Chapter 3 BACKGROUND TO WATER RESOURCE ASSESSMENT ON SMALL ISLANDS

3.1 Introduction

Groundwater assessment can be difficult to comprehend; groundwater flows beneath the Earth's surface and is therefore invisible. Groundwater resources can also vary both spatially and temporally. This chapter provides background information on groundwater resource assessment in general and for small islands specifically. The background information has been subdivided into the following sections:

- Global perspective
- Why small islands
- Water supply/availability
- Water demand
- Integrated water resource management
- Modeling

3.2 Global Perspective

An understanding of groundwater resource assessment from a global perspective is useful in providing a context for the small island scenario. There is a limited supply of freshwater controlled by the hydrologic cycle (Clarke *et al.,* 1996). The total volume of potable water on Earth has varied on a per capita basis from 30,000 m^3/person/year in 1900 to 7,000 m^3 /person/year in 2000. It is forecast to continue to decrease until about 2050 in conjunction with increasing global population (Gleick, 2000). Postel *et al.* (1996) estimate that currently humans utilize 54% of the accessible runoff on earth. On the basis of increased demand from increasing population and economic development, Postel *et al.* (1996) predict that by 2025 this number could increase to 70%. For small islands with limited potable water supplies, increases in population may exacerbate already low per capita water resources. Gleick (2002) points out, that it is well understood that clean freshwater is a fundamental necessity for human and ecological health, the production of food, goods, and services, and the generation of power; how, then, can the resource be assessed, monitored and managed in a reasonable manner? There is then an obvious reliance by humans on freshwater for their existence as well as for its aesthetic, social and economic values. Groundwater reliance, by humans, also includes the groundwater requirements of the environment itself.

Miloradov and Marjanovic (1998) state that in light of the freshwater resources' finite nature and the increasing demands placed on these resources, water management must be undertaken in a rational manner based on a thorough understanding of water availability and movement (physical setting). Groundwater resource management represents an extremely complex blend of physical and social science, as a result, there is a difficulty defining problems, or more aptly, a "wicked" problem scenario as defined by Pacanowsky (1995).

Heathcote (1998) presented a conceptual model of the interrelationship between the various natural processes impacting a watershed (Figure 3.1); that can be equally applied to groundwatersheds. The interrelationships clearly illustrate that a change in any one process results in changes to all other processes, showing similarities to the thermodynamic closed system concept. It can also be the case that change in, for example, human activities, alter the local climate and that change in turn influences human activities. The result is a rather muddled set of continuous interactions. Unlike a closed thermodynamic system, small islands are influenced by climatic conditions, anthropogenic activities and other environmental factors occurring great distances away.

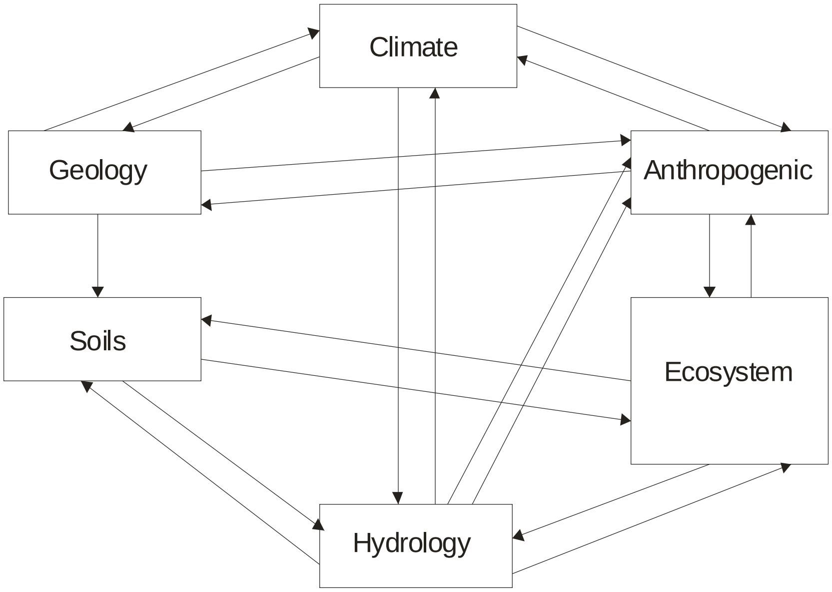

Figure 3.1: Interaction of natural processes in a watershed ecosystem (adapted from Heathcote, 1998).

The spatial and temporal scales and their inherent uncertainty add to the difficulty of groundwater resource management on large land masses and small islands alike. The interrelationships presented in Figure 3.1 become significantly more complex when viewed with the varying spatial and temporal scales involved. Impacts from a change in one process may not be noticed within a specific time frame until it is impossible to alter the outcome without significant expenditure of human capital. Climatic conditions can be highly variable with no distinct pattern; although general patterns exist, they should not be relied upon. As a result, climatic variables will have a major influence over the other processes presented in Figure 3.1 in both the short term and long term. Since groundwater resources are invisible, often slow moving and generally not well monitored, it has been found that there can be a significant time lag before negative impacts are noticed (Berardinucci and Ronneseth, 2002).

From a historical perspective, water supply has been a constant concern. The ancient Greeks located their towns and villages around suitable water supplies such as springs, lakes and rivers (Crouch, 1993). As population increased, water supply became stressed and alternative sources of water were supplied from ever-increasing distances through construction of aqueducts

(Crouch, 1993). The emphasis on increasing water supply to meet human requirements, from ancient to modern times, has been documented by a number of researchers (Crouch, 1993; Gleick, 1998; Gleick, 2000; Bono *et al.*, 2001; Bakker, 2003; Cech, 2003). The need to increase water supply has also led to significant innovation throughout time (Homer-Dixon, 2000).

During the 1950s, some water experts began espousing the advantages of working with the existing water supply by controlling demand (Wolfe and Brooks, 2003). It is important to have knowledge of the physical resource base (supply) in order to work within a sustainable context, as was stated several decades ago by Ozoray (1973). It is, then, clear that the physical resource base for groundwater supply becomes the driving force behind the social, cultural, economic and political aspects required for groundwater management.

Current theoretical models can easily deal with scenarios of no potable water resources. A number of models exist that can effectively evaluate groundwater flow and surface hydrology - in essence, the physical aspects of water flow (National Research Council, 1999). Only a few of the existing models have application for dealing with fluid flow in fractured rock and those models have been developed predominantly for petroleum extraction, not groundwater.

