied during the course of the investigation. The applicability of TEM was limited by sources of cultural noise due to the human development on the islands (power lines, pipelines, fences, and buried cables). TEM sounding locations were restricted due to the transmitter loop sizes required. Depths of exploration approached 125 m with this technique.

By means of inverse modeling, a geological model may be derived that best fits the TEM sounding data in a least squares sense. The results of the interpreted electrical imaging and seismic refraction investigations were used to assist in the determination of a starting model for the inversion process. The Interprex TEMIXXL v4 software package was used for data processing (Stoyer, 1985). The software uses a regression approach to successively adjust the parameters of the starting model. An example of inverse modeling results from Roes Island, North Pender Island is presented in Figure 2.14. The use of complementary geophysical methods to develop the starting model assisted in reducing the equivalence for the final model. The Principle of Equivalency indicates that there are many different and equally valid solutions for a given TEM sounding data set (Kaufman and Keller, 1983). Constraints were placed on the interpretation through incorporation of the results of complementary geophysical investigations thereby reducing equivalence.

Figure 2.14 illustrates the variability that can be encountered for the interpreted thickness and depth of occurrence of each layer. The least variability occurs in the depth to and the resistivity of the basal conductive unit, making the use of time-domain electromagnetic soundings ideal for mapping the thickness of the freshwater column on islands. The variability is analogous to the equivalency. For this example, the basal conductive unit is saline water. It is not possible to mistake the resistivity associated with this layer for the resistivity of any other material in this geologic environment. The equivalence can be reduced when additional complementary geophysical and/or geological data are used to constrain the model.

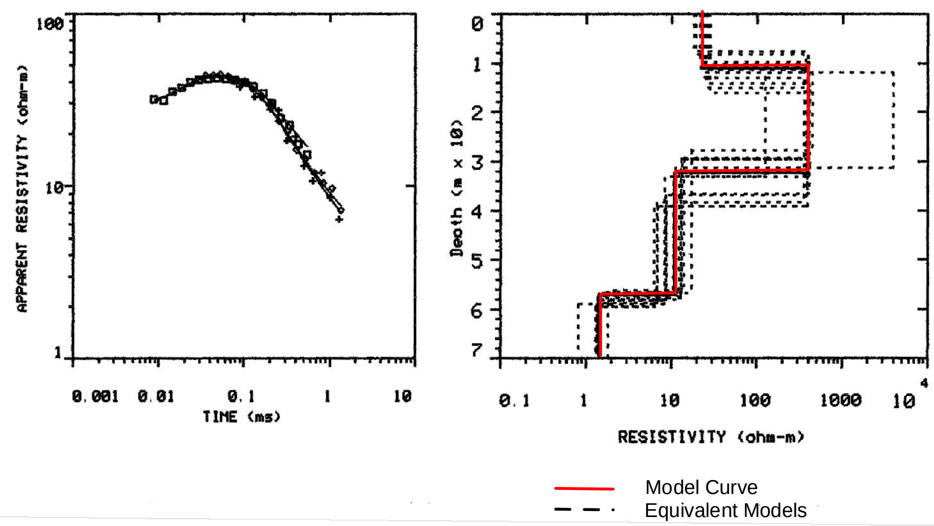

Figure 2.14: The apparent resistivity curve on the left illustrates the field data along with the model curve that fits the data. The model used is shown in red on the right with equivalent models shown by dashed lines. The data are from Roes Island, North Pender Island.

2.7.2 Geophysical Methods Not Utilised

Other geophysical methods were investigated as part of the research but were not utilized in the field due to the geologic setting of the island (steeply dipping horizons, lack of homogeneity within formations). These methods include seismic reflection, nuclear magnetic resonance, ground penetrating radar, frequency domain electromagnetics, gravity and magnetics.

Seismic reflection would have been a very useful geophysical research method if it were not for the steeply dipping strata on North and South Pender Islands. Nuclear magnetic resonance (NMR) is a relatively new approach and would have proven beneficial in defining the groundwater resources (Legchenko, 2002). Unfortunately, the technique was so new at the time of the field investigation that no commercially available equipment was available in North America. NMR cannot, however, distinguish between potable and saline groundwater. It is limited in its depth of exploration to approximately 150 m.

Ground penetrating radar was considered as a geophysical research method able to map depth to bedrock and structure within the bedrock; however, this method was rejected because it also suffers in steeply dipping strata (Butler, 2006). It is also limited in its depth of penetration in the presence of any conductive (clay-rich) soils and would be negatively impacted by the cultural noise (power lines, pipelines, and buried cables) present along the roads.

