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NORTH SASKATCHEWAN WATERSHED ALLIANCE

North Saskatchewan River Basin

Overview of Groundwater Conditions, Issues, and Challenges

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SYNOPSIS

"Groundwater is a covenant with future generations. It is a necessary backup supply for emerging needs and to provide flexibility in responding to hydrological variability and to climate change. This generation could provide an important legacy to descendents by attending to emerging groundwater governance issues now."

- Ingram et al. 2007, "the Rosenberg Report"

Groundwater resources will play a critical role in defining the future economic and environmental well-being of the North Saskatchewan River basin. However, little detail is known of how much usable groundwater is stored in the basin, or of its dynamics of recharge and discharge, or ambient quality. The western basins are believed to be important areas of regional groundwater recharge and baseflow to the North Saskatchewan River, but regional quantities are unknown, as are specific sensitivities to forestry practices, land-use change, or climate change. Water in the central basins is under increasing demand due to agricultural, energy, industrial, and municipal development. Again, we have little explicit understanding of how the groundwater systems in the basins are responding cumulatively to groundwater extraction and human land use. In the eastern basins, water is generally less available and the reservoir of usable groundwater becomes thinner. At the same time, groundwater to the east is proportionately more important for agricultural, ecosystem, and municipal purposes. To date, groundwater information across the North Saskatchewan River basin has not been effectively synthesized or interpreted in terms of quantity or quality. Nevertheless, understanding of groundwater resources is essential for the health of the basin and requires a strong coordinated effort by this generation now. Key areas of further study are the dynamics of the regional groundwater flow system in the headwaters of the basin and their sensitivities to land use and climate change. In addition, groundwater management frameworks should be developed for sub-basins or local areas having more dense population and competing land use, to establish a consistent and systematic approach to characterizing, monitoring, and protecting groundwater resources.

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1. INTRODUCTION

1.1 General

This report provides a broad overview of groundwater conditions, issues, and challenges within the North Saskatchewan River basin. The study provides:

- a snapshot of the current state of knowledge of the groundwater resources in the North Saskatchewan River basin; and
- an integration of recent available information on water use and human activity to indicate where groundwater resources may be vulnerable or where knowledge is weak.

The overall goal of this study was to compile the available knowledge of regional groundwater resources of the North Saskatchewan River basin, and evaluate it in the context of groundwater availability, use, and vulnerability within the basin. The report is intended to serve as a platform from which to manage and prioritize future key points of groundwater study for the North Saskatchewan Watershed Alliance and affiliated agencies.

1.2 Methods and Scope

All basins within the greater North Saskatchewan River watershed (within Alberta) were assessed in the work. To provide an understanding of the hydrogeology, available public data sources on groundwater were reviewed such as Prairie Farm Rehabilitation Administration, Alberta Geological Survey, Alberta Research Council, and Alberta Environment reports. The second major element of the study is a summary of groundwater use and vulnerability within the basin. The water use data are synthesized from an AMEC Earth & Environmental (2007) study to provide an overview of active water allocations, reported actual water use, and forecasted water use. Major communities that rely on groundwater are identified. From data in the State of the Watershed Report (North Saskatchewan Watershed Alliance 2005), land use and areas where groundwater may be vulnerable to contamination or overuse are identified.

The final element of the study highlights areas where the effective management of groundwater resources is challenged. Such challenges arise because of uncertainty, where prediction of risk to groundwater resources is limited by inadequate hydrogeologic knowledge and monitoring. Challenges also arise in areas where industrial, municipal, agricultural, and ecosystem interests all affect or depend on the groundwater. We identify and make broad recommendations regarding areas where groundwater resources appear most vulnerable to contamination or overuse. Finally, we recommend key areas of study of groundwater resources to improve watershed management.

2. OVERVIEW

2.1 Water for Life

Watershed health is an important global issue. Approximately 70 percent of the Earth's surface is covered with water, but less than three percent of it is fresh (Figure 1). Of the freshwater, over 97 percent of the accessible water (i.e., not locked in remote areas like ice caps or glaciers) is groundwater and less than three percent is surface water. Groundwater represents a vast reservoir of freshwater, but we know very little of the dynamics of this reservoir. Considering groundwater as a bank account, we have almost no specific information on how much capital is entering, leaving, or stored in the account, or the changing quality of the assets. Management of the groundwater resource cannot be effective without knowledge of such key characteristics as recharge and discharge rates, cumulative drawdown, and risks to groundwater quality and quantity. At the same time, groundwater represents an enormously valuable resource that will serve us well into the future if managed properly.

In Alberta, we have been largely dependent on surface water for most of our water needs. In recent years, however, Alberta has begun to face increasing pressures on surface water resources due to drought and agricultural, industrial, and municipal growth. Shortages of water are a risk to the health and well-being of ecosystems and the economy. In response, the Alberta Government unveiled its Water for Life strategy in 2003. The three main goals of the strategy are:

- safe, secure drinking water supply,
- healthy aquatic ecosystems, and
- reliable, quality water supplies for a sustainable economy.

Water for Life was based on the following commitments to Albertans:

- we will be assured that drinking water is safe;
- we will be assured that aquatic ecosystems are maintained and protected;
- we will be assured that water is managed effectively to support sustainable economic development.

A renewed Water for Life strategy was released in 2008, in which the government reaffirmed its commitment to the Water for Life approach, and recognized that the effects of climate change are becoming more prominent, and that groundwater resources have gained in importance as surface water allocations became more limited.

The Alberta Water Council recommended renewing the strategy around two key themes:

- safeguarding our water sources, including addressing aquatic ecosystem degradation, more fully integrating water and land management, and continuing to create, enhance and use innovative tools and best practices;

- being more proactive and accelerating actions to protect water sources now, including clarifying roles and accountabilities, improving data collection and analysis, and increasing public awareness.

The government accepted the recommendations. For aquatic ecosystems, key actions included developing a provincial action plan to improve the health of significantly-impacted aquatic ecosystems, setting water conservation objectives on all major basins, and finalizing and implementing a new wetland policy for Alberta. The government also recognized that having more comprehensive and robust information and knowledge of our provincial water resources is a critical element for effective water management. Key actions are to include:

- enhancing the provincial water monitoring and evaluation program including information on wetlands, groundwater, aquatic health, water quality, drinking water, and water supply; and
- enhancing the Alberta Water Information Centre to provide a web-based public information centre to report on the status of Alberta's water resources.

It was recognized that within each watershed a limited amount of water can be withdrawn while still maintaining healthy aquatic ecosystems. It was further acknowledged that the solution to water challenges must come from a combination of comprehensive knowledge and monitoring of the resource, along with improved water capture and storage options, and better water conservation practices.

2.2 The Rosenberg Report

The Rosenberg International Forum on Water Policy is based at the University of California. The Forum has two main objectives: (1) to emphasize the role of science in water management and water policy, and (2) to promote interaction between scientists and policy-makers in the making and executing of water policy. A Rosenberg workshop was convened at the request of Alberta Environment in June 2006, during the Water for Life renewal process. Alberta Environment asked the workshop panel to review the Water for Life strategy, identify weaknesses, and make recommendations to strengthen it. The panel was also asked to review the existing arrangements for governing and managing groundwater in Alberta, and make recommendations about how those arrangements could be improved. The outcome of the work is provided in Ingram et al. (2007), known as the "Rosenberg Report".

With respect to groundwater, key recommendations included the following.

- It is essential that the Water for Life strategy consider watersheds and aquifer systems together as the focus of management. Integration of these is essential if conjunctive use opportunities are to be addressed effectively.
- A lack of comprehensive water monitoring systems was identified as a critical weakness. Existing monitoring systems, especially those for groundwater, are inadequate. Without effective monitoring, the goals of the strategy (safe drinking water, healthy ecosystems, and reliable supplies) cannot be achieved. Timely interpretation of monitoring data is also essential.

- Groundwater monitoring networks thus need to be installed and maintained over time to ensure proper tracking of water level and water quality changes. The approach to monitoring should include on-going measurement of contamination and ecosystem health indices in the vicinity of agricultural, industrial, and municipal operations.
- It is also critically important to develop an inventory of water users, water uses, and water rights.
- Priority should be given to groundwater monitoring, data management, dissemination, and use with tools of analysis (including models) to generate groundwater level and groundwater quality maps and time-series graphs to understand and manage the groundwater resource.

As stated in the Rosenberg report, "previous practices of groundwater monitoring and management were appropriate to an era in which groundwater was a relatively minor source of supply in most areas. These practices will not be adequate in an era of intensifying pressure to develop groundwater resources."

2.3 Land-Use Framework and Cumulative Effects Management

Alberta's recently-introduced Land-use Framework sets out an approach to manage public and private lands and natural resources to achieve long-term economic, environmental, and social goals. It is intended to provide a blueprint for land-use management and decision-making that addresses growth pressures, while recognizing that lands should be managed to ensure healthy ecosystems.

The Land-use Framework creates seven regions for Alberta based on the major watersheds. Cumulative effects management will be used at a regional level, where cumulative effects means the combined effects of past, present and reasonably foreseeable human activities on a region's environmental objectives. Environmental objectives are to be established based on an understanding of environmental risks and socioeconomic values. Once the objectives are set, cumulative effects systems are intended to manage the environmental outcomes, recognizing that watersheds, airsheds, and lands are finite.

The government is to develop a process to identify appropriate thresholds, measurable management objectives, indicators and targets for the environment (air, land, water, and biodiversity) at the regional levels and, where appropriate, at local levels. Land-use planning and decision-making will be based on balancing these environmental objectives with economic and social considerations.

The Cumulative Effects Framework proposes the development of Environmental Sustainability Objectives and Environmental Sustainability Strategies generally for the province and for specific planning areas. The objectives would establish quantitative, measurable levels of ambient environmental quality for planning areas. The objectives developed would be specific to desired environmental results while considering the economic, health, and social implications.

The new cumulative effects management approach is being modelled first in the Industrial Heartland, an area north-east of Edmonton that has a strong existing industrial base and potentially-significant future industrial development. As part of the Industrial Heartland project, a series of science-based targets, outcomes, and actions have been set for the area to protect the air, land, and water. For example, these actions include:

- using science-based thresholds, baseline data and limits on 100 different parameters to ensure water quantity and quality outcomes are achieved; and,
- protecting wetlands and groundwater, ensuring that land is reclaimed, and mitigating any potential harmful changes to wildlife or habitat by implementing minimum setbacks from the North Saskatchewan River.

The environmental outcomes set for the Industrial Heartland are to be reviewed with stakeholders in the near future to determine the best and most efficient way to implement them, including establishing working groups to further refine the targets and assess how they can best be achieved.

3. NATURAL SETTING AND CONCEPTUAL FRAMEWORK

In the following sections, we describe in general terms the relations between groundwater, land use, and water use. We define basic concepts of groundwater flow, groundwater-surface water interaction, groundwater vulnerability, and the possible effects of climate change on water resources. We also describe briefly the existing Provincial groundwater monitoring network, current water supply, and broad water use issues in the North Saskatchewan River basin. Finally, we summarize the findings of the most recent state of the watershed report and outline the main goals of the integrated watershed management planning process.

3.1 Watersheds, Basins, and Groundwater

Strictly-speaking, a watershed is a topographic divide that separates one drainage area from another. The term is also used generally to mean a drainage basin or catchment area. A drainage basin is an area of land where water from rain or snowmelt drains downhill into a body of water, such as a stream, lake, or ocean. A drainage basin comprises the land surface from which the water drains and the streams that convey the water. The land surface topography determines where the water flows. Basins drain into other basins in a hierarchical form, with smaller ones or sub-basins grouped into larger ones. The drainage basin of the North Saskatchewan River in Alberta consists of 12 sub-basins (Figure 2). In this report, the sub-basins are grouped informally into “western”, “central”, and “eastern” basins as follows:

- western: Cline, Brazeau, Ram, and Clearwater;
- central: Modeste, Sturgeon, Strawberry, White Earth, and Beaverhill; and
- eastern: Vermilion, Frog, and Monnery.