Heathcote (1998) subdivided water resource management into several categories, including water availability, requirement and use; water quality; and water management and institutions. The current issues in water resource management are presented in Table 3.1. The table indicates the relative importance of the legal and institutional frameworks under which groundwater management exists, as well as the significance of the relationship of water to the overall environment.

Table 3.1: Current issues in water management (adapted from B.C. Environment, 1993a, and Heathcote, 1998)

Water availability, requirement and use	• Protection of aquatic and wetland habitat • High well development • Management of extreme events (drought, flood, etc.) • Excessive extraction from surface and ground waters • Climate change • Land use
Water quality	• Coastal and ocean water quality • Safe drinking water supply • Lake and reservoir protection and restoration • Water quality protection including effective enforcement of legislation • Impacts on land/water/air relationships • Health risks
Water management and institutions	• Coordination and consistency • Lack of data for decision making • Effective monitoring • Capturing a regional perspective • Respective roles of federal, state/provincial and local agencies • Respective roles of projects and programs • Financing and cost sharing • Information and education • Appropriate levels of regulation and deregulation • Water rights and permits • Infrastructure • Population growth • Water resource planning • Management of point and non-point source pollution

3.3 Why Small Islands?

As stated previously, small islands represent the equivalent of natural hydrogeological laboratories in view of the well-defined boundary conditions (Salvati, 2002). Small islands simply represent a smaller scale version of larger groundwatersheds on larger landmasses (National Research Council, 1999). It is within the context of natural hydrogeological laboratories that small islands are explored in this dissertation, as they represent ideal water management research locations. Since water management issues are often exacerbated by physical limits placed on small islands, they represent a looking glass on the remainder of the globe. In addition to their limited size, the major influences on small islands hydrogeology include climate, physiography, geology, geomorphology, and vegetative cover (Falkland, 1991). There are also human influences on hydrogeology, and these influences tend to become accentuated with proximity to large landmasses (South Pacific Applied Geoscience Commission, 1998).

The problems encountered on small coastal islands closely parallel those of larger landmasses (Falkland, 1991) since small islands can be considered analogous to groundwater basins on larger landmasses. The physical characteristics of small islands can be highly variable and will impact the hydrogeological properties. These physical characteristics combine to influence the parameters comprising the water balance equation.

South Pacific Applied Geoscience Commission (1998) recommended that small island countries concentrate their water management efforts on the rational and systematic assessment, development and management of naturally occurring freshwater resources before other, more expensive and complex technologies are planned or introduced. An assessment to determine water resource potential on small islands has also been stressed as a precursor to sustainable water development and water resources management at a number of recent conferences, including the Rio Summit in 1992, the Barbados Programme of Action for the Sustainable Development of Small Island States in 1994, and the Third World Water Forum in 2003 (Slade, 1998; South Pacific Applied Geoscience Commission, 2003).

One advantage of small islands is that they represent the simplest socio-political form, since there are rarely political boundaries to contend with; there can be limited social and cultural differences; and the institutional frameworks are relatively well-defined (Miloradov and Marjanovic, 1998). The minimization of socio-political variability also makes small islands ideal research venues, and enables the hydrogeological parameters of the islands to be more readily researched. The environmental sensitivity of many small islands, combined with the complexity of the physical system controlling water resource availability, involves both economical and ethical issues related to sustainable development. Poor understanding of environmental sensitivity has contributed to the collapse of civilization on small islands in the past (Diamond, 2005).

According to Homer-Dixon (2000), the stresses of water scarcity placed on island residents would result in their being pushed to develop both social and technological ingenuity. The physical constraints of small islands place restrictions on alternative water sources, so there is an emphasis on ingenuity (Khaka, 1998). Social and technical ingenuity requires available resources, both economic and physical, to successfully resolve water scarcity problems.

3.4 Water Supply/Availability

The basic model for water supply is the hydrologic cycle, in which there is continual reuse and recycling of water in the system (Davis and DeWiest, 1966). The hydrologic cycle can be defined by the water balance equation, also known as the hydrologic equation, which simply states (Domenico and Schwartz, 1998):

$$\text{Inputs} = \text{Outputs} + \text{Changes in Storage} \qquad (3.1)$$

The inputs to the water balance equation for many small islands are restricted to precipitation (Falkland, 1991). As a result, the water balance equation can be rewritten in the following manner (Balek, 1989):

$$P = R \pm O \pm G \pm S \pm I \pm C \pm M + E, \qquad (3.2)$$

where P = precipitation, R = surface runoff, O = groundwater outflow, G = change in groundwater storage, S = change in soil moisture, I = interception, C = communication with surrounding area, M = water recharge/discharge due to human activity, and E = evapotranspiration.

Milly (1994), American Society of Civil Engineers (1996), Mays (1996), Brooks *et al.* (1997), Domenico and Schwartz (1998), and Weight and Sonderegger (2001) provide detailed descriptions of the variables in the water balance equation. For small islands, fresh water sources may be classified into two general categories: conventional and nonconventional. The conventional resources comprise rainfall, groundwater, and surface water; nonconventional sources consist of desalinized sea water, water importation, water re-use (treated wastewater), conservation, fog harvesting, dew harvesting and the use of saline or brackish water (adapted from Gleick, 2002).

3.4.1 Conventional Sources

Until recently, increasing water supply had been viewed as the primary means of meeting increasing water demands (Gleick, 1998). The requirement to increase water supply has led to the development of many man-made storage structures. Storage structures have not always been a viable alternative in small island environments because of the islands' limited size. A number of researchers state that, in order to adequately manage a resource, one must undertake an assessment of the resource base (Ozaray, 1973; Spinks and Wilson, 1990; LeMoigne *et al.*, 1994; Meko and Graybill, 1995; National Research Council, 1997; Miloradov and Marjanovic, 1998; Gleick, 2002; Falkland 2003).

Water represents one of the few natural resources required for human existence for which there is no substitute. Understanding the supply as well as demands and constraints on the resource is therefore a necessity (Postel, 2003). It is a much more cost effective scenario to utilize conventional water sources before considering the use of nonconventional water sources.

3.4.1.1 Surface Water

Surface water may be present on small islands in the form of streams, small lakes, swamps or marshes, and springs. Falkland (1991) notes that springs on small islands are often intermittent and highly variable. In view of the areal constraints of small islands, there is likely to be insufficient, consistent flow in creeks and rivers to provide the input of freshwater required to sustain water quantity and quality in lakes. Both water quality and quantity can be negatively impacted by human activity close to the lakes (Falkland, 1991).