Frequency domain electromagnetics were considered but not used, due to the potential interference from cultural noise along the roads used for the investigation. These methods are used routinely to map fracture zones as part of mineral exploration programs (Telford *et al.*, 1980) and would have proven useful in mapping zones of enhanced secondary porosity and permeability.

Gravity and magnetics surveys were also considered. Gravity could have provided an estimate of depth to bedrock, but not with the same degree of accuracy as seismic refraction. Magnetics would have proven useful to map structure, and as a result, zones of enhanced secondary porosity and permeability; however, a magnetic survey would have also been negatively impacted by the cultural noise present along the roads used in the investigation.

2.8 Correlation with Water Wells

The Government of British Columbia operates a website (www.gov.bc.ca/cgi-bin/env_exec/wwwapps/waterbot/gwellout.) that includes water well data from North and South Pender Islands. Water well data were used to correlate the results of the geological and geophysical field investigations by providing some information on soil type, depth to bedrock and bedrock type.

Typical water well records are presented in Figures 2.15 and 2.16. Figure 2.15 illustrates a poor producing water well. There is not a great deal of information available from the record, which is typical of most of the wells in the database, as is illustrated by the lack of detail in description of soil types, bedrock type and static water level. On the basis of geological mapping, conglomerate is not anticipated in the vicinity of the well; it should also be noted that if present, conglomerate tends to be relatively resistant, not soft. In contrast, Figure 2.16 shows a detailed well record for a good producing water well. As with the previous example, many of the categories on the detailed well record have been left blank. The water-bearing zone appears to be located at a contact between two bedrock types at a depth of 275 feet. These two wells are located near one another, but they yield drastically different rates of water production. The data from the water well logs must not be relied upon completely but should be reviewed as complementary information to the geological and geophysical mapping to identify zones within the bedrock that provide the source of water,. The water wells do not provide any information on soil types and the bedrock types do not always match the known bedrock from geological mapping.

Reporting requirements from the Groundwater Protection Guidelines of the Water Act (B.C. Government, 2005) were recently instituted. Under the guidelines, it is not necessary to provide information on subsurface stratigraphy, depth to water bearing horizons, flow rates, or location of the water well with respect to potential contaminant sources. Yet, this information is critical to the understanding and management of groundwater resources.

Since not all of the water wells drilled or dug to date have been included in the B.C. Land, Water, and Air groundwater well database, the results as presented in this dissertation should be used as a guide only. Additionally, when the information in the database is used, the following limitations should be fully understood:

- Poor geological definition of stratigraphy or inaccurate description
- Reliance on drillers' estimate of water production
- Lack of consistency between drillers
- Inaccurate construction dates
- Little (if any) information on water quality
- No water wells drilled after 1994 in database at the time of the research

It would be useful to have the surface elevation of the well, as well as, the elevation of the static water table noted. This would enable calculations to be made of the thickness of the freshwater column as will be discussed in Section 2.8. For most of the water wells in the data base, they are located by lot number versus UTM coordinates. The lack of accurate water well location makes it difficult to determine even the surface elevation. It would be possible to get this information cost effectively by hiring a summer student to use a Global Positioning System to locate the water wells.

2.9 Water Supply Calculations

It was necessary to determine the water available from precipitation to recharge groundwater supplies. The researcher performed several relatively simple calculations using equations from Solley *et al.* (1998) to determine the volume of water supply per millimetre of rainfall per square kilometre, and equations from Balek (1989) to determine the losses due to evapotranspiration. When combined with the porosity and permeability of the bedrock units from the geologic and geophysical investigations, this information enabled estimates to be made of storage capacity and groundwater resource potential for the islands.

BRITISH COLUMBIA

Report 1 - Detailed Well Record

Well Tag Number: 62222

Owner: MEYER DEV. CORP.

Address: COMMON LAND- NR LOTS 10 & 11

Area: SUBD. SPALDING RD.

WELL LOCATION:
COWICHAN Land District
District Lot: Plan: 40899 Lot:
Township: Section: 4Range:
Indian Reserve: Meridian: Block:
Quarter:
S. PENDER Island
BCGS Number (NAD 27): 092B074422 Well: 38

Class of Well:
Subclass of Well:
Orientation of WEll:
Status of Well: New
Well Use: Domestic
Observation Well Number:
Observation Well Status:
Construction Method: Drilled
Diameter: 0.0 inches
Well Depth: 250.0 feet
Elevation: 0
Bedrock Depth: 5 feet

Construction Date: 1994-06-30 00:00:00.0

Driller: Tri-K Drilling
Well Identification Plate Number:
Plate Attached By:
Where Plate Attached:

PRODUCTION DATA AT TIME OF DRILLING:
Well Yield: 0 (Driller's Estimate)
Artesian Flow: 0
Static Level: feet