The drainage basin is a basic unit of surface water hydrology. In groundwater hydrology, the basic unit of study is the groundwater basin, which is the subsurface volume through which groundwater flows, also in response to topography, but three-dimensionally in the subsurface from recharge to discharge areas. Whereas surface water flow rates are on the order of a few metres per second, groundwater flow rates are on the order of a few metres per year or less in deep, regional groundwater flow systems. The boundaries of a surface water basin and a groundwater basin do not necessarily coincide, as for example when a local sub-watershed is underlain by a regional groundwater flow system. Figures 4 to 8 provide regional information on land surface topography, temperature, precipitation, potential evapotranspiration, and land cover, which are discussed in the following sections.

3.2 Natural Regions and Subregions

Natural Regions are used to describe ecological units regionally in Alberta. Ecological land classification systems are a tool of resource management. Natural Regions are units on the land surface that are mapped on the basis of similar landscape features, which result from the combined effects of climate, topography, and geology. Features considered in the definition of a particular Natural Region are climate, physiography, vegetation, and soils. To the extent that wildlife and humans respond to climatic and land feature influences, wildlife distribution patterns and human land use patterns may also be useful in mapping Natural Regions. Natural Subregions are subdivisions of a Natural Region, generally characterized by climatic, vegetation, or physiographic differences within a given region (Natural Regions Committee 2006). The North Saskatchewan River basin in Alberta crosses four Natural Regions (Figure 3). To the west are the Rocky Mountain and Foothills Natural Regions. Across the central and eastern portions of the basin are the Boreal Forest and Parkland Natural Regions.

3.2.1 Rocky Mountain Natural Region

The Rocky Mountain Natural region has mountains, high foothills, and glacial valleys. It encompasses virtually the entire Cline watershed. Ground elevations generally decrease from west to east, from approximately 3,600 m above sea level (masl) along the continental divide to 1,500 to 1,000 masl in the lower valleys (Figure 4). Summers are short and cool. Mean annual temperatures range from -2.4^{o}C in the Alpine Subregion to 2.3^{o}C in the Montane Subregion (Figure 5). Average annual precipitation (approximately 800 mm) is geographically variable but relatively high compared to other Natural Regions (Figure 6). Evapotranspiration (see Section 3.3.1) also tends to be lower (Figure 7). Because storms generally move east, the west sides of the mountains receive the most precipitation while the eastern lowlands are in the rain shadows. Trees are absent at the higher elevations (Alpine Subregion), while coniferous forests are dominant at the lower elevations (Subalpine Subregion), with grasslands and mixedwood forests at the lower elevations (Montane Subregion) where locally warmer conditions may prevail (Figure 8).

In the Alpine Subregion, water exists mainly as glaciers and snowfields, generally near the continental divide. Alpine lakes and the headwaters of the North Saskatchewan and Brazeau Rivers are fed by glacial meltwaters. Lakes and wetlands are generally uncommon or small in the Rocky Mountain region but may occur in valley bottoms. An exception is Abraham Lake, which is a relatively large artificial lake that was created on the North Saskatchewan River by the 1972 construction of the Bighorn Dam. Calcareous fens and marshes are present in the Montane Subregion (Natural Regions Committee 2006).

3.2.2 Foothills Natural Region

The Foothills Natural Region has steeply sloping hills and coniferous forests at higher elevations (approximately 1,500 masl) and strongly rolling to gently undulating hills and deciduous or mixedwood forests at lower elevations. The Foothills Region occupies the eastern portions of the Brazeau, Ram, and Clearwater watersheds (Figure 3). The mean annual temperature varies from approximately 1.3^{o}C in the Upper Foothills to 1.8^{o}C in the Lower Foothills. Mean annual precipitation is approximately 540 mm in the Upper Foothills Subregion and approximately 465 mm in the Lower Foothills Subregion, of which two-thirds falls between May and September in both subregions. Average July precipitation (approximately 110 mm) is higher in the Foothills Region than in any other Natural Region in Alberta at that time of year. Deciduous and mixedwood forests (e.g., aspen, balsam poplar, white Birch) are typical of the lower elevations, and coniferous forests are dominant at the higher elevations. Lodgepole pine stands distinguish the Foothills Natural Region from the Boreal Forest Natural Region (Natural Regions

Committee 2006). The mountain pine beetle has killed mature lodgepole pine over eight million hectares in British Columbia and is becoming established east of the Rocky Mountains in the Peace District and several locations in western Alberta.

Few lakes are in the Foothills Natural Region, although the man-made Brazeau Reservoir is an exception. Wetlands occupy about 10 percent of the Upper Foothills Natural Subregion, and are confined to the major valleys. In the Lower Foothills, wetlands can cover up to 40 percent of an area of valley bottom.

3.2.3 Boreal Forest Natural Region

Level to undulating plains interspersed with extensive wetlands predominates in the Boreal Forest Natural Region, although hummocky landscapes and extensive dune fields (i.e., eolian deposits) also occur. Portions of the Boreal Forest Region occur in the Central and Eastern watersheds (Figure 3). The mean annual temperature varies from approximately 0.2°C in the Central Mixedwood Subregion to 1.1°C in the Dry Mixedwood Subregion, while mean annual precipitation is approximately 470 mm in both cases. About 70 percent of the annual precipitation falls from April to August. Peak precipitation is in June and July and is often associated with intense storm events. A unit of the Boreal Forest Dry Mixedwood Subregion occurs east of Edmonton in the Cooking Lake area in association with the Beaver Hills. The Boreal Forest Natural Region is generally described as a mosaic of upland forests and extensive wetlands in low-lying areas. Aspen and balsam poplar are the most common deciduous species. White spruce, black spruce, and jack pine are the dominant conifers. Clean forests of jack pine with lichen understory can develop on dry, well-drained sandy soils. Wetlands are dominantly black spruce, shrub, or sedge fens. Even subtle differences in local ground elevation (i.e., on the order of 0.5 m) in the Boreal Forest Natural Region can produce large differences in moisture and the corresponding development of upland or wetland communities (Natural Regions Committee 2006).

3.2.4 Parkland Natural Region

The topography of the Parkland Natural Region is generally level to undulating. The Parkland Region generally occurs in the central watersheds around Edmonton and in the eastern watersheds south of the North Saskatchewan River. The mean annual temperature is similar to the Montane Subregion (approximately 2.3°C) but mean annual precipitation is less (approximately 441 mm). Average July precipitation is approximately 80 mm. Within and surrounding the City of Edmonton, the region has relatively dense urban and residential rural populations. Outside of Edmonton, the region is covered largely by agricultural land use. Farmland is cultivated on Black Chernozems, although remnant native vegetation can occur on hummocky to rolling terrain where cultivation is difficult. The rich Chernozemic soils reflect the past occurrence of productive grasslands that developed under long, warm growing seasons and resulted in the gradual accumulation of organic matter into deep humus layers (Natural Regions Committee 2006). Solonetzic soils, which develop where parent materials or local groundwater discharge are saline or sodic, can cover significant areas in the Central Parkland Subregion. Gleysols are associated with wetlands, which reportedly occur over approximately 5 to 10 percent of the Central Parkland.

The wetlands of the Central Parkland Subregion have been called the "Duck Factory" of North America. Although few species are unique to the Parkland Region, combinations of plant communities and wildlife assemblages create a diversity of distinct habitats. The Parkland Natural Region is unique to North America and occurs mainly in Canada (Natural Regions Committee 2006).

3.3 Concepts of Hydrogeology

3.3.1 Groundwater Flow

Groundwater occurs in the empty spaces of the rocks and soils beneath our feet. The water storage and transmission properties of the rocks and soils depend on their structure, texture, and composition. Porosity refers to the proportion of rock or soil that is empty space. The storage properties of a rock are related to porosity. High porosity does not necessarily translate to high permeability if the empty spaces are poorly connected. Permeability or hydraulic conductivity is a measure of a soil's ability to transmit water. Permeability tends to be high in sands and gravels and low in silts and clays.

In a given area, precipitation falls more or less equally across the land surface. Some of the water quickly evaporates back to the atmosphere (evaporation) or is taken up by plants (transpiration), some of it flows overland as surface water, and some of it infiltrates into the ground and arrives at the water table as groundwater recharge (Figure 9). It is generally difficult to separate the water lost as vapour by evaporation from the water lost to the atmosphere by plant uptake, so the total is lumped together as evapotranspiration. Potential evapotranspiration is calculated on the basis of average air temperature and sunlight (Thornwaite and Mather 1955) and assumes there is sufficient soil water to meet the demand of vegetation. Frequently, soil moisture is not sufficient, so that actual evapotranspiration is used to describe the amount of evapotranspiration that actually occurs under field conditions. Actual evapotranspiration is always less than potential evapotranspiration. Most of the water lost to evapotranspiration takes place during the summer months. Evapotranspiration is the largest consumptive use of water in all but the most humid and cool watersheds.

The pores in the soil or rock below the water table are generally saturated with water. In Alberta, the depth to the water table is generally from 1 to 10 m below ground surface (mbgs). The base of groundwater protection or depth to "non-saline" groundwater (i.e., mineralization less than 4,000 mg/L total dissolved solids or TDS) generally varies from 100 to over 600 mbgs (EUB 2007). The zone between the water table and the base of groundwater protection is the usual zone of interest in groundwater resource assessment. Generally, expected mineralization of groundwater in the upper 100 mbgs is 1,500 mg/L TDS or less, but groundwater with mineralization between 4,000 and 10,000 mg/L TDS can now be treated economically and is an important resource in many parts of the world (Ingram et al. 2007).

Aquifers are geologic units that can provide water of sufficient quantity and quality for an intended use. An aquifer for a household may not be an aquifer for an industry. Aquitards are lower permeability geologic units that impede groundwater flow. An unconfined aquifer has the water table as its upper surface (Figure 10). A confined aquifer is bound above and below by an aquitard. In Alberta, from the point of view of potential water supply, there are two main types of aquifer: sandstone or fractured coal units in the uppermost bedrock formations and buried pre-glacial valleys incised on the bedrock surface and filled with sand and gravel deposits. Shallow dune or glacial stream deposits can also be important for transmission and storage of water, particularly for local residential purposes or ecosystems (e.g., springs, wetlands).

In continental areas, groundwater flow is controlled mainly by differences in topography. The water table configuration generally mirrors the ground surface topography. Differences in the energy of the groundwater, owing to differences in land surface topography (and hence water table elevation, and hence position of the water in the earth's gravitational field), continuously drive the flow of groundwater. The groundwater system as a whole is a hydraulically-continuous, three-dimensional flow field that crosses all manner of geologic boundaries. Differences in scale of topography result in differences in scale of groundwater flow system (Figure 11). Regional groundwater flow systems originate in regional-scale topographic highs (i.e., mountains) and discharge hundreds of kilometres away in regional-scale topographic lows (i.e., large lakes or rivers). It can take millennia for groundwater to travel across such systems. In local flow systems, groundwater is recharged in local hills and discharged in local depressions. Groundwater travel times in local systems can range from a few years to decades to centuries (Figure 12).

Changes in groundwater quality naturally occur as the groundwater flows through the subsurface and dissolves or exchanges mineral matter. In recharge areas, groundwater has low mineralization (i.e., approximately 500 mg/L TDS or less). The predominant cations (i.e., positively-charged ions) are calcium and magnesium and the dominant anion (i.e., negatively-charged ion) is usually bicarbonate, so the groundwater is called a "calcium-magnesium-bicarbonate hydrochemical type". In zones of active flow in bedrock, the calcium and magnesium are exchanged for sodium and the water is generally a sodium-bicarbonate type with mineralization less than 1,500 mg/L TDS. Most bottled mineral water is either a calcium-magnesium or sodium-bicarbonate type with mineralization less than 1,000 mg/L TDS. In deep, regional flow systems water can be a sodium-chloride type with mineralization far exceeding 10,000 mg/L TDS.