Springs are fed from groundwater flow and often exhibit superior water quality as compared to other surface sources. They are, however, susceptible to overpumping of groundwater close to the spring.

To exploit surface water, Falkland (1991) classifies development as:

- Intake structures on streams;
- Dams or impoundments;
- Spring cappings; or
- Intake structures on lakes or pools.

Dams or impoundments require large land areas that are not necessarily available on small islands, while intake structures require significant engineering design, construction costs, monitoring, and environmental approvals.

3.4.1.2 Groundwater

Many small islands rely entirely on groundwater for their freshwater (Falkland, 2003), so the hydrogeological characteristics of the subsurface play a controlling role in water supply. The climatic variability on small islands only adds to the requirement for an understanding of the resource base (Stoddart and Walsh, 1992). To adequately estimate the resource base, one must not only research the climatic controls; one must also map the geological controls on storage capacity and groundwater flow in conjunction with the institutional and legal frameworks. The complexity of the natural hydrogeological conditions in combination with climatic controls increases the uncertainty involved in groundwater resource evaluation, so that it is difficult to provide adequate monitoring of extraction (Foster *et al.*, 2000).

On small islands, another concern is the location of 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 (2.4).

3.4.1.3 Rainfall Harvesting

Rainfall capture represents the most cost-effective and practical means of augmenting water supply for residents of small islands (Falkland, 2003). In small island environments, rainfall capture is a common means of augmenting water supply (South Pacific Applied Geoscience Commission, 1998). In general, rainfall harvesting is relatively inexpensive and requires no significant expertise to operate. Many island states have legal requirements for cisterns incorporated into their building codes. Building codes often require that new buildings include gutters and minimum rainwater storage (Ward, 1997; Samoa, 2003). The efficiency and water quality of rainwater harvesting are influenced by the effective roof area and the material utilized in roof construction (South Pacific Applied Geoscience Commission, 1998).

For rainwater harvesting, the storage tank, gutters and drainpipes should be checked and cleaned on a regular basis. Additionally, the storage tank should be covered and ventilated to avoid mosquito breeding and minimize algae growth.

Rainwater harvesting is subject to the vagaries of climate, in that it is totally dependent on the frequency and amount of rainfall. Rainfall harvesting is best suited to small islands possessing an even distribution of rainfall throughout the year. Other drawbacks to rainfall capture may be that water quality is not always suitable for human consumption and that storage areas must be found. The water quality problems can be overcome through the use of some form of “first flush” device, since the majority of pollutants wash off the roof shortly after the first heavy rainfall (Falkland, 2003). The availability of storage capacity is a limit to the volume of rainwater that may be harvested

One advantage of rainwater harvesting is that it tends to encourage water users to conserve water, since responsibility for the operation and maintenance of the system rests solely on the user (South Pacific Applied Geoscience Commission, 1998). Applicability of rainwater harvesting is not limited to small island environments. It is a common practice in Denmark to augment the water supply for toilet flushing and washing of clothes (Mikkelsen *et al.*, 1999). .

3.4.2 Nonconventional Water Sources

There are a number of unconventional means available to augment water supply on small islands, but each has its own limitations. Non-conventional water sources include conservation, desalination, importation, wastewater re-use, fog harvesting, dew harvesting and the use of saline or brackish water.

3.4.2.1 Conservation

The impact of water conservation measures will vary according to the current conservation measures in place, social behaviour patterns of citizens, and the costs required to make changes.

Stave (2003) suggests that water conservation can be successful only if water users are convinced to use less. This shift in behaviour can be achieved partially through economic incentives and regulations, but more through education of consumers. Stakeholders must understand the causes of the problems and related policy decisions. Rodda (2001) provides a list of means of water conservation including scientific and technical, economic, legal and administrative, operational, educational, and political (Table 3.2). These approaches are complementary and work much better in tandem than individually.

Table 3.2: Methods of saving water to improve water use efficiency (Rodda, 2001)

Scientific and Technical	Water conservation, recycling, water saving technology including retrofitting, leakage control, crop variety, cropping patterns, crop breeding, crop substitution
Economic	Subsidies, incentives, tax and price policy, tariffs
Legal and Administrative	Water law, water rights, licenses, regulations, penalties, enforcement
Operational	Operating rules, water allocations
Educational	Capacity building, awareness raising, media, communication
Political	Priorities, objectives

Water-saving devices for the individual household can significantly reduce water usage. These include such features as low-flow showerheads, waterless toilets, and efficient dishwashers and clothes washers. Economic considerations for water efficiency and the resulting conservation revolve around using pricing structures to control consumption. Chambouleyron (2003) states that if the charge for water is not based on actual consumption, then the water user has no incentive to reduce consumption. Water conservation and pricing mechanisms will be discussed in greater detail in Section 3.5.

3.4.2.2 Desalination

An alternative strategy is desalination, which is utilised in a number of countries (South Pacific Applied Geoscience Commission, 1998). As Hoekstra (1998) states, the oceans represent an almost limitless water supply as the ultimate source and sink of all freshwater. There are, however, high energy requirements and therefore desalination plants are generally operational only in relatively wealthy countries (South Pacific Applied Geoscience Commission, 1998). Falkland (2003) states that desalination costs are higher simply due to the high operating costs. He found that desalinized water was twice as expensive as groundwater on the island of Betio, Tarewa, while the energy costs were 16 times higher for desalination than for groundwater. As such, it simply makes sense to use desalination as an alternative water source once conventional sources have been fully utilized.

There are several desalination technologies currently in use. These include distillation, electrodialysis, reverse osmosis, and solar. Distillation represents approximately 65% of the current desalination operations on a global basis (South Pacific Applied Geoscience Commission, 1998). Distillation processes can be subdivided into multi-stage flash (MSF), multiple effective distillation (MED), and vapour compression (VC). Generally these systems are large, complex, and expensive, requiring significant community buy-in to ensure that financial considerations as well as operations and maintenance are in place for the long term (South Pacific Applied Geoscience Commission, 1998). Distillation does, however, represent proven technology, as evidenced by its large proportional share of the global desalination market.

Electrodialysis accounts for approximately 5% of desalination operations globally (South Pacific Applied Geoscience Commission, 1998). Electrodialysis requires an experienced operator, chemicals for pre-treatment of feedwater, and a reliable energy source. It is deemed to be the optimal desalination process when the feedwater contains high concentrations of suspended solids (South Pacific Applied Geoscience Commission, 1998).