Water Utility:
Water Supply System Name:
Water Supply System Well Name:

Surface Seal Flag:
Surface Seal Material:
Surface Seal Method:
Surface Seal Depth:
Surface Seal Thickness:

Lithology Info Flag:
Pump Test Info Flag:
File Info Flag:
Sieve Info Flag:
Screen Info Flag:
EMS ID:
Water Chemistry Info Flag:
Field Chemistry Info Flag:
Site Info (SEAM):
Site Info Details:
Other Info Flag:
Other Info Details:

GENERAL REMARKS:
DRY HOLE

From 0 to 5 Ft. OVERBURDEN
From 5 to 250 Ft. DARK SOFT CONGLOMERATE OR MUDSTONE

Figure 2.15: Typical water well record.

BRITISH COLUMBIA

Report 1 - Detailed Well Record

Well Tag Number: 62203

Owner: MEYER DEV. CORP.

Address: LOT 1 PHASE 1 SPALDING ROAD

Area:

WELL LOCATION:
COWICHAN Land District
District Lot: Plan: 40899 Lot: SL1
Township: Section: 4Range:
Indian Reserve: Meridian: Block:
Quarter:
S. PENDER Island
BCGS Number (NAD 27): 092B074422 Well: 33

Class of Well:
Subclass of Well:
Orientation of WEll:
Status of Well: New
Well Use: Domestic
Observation Well Number:
Observation Well Status:
Construction Method: Drilled
Diameter: 0.0 inches
Well Depth: 300.0 feet
Elevation: 0
Bedrock Depth: 6 feet

Construction Date: 1994-05-31 00:00:00.0

Driller: Tri-K Drilling
Well Identification Plate Number:
Plate Attached By:
Where Plate Attached:

PRODUCTION DATA AT TIME OF DRILLING:
Well Yield: 100 (Driller's Estimate) Gallons
Artesian Flow: 0
Static Level: feet

Water Utility:
Water Supply System Name:
Water Supply System Well Name:

Surface Seal Flag:
Surface Seal Material:
Surface Seal Method:
Surface Seal Depth:
Surface Seal Thickness:

Lithology Info Flag:
Pump Test Info Flag:
File Info Flag:
Sieve Info Flag:
Screen Info Flag:
EMS ID:
Water Chemistry Info Flag: Y
Field Chemistry Info Flag:
Site Info (SEAM):
Site Info Details:
Other Info Flag:
Other Info Details:

GENERAL REMARKS:
ONLY TOTAL COLIFORMS TESTED.

From	0	to	6	Ft.	OVERBURDEN
From	6	to	190	Ft.	MEDIUM HARD CONGLOMERATE
From	190	to	275	Ft.	SOFT BLACK SHALE WATER @ 275'
From	275	to	300	Ft.	HARD LAYERS OF SANDSTONE & CONGLOMERATE
From	0	to	0	Ft.	null

Figure 2.16: Typical water well record.

Another concern on small islands is saline water (Fitterman and Hoekstra, 1984; Mills *et al.*, 1988). Fresh water is less dense than salt water and as a result generally forms a lens floating on top of the salt water (Falkland, 1991). The depth to the salt water has been estimated by the Ghyben-Hertzberg equation:

$$h_s = (P_f / (P_s - P_f))(h_f) \tag{2.4}$$

where h_s is the depth of freshwater below sea level, P_f is the density of freshwater, P_s is the density of sea water, and h_f is the height of the freshwater table above sea level (ASCE, 1996).

The Ghyben-Hertzberg equation can be used to provide an estimate of the freshwater column thickness. This estimate can be useful in determining optimal depths and pumping rates for water wells to limit the risk of saline intrusion, as well as in enabling a better understanding of the groundwater resources available.

A water balance has been calculated for the Municipal Improvement District of Trincomali (see Section 7.2.4.3). This district represents the only portion of the island in which there is sufficient control of groundwater extraction. A water balance has also been calculated for both North and South Pender Islands using estimates of per capita water consumption (see Section 7)

2.10 Case Study Area

As part of the research for this dissertation, two of the Gulf Islands (North and South Pender Islands), which are located approximately 160 kilometres off the southeast coast of Vancouver Island (Figure 2.17), were selected as a case study area. North and South Pender Island are located close to the population centres of Vancouver, Victoria and Seattle. North Pender Island encompasses an area of 2730 ha while South Pender Island is smaller having an area of 930 ha.