The flow of groundwater and thus transport of dissolved matter can result in a myriad of natural phenomena. Local discharge of sodium-sulphate type waters, for example, can lead to naturally saline soils. Many wetlands depend on a relatively stable flux of groundwater, which is a steady supply of water maintained despite changing seasonal and annual weather conditions. If the groundwater flow patterns are maintained for a sufficiently long time, the transport processes may produce characteristic hydrological, hydrochemical, soil chemical, geomorphological, thermal, and other conditions on the land surface. These conditions, in turn may have a controlling influence on an ecosystem by encouraging certain flora and fauna while constraining others (Tóth 1990). On a geological scale of time and regional scale of distance, gravity-induced cross-formational flow can lead naturally to the accumulation of hydrocarbons and certain types of metallic (e.g., copper or lead-zinc) ore-deposits (Tóth 1984).

3.3.2 Groundwater, Surface Water, and Land Use

Understanding the interaction of groundwater, surface water, and land use is essential to water scientists and water managers, and fundamental to the development of effective water resource management and policy. For example, groundwater contamination in agricultural or industrial land use settings usually occurs in shallow aquifers that are more likely directly connected to surface water. Contaminated groundwater can be a long-term contributor to surface water contamination, or conversely, clean groundwater can help to improve surface water quality. Determining the ways that groundwater can diminish or improve surface water quality is a critical element of effective watershed management. As another example, wetlands can be highly sensitive to the effects of groundwater extraction or land-use changes that modify the groundwater level, flow, or chemistry conditions critical for wetland ecosystems. As well, groundwater moves on a different time scale than surface water, and the effects of change may be manifested very slowly.

Streams interact with groundwater in different ways (Figure 13). Streams can gain water by the inflow of groundwater through the streambed (i.e., gaining stream) or lose water to groundwater by the outflow through the streambed (i.e., losing stream) or both, by gaining in some reaches and losing in others. Change from gaining to losing can be induced by groundwater pumping (Figure 14). Bank storage is the process whereby a rapid rise in stream stage, due to a storm event for example, causes water to move from the stream into the stream banks, tending to attenuate flood peaks. After the storm event, water in bank storage can return to the stream over a period of days or weeks to later supplement streamflows. Contribution of bank storage must be distinguished from groundwater discharge in the analysis of baseflow regression hydrographs.

The hyporheic zone is the region beneath and lateral to a streambed. It can extend from a few to many tens of metres, and is an important zone of dynamic mixing of groundwater and surface water. Mixing of the two has major effects on the chemistry (e.g., acidity, temperature, dissolved oxygen, and nutrients) of aquatic environments (Winter et al. 1999). The interface creates a dynamic habitat for aquatic fauna. Changes in the biogeochemical processes that occur in the hyporheic zone, as may be caused by human activities, can have a major effect on aquatic ecosystems, for example fish spawning in sediments where concentration of dissolved oxygen is high. Hyporheic zones serve as sites for nutrient cycling. Delivery of dissolved oxygen, carbon, and nitrogen can stimulate the biological uptake of nitrogen by microbes in the sediment, for example, thus improving water quality by reducing the concentration of dissolved nitrogen in the stream (Winter et al. 1999).

Like streams, wetlands can also receive groundwater inflow or recharge groundwater or both. Unlike streams, wetlands do not always occur in topographically low areas of a drainage basin. Fens occur on slopes and tend to receive a continuous source of groundwater discharge. A constant source of water allows the growth of wetland plants. Bogs receive most of their water from precipitation and occur on uplands or flatlands that drain slowly. Since wetlands are frequently underlain by fine-grained and decomposed organic sediments, the transfer of water and dissolved matter occurs more slowly than, for example, a stream or lake bedded by sand or gravel. The biogeochemistry of wetlands can be significantly affected by the chemistry of the groundwater and the direction and magnitude of flow, but change may occur very slowly (Winter et al. 1999).

A spring is a place where the groundwater surface meets the land surface. Springs can have cultural significance, in terms of First Nations or later roles in human habitation. Springs can also have therapeutic, aesthetic, and ecological values. Springs may have constant or variable discharge. They can be permanent or ephemeral. Topographic lows or depression springs (Figure 15) offer the simplest mechanism for spring formation. Contact springs can result where outcropping permeable rocks overlie lower permeability rocks. In Alberta, many springs are located in the Foothills where topographic relief is great, and in central areas where relatively permeable sandstone beds (e.g., Paskapoo Formation) happen to outcrop in hydraulically-downgradient areas. Springs can be a valuable, natural source of information on the hydrogeology of a watershed, and the data are available at comparatively little cost (compared to the installation and maintenance of monitoring wells).

Human activities on the land surface can affect the distribution, quantity, and quality of water resources. Tillage for agriculture causes changes in the infiltration and runoff characteristics of the land surface, which can affect evapotranspiration, groundwater recharge, and sediment transport to surface water. Irrigation systems can use groundwater or surface water. Up to 75% of the applied water can be lost to evapotranspiration or retained in the crops (Winter et al. 1999). The remaining water is returned either as drainage or groundwater recharge. The water not lost to evapotranspiration has relatively higher concentrations of salts and other constituents, which tend to accumulate in the soil zone. The accumulation increases as irrigation continues. To prevent excessive build-up of soil salinity, more water than is needed by the crops is required to flush the salts into the groundwater system, leading to degradation of groundwater quality and the surface water system that receives the groundwater discharge.

Drainage of the land surface is practiced in some areas to increase cultivated area. Drainage can be done with open ditches or tile drains. Drainage of wetlands often results in deep, organic rich soils, but it can change the distribution of groundwater recharge and discharge areas, and ultimately the baseflow to streams. On lower permeability terrain, drainage systems can change the capacity of topographic depressions leading to decreased groundwater recharge (Winter et al. 1999).

Agricultural chemicals, such as fertilizers, herbicides, and pesticides can also affect water quality. Ammonium from confined feeding operations or fertilizers is soluble and can transform to nitrate, which is also relatively soluble, and thus transported by groundwater and delivered to surface water. High concentrations of nitrate can contribute to excessive growth of aquatic plants, depletion of oxygen, and fishkills. Atrazine is a widely-used but controversial herbicide commonly detected in groundwater, especially in the United States (Winter et al. 1999). Atrazine was banned in the European Union in 2004 because of its persistence as a groundwater contaminant, possible human carcinogenicity, and visible endocrine-disruption effects, such as hermaphrodism in frogs (Ackerman 2007). In terms of agricultural practice in Alberta, little is known of the effects of confined feeding operations on groundwater resources. Few studies are available on the presence or fate of livestock nutrients, pharmaceuticals, or pathogens in groundwater.

Urban and industrial development can affect groundwater quality and groundwater quantity. In terms of direct discharge to surface water, point sources of contamination include discharge from sewage treatment plants, industrial facilities, and stormwater drains. Point sources of groundwater contamination in urban and industrial settings include septic tanks, above-ground or underground chemical or fuel storage tanks, landfills, and industrial waste storage lagoons. If a contaminant has solubility and reaches the water table, the contaminant will be transported by the flowing groundwater. Subsurface processes like adsorption and biodegradation tend to attenuate contaminant migration, especially in the case of simple petroleum hydrocarbons, but in some cases the contaminants may reach sensitive receptors like rivers, wetlands, or water supply wells at significant concentrations (Figure 16).

Salt contamination, as in the case of highway maintenance yards for example, is not subject to natural attenuation processes, unlike organic contaminants. Migration of salt from a poorly-managed salt-storage facility and local groundwater discharge can thus kill large patches of forest or agricultural land. In complex hydrogeologic settings, other types of organic contaminants like chlorinated solvents can migrate vertically as a dense immiscible liquid (e.g., pure carbon tetrachloride in a beaker of water) and continue to sink below the water table remaining as a separate phase, potentially acting as a continuous source of dissolved-phase contamination for decades or longer. In such scenarios, clean-up of groundwater to background conditions may be technically infeasible because of subsurface heterogeneity and hydraulic trapping of the organic liquid (Cohen and Mercer 1993).

Contamination associated with upstream petroleum industry activity usually comes in the form of point sources of hydrocarbons or salinity or both, from pits, ponds, or tanks. Contamination can be negligible or a plume can extend for hundreds of metres depending on the volume released and the hydrogeology. The risk is generally managed by delineating the plume with respect to potential sensitive receptors of contamination (e.g., streams) and removing the source of contamination. Groundwater monitoring and remedial action plans are a necessary condition of an Alberta Environment Approval at larger oil and natural gas gathering and processing facilities.

Of potential concern, especially in rural settings, are the large numbers of older wells drilled in the past for energy purposes. Thousands of wells have been drilled and many are no longer active. As old conventional energy sources are depleted, new ones are emerging such as coalbed methane, shale gas, and in-place coal gasification. Injection wells for carbon sequestration are also becoming more of a possibility. Difficulties may arise if older wells begin to corrode and leak along their casing, allowing potential gas migration upward from deeper zones. In older well fields where new energy sources are proposed, it would seem especially important to obtain background data on groundwater quality, including dissolved gas content and isotopic character, before the new development is to proceed. Isotope ratios can help distinguish between biogenic (i.e., shallow) and thermogenic (i.e., deeper) gas.

Improperly abandoned water supply wells, monitoring wells, or seismic holes can also pose a threat to groundwater quality in rural settings. Potentially contaminated surface water can be allowed easy access to groundwater zones by draining into an improperly abandoned well. Improperly constructed or abandoned water wells can also cross-connect different aquifers naturally separated by low permeability layers.

Urban and urban industrialized settings can affect groundwater. Flood flow could increase and groundwater recharge decrease as urbanization replaces permeable soil with impermeable pavement. Changes in groundwater recharge in one part of the system could cause changes at a distance in a hydraulically-connected groundwater discharge area. Urbanization can also increase evapotranspiration, even as the vegetative cover has decreased because of the heat of paved areas (Fetter 2001). In rural areas, linear development like roads (and ineffective culverts) can prevent overland flow directly to lakes or streams during important times of system recharge, like spring-runoff when evapotranspiration is still relatively low.

Forests have a significant role in the hydrology of a watershed. Changes in forest cover are expected to change evapotranspiration and infiltration to groundwater, change the baseflow to streams, and potentially increase storm runoff and soil erosion. Uncoordinated forestry practices, for example, can potentially exacerbate flooding. Groundwater recharge is affected by forests compared to grasslands, due to the uptake of soil water by trees and to the increased water-holding capacity of forest soils. On the other hand, cooler air temperatures and less wind prevail in forests compared to grasslands. Again, changes in groundwater recharge conditions are expected to affect discharge conditions, including groundwater quality due to changes in mineral dissolution and nutrient cycling. However, few studies appear available on the effects of forestry practices in Alberta on surface-subsurface water flow, biogeochemistry, and the ecohydrology of boreal forest watersheds.

3.3.3 Groundwater Vulnerability

Contamination

Groundwater vulnerability may be expressed in terms of vulnerability to contamination and vulnerability to overuse. The Alberta Geological Survey (AGS) published a map of the natural suitability of geological setting for waste management in Alberta (Andriashek and Waters 2005). On that map (Figure 17), land is classified as suitable, unsuitable, or uncertain, on the basis of: (1) the permeability of bedrock formations, (2) the location of buried valleys, (3) drift thickness, and (4) the permeability of the drift (i.e., the unconsolidated deposits between the bedrock and land surface). Areas in the Rocky Mountains or Foothills are automatically deemed “unsuitable”, as are areas located over buried valleys, or with highly permeable surficial deposits (e.g., eolian or glaciofluvial sand). Areas deemed “suitable” have drift thickness greater than 15 m or are underlain by low permeability bedrock. Areas are also deemed “unsuitable” if drift thickness is less than 15 m and the underlying bedrock is highly permeable. The AGS map was intended for reconnaissance-level waste management siting, since the finest spatial resolution was 500 m. Therefore, within areas deemed regionally as “suitable”, smaller local features (e.g., steep slopes or surface water) may make a site entirely unsuitable.