Reverse osmosis represents the remaining 30% of global desalination operations. This technology also requires an experienced operator, chemicals for pre-treatment of feedwater, and a reliable energy source. According to South Pacific Applied Geoscience Commission (1998), membranes should be replaced every 3 to 5 years and the membranes represent one-third of the system cost, so this is an expensive technology to maintain. Reverse osmosis has the advantage of having the ability to remove both ionic and non-ionic substances but is very sensitive to the presence of suspended solids.

Solar systems are largely experimental. They too require constant maintenance, although they are easy to operate. One of the major drawbacks for use on small islands is the requirement for a large land area to house any major solar facility (South Pacific Applied Geoscience Commission, 1998).

For a number of small islands, desalination represents a reasonable means of supplementing water supply during times of water scarcity (i.e., droughts). Examples exist in the Caribbean, South Pacific, and the Maldives, where desalination has been utilized to meet this function (South Pacific Applied Geoscience Commission, 1998, and Falkland, 2003). In the Maldives, in response to rapid population growth and groundwater contamination in the vicinity of Male, the local government had little option but to turn to desalination to meet demand (Ibrahim *et al.*, 2003).

Environmental implications of desalination include groundwater contamination from leaking feedwater pipelines, disposal of salt, and the increased risk of chemical spills.

3.4.2.3 Importation

A number of islands currently import water, although it is expensive (South Pacific Applied Geoscience Commission, 1998). Importation may consist of water supplied via barge or submarine pipelines, or simply bottled water. With a few exceptions (Bahamas, outer islands of Fiji and Tonga), barging is rarely used as a primary source of potable water except during emergency periods such as droughts and after severe hurricanes (South Pacific Applied Geoscience Commission, 1998; Falkland, 2003). The use of barges to transport potable water requires significant capital expenditures for loading and unloading facilities, as well as storage capacity once the water has been unloaded. To reduce the risk of contamination, tanks on barges should be checked and cleaned regularly. Supply by barge can be limited due to sea conditions; the use of barges is therefore an expensive yet unreliable source. In the Gulf Islands of British Columbia, potable water is imported by tanker truck and ferry (personal observation). For North and South Pender Islands, water is currently being imported, as the shelves of the local stores are full of bottled water sourced from off island. Much of the fruit and vegetables sold locally are also produced off island and represent a form of imported water.

Submarine pipelines have a high capital cost, as well as potential for maintenance difficulties (South Pacific Applied Geoscience Commission, 1998). They are currently used to supply islands that are located close to large landmasses such as the Seychelles and Samoa (Falkland, 2003). Alley (2000) reports that in Wildwood, New Jersey, water is withdrawn from wells located 5 miles inland to meet the island's water needs during the summer. The utility takes the water and injects it into a shallow aquifer on the island during low periods of use, withdrawing it during high periods of use. This solution has spared the community the expense of large pumping facilities and transmission lines.

Water availability from an importation perspective can also be severely impacted by the existing legal and institutional framework. At present the Gulf Islands of British Columbia are managed by the Islands Trust which has as one of its mandates that there should be no off island source of water. There is no enforcement of this mandate. Water trucks remain a common site on the ferries to the Gulf Islands in the late summer and early fall and, on a much smaller scale, bottled water sourced off island is sold in the local stores (personal observation).

3.4.2.4 Wastewater Re-use

Wastewater can be used to augment water supply. Freidler (2001) suggests that treated wastewater can be considered a new water resource and as such, can be added to the water balance. On the Pender Islands, all residents could presently re-use water through the employment graywater. Treating wastewater and re-using the resultant water could be undertaken in Magic Lake Estates and possibly Poets Cove. Treated wastewater and graywater systems could be used for a number of applications that do not require potable water such as toilet flushing, clothes washing, and watering the garden (Drangert and Cronin, 2004).

Drangert and Cronin (2004) note that increased use of treated wastewater results in decreased demand for groundwater thereby conserving groundwater quality and reducing costs of sophisticated treatment costs to deal with poorer quality groundwater. The use of treated wastewater can require a dual distribution system, which is not without additional costs, including higher capital cost as well as increased operating and maintenance costs (South Pacific Applied Geoscience Commission, 1998). Dual water distribution systems are currently in use in the US Virgin Islands, St. Lucia, the Bahamas, Kiribati, and the Marshall Islands (South Pacific Applied Geoscience Commission, 1998).

3.4.2.5 Other Sources

A number of other unconventional water sources have been utilized in the past; there are some instances of ongoing research. Gleick (2002) quotes Falkland (1998) as saying that during severe droughts and natural disasters, residents of some of the smaller islands of Fiji and the Marshall Islands have relied on coconuts as a substitute for potable water.

Along the Chilean coast, the Canadian government sponsored a fog harvesting operation to supply much needed freshwater to a community (Brooks, 2002). The test appeared to be a success, but it has since been determined that the communal effort required to construct and maintain the system is too great. Research has shifted to dew harvesting, which has proven successful even in desert environments in preliminary trials (Brooks, 2002). Fog harvesting has also been utilized on the Island of Madeira (Prada and da Silva, 2001), where it was found that fog drip beneath the vegetation cover was three and one-half times greater than the annual precipitation.

Saline or brackish water can be used for toilet flushing and firefighting (South Pacific Applied Geoscience Commission, 1998). The use of saline and/or brackish water requires optimization of design and construction materials.

3.5 Water Demand

Robins *et al.* (1999) define water management as the need to manage the total quantity of water taken from the environment using measures to control both consumption and waste. Demands for water resources are often not coordinated with existing supplies, as demonstrated by the increased demands on water resources by tourists during the driest seasons of the year on small islands (Falkland, 1991). Falkland (2003) states that in the past, a water consumption rate, of 50 litres/person/day, was deemed to be sufficient to meet normal expectations of reasonable water consumption, but that it now appears that between 100 and 150 litres/person/day may be required, due to changing perspectives on water. To alleviate that situation, many areas are beginning to rely on water demand management. Through a decrease in water demand, it is possible to increase water supply/availability, so in many respects, water demand is simply a subset of water supply.

Population plays a significant role in both water supply and demand. In the last 50 years, however, the global population has grown at such a rate that the renewable supply of freshwater has fallen 58% on a per capita basis (Wolf, 2002). This per capita reduction further accentuates the need for demand management, as the supplies are deemed to be limited. The problem is not simply a matter of the increasing population on any given island but also changing land use and population growth in the surrounding area, which can cause concerns with respect to water scarcity. On North Pender Island, British Columbia, the population grew at a rate of 466%

between 1966 and 1991 (Henderson, 1998). It is estimated that the population of British Columbia will increase by over 36% between 2001 and 2031 (B.C. Ministry of Management Services, 2005) and that increase will place additional stress on water resources through a rise in tourism, particularly during the dry summer months. Many other islands (i.e., Samoa, the Maldives, and Hawaii) are experiencing similar population increases and the resulting pressures on fresh water resources (South Pacific Applied Geoscience Commission, 1998).