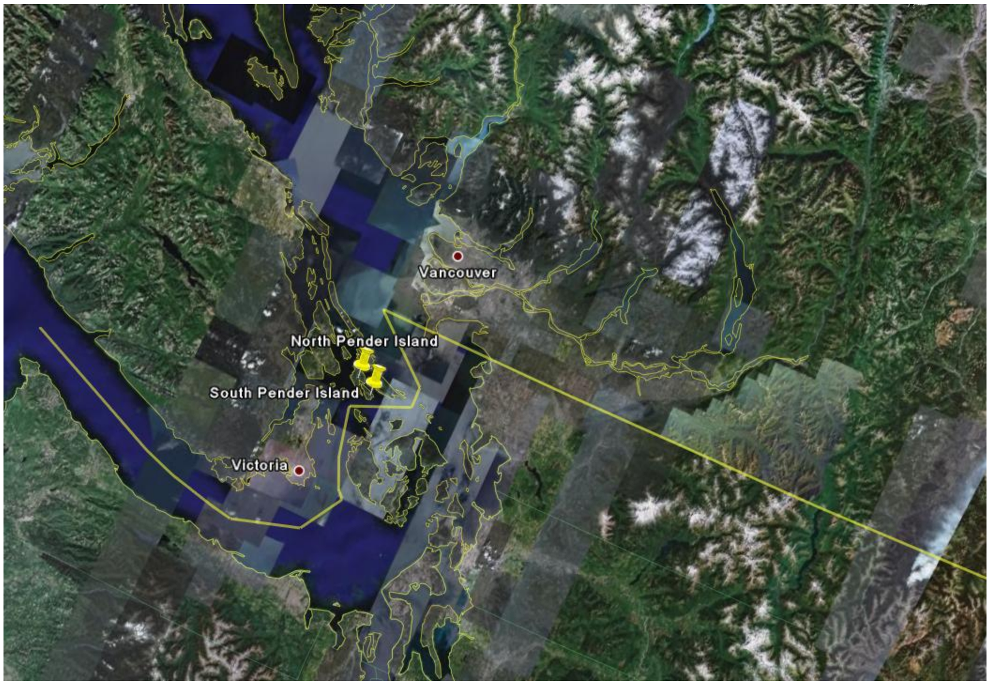

Figure 2.17: Composite satellite image of Gulf Islands, Vancouver, Victoria

The topography of the islands is variable with topographic highs oriented in a southeast to northwest direction. The topography reflects the glacial history of the islands. The topography on North Pender Island ranges from sea level to in excess of 200 metres above sea level (a.s.l.) on Cramer Hill. A similar range of topography is present on South Pender Island with the highest peak being Mount Norman with an elevation of in excess of 200 metre (a.s.l.).

The islands are part of the Coastal Douglas Fir Zone (CDFa) which represents the driest mesothermal zone within British Columbia. Water resources are of concern on the islands as illustrated by the studies undertaken by B.C. Environment (1994a) and the results of a questionnaire on water resources (Henderson, 1998).

The evaluation of groundwater resources on North and South Pender Islands enables a comparison of two adjacent islands representing opposite ends of the development spectrum for the Outer Gulf Islands. North Pender Island has the highest level of development of any of the Outer Gulf Islands and therefore has fewer remaining options for resource management while South Pender Island is one of the least developed. Each island will be discussed separately, with an explanation of the water resources in the context of the current level of the island's development. Then, the islands will be compared and contrasted. The evaluation of the groundwater resources is based on the integration of the geological mapping, geophysical surveying, precipitation records and review of the water well database, as well as estimates of population at the current anticipated level of maximum development. There has been no attempt made to estimate secondary porosity and permeability, other than to map the major structural features that would increase these parameters. This treatment of secondary porosity and permeability reflects the conservative nature of the estimates, representing a prudent approach to groundwater assessment. A much more detailed geophysical investigation would be required to provide estimates of secondary porosity and permeability. The complex geology for the islands limited the applications of some geophysical methods that would have assisted in these calculations.

2.11 Summary

The literature review portion of the research provided insight into water demand and integrated water resource management. The fieldwork of geologic mapping and geophysical investigations provided a better understanding of groundwater on the islands while a review of climatic and water well data, enabled the water balance for North and South Pender Islands to be determined. The combination of the literature review and the field component of the research defined the physical setting in the study area, while the integration of the literature review and the enhanced knowledge of the physical setting helped define the approaches for governance and risk assessment for the groundwater resources. The integration of the two approaches, following the matrices outlined in Figures 2.1 and 2.2, ultimately provides the basis for development of conceptual models for water resource assessment in the study area and the extrapolation to a more global approach to water assessment and management of groundwater basins.

Chapter 3 provides background information on water resources with an emphasis on small islands while Chapters 4, 5 and 6 present a more detailed discussion of the climatic data, geological mapping and geophysical investigations respectively.