For somewhat more detailed assessment of groundwater vulnerability, systems like the DRASTIC method have been developed. The DRASTIC method (Aller et al. 1987) is a qualitative indexing method that was created for the United States Environmental Protection Agency (EPA) to provide the user with a tool to measure groundwater vulnerability to contamination. It is a point count system that identifies relevant parameters, and applies a weight to each to reflect relative importance. In the DRASTIC method, the parameters are: **D**epth to water, net **R**echarge, **A**quifer media, **S**oil media, **T**opography, **I**mpact of vadose (i.e., unsaturated) zone, and hydraulic **C**onductivity (Figure 18). The final numerical score is obtained by multiplying the score assigned to the parameter by a weighting factor and summing the results. The vulnerability score is then mapped across an area to identify areas more susceptible to contamination. The method has been criticized on the basis of excessive subjectivity if few data are available, as well as a failure to account for some possibly important factors, such as preferential flowpaths and natural attenuation of specific contaminants. Nevertheless, it does provide a useful framework for more detailed mapping of groundwater resource vulnerability in an area.

DRASTIC can be classified as a regional or reconnaissance-level tool. A next step for a particularly vulnerable area would be to prepare a quantitative vulnerability map, involving a groundwater flow and contaminant transport model, to estimate the susceptibility of an aquifer to contamination.

Overuse

To understand groundwater overuse, the concept of safe yield of a well must be distinguished from sustainable yield of groundwater in a watershed (Devlin and Sophocleous 2005; Maathuis and van der Kamp 2006). Safe yield of a groundwater production well in Alberta is generally calculated on the basis of available drawdown in the well and permeability (e.g., Farvolden Method; Alberta Environment 2003). However, Theis (1940) indicated that "Under natural conditions… previous to development by wells, aquifers are in a state of approximate dynamic equilibrium. Discharge by wells is thus a new discharge imposed upon a previously stable system, and it must be balanced by an increase in the recharge of the aquifer, or by a decrease of the old natural discharge, or by a loss of storage in the aquifer, or by a combination of these." These relations are illustrated graphically in Figure 19. A well may willingly provide a given volume of water for a long time, but there will be implications for the larger hydrologic system. Pumping can increase recharge by capturing water that would otherwise be rejected by the groundwater system and pond at the land surface. Pumping can also cause discharge to streams to decrease or even reverse so that a stream is now losing (Figure 14). Wells in close proximity may interfere and cause a cumulative drawdown (Figure 20).

In the past, it was presumed that the volume of water that could be removed from an aquifer was equal to the volume of groundwater recharge. This volume was also called safe yield. It is now understood that extraction must be considerably less than recharge to sustain the quantity and quality of springs, wetlands, and streams, and the ecosystems that depend on them (Sophocleous 2000). Sustainability has thus become a broader term that transcends expected long-term well yield and includes issues of water supply, water quality, ecosystem functioning, and human and environmental welfare (Devlin and Sophocleous 2005) as well as the monetary valuation (and replacement costs) of natural features like wetlands (e.g., Olewiler 2004). It also forces us to manage water resources in ways that are compatible with maintaining them for future generations, thus constraining our present management of water (Sophocleous 2000).

Study of the dynamics of a system of pumping wells, groundwater flow, recharge, discharge, and surface water interactions requires simultaneous consideration of equations of mass balance, water flux, hydraulic conditions at aquifer boundaries, and aquifer permeability and storage properties. Resolving all these functions requires mathematical modelling. A mathematical groundwater model is a tool with which to investigate the dynamics of aquifer systems. It is only through the development and application of such models that the effects and timing of an imposed stress like pumping can be fully determined (Bredehoeft 2002). The development of a mathematical model is always preceded by development of a conceptual model, which itself frequently leads to greater understanding of the strengths and weaknesses of our understanding of the hydrologic system (Ingram et al. 2007).

Conjunctive Use

Conjunctive use, broadly-speaking, is to manage surface water and groundwater resources so as to maximize their use. It can include aquifer storage and retrieval, or pumping an alluvial aquifer hydraulically connected to a stream. Typically, it involves both groundwater and surface water used for water supply. Studies of the economics of conjunctive use indicate that it adds value to society by adding to the average yield from the system and the reliability of supply (Bredehoeft and Young 1983). However, conjunctive use may be incompatible with water management by the doctrine of prior appropriation (i.e., “first in time, first in right”, as in Alberta), since the water rights of senior surface water users can be damaged by groundwater pumping, especially during periods of drought. Groundwater users are invariably the junior users because efficient drilling and pumping methods are a relatively recent technical development. Conjunctive use is likely to be more successful when there is reasonable compromise between senior surface water users and junior groundwater users (Bredehoeft 2007). Well-defined water rights and rules for measuring, monitoring, and transferring water are also necessary (Schlager 2007).

For ecosystems, groundwater extraction from shallow, alluvial aquifers can cause streamflow reductions in hydraulically-connected streams. Streamflow depletion can significantly impact the environment when flow is reduced to below a minimum level required to sustain an established, healthy ecosystem. Instream-flow science is a relatively new field that bridges many disciplines to answer the broader question of how much water should be left in the stream to meet ecosystem requirements, and not extracted for industrial, municipal, or agricultural purposes (Sophocleous 2007). Mathematical models of stream-aquifer systems have been used to provide insight into the possible trade-offs between instream-flow needs and groundwater development options (e.g., Barlow et al. 2007).

Possible Effects of Climate Change on Water Resources

General circulation models (GCMs) consider the physical processes related to the atmosphere, oceans, land surface, and cryosphere (i.e., frozen areas of the Earth) to predict possible changes in global climate due to increases in greenhouse gas concentrations. GCMs function by dividing the atmosphere and oceans of the earth into a 3-dimensional network of rectangular cells (i.e., grid cells). The grid cells are typically 250 to 600 km across, and up to 20 layers of cells may be used to represent the atmosphere, while up to thirty layers may be used to represent the oceans (International Panel on Climate Change 2007). Due to the large size of the cells, the GCMs do not have the resolution to simulate and predict localized effects, such as cloud formation (International Panel on Climate Change 2007), which affect precipitation patterns.

Numerous climate models have been developed to predict the effects of increasing atmospheric greenhouse gas and particulate levels on the world’s climate. The Canadian Institute for Climate Studies (CICS 2007) publishes predictive results from several prominent climate prediction models. Overall, the GCMs are consistent in their prediction of rising global temperatures, with the greatest increases in temperature expected to occur in the northern latitudes (International Panel on Climate Change 2007).

Chaikowsky (2000) investigated trends in mean, minimum, and maximum temperatures for 25 climate stations across Alberta and the trends were calculated over two time frames: 1938 to 1995 and 1960 to

1995. Warming occurred over both time periods in Alberta. The mean warming, given by the average of all 25 stations, was approximately 0.6°C, or 0.1°C per decade, over the 1938 to 1995 period, and 1.3°C, or 0.4 °C per decade over the 1960 to 1995 period, indicating that the average rate of warming in Alberta over the shorter, more recent time frame was approximately four times the average rate of warming over the entire time period. The predictions of GCM models offer less consistency with respect to precipitation, with some scenario outcomes predicting increases, and other predicting decreases in precipitation.

Nevertheless, Table 3-1 provides a summary of the possible risks that climate change may pose to the water resources of the North Saskatchewan River basin.

Table 3-1 Possible Implications of Climate Change for Water Resources in the Basin

Potential Scenario	Implication for Water Resources
Increased Average Annual Temperature	Longer growing seasons and increased irrigation may increase demand for water
	Earlier spring melting may shift growing season forward and limit water use in later drier months
	More precipitation lost as evaporation, and less available to recharge aquifers
Decreased Rainfall	Decreased streamflows and an increased reliance on groundwater for water supply
	Decreased groundwater recharge
More intense rainfall events [a]	Increased proportion of rainfall occurring as runoff, at the expense of the proportion providing groundwater recharge
More rapid spring snowmelt [a]	Increased runoff volumes at the expense of groundwater recharge.

[a] Martz et al. 2007

For most of western Canada, snowmelt and glacier runoff from the Rocky Mountains are a primary source of water supply for downstream regions (Lemmen et al. 2004). With warming, the seasonal and long-term storage capacity of alpine areas may decrease due to thinner snowpacks, more rapid spring runoff, and decreased snow and ice coverage (Ryder 1998). These decreases, in turn, would result in lower summer river flows and greater water shortages during periods of peak demand. Trends observed on the eastern slopes of the Rocky Mountains suggest that the impacts of diminishing glacier cover on downstream flows are already occurring (Demuth et al. 2002). Across southern Canada, annual mean streamflow has decreased significantly over the last 30 to 50 years, with the greatest decrease observed during August and September (Zhang et al. 2001).

As the demand increases for a decreasing supply of surface water, groundwater utilization would increase. Despite groundwater's importance, effects of climate change on groundwater recharge dynamics are poorly understood (Maathuis and Thorleifson 2000). It is expected that shallow aquifers would be most sensitive to climate change because of decreases in groundwater recharge and greater accessibility for rural residential or agricultural water supply. Deeper aquifers are expected to be less directly affected by climate change in the short term, since recharge of these aquifers is slower. However, greater demand with time may be placed on the deeper aquifers for larger-scale water use.

3.4 Provincial Government Groundwater Monitoring

A decision to establish a Groundwater Observation Well Network (GOWN) followed a round-table conference on groundwater resources and development in Alberta held in 1955. The rationale for the GOWN was to “establish a modest and effective water level observation program to keep a long-term check or inventory on available groundwater”. The objective was to provide information for the preparation of a province-wide hydrological map series and other groundwater studies. The Alberta Research Council (ARC) took first responsibility for GOWN, but control was transferred to the Earth Sciences Division of Alberta Environment in 1982. In the 1980s, provision of a High Quality Well Network was mandated. The purpose was to allow temporal tracking of natural changes in groundwater quality in Alberta as part of GOWN. It was later renamed the Provincial Ambient Groundwater Quality (PAGQ) Monitoring Program.

By the early 1990s, there were approximately 500 observation wells with digitized water level data, and approximately 200 of these are still periodically monitored. Approximately 50 wells are located in the North Saskatchewan River basin (Figure 21). Groundwater quality monitoring (PAGQ) was added to GOWN in 1988. The original plan was to sample the PAGQ wells annually until results indicated that water quality was stable or bracketed, at which time subsequent monitoring would be reduced to approximately once every five years. Budget and manpower priorities shifted and the sampling schedule was not maintained. An inventory of springs was conducted in the early 1980s by the ARC. Samples were collect for chemical analysis and flow rates were estimated. Some of the data are available through the provincial Groundwater Information System.

Currently, data regarding the provincial groundwater monitoring network and general groundwater information are available through three primary avenues. Temporal water levels trends, in the form of hydrographs, are available through an Alberta Environment website. Water well drilling records are available through the Groundwater Information Centre. Specific information about the GOWN or PAGQ wells, such as available chemistry data, borehole geology, or completion details, are available from Alberta Environment on request. Whereas large amounts of data are available, no single point of access to the data exists. Moreover, no province- or watershed-wide institutional framework exists to interpret the hydrogeological data gathered over the past 50 years and to evaluate its significance.

3.5 Natural Water Supply and Water Use

3.5.1 Natural Water Supply

Golder Associates Ltd. (2008) completed an assessment of water supply and its variability in the North Saskatchewan River basin under natural hydrologic and present climatic conditions, based on analysis of streamflow hydrographs and drainage areas. The mean annual natural discharge in the North Saskatchewan River is 7.51 million decametres (dam^3), which is areally equivalent to an annual yield of 179 mm during average hydrologic conditions. The Cline basin alone with an area of only 4,110 km^2 (compared to the total drainage area of 56,860 km^2 for the North Saskatchewan River basin) contributes almost 50 percent (3.6 million dam^3) of the annual cumulative yield, as measured at the Alberta-Saskatchewan boundary. The cumulative mean annual flow of the western basins (i.e. Cline, Brazeau, Ram, and Clearwater) is 6.7 million dam^3 or 89 percent of the total. Near the downstream outlet of the Beaverhill basin, the cumulative mean annual flow increases to only 7.3 million dam^3. In other words, the central basins account for only about 8 percent of the flow. Further downstream, to the Saskatchewan border, the eastern basins contribute only approximately 0.2 million dam^3 (or 3 percent) of flow to the annual cumulative volume (Golder Associates Ltd. 2008).