With the increased demand placed on limited fresh water supplies, the perspective began to change in the early 1990s from being supply-dominated to demand-dominated (Tate, 1990). Research indicates that effective pricing mechanisms can be successfully employed to reduce demand and thereby increase supply (Jordan, 1994). Rogers *et al.* (2002) presented three generally accepted pricing strategy effects: demand reduction, efficient reallocation, and increased supply. It is difficult to envision a reallocation of water resources on a number of small islands. A small population base results in higher costs per capita for water distribution systems; there is limited surface area for storage facilities; and costs for desalination would be high but should also include a distribution system.

Rogers *et al.* (2002) presented three strategy effects not generally associated with pricing policy: improved equity, improved managerial efficiency, and improved sustainability of the resource. Each of these strategy effects has the potential to have a significant impact on small island groundwater resource management. For small islands possessing a wide range of water delivery systems (from individual water wells to community water distribution), these strategy effects may be difficult to achieve without changes to the regulatory framework.

Research by Cavanaugh *et al.* (2001) indicates that the age and size of a house can be impacted by water pricing mechanisms, since older homes tend to use more water. This is related to the fact that generally, the older the home, the greater the potential for leaks and lack of water conserving appliances. It could be argued that the proper pricing policy would result in greater incentive to install such appliances. The research of Cavanaugh *et al.* (2001) did indicate a practical limit in house age, as there was a range (approximately 30 years) beyond which renovations to upgrade would generally have been already undertaken.

Jordan (1994) and Cavanaugh *et al.* (2001) show that increasing block rates for water result in lower consumption rates. In an increasing block rate scenario, the price per unit of water consumed increases as water consumption increases (Tietenberg, 1996). This approach can promote water conservation or decreased demand through a pricing structure that makes the marginal cost of consuming additional water quite high. A review of water system rate structures by Gleick (2002) indicated that with few exceptions (notably Turkey and Spain), few countries of any size are fully utilizing increasing block rates.

Agth and Billings (2002) researched the impact of water pricing on apartment complexes and discovered that the owners could control outside water use to reduce the impact of block pricing increases, but that there was little or no incentive for residents to control indoor use when all apartments share a common meter. It was felt that residents treated water as a free good. One means of alleviating this situation would be to install individual meters so that residents would have a sense of ownership over their water consumption. Meter installation would also send a clear message that water is not a free good.

A similar approach could be undertaken on small islands for hotels and other visitor accommodations. If each individual room had its own water meter, then a user pay principle could be adopted. Charges for water use could be treated in much the same manner as the current charges for telephone calls in hotels. For many locations, the additional charge for water would have little impact on the numbers of tourists. The funds from water usage should not stay with the hotel but rather revert back to the local community to fund water management programs. Reductions in water consumption could also result in reductions in energy consumption for the hotel, and that benefit would provide a reasonable pay back for water meter installation. Falkland (1991) estimated that water usage rates by tourists of 500 litres/day (130 gallons/day) are not uncommon. On the Maldives, specific islands have been set aside solely for tourism. These islands all have desalination plants to supply household water, while drinking water is generally from bottled water sold at what Ibrahim *et al.* (2003) refer to as a reasonable profit. Ibrahim *et al.* (2003) state that this is an affordable approach only as a result of the large revenue stream generated by the islands' tourism. Thus, a user pay system need not necessarily have a negative impact on tourism.

With increasing population, there is an increased demand for water delivery systems. All water delivery systems have leaks, so the use of water meters should be promoted as a means of identifying and locating leaks. Research by Colombo and Kerney (2002) found that leaky distribution systems are costly in terms of lost water, potential adverse effects on water quality, and energy consumption. On North Pender Island, Magic Lake Estates has had no water meters installed. It was estimated in 1996 that Magic Lake Estates were losing up to 45% of the water in the system to leaks (Island Tides, 1996), but meters have not yet been approved for installation. The pipeline system was replaced during the summer of 2003. The timing of the pipeline repairs could not have been better; due to low precipitation during the normally wet winter months of 2002, the Magic Lake Estates reservoir was at 48% of capacity and water was already being rationed (Island Tides, 2003). Gleick (2002) reports that on some South Pacific Islands, water losses of up to 70% have been noted – losses due to aging and poorly installed infrastructure. The proper maintenance and management of water delivery systems can be a means of meeting increased demand through more efficient use of the existing water supply.

There is a current trend toward the commodification of water (Gleick, 2002). Unlike the case of other fluid commodities, there are no rules governing the exploitation and trading of water. This absence of regulation contrasts, for example, with the Securities Commission National Policy 41-101 governing the definition of resources and reserves for oil and gas (Canadian Securities Commission, 2006). The commodification of water raises some interesting ethical questions, because a private company is in business to make a reasonable return on investment for shareholders. A private enterprise will not have the same motivation as a public corporation to conserve water and sell less. Instead, for the private company, increased consumption would translate to increased profit.

It is often difficult to separate the influence of pricing policy from conservation measures, since a well-conceived pricing scheme would also promote conservation (Cosgrove and Rijsberman, 2000). Tate (1990) states that use of water meters alone can reduce municipal water consumption by 15 - 20% over pre-metering levels. The implementation of a block pricing scheme would likely significantly reduce water consumption even further. Water-efficient plumbing fixtures have been proven to reduce water consumption (City of Calgary, 2002). In 1992, the implementation of the National Plumbing Standards in California offered the potential to reduce average per capita indoor water use by approximately 35% (Chaplin, 1998). Additional improvements in efficiency of fixtures since that time provide the opportunity to further reduce consumption.

Table 3.3: Savings per household from changing to water efficient fixtures (adapted from City of Calgary, 2002)

Fixture	**Rate of Use, 1970**	**Rate of Use, 1992**	**Rate of Use, 2003**	**Annual Savings 1970-2003**
Showerhead[2]	10 litres/min	6 litres/min	4 litres/min	54312 litres
ClothesWasher[3]	n/a	8 litres/min	6 litres/min	9052 litres
Dishwasher[4]	n/a	40 litres/load	26 litres/load	4380 litres
Toilet[5]	20 litres/flush	6 litres/flush	3.8 litres/flush	77424 litres
Faucet[6]	19 litres/min	6 litres/min	2 litres/min	153884 litres

The table is based on these assumptions:

1) There are 2.7 persons/household.
2) Based on an average of 37 minutes showering/person/week.
3) Based on an average of 3 loads of laundry/person/week.
4) Based on an average of 2 loads of dishes/person/week.
5) Based on an average of 36 toilet flushes/person/week.