The Cline basin has an annual yield of 870 mm while the easternmost regions have yields of approximately 30 mm. These lower yields can be attributed to lower precipitation, higher temperature, higher evapotranspiration, and larger non-contributing areas in the eastern half of the North Saskatchewan River basin (Figure 22). “Non-contributing” refers to areas that do not drain to the main receiving stream but instead drain to local surface water features. “Non-contributing” seems like somewhat of an unfortunate term, since hummocky terrains in topographically-elevated areas (e.g., the Beaver Hills) may nevertheless contribute to basin hydrology by groundwater recharge. Less than 50 percent of the area of the eastern watersheds contributes to the North Saskatchewan River during years with average hydrologic conditions, because of relatively lower precipitation, higher evapotranspiration, and higher percentage of non-contributing run-off areas (Golder Associates Ltd. 2008).

In the eastern basins, the monthly yield peaks in April due to snowmelt as temperatures begin to increase in spring. In the western basins, the peak occurs in July because of the gradual rise in temperature during spring and early summer at higher elevations. At the Alberta-Saskatchewan boundary, the monthly cumulative yield peaks in July owing to the large contribution of the western basins.

Streamflow hydrographs reflect two very different types of contribution from a watershed (Freeze and Cherry 1979). The peaks are delivered to the stream mostly by overland flow. They are the fast response to short-term changes in the flow system. The baseflow is delivered to the stream by groundwater flow. It is the result of a slow response to long-term changes in the groundwater flow system. It is possible to separate streamflow hydrographs into their surface water and groundwater components using baseflow recession techniques (e.g., Meyboom 1961, Farvolden 1963) to reach interpretive conclusions regarding the relative contributions of surface water and groundwater. Specific studies should be completed within the North Saskatchewan River basin to better understand, temporally and spatially, the relative contributions of surface water and groundwater to cumulative yield across the basin.

3.5.2 Water Use

The NSWA commissioned AMEC Earth & Environmental (AMEC) to complete a study of current water allocations, licensed use, and actual water use forecasts for the North Saskatchewan River basin and its sub-basins (AMEC 2007). The assessment differentiated between water allocations, licensed water use, and actual water use. “Water allocation” refers to the amount of water that licensees are entitled to withdraw from surface or groundwater sources. “Licensed water use” is the amount of water that licensees are expected to consume, including any losses that occur. “Consumption” means that the water is taken out of the basin and unavailable for re-use (e.g., oilfield injection or export crop production). The difference between water withdrawal and water consumption is called return flow, which is put back in the basin and available for re-use, although water quality may have changed during use (e.g., treated sewage, irrigation run-off, industrial cooling water). Actual water use is the actual amount of water consumed (or lost to re-use), and is the difference between the volume actually withdrawn and the volume actually returned.

The AMEC (2007) assessment differentiated between surface water and groundwater use. It focused on estimation of actual water use in six sectors: municipal and residential, agricultural, commercial, petroleum, industrial, and “other”. “Other” generally referred to water use for purposes of flood control, lake stabilization, and fish, wildlife, and habitat enhancement. In addition, water use forecasts were prepared for five-year intervals up to 2025 starting in 2005. The forecasts were based on expected changes in population and economic activity, as described using available projections under low, medium, and high growth scenarios.

As of December 2005, total allocated volume in the North Saskatchewan River basin was 1.996 million dam^3 (or 27% of the mean annual discharge of 7.5 million dam^3). Of this, 1.971 dam^3 was for surface water and only 0.025 dam^3 was for groundwater. The industrial sector accounted for 83 percent of allocations, followed by the residential and municipal (8%) and petroleum sectors (5%). The agricultural, commercial, and other sectors combined accounted for the remaining 4 percent of allocations.

AMEC (2007) estimated that 201,846 dam^3 of water was consumed in 2005. The industrial sector accounted for 46 percent of actual water use, followed by the petroleum sector (18%), the other sector (13%), agriculture (12%), commercial (6%), and municipal (5%). Under the medium-growth scenario, water use was predicted to increase to over 275,677 dam^3 by 2025, i.e., a 37 percent increase from 2005. The central basins combined (i.e., Modeste, Sturgeon, Strawberry, White Earth, and Beaverhill) consumed 86 percent of the water, compared to 2 percent for the western basins and 12 percent for the eastern basins. More detail on estimated actual water use in each basin is provided in Section 5.

3.6 State of the Watershed Report (2005)

A State of the Watershed report was completed in 2005 (North Saskatchewan Watershed Alliance 2005). The report quantified land-use and commented on water quality, water quantity, environmental integrity, and key data gaps. Four main indicators of watershed health were applied: water quality, water quantity, land use, and biological. The main findings are described below.

Human population is least in the headwaters and most in the greater Edmonton area. Land use across the watershed includes recreation, forestry, resource exploration and extraction, agricultural, urban centres, and rural residential. Water use along the North Saskatchewan River includes human consumption, waste assimilation, resource extraction, agriculture, and cooling water for industrial purposes. Abraham Lake and the Brazeau Reservoir provide hydroelectric power generation and their dams augment winter flows for downstream residents, agriculture, and industry. Several towns and cities in the watershed have either wastewater treatment plants or wastewater lagoons that discharge treated effluent into the North

Saskatchewan River or its tributaries. Downstream, the water quality deteriorates, as indicated by increasing nutrients (notably phosphorus), bacteria, and pesticides concentrations. Dissolved oxygen decreases downstream of larger urban populations.

The western basins (Cline, Brazeau, Ram, and Clearwater) are critical to source water quantity and quality in the larger watershed, but data gaps are large. Glaciers, mountain snowpack, forests, and wetlands act to ensure a supply of good quality water to tributaries and the main stem of the river. The headwaters are also key recreational and tourism areas and increasing activity has the potential to place more risk on integrity of the watershed at its source. Minimizing linear disturbance and uncontrolled access, along with sustainable forest practices in these areas would benefit forest structure, cold water fisheries productivity, and natural biodiversity. Available data on biological indicators (e.g., aquatic macrophytes, fish population estimates, vegetation types, and benthic invertebrates) were sparse, and therefore inadequate to properly assess watershed health in these terms. Nevertheless, management practices to protect riparian areas in all of the basins were considered critical to watershed health (North Saskatchewan Watershed Alliance 2005).

Compared to the headwaters, the central basins (Modeste, Strawberry, Sturgeon, Beaverhill, and White Earth) have much more agricultural activities, including manure production, and urbanization. Change in land use from natural and agricultural to urban and industrial increases the susceptibility of surface water and groundwater resources to impacts both of natural (e.g., drought, flooding) and anthropogenic events (e.g., flooding, industrial spills, and urban stormwater run-off). Human impacts on the watershed are addressed mainly through water treatment processes and the assimilative capacity of the river. Retention and restoration of riparian (i.e. interface between land and water) health and functional wetlands are critical in providing good water quality and storing water on the landscape for the benefit of the entire watershed. The cumulative impact of land disturbance needs to be better addressed on a regional scale in this area of the watershed (North Saskatchewan Watershed Alliance 2005).

Water quantity and water quality impacts from the City of Edmonton concerned residents in the eastern basins. At the same time, the eastern basins have some of the most altered landscapes in the watershed, resulting in impaired natural functions of water storage, groundwater recharge, flood attenuation, and base flow contributions to streams. Livestock densities in these basins are moderate, and so livestock and manure management are important considerations. Riparian health and wetland restoration should be future areas of focus in the eastern reaches (North Saskatchewan Watershed Alliance 2005).

The health of the entire watershed was rated generally as fair (on a scale of excellent, good, fair, and poor) and included some basins where ecosystem functioning appeared significantly impaired by human activity. Through the assessment methods used, the watershed is most healthy in the headwaters. East of the headwaters, where livestock density, human activity, and populations are greatest, riparian health scores and wetland cover were lowest. Disturbances of note included the greater City of Edmonton's impacts on the main stem from treated wastewater and storm water outfalls, for example, due to increases in *E. coli* counts and phosphorus concentrations. However, the impact of the City has been lessened considerably by recent improvements in wastewater treatment technology.

Relatively high agricultural intensity in the Modeste, Strawberry, Vermilion, and Frog basins was reflected in higher nutrient concentrations, lower riparian health scores, and lower wetland densities. Pesticides were detected in several basins, but concentrations did not exceed applied surface water quality guidelines. Several pesticides detected, however, did not have established guidelines. Pharmaceuticals (human and livestock) are considered emerging contaminants, but little is known of their presence or effects on humans and aquatic life.

Key recommendations included the following.

(1) Active study of glacier recession and snow pack change, implications for the health of the North Saskatchewan Watershed, and linkage to climate change models for predictive scenarios.

(2) Develop a suite of indicators to allow proper evaluation of the biological aspects of watershed health.

(3) Support urban sustainability initiatives (e.g., Smart Growth) such as conservation planning, riparian area protection, wetlands restoration, and upgrades to return water treatment.

(4) Support riparian assessment experts to develop a consistent GIS-based riparian assessment process, and to determine best practices to be consistently incorporated into land management.

(5) Complete a comprehensive wetland resource inventory, including drained wetlands, as a key component of a complete land use inventory for the North Saskatchewan Watershed.

(6) Characterize groundwater quantity and quality of major groundwater sources in the watershed.

(7) Encourage research of emerging contaminants such as pharmaceuticals.

(8) Promote management practices that result in increased biodiversity in the watershed.

This first state of the watershed report is to be followed by subsequent reports on watershed health.

3.7 Integrated Watershed Management Plan

The NSWA has recently embarked upon an Integrated Watershed Management (IWMP) planning process. The main goals are to:

- develop strategies (including the establishment of Water Conservation Objectives) that will support sustainable use and management of land and water resources;
- identify land uses that could adversely affect the future sustainability of the watershed and propose strategies to address these land-use issues; and
- prepare the IWMP in collaboration with watershed communities and the public so that the IWMP meets local and regional needs.

NSWA plans to complete the IWMP process by 2010. The IWMP is to provide a framework for protecting, maintaining, and restoring a healthy, natural watershed system, in which economic and social needs are balanced with ecological needs. It will address surface water, groundwater, land use, social, cultural, and economic issues. Land-use issues affecting water will be identified and basin recommendations made.

4. GENERAL HYDROGEOLOGY OF THE NORTH SASKATCHEWAN WATERSHED

4.1 Western Watersheds

4.1.1 Hydrogeology

The Cline, Brazeau, Ram, and Clearwater watersheds occur mainly in the Rocky Mountains and Foothills Natural Regions (Figure 3). In the western mountain ranges of North America, the hydrogeologic framework is generally characterized by thin soils over fractured rocks of Paleozoic to Cenozoic age (Figure 23) alternating with valleys overlain by Recent alluvial and Pleistocene glacial deposits. The mountain ranges are the result of thrusting and uplift from the convergence of tectonic plates. The ranges, reaching elevations of approximately 3,500 masl, tend to be separated by narrow valleys with bottom elevations at approximately 1,500 masl.

Knowledge about groundwater conditions in many mountainous areas is limited because of the remoteness, harsh climate, complex geology, and limited groundwater utilization (Heath 1988). Few wells are usually available to provide detailed subsurface information. The consolidated bedrock units generally have little primary porosity or permeability. Secondary openings resulting from jointing, fracturing, and solution-enlarged openings in calcareous rocks can result in increased permeability of the rock but not necessarily the storage capacity. Intense fracturing can significantly increase permeability.

Detritus at valley bottoms can serve as good aquifers, depending on the type of bedrock from which the deposits have been derived (i.e., coarse- or fine-grained). Folding and faulting can enhance groundwater recharge, if for example, bedded permeable rocks are exposed near the land surface (i.e., outcrop or subcrop). In many mountainous areas, the annual precipitation exceeds the intake capacity of the exposed soil or rock. The topographically higher zones generally receive more than enough water, and the excess runs downslope to recharge valley-fill aquifers or streams. Climatic conditions in the mountains favour recharge since a considerable proportion of annual precipitation occurs in winter and spring when evapotranspiration is less (Foxworthy et al. 1988).