6) Based on an average of 57 minutes of tap running/person/week.

Table 3.3 presents a chart of water savings per household in Calgary, Alberta, through the use of higher efficiency water fixtures. It can be seen that the increases in water efficiency were high between 1970 and 1992, and somewhat lower between 1992 and 2003; this pattern shows the law of diminishing returns. The 2003 levels will likely not be reduced substantially in the future, although it is possible to have a toilet requiring almost no water and there are further opportunities for reduced potable water consumption through increased graywater use (Chaplin, 1998). Chaplin (1998) also notes that a study in Los Angeles found that graywater use could reduce household consumption of potable water by 50%. The total annual saving per household if changes had been made from 1970 to 2003 would be approximately 300,000 litres (79,260 gallons), which translates to about 820 litres/day/household (216 gallons/day/household). Given a daily human requirement of 50 litres (13.2 gallons) (Gleick, 1998b), the savings would represent the water needs of the equivalent of over 16 persons/household. The impact of water conservation measures is enormous. Additional benefits of water-use efficiency include reductions in peak water system loads and in peak energy demands (Gleick, 2002).

If the benefits of water conservation are to be maximized, effort must be expended on education. The City of Calgary (2002) distributes an educational newsletter with their monthly water bill in an effort to encourage conservation measures. On small islands, there are often many residents who are not a part of a water distribution system, and that reality can jeopardize the success of this educational approach. Heath and Mitchell (2002) quote Benninger and Robinson (1984), who found that a 10% reduction in water demand could be achieved through education alone. On the basis of the general conclusions drawn from Table 3.3, potential rewards are worth the effort of educating, even at the individual well owner level. In Des Moines, Iowa, Peckumn (2003) instructs citizens on water use practices; Peckumn places special emphasis on elementary age students since their research indicated that it was important to target young children. Other researchers have found that the more clearly citizens understand issues, the more apt they are to assist in developing effective solutions (Ammons and Rawls Hill, 2000).

Part of the education process for both water conservation and re-use is geared towards altering existing behaviour patterns. The challenge, according to Burby (2003), is to use information, persuasion and other means to bring about mutual understanding, minimize or resolve potential conflicts, and achieve consensus on a course of action. These goals could be viewed under the umbrella of social marketing. Heath and Mitchell (2002) promote the use of social marketing to break down the barriers to the adoption of a belief or behaviour needed to change water consumption patterns, but there has been limited research beyond the local scale. Crouch (1993) remarks that although the behaviour of water is consistent, humans are on a vicious cycle of repeatedly rediscovering information about that behaviour. There are many different value and cultural systems within the global framework, and the increased mobility of humans has brought about a mixture of global and local values. A great deal of research is required to investigate the implications of these variations for water resources management (Vaux, 2002).

The perception of groundwater issues by the public often results in conflicts between those for and against development. Creating public awareness of water issues through public forums, demonstrations on how to achieve water savings, distribution of water conservation booklets, presentations in local schools, and educating planning committee members on water topics related to planning (Lyman, 1993).

A strong institutional framework is needed to encompass society’s differences in perspective on the goals and approaches for water management. Kreitler (2000) states there will always be those who believe that their use of water is more important than the needs of someone else, and as long as we have differing perspectives on the use of shared water in society, there will be a need for checks and balances to prevent excessive uses of water by any individual or group.

In many ways, institutions can play a role in water resources management. Their role is even more critical on small islands where financial resources can be as scarce as the water resources that are to be managed. Kreutzwiser and de Loe (2002) determined that local governments play a key role in water resources protection and management since they have the ability to direct and influence land use.

Narasimhan (2003) believes that the responsibility of government is to provide a guarantee of resource stability, although he notes that this includes the recognition that natural systems do change both naturally and anthropogenically. In this context, the role of institutions is also going through a series of innovations as the system of assuring water resource stability that had been devised in the nineteenth century, is now changing and stakeholder participation is now deemed a requirement (Vaux, 2002). It has been realized that when citizens have a part in shaping policy proposals, they are more likely to develop a sense of ownership and control (Burby, 2003). On North Pender Island, the Improvement District of Trincomali was formed at the request of its citizens to manage water resources (Henderson, 1998; Henderson and Revel, 2000). A question remains concerning how the next generation of property owners will respond to the demands of operating and maintaining a system that they had no part in setting up. The sense of ownership may not be there, but since the community is so small, it is possible that community interests will override individual wants and needs.

3.6 Integrated Water Resource Management (IWRM)

Integrated water resource management represents a holistic, systems-oriented approach to water management that places emphasis on stakeholder participation and partnership (Ramir, 2004). According to Ramir (2004), no single, unified definition for the concept of IWRM currently exists.

Integrated water resource management (IWRM) requires a balanced evaluation of both the water supply and water demand management options to meet future demands at a minimal economic cost and environmental impact (Song, 2000). As the Global Water Partnership (2002) states, we all live downstream regardless of whether we are discussing surface or ground waters. For North and South Pender Islands, knowledge of the groundwater resource base should be a requirement. This knowledge would enable an unbiased evaluation of water supply and demand management options.

Heathcote (1998) provides a simple graphical illustration of the multiple forces affecting integrated water resource management (Figure 3.2). IWRM represents a departure from the classical approach of simply attempting to increase supply by viewing aquifers as resources to be exploited to meet human needs; IWRM recognizes the life support role played by the aquifers (Postel, 2003). This changing viewpoint raises new questions concerning the value of water from a physical, social, economic and political perspective. For example, how much water can be extracted from an aquifer before water quality decreases (Gossling, 2001)? These new questions result from the incorporation into integrated water resource management of not only physical sciences but also social sciences. The UN Agenda 21 states that IWRM is based on the perception of water as an integral part of the ecosystem, a natural resource, and a social and economic good (Gleick, 2002). This approach places water in a unique position from a resource perspective. Water is deemed to be both a commodity and a social good, yet it has no substitutes. Miloradov and Marjanovic (1998) note that since a portion of the available water must remain in place to support the ecosystem, the quantity and quality of water that can be managed is less than that available for human use. Thus, it is more difficult to provide useful, accurate information concerning water resource potential for any given island. Because of the lack of any guidelines for water resource assessment, planning decisions are being made with little or no knowledge of the actual resource potential and the impacts of exploitation of the resource. This is certainly the case in the Gulf Islands of British Columbia.