Mean annual temperature varies from -6°C at the Columbia Icefield to 1°C at Nordegg. Mean annual precipitation also increases with increased altitude varying from 1050 mm at the Columbia Icefield to 550 mm at Nordegg. Mean annual potential evapotranspiration (estimated by the Thornwaite method) varies from 0 mm at the Columbia Icefield to 365 mm at Nordegg (Barnes 1978). Across the western basins, the mean annual precipitation ranges from 450 mm to over 600 mm, of which snowfall is between 150 to 200 mm. Annual evapotranspiration, between 300 mm and 385 mm, is less than precipitation (Golder Associates Ltd. 2008). Annual groundwater recharge in the western mountain regions can reach 50 mm (Heath 1988).

The hydrogeology of the Mountains and Foothills west of Rocky Mountain House was described by Tokarsky (1971) and Barnes (1978). Drift cover is thin (less than 15 m) over most of the region (Figure 24) and consists mainly of till (Figure 25). Preglacial valleys containing buried sands and gravels are uncommon or absent (Figure 26). However, terraces of post-glacial sands and gravels are numerous along the North Saskatchewan River west from Rocky Mountain House and along the South Ram River. Gravel thicknesses can range from 10 to 25 m. Alluvial gravels in the broad valleys of the Clearwater, North Saskatchewan, and North Ram Rivers were reported to have yielded 700 to 3,600 m^3/day to a single well. Induced infiltration from rivers or streams may also be an effective source of water supply [Tokarsky (1971), Barnes (1978)].

Below the drift, most of the eastern half of the area is underlain by the bedrock of the Paskapoo Formation, whereas to the west the uppermost bedrock units are the successively older Cretaceous Brazeau Group, Alberta Group, and Blairmore Group, and the mountain-forming, predominantly Paleozoic successions (Figure 23). The Paskapoo Formation consists of interbedded mudstone, siltstone, and sandstone. The Brazeau Group is a non-marine succession of interbedded mudstone, siltstone, and fine-grained sandstone, with subordinate but prominent coarse-grained sandstone layers (Glass 1990). The Alberta Group mainly comprises dark grey, silty mudstone, although a prominent sandstone sequence (Cardium Formation) lies within the Alberta Group. The Blairmore Group comprises interbedded sandstone, mudstone, and coal, and contains a basal, coarse-grained conglomerate unit (the Cadomin Formation). The generalized stratigraphy is summarized below.

Table 4-1 Generalized Stratigraphic Column – Foothills

PERIOD	GROUP OR FORMATION		AQUIFER POTENTIAL
Recent	alluvial		local
Tertiary	Paskapoo Formation		good
Upper Cretaceous	Brazeau Group		good
	Wapiabi Formation	Alberta Group	poor
	Cardium Formation		good
	Blackstone Formation		poor
Lower Cretaceous	Upper Blairmore	Blairmore Group	poor
	Cadomin Formation		good
Paleozoic	Rundle Group		good

“Aquifer potential” refers to the probability that a formation can supply usable groundwater. Expected groundwater yields for the Paskapoo Formation are generally in the range from 70 to 700 m^3/day. To the west, in the Brazeau and Alberta Groups, expected well yields are less (approximately 40 to 700 m^3/day), due to better cementation in this area. The most prospective bedrock aquifers of the Foothills belt occur in the Lower Cretaceous Blairmore Group (Barnes 1978). Fracture permeability is well developed in thick sandstone units and coal beds. Yields between 150 to 700 m^3/day may be obtained from these aquifers in topographically low positions. Further west, yields are generally low, except in local karstic areas of

Devonian-Mississippian Paleozoic carbonate rocks where yields can be extremely high. Within the Rocky Mountain Ranges and Front Ranges, limestone and dolomite are the dominant rock types. Conduits and fractures are the major mode of storage and transmission of groundwater within the Paleozoic carbonates (Barnes 1978).

Springs are numerous in the western watersheds (Figure 27). Measured spring flow rates from alluvial gravels reportedly ranged up to 70,000 m^3/day (Tokarsky 1971). Contact springs from the base of the major terraces reportedly flowed at rates of up to 3,600 m^3/day. Flow rates of springs from the Paskapoo Formation rarely exceeded 700 m^3/day, except for one spring near Crammond, which flowed at from 14,000 to 29,000 m^3/day (Tokarsky 1971). Barnes (1978) noted two unusual groundwater discharge features located on gravel terraces of the Brazeau River valley. The larger of the two features, located in Sections 23 and 24 Township 44 Range 20 W5th Meridian, was a spectacular group of lakes covering an area of about 1.5 km^2. The other was located in LSD 5 Township 42 Range 20 W5th Meridian, and had a smaller but “equally-striking” ponded discharge area. Sulphur springs occur where streams have cut through uplifted Paleozoic rocks (Tokarsky 1971).

Groundwater quality was considered excellent over most of the area (Tokarsky 1971). Total dissolved solids rarely exceed 1,000 mg/L and groundwater predominantly of the bicarbonate type was expected. Sulphate-type waters with mineralization in excess of 1,500 mg/L TDS occur in associated with shales of the Alberta Group and the Paleozoic carbonates. Sodium-bicarbonate type water with total dissolved solids content of 800 to 900 mg/L were reported to persist to depths of 250 to 350 m in thick sandstones of the lower part of the Paskapoo Formation east of Rocky Mountain House. Within the Foothills and Rocky Mountains, the base of groundwater protection is set, somewhat arbitrarily, at 600 m below ground surface. Beneath Rocky Mountain House, the depth to the base of groundwater protection is approximately 780 mbgs (EUB 2007).

4.1.2 Land Use

The Cline watershed is the healthiest in the North Saskatchewan River watershed (North Saskatchewan Watershed Alliance 2005). It is a striking landscape with 71 percent of its area in Banff and Jasper National Parks and the Siffleur and White Goat Wilderness areas. Provincial Forest Management Units (FMUs) comprise the remaining 29 percent of the watershed. Hence, most of the watershed is protected, and linear development and land disturbance are low (Figure 28).

The Brazeau watershed includes icefields, lakes, streams, and reservoirs. It includes the Brazeau Canyon Wildland Provincial Park, the Marshybank Ecological reserve, and part of Jasper National Park. The watershed is sparsely populated but recreational activities are popular. Only about 1.4 percent of the land area is taken up by linear development, but 83 percent is within a FMU. Livestock densities are low. Although land disturbance appears low, future studies could focus on the potential cumulative effects of linear development, forestry, and recreational uses (North Saskatchewan Watershed Alliance 2005).

The Ram watershed includes a portion of the towns of Rocky Mountain House and Nordegg, as well as Crimson Lake Provincial Park, the Bighorn 144A First Nations Reserve, and many parks and campgrounds. The economic base of the region consists of oil and gas, forestry, agriculture, and tourism.

Large areas of the watershed are unprotected by parks or protected areas. Ninety-nine percent of the watershed is within a FMU. Linear development covers 1.6 percent of the land area. In addition, 2 percent of the developed area is municipal or reserve area and a small area is affected by well sites and other energy facilities. Approximately 31 percent of the watershed has been classified on the basis of the PFRA Land Classification System (North Saskatchewan Watershed Alliance 2005), of which 83 percent is trees, 8 percent is forage, and the remainder (9%) is grassland, shrubs, and water bodies.

FMUs also cover a large portion (approximately 87%) of the Clearwater watershed and only a small portion is a within park or protected area (1.4%). Waterbodies cover about 1.6 percent of the watershed. Like the Ram watershed, the economic base consists of oil and gas (Figure 29), forestry, agriculture, and tourism. Two percent of the land area in the Clearwater watershed is taken up by various linear developments. Less than a third of the area has been classified under the PFRA Land Classification System (North Saskatchewan Watershed Alliance 2005). The area that has been classified has about 60 percent trees and 40 percent as forage, grassland, water bodies, and croplands. Livestock densities are low in most of the Clearwater watershed; however, manure production is relatively high near Rocky Mountain House. Little information is available on wetland areas, but peatlands are thought to be abundant in some areas (North Saskatchewan Watershed Alliance 2005).

4.1.3 Water Use

According to AMEC (2007), estimated total water use in the western watersheds in 2005 was 4,993 dam^3 of a total use of 201,846 dam^3. The Cline, Brazeau, Ram, and Clearwater basins provide almost 90 percent of the total yield of the basin but use only 2 percent. Of the 4,993 dam^3 used, a relatively large proportion (48%) was groundwater (Figure 30). The groundwater is used mostly for petroleum (44%) and agricultural (39%) purposes. Most of the petroleum water-use was for injection. In 2005, Clearwater County within the Ram basin had a groundwater allocation of 40.5 dam^3. No other municipal water licenses were issued for groundwater use (AMEC 2007).

AMEC (2007) assumed that 75 percent of unlicensed rural residents rely on groundwater. Under a moderate growth scenario, future water consumption was projected to decrease from 4,993 to 3,957 dam^3 in 2025 (Figure 31), even though population and agriculture are expected to grow moderately, since conventional petroleum operations in this part of Alberta are expected to decline (AMEC 2007). However, development of new sources of energy (e.g. coal gasification) may increase.

4.1.4 Groundwater Vulnerability

Groundwater recharge in the western basins is expected to be high because precipitation is high, evapotranspiration is low, drift cover is thin, and permeability of the uppermost bedrock units tends to be high. The considerable topographic relief is expected to result in a complex hierarchy of flow systems from the local to the regional scale. The flow paths are complex because the groundwater flow extends deep into heterogeneous stratigraphy. Subsurface volume of potable groundwater is large and depth to the base of groundwater protection likely extends to at least 800 mbgs (EUB 2007). Hence, the groundwater in the western watersheds is expected to represent a significant source of usable water within the North Saskatchewan basin as a whole.

Since water is abundant and demand is low, issues of groundwater supply are not expected, at least on a local scale. On the other hand, we know little of the contribution of groundwater flow in the headwaters to overall yield to the North Saskatchewan River. Almost 90 percent of the total yield to the North Saskatchewan River is provided in the western basins. Of that, the relative contribution of groundwater is unknown, as are the location and nature of key groundwater recharge areas and their sensitivities to large-scale climate or land-use change.

A large component of the groundwater recharged in the western basins can be expected to flow generally northeast within the Paskapoo Formation across the central basins. Key questions include: how much water in the Paskapoo Formation is due to regional recharge in the most topographically-elevated portions of the western basins, compared to local recharge in the more central areas? What are the groundwater residence times? Where does the groundwater discharge? If recharge is affected by the large-scale climate or land-use change, what influence would it have on discharge and baseflow to the North Saskatchewan River (especially in winter), wetlands, streams, or ecosystems? We have no answers to these fundamental questions because there has been little effort since the 1970s to instrument Alberta's groundwater systems with monitoring stations, measure spring flows, develop conceptual or mathematical models of groundwater flow, or test the models against observations.

Little is known of the effects of forestry practices on groundwater systems in Alberta. How do forestry practices affect groundwater recharge in the foothills? If recharge conditions are changed, can it affect regional or local discharge, in terms of both groundwater quality and quantity? What are the consequences for base flow in streams or wetlands or their ecosystems? Large areas of the western basins are covered by FMUs but we know little of the effects of forestry (or pine beetle activity) on groundwater recharge/discharge relations.

The hydrogeological features that make the western watersheds a substantial reservoir also make it particularly vulnerable to contamination. The drift thickness is thin or absent over most of the region and so the aquifers are more vulnerable to contaminant release at the ground surface. Higher rates of infiltration thus require more urgent response when contaminants are released. Fractures can be common, which significantly increases the rates of contaminant migration and technical challenge of clean-up. Solutes tend to move much more quickly in fracture systems and in ways that are difficult to predict. Although agricultural, industrial, and municipal development is light compared to the central watersheds, vulnerability to contamination is high because rates and volumes of recharge are high.

Local groundwater management plans may be necessary where surface activities (e.g. livestock and petroleum activity) and water well occurrence are dense, for example near Rocky Mountain House. In the general area, thin drift appears to overlie Paskapoo sandstone and the North Saskatchewan River is in close proximity. The general intention of a local groundwater management framework would be to integrate water protection with cumulative environmental effects management and integrated land-use planning. Such a framework would also encourage consistency of groundwater monitoring and remediation efforts.