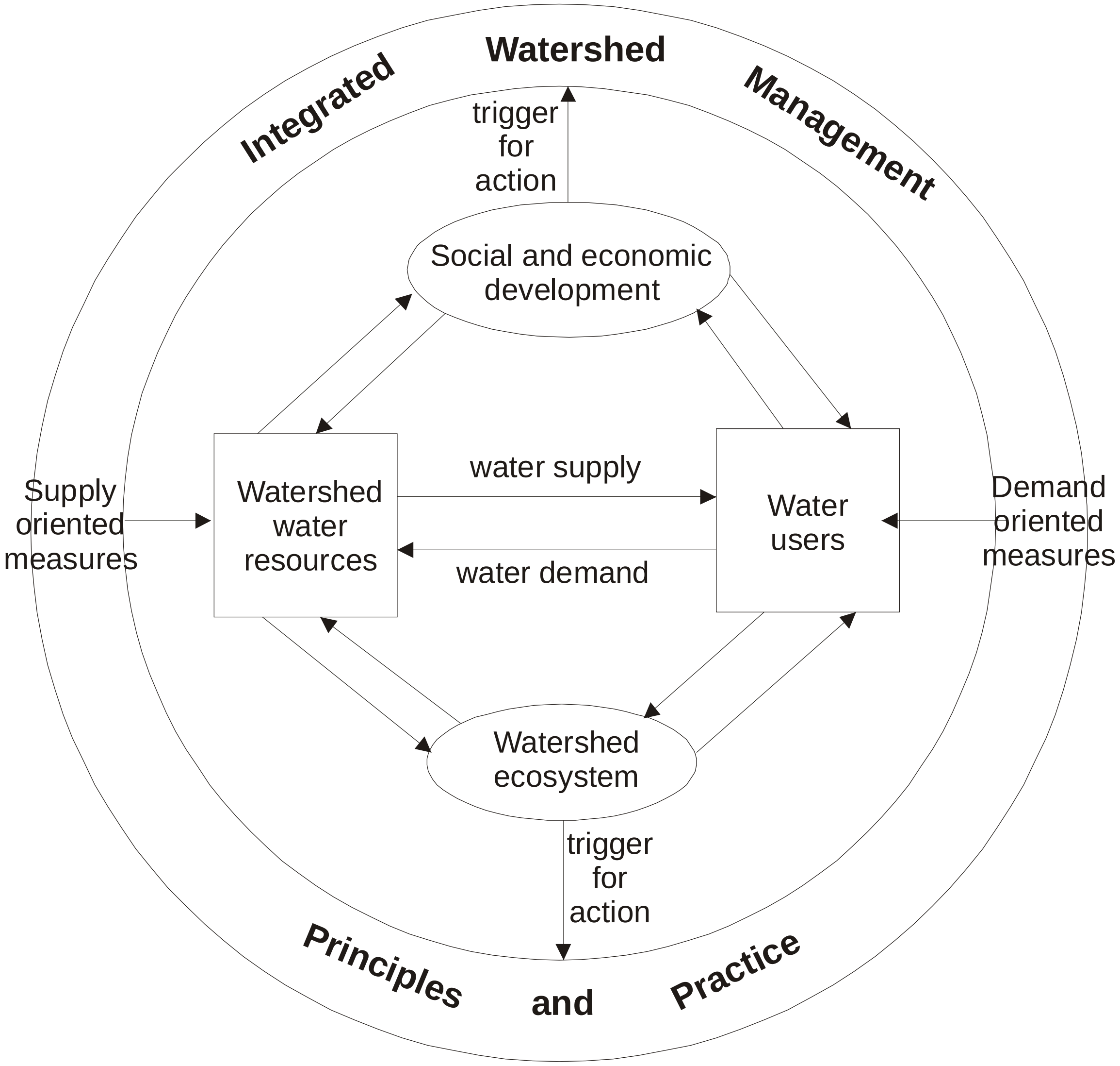

Figure 3.2: Forces affecting integrated watershed management (Heathcote, 1998).

A method espoused by the OAS (1996) to support IWRM is conducting water resource assessments to provide knowledge of the physical quantity and quality of the water to be managed. The Global Water Partnership (2002) has taken steps to promote the application of IWRM by preparing a "toolbox" available on the web at www.gwpforum.org/iwrmtoolbox to assist in the implementation of principles and practices. The toolbox has been subdivided into the following three categories:

- Enabling Environment, consisting of policy, legislation, financial support;
- Institutional Roles, including organizational framework, institutional capacity building;
- Management Instruments, including water resource assessment, IWRM plans, demand management, social change, conflict resolution, regulatory instruments, economic instruments, information management and exchange.

There are barriers to the implementation of IWRM. Ramir (2004) states that there is currently no operational model that sets out the procedural elements of IWRM and there also exist significant political, institutional, academic and scientific barriers to successful implementation. Mitchell (1990) notes that because of the vertical and horizontal fragmentation of institutions in Canada, an environment is created that rewards only those who concentrate on their own area of interest. That approach is not conducive to the interaction required between agencies for IWRM.

3.7 Modelling

In water studies, models of many varieties are used as a guide to assist analysts in their investigations. Mitasova and Milas (1998) define process modelling as the theoretical concepts and computational methods that describe, represent and simulate the functioning of real-world processes. As Tidwell *et al.* (2004) note, models are needed to couple the complex physics governing water supply and the diverse social and environmental driving forces of water demand. The accuracy of any model is a function of the accuracy of the parameter estimations (Mays, 1996). In general, since physical reality is so complex, the more parameters that are included in a given model, the less stochastically uncertain the model will be (Fisher *et al.*, 2002). Additionally, the reliability of the initial and boundary conditions have a significant influence on model accuracy (Mays, 1996). Fisher *et al.* (2002) point out that different models using the same data can yield different results and as a result, there is no unique solution for a given groundwater system. Bredehoeft (2002) defines the groundwater model as a tool with which to investigate the dynamics of a real-world aquifer. By simplifying process parameters, one can simulate groundwater flow and storage and so acquire a better understanding of aquifer dynamics and determine the impact of stresses imposed upon the aquifer. The mere act of simplifying processes results in the introduction of assumptions, which lead to inaccuracies. Simplifying models can add to the non-uniqueness of solutions for a given groundwater system (Bear and Verruijt, 1987; Reddi, 1990).