Table 4-2 Summary of Groundwater Conditions and Vulnerabilities– Western Basins

	Aquifer Potential	Depth to Base of Groundwater Protection	Land-Use	Water Yield	Water Use
	Several alluvial and bedrock aquifers	800 m	Largely forestry, some municipal and agricultural development; significant natural areas	Approximately 50% of NSR basin	Approximately 2% of NSR basin; of which approximately 50% is groundwater use
Groundwater Issues	**Key questions:** • Dynamics of regional groundwater recharge and contribution to basin yield • Effects of forestry, land-use change, and climate change on regional groundwater resources • Need for regional groundwater monitoring and local groundwater management plans (use and quality) near population centres				

4.2 Central Watersheds

4.2.1 Hydrogeology

The central watersheds (Modeste, Sturgeon, Strawberry, White Earth, and Beaverhill) stretch across a densely populated area of Alberta. Topography is variable, and includes rolling hills to level plains, river terraces, hummocks, lakes, and wetlands. Higher relief areas lying to the southwest are erosionally-resistant remnants of Paskapoo Formation sandstones (Ceroici 1979). Most of the area to the east has lower topographic relief due to uniform erosion of the generally finer-grained Horseshoe Canyon Formation. The geology too is variable, spanned by five major subcropping bedrock units (Figure 23), the upper surfaces of which are incised by a network of ancient river channels (Figure 26) that formed as a result of mountain-building to the west but before continental ice sheets covered much of the Earth's northern hemisphere.

Mean annual temperature ranges from approximately 2°C to 5°C. Generally across the central basins, the mean annual precipitation ranges from 600 mm in the west to 450 mm in the east, of which snowfall is generally between 200 mm (west) to 100 mm (east). At Edmonton, about 70 percent of the precipitation is rain that comes mostly in June to August. The summer precipitation is mostly lost to evapotranspiration. Mean annual potential evapotranspiration is between 365 mm (west) and 425 mm (east) (Golder Associates Ltd. 2008). Average water deficit is approximately 130 mm during the growing season (Bibby 1974). Recharge on the prairies generally ranges from less than 1 percent to 7.5 percent of annual precipitation (Meyboom 1967). Annual recharge, therefore, could range from less than 5 mm to approximately 40 mm.

In the eastern part of the area the near-surface bedrock unit is the Belly River Group, which consists of interbedded mudstones to fine-grained sandstones with subordinate coarser-grained sandstone beds (Glass 1990). A sandstone unit is present in the lower 10 to 30 m, which is generally fine- to medium-grained. The stratigraphy is summarized below.

Table 4-3 Generalized Stratigraphic Column – Central Regions

<table>
<tr><th>PERIOD</th><th colspan="2">FORMATION</th><th>AQUIFER POENTIAL</th></tr>
<tr><td>Quaternary</td><td colspan="2">glacial drift</td><td>local</td></tr>
<tr><td rowspan="2">Tertiary</td><td colspan="2">Empress Formation</td><td>good</td></tr>
<tr><td colspan="2">Paskapoo Formation</td><td>good</td></tr>
<tr><td rowspan="8">Upper Cretaceous</td><td colspan="2">Scollard Formation</td><td>good</td></tr>
<tr><td colspan="2">Battle Formation</td><td>poor</td></tr>
<tr><td colspan="2">Whitemud Formation</td><td>good</td></tr>
<tr><td>Horseshoe Canyon Formation</td><td rowspan="3">Wapiti Group</td><td>good</td></tr>
<tr><td>Bearpaw Formation</td><td>poor</td></tr>
<tr><td>Belly River Group</td><td>poor (west) to good (east)</td></tr>
<tr><td colspan="2">Lea Park Formation</td><td>poor</td></tr>
</table>

Above the Belly River Group is the Horseshoe Canyon Formation, which is the near-surface bedrock unit across the central areas. The Horseshoe Canyon typically consists of soft, fine-grained, bentonitic, feldspathic sandstones, bentonitic and carbonaceous shales, and coal seams. Thickness is approximately 230 m. The Horseshoe Canyon formed as the Rocky Mountains were uplifted, during the last days of the dinosaurs, in a semi-tropical deltaic environment at the edge of an inland sea. The formation outcrops in the North Saskatchewan River valley in Edmonton. In the Drumheller area, the formation constitutes the badlands. Above the Horseshoe Canyon Formation are the relatively thin (up to 10 to 20 m thick) Whitemud and Battle Formations. The Whitemud Formation has interbedded shale and sandstone, whereas the Battle Formation is bentonitic shale with an upper layer of volcanic ash called the Kneehills Tuff.

In the western part of the area, the Horseshoe Canyon Formation is overlain by the thin but important Paleocene/Upper Cretaceous Scollard Formation. The Scollard Formation is important because it contains a number of thick coal seams, including the Nevis Coal Seam and the Ardley Coal Seam. The Ardley Coal Seam is the most-extracted coal unit in the west-central Alberta Plains (Glass 1990). The Ardley Seam has been referred to as the “Big Seam” on the North Saskatchewan River west of Edmonton. It is the seam that is mined near Lake Wabamun and a target of coal bed methane development. The Cretaceous-Tertiary Boundary, which marks the mass extinction of dinosaurs, lies at the base of the Nevis Coal Seam.

The Paskapoo Formation is above the Scollard Formation. It consists of interbedded mudstone, siltstone, and sandstone, with some fossiliferous limestone, coal, and bentonitic beds. Prominent are 15 to 20 m thick medium- to coarse-grained sandstones. Thickness of the Paskapoo Formation increases from zero in the east (as the present-day erosional surface) and can range up to 1,000 m to the west (Glass 1990). Although the Paskapoo Formation is one of the single largest sources of potable groundwater in the Canadian Prairies, little information is available regarding the sustainable yield and regional distribution of groundwater supply within the aquifer system (Grasby et al. 2008).

In the Modeste watershed and the western portion of the Strawberry watershed, the best aquifers are sandstones of the Paskapoo Formation, from which yields of 150 to 650 m^3/day can be obtained across most of the area (Ozoray 1972). Depth to the base of groundwater protection in the Modeste watershed is on the order of 500 mbgs. Expected groundwater quality is very good with mineralization usually below 1,000 mg/L and often below 500 mg/L TDS. The chemical character is generally calcium-magnesium-bicarbonate. In discharge areas of longer flow systems, sodium is the predominant cation. Naturally-elevated sulphate, chloride, or iron concentrations are limited to small areas in isolated locations (Ozoray 1972).

Within large portions of the Sturgeon, Strawberry, and Beaverhill watersheds, the uppermost bedrock unit is the Horseshoe Canyon Formation. The Horseshoe Canyon Formation is highly heterogeneous laterally and vertically, consisting of shales, fine-grained bentonitic sandstones, and lenticular coal seams (Bibby 1974). Abundant fractured coal lenses generally have high permeability, but are usually of limited areal extent, although Stein (1976) reported several good groundwater zones within laterally-extensive fracture zones. Indeed, to the southeast, fractured coal seams within the portions of the Horseshoe Canyon are important aquifers, and due to their presence in areas of high rural population density, tend to be the most heavily utilized. Coal fracturing is most pronounced along the flanks of the Vegreville buried pre-glacial valley. Fractured coal seams more than 75 mbgs are said to be capable of producing water at rates of 140 to 720 m^3/day (Stein 1982).

Sandstones capable of yielding between 10 to 40 m^3/day are also considered important aquifers within the Horseshoe Canyon Formation (Ceroici 1979). The “Millet” sandstone, located within the upper 50 m of the formation, can yield from 140 to 720 m^3/day. The Horseshoe Canyon is reported to be relatively more permeable in both the Millet area and north of Devon. Both areas are underlain by extensive eolian deposits (Figure 25). According to Stein (1976), higher permeability in bedrock overlain by high permeability surficial deposits may be due to the “solution of cementing material by persistent and relatively intense groundwater flow caused by high rates of infiltration and precipitation through the surficial deposits.” Depth to the base of groundwater protection in the Sturgeon and Beaverhill watersheds is on the order of 500 mbgs, and 200 mbgs in the White Earth watershed, where the Belly River Group is underlain by the Lea Park Formation, which is a thick, low permeability shale aquitard of regional extent.

At greater depth in central areas, yields of 720 to 2,900 m^3/day are thought to be obtainable from the basal sandstone of the Belly River Group, but at depths of 250 to 600 mbgs, where groundwater mineralization exceeds 10,000 mg/L TDS.

The Belly River Group is a better groundwater resource to the east and northeast, where it becomes the near-surface bedrock unit across most of the White Earth watershed, and the eastern third of the Beaverhill watershed (Figure 23). The Bearpaw Formation occurs between the Horseshoe Canyon and

Belly River Group within the Beaverhill watershed but is considered an aquitard. The Belly River Group is approximately 300 m thick and contains two distinct zones of increased sandstone content: (1) the lowermost contains from one to three individual sandstones, each up to 15 to 20 m thick, referred to informally as the “basal Belly River sandstones”, and (2) the uppermost contains the Lower and Upper Birch Lake sandstones (Stein 1982). Expected yield for the basal Belly River is 260 m^3/day. To the northeast, the Birch Lake Members are capable of yielding from 10 to 35 m^3/day (Stein 1976).

The bedrock groundwater in these formations is generally of the sodium-bicarbonate type with mineralization usually between 1,000 and 2,000 mg/L TDS. More highly mineralized groundwater of either the sulphate or chloride types can occur locally (mineralization up to 6,000 mg/L TDS) in discharging portions of local or regional flow systems (Stein 1982).

The bedrock surface is cut by a system of buried pre-glacial valleys (Figure 26). Across the central area, the most prominent of these are the Onoway, Drayton, Beverly, and Vegreville buried valleys. Gravels and sands deposited in and along the buried valleys are informally termed the “Empress Formation” or “Saskatchewan Gravel and Sand” (Glass 1990). These deposits lie unconformably on the Cretaceous or Tertiary bedrock surface. Based on their chert and quartzite content (and a complete absence of granitic fragments from the Precambrian Shield) the lowermost deposits (“Empress Formation – Unit 1”) are known to be derived from rivers that developed as the Rocky Mountains were uplifted and eroded, but prior to continental glaciation. The Beverly Valley stretches continuously from west of Edmonton to the Saskatchewan border.

Groundwater yields in the Beverly Valley deposits can range from approximately 40 to 700 m^3/day, depending on saturated thickness and whether the deposits are in hydraulic connection with surface water (Stein 1976). Across a large portion of the central area, the Beverly Valley aquifer is in direct hydraulic connection with the North Saskatchewan River, with the water levels in the aquifer varying with the river stage. Tributaries to the main buried valleys (e.g., New Sarepta and Ellerslie valleys) have an expected yield in the range of 40 to 140 m^3/day. Expected yield is generally less because the deposits are thinner and the available drawdown is less (Ceroici 1979). The permeable sand and gravel deposits in the Vegreville valley are thought to be relatively discontinuous (Stein 1982). Thicknesses of preglacial sand and gravel deposits can vary from less than 3 m to more than 75 m (Stein 1976).

Water within the lower portions of the area’s buried valley system is generally of the sodium bicarbonate type with mineralization less than 500 to approximately 1,500 mg/L TDS. Mineralization greater than 1,500 mg/L TDS is generally associated with naturally higher sulphate content. Hydrochemical type can range from calcium-magnesium-bicarbonate to sodium-sulphate type, depending on groundwater residence time and position within a flow system.

Shallow, more local aquifers can be found in glaciofluvial (i.e., sand and gravel meltwater channels within clayey till), as well as eolian deposits. Glaciofluvial channels can be productive where extensive, as for example, the Andrew municipal well, and some provide flowing wells (Stein 1976). Recent alluvial deposits in the lower terraces and floodplains of the North Saskatchewan River generally contain significant proportions of sand and gravel and, where saturated, can function as good aquifers.

The chemical composition of groundwater in the drift is more variable than in bedrock, reflecting the more local nature of groundwater flow systems and lithologic variation within the drift. Groundwater in areas covered by lower permeability clayey till are typified by elevated sulphate and higher mineralization (Bibby 1974). Mineralization can vary naturally from less than 500 mg/L TDS in eolian deposits to more than 5,000 mg/L in clayey till. Drift waters can be characterized by high iron content (i.e., up to 5 mg/L).

Stein (1976) reported that many shallow wells in drift aquifers contain substantial amounts of nitrate. Forty-three percent of wells contained nitrate in excess of the then-recommended drinking water limit of less than 15 mg/L. According to Stein (1976), the most likely source of nitrate was from animal and human waste, and suggested that improvements either in practices of well construction, well location, or waste disposal location were necessary.

Ceroici (1979) developed a conceptual and mathematical model of the groundwater flow systems in the area southwest of Edmonton. A major groundwater recharge area was thought to be the unnamed topographic high adjacent to Pigeon Lake. Groundwater then moves downward to recharge bedrock aquifers, and laterally southwest to discharge at Pigeon Lake, and northeast to discharge in numerous outwash lakes (Wizard Lake, Long Lake) and the North Saskatchewan River. Most of the groundwater flow is concentrated in the more permeable sandstone units of the Paskapoo Formation. Regional topographic lows in the study area, such as the North Saskatchewan River, act as major discharge areas.

The dune field southeast of Stony Plain (Ceroici 1979) is a groundwater recharge area, from which groundwater moves east and south towards the North Saskatchewan River. Within the dune field, numerous local flow systems are also developed, where groundwater is recharged at local topographic highs and discharged at nearby topographic lows. Surface water bodies in the dune field are considered “outcrops” of the groundwater surface (Ceroici 1979).

Topographic depressions tend to be discharge points for local and intermediate groundwater flow systems. The Wagner Natural Area, located west of Edmonton, is a local groundwater discharge area. Within the fen is a rich peatland that supports dozens of unusual species of plants and lichen, along with insects, frogs, and birds. Without the consistent supply of groundwater at a relatively constant temperature, the specific conditions that make the fen and support the unique ecology would not exist. The recharge area is located south of the fen, reportedly in agricultural and Reserve land, but an industrial park is also located nearby (Wagner Natural Society 2001).

Ozoray (1972) noted, in the wooded parts of the Wabamun area, a number of calcareous tufa or marl-depositing springs. The marl formed encrustations, pools, or, as at Jackknife Springs (10-14-47-10 W5M), crater-like tufa cones. The spring water was cold (3 to 5^{o}C) and had mineralization generally of about 250 mg/L TDS, indicating that they were discharge features of short, local flow systems.

To the east, Stein (1982) described the groundwater of the Beaver Hills. The Beaver Hills are an elevated area of hummocky disintegration moraine (the “Cooking Lake Moraine”) between Beaverhill and Cooking Lakes. High relief, knob-and-kettle topography, and relatively low bulk permeability result in numerous surface water bodies over much of the area (Stein 1982). The drift is underlain by shale, coal, and sandstone of the Horseshoe Canyon Formation. Groundwater flows from the upland areas of the Beaver Hills to the Vegreville Valley, and then in an easterly direction within the valley. Flowing wells and springs near the eastern edge of the coal zones of the Horseshoe Canyon Formation (Figure 27) indicated that water recharging in the uplands moved downward into the coal zones and laterally to discharge at the subcrops. The relatively low permeability of the underlying Bearpaw Formation would enhance this situation (Stein 1982). Similarly, flowing wells, springs, and seepages on the southwestern portions of the Elk Island High are associated with areas of Horseshoe Canyon subcrop (Stein 1976).

4.2.2 Land Use

The Modeste watershed includes several small towns, villages, and First Nation's Reserves. The Jack Pine and Buck Mountain Provincial Grazing Reserves are within the watershed. The economic base of the region is primarily oil and gas, with agricultural and forestry activity. The Highvale Coal Mine is a surface strip mine that supplies coal to the nearby TransAlta Utilities Corporation Keephills and Sundance power plants. Waterbodies cover approximately 4 percent of the watershed. The larger lakes are Wabamun, Buck, and Jackfish. More than 3.5 percent of the land is taken up by linear development. The majority of the watershed is in various land uses related to agricultural production, including forage (43%), grassland (23%) and cropland (1%). About 19 percent of the watershed is forested, but 100 percent lies in a FMU. About 3 percent of the land area has been disturbed by development such as oil and gas wells, gravel pits, open pit mines, and power stations. Livestock densities in the watershed are generally moderate, but density increases to the east. An inventory completed by Ducks Unlimited Canada for part of the watershed indicated that permanent and temporary wetlands cover approximately 4 percent of the area. Overall, the Modeste watershed has a moderate level of agricultural and industrial development (North Saskatchewan Watershed Alliance 2005).

The Sturgeon watershed encompasses many larger communities and parts of the City of Edmonton. The soils are of high quality. The area is also strongly impacted by urban development. More than 3 percent of the land is taken for linear development. Water bodies cover approximately 5 percent of the watershed. Most of the watershed is classified in various land uses related to agricultural production, including cropland (31%), forage (25%), and grassland (22%). Only 11 percent of the watershed is treed. Almost 71 percent of the land area has been disturbed by various forms of development. The majority (94%) of this disturbance is due to municipalities and urban centres. The remainder of the land disturbance is related to linear developments, wellsites, industrial sites, and gravel extraction. Livestock densities in the watershed are considered moderate. An inventory by Ducks Unlimited Canada found that 6.8 percent of the area included permanent and temporary wetlands. The Big Lake wetland near the City of St. Albert is recognized as a globally-significant birding area because of the number and diversity of birds using it for breeding, staging, and migration (North Saskatchewan Watershed Alliance 2005).

The Strawberry watershed lies in both the Boreal Forest and Parkland Natural Regions and encompasses several larger towns as well as the City of Edmonton and a First Nations Reserve. Most of the landscape has been developed for agriculture. Significant oil and gas reserves (and the Leduc No.1 well) have also been developed in the area. About 19 percent of the land area in the watershed has been disturbed by various forms of development. Most of this disturbance (11 percent of the watershed) is due to municipalities. The remainder of the land disturbance is related to linear development (4%), wellsites (2%), and industrial sites. Water bodies cover less than 2 percent of the watershed. The majority of the watershed is classified into various land uses related to agricultural production: forage (54%) cropland (23%) and grassland (10%). The treed area of the watershed is only about 3.5 percent. Livestock densities are considered moderate. A Ducks Unlimited inventory found that wetlands covered a total of 23.5 percent of the watershed area. However, data from both the Alberta Sustainable Resources Development database and PFRA Land Classification showed no wetlands in the watershed. This is an important discrepancy to resolve (North Saskatchewan Watershed Alliance 2005). The City of Edmonton is attempting to conserve remaining natural wetlands and upland areas within its boundaries. Natural wetlands are now incorporated where possible into drainage infrastructure for stormwater management.

The City of Edmonton and surrounding water service areas have the largest attributable impact on the North Saskatchewan River's water quality, due to return flows of treated wastewater and urban stormwater runoff (North Saskatchewan Watershed Alliance 2005). Treated wastewater from the Gold Bar and Capital Region wastewater treatment plants are major sources of BOD (biological oxygen demand), fecal coliform bacteria, and nutrients (nitrogen and phosphorus). Stormwater outfalls from the City also add suspended solids to the river. Combined sewer overflows are a major source of fecal coliforms. To address this issue, the City is required to submit Alberta Environment a combined sewer discharge strategy by June 1, 2013. In addition, the City is continually improving sewer infrastructure (pipes, weirs, storage facilities) and treatment processes to reduce sewer overflows.

The White Earth watershed lies entirely in the Boreal Forest Natural Region. The Smoky Lake and Thorhild Provincial Grazing Reserves lie in the watershed. Many environmentally-sensitive areas within these reserves have been left as natural habitat. White Earth Natural Area was created to protect the slopes of Long Lake and White Earth Creek. The White Earth watershed is sparsely populated. Its main community is the town of Thorhild. Soils are excellent and the primary economic activities are agriculture, including many mixed farming operations, and hydrocarbon development. Long Lake Provincial Park provides recreational opportunities. Water bodies cover 3 percent of the watershed. The majority of the watershed is classified in various agricultural land uses: cropland (38%), grassland (28%), and forage (11%). About 20 percent of the watershed is forested and about 3.5 percent has been disturbed by the linear development. Livestock densities are generally moderate. A Ducks Unlimited inventory found that 3.5 percent of the watershed area is covered by wetlands. However, the available PFRA Land Classification shows wetlands on 0.3% of the watershed (North Saskatchewan Watershed Alliance 2005).

The Beaverhill watershed contains a combination of ecologically-significant natural areas, recreational opportunities, and centres of high urban activity. The watershed lies in the Boreal Forest and Parkland natural regions. Economic activity in the watershed includes agriculture, oil and gas-related industries, urban and rural subdivision, development and manufacturing, including fertilizer, chemical, and petrochemical plants (North Saskatchewan Watershed Alliance 2005).

A large proportion of the watershed is the Beaver Hills treed upland area, which supports a diversity of vegetation, waterfowl, mammals, and birds. The area is rich in natural wetlands and aspen-dominated Boreal mixedwood habitat. The Beaverhill watershed includes several larger towns and part of the City of Edmonton, as well as Sturgeon County, Elk Island National Park, and Miquelon Provincial Park.

In 1982, Beaverhill Lake was declared a National Nature Viewpoint by the Canadian Nature Federation, and designated a Wetland of International Importance in 1987 by the RAMSAR Convention (North Saskatchewan Watershed Alliance 2005). Within the Beaver Hills, the assemblage of grasslands, woodlands, and wetland habitats is important for many parkland species, including endangered and threatened species like the Piping Plover, the Trumpeter Swan, the Loggerhead Shrike, and Sprague's Pipit. With the exception of the wetlands, few of the surrounding landscapes retain native vegetation. Elk Island National Park and Miquelon Lake Provincial Park both provide critical habitat for wildlife as well as recreational activities (North Saskatchewan Watershed Alliance 2005).

Proportion of land use related to agricultural use is grassland (25%) cropland (27%) and forage (11%). Livestock densities in the Beaverhill watershed are moderate, with higher densities in areas to the east and southeast of Edmonton. About 20 percent of the watershed is treed. Water bodies cover about 9 percent of the watershed. The relatively large proportion of treed land and water bodies supports a high diversity of vegetation, mammals, and birds. About 14 percent of the land area has been affected by various forms of development. Most of this disturbance (10%) is due to municipalities and the remainder is related to linear development (3%), wellsites (0.6%), and industrial sites (0.1%). Only 7.3 percent is allocated to a FMU (North Saskatchewan Watershed Alliance 2005).

4.2.3 Water Use

The central basins provide only 7 percent of the total yield of the North Saskatchewan River basin. Estimated total water use in the central watersheds in 2005 was 173,628 dam^3 of a total use of 201,846 dam^3, which equals 86 percent of the total used across the basin (AMEC 2007). Of the total used, only 6 percent was groundwater (Figure 34). However, a large proportion of the groundwater (50%) is used for agricultural purposes.

Within the Modeste basin are 19 active water licenses, which allocate 851,255 dam^3 of water to the industrial sector. These allocations account for about 43 percent of total allocations in the North Saskatchewan River basin. Almost all allocated is surface water (851,190 dam^3) and almost all is for cooling for thermal power generation. Estimated actual use for cooling purposes is relatively small (64,387 dam^3) compared to the allocation. Actual municipal water use is also small compared to allocation. In fact, the Edmonton Capital Region returned more water (128,088 dam^3) to the North Saskatchewan River from its two waste water treatment plants than it withdrew (127,012 dam^3) but the returned water is of lesser quality. Return flows exceeded withdrawals because the wastewater treatment plants also treat stormwater and groundwater that enters the wastewater collection systems from areas in the larger Capital Region (AMEC 2007). Municipal groundwater allocations within the Modeste basin in 2005 included (AMEC 2007):

- the Village of Breton (126.8 dam^3),
- Brazeau County (31.8 dam^3), and
- County of Wetaskiwin No.10 (24.7 dam^3).

Although total allocation within the Sturgeon basin was relatively small (26,183 dam^3), the "other" sector accounted for 68 percent of the total allocation and the agricultural sector accounted for 14 percent. The "other" sector is dominated by surface water allocations for water management, largely within the County of Westlock. Agricultural water use in the Sturgeon basin is estimated to be about 3,191 dam^3, of which 36 percent is for stockwatering