Models are required to simplify reality and enable stakeholders to understand natural processes. Models can be classified by area of concentration such as area of application, type of spatial distribution, nature of spatial interactions, and underlying physical or social process (Mitasova and Milas, 1998).

The first simulation attempts relied upon analog models of physical systems (ASCE, 1996). These models were useful but limited due to physical and economic restrictions and lack of flexibility of application (ASCE, 1996). In recent times, numerical models have routinely been applied to regional watershed and groundwater investigations.

Adams (2002) states that water resource managers and planners cannot be expected to have much faith in hydrologic analysis or model predictions unless there is sufficient data available to both verify and drive the models. Generally time and effort have to be expended to plan and acquire sufficient data before modeling starts. This requirement increases the cost of modeling. With increased time, fewer options may become available for management action, due to a decrease in resource potential or degradation of resource quality. Time frames, on the order of decades, have been recommended by Taylor and Alley (2002), so that a sufficient hydrologic record can be compiled, encompassing the range of potential values to be considered in the tracking of trends. This point was also stressed by Grondin *et al.* (1990) over a decade earlier when they correlated the unreliability of predictions to inadequate and insufficient data.

Models for groundwater storage and flow include conceptual, economic, management, political, numerical, and analytical. The models thus cover the full spectrum from social science to natural science. Each type of model has a beneficial role to play during times of limited supply.

In 1990, the National Research Council conducted a review of groundwater modeling and concluded that properly applied models are useful tools for: 1) identifying problems, 2) designing remediation strategies, 3) conceptualizing and studying flow processes, 4) providing decision-making information, and 5) recognizing the limitations of the data and acting as a guide for collection of additional data.

If a model is to be useful, there should be a clear and concise set of objectives. Some models can cover a wide range of circumstances while others have very specific applications. Bachmat *et al.* (1980) propose that the concise statement of a problem is a prerequisite to the solution, although they also point out that managers often find it difficult to state objectives explicitly. The objectives of a water-modelling program must include forecasting water scarcity and should be closely related to the root cause of the scarcity. Resources might be limited due to circumstances such as increased population, aquifer depletion, drought, aquifer contamination, or salt water intrusion. Each of those circumstances would demand a different modelling approach. As with most aspects of water resources, there is a degree of overlap within these causes. Some consideration must also be given to the time scale of the limited resources. The time and spatial scales can be as important for modelling as the understanding of the initial conditions (Heathcote, 1998). Is the time scale of short duration due to a drought or seasonal influx of tourists, or are we dealing with a longer term issue related to overpopulation within the community or with aquifer contamination? Hsaio and Chang (2002) stated that the temporal nature of water resource systems requires simulation models to be dynamic to yield satisfactory results. In a proactive approach, even during a short duration water scarcity period, modelling may identify means of avoiding long-term periods of limited water resources in the future.

It is important to have a clear understanding of the limitations of modelling. The accuracy of any model is a function of the accuracy of the parameter estimations, the heterogeneity of aquifer characteristics, and the number of discrete observation points (Alley *et al.*, 2002). Initial state and boundary conditions also have an impact on model accuracy (Mays, 1996), and rarely is the initial state ever duplicated. The nature of water resources is chaotic. Faybishenko (2002) cites the use of chaos theory to describe flow processes because the processes are non-linear, sensitive to initial conditions and dissipative. The use of chaos theory also correlates well with the variable nature of climatic conditions in time and space.

There are many different groundwater models to choose from, and this wide choice can add conflict and confusion. The National Research Council (1990) reviewed approximately 300 groundwater modelling programs. The majority of the programs use numerical or analytical approaches to solve groundwater flow and contaminant transport problems. There are currently many more groundwater modelling programs on the market (Appendix A). Because we are dealing with a small island scenario and investigating the social, economic, and political, as well as the physical groundwater modelling, many of these programs are inadequate to meet current needs. Falkland (2003) states there are only limited analytical solutions available for island scenarios and that they assume idealized boundary conditions. One of the best programs currently in wide use is MODFLOW, prepared by the US Geological Survey and available at no cost from their website (Harbaugh, 2007). MODFLOW is a modular, three-dimensional, finite difference approach to groundwater modeling that has been developed so that other modelling packages can be incorporated into it (Harbaugh *et al.*, 2000). By itself, MODFLOW does not address non-scientific issues such as how policy changes would impact water availability but could be incorporated into a systems dynamics modelling approach that would address non-scientific issue.

Reddi (1990) recommended the inclusion of the following in the selection and use of any groundwater model:

- An evaluation of the magnitude of the problem under consideration.
- A conceptualization of the problem.
- A review of the parameter availability.
- A sensitivity analysis of the results.

If an appropriate model can be found, its predictive capability is important; the model should enhance understanding of current conditions while providing a forecast of water supply in response to drought conditions or aquifer contamination (Alley *et al.*, 2002). As Stave (2003) suggests, any model must be validated against observed data. The validation process assists in getting the public to accept the modeling process. One of the greatest difficulties in application of water models to North and South Pender Islands is that the bulk of the groundwater resources occur along discrete faults and fractures within the bedrock, the distribution and properties of which are mostly unknown.

Recently efforts have been made to develop comprehensive, easy-to-use decision-support systems that are capable of addressing a wide range of issues including (BGR, 2003):

- Determine limits of development
- Evaluate impact of new legislation
- Assess environmental impact of water related development

There is software, WaterWare, developed by Water Resource Systems Research Laboratory and Environmental Software and Services that presents an integrated, model-based information and decision-support system for water resources management. WaterWare can perform scenario analysis, as well as related engineering, environmental and economic aspects of water resource management (BGR, 2003). WaterWare is, however, designed more for surface water than for groundwater resource management.

3.8 Summary

This chapter has provided background information on groundwater assessment in general and for small islands in particular through an examination of the components of the water balance equation. These components have been reviewed in light of how they influence water availability and demand with the reliance on precipitation as a temporally and spatially variable water source highly evident. The variability in the major water supply source warrants inspection of alternative sources with which it may be possible to reduce some of the peaks and troughs in water supply while making management of water resources an easier task.

The following three chapters investigate the climatic conditions, geological, hydrogeological and geophysical properties of the soils and bedrock types on North and South Pender Islands. The information presented in the following chapters can be used to better understand the physical setting for groundwater resources within the study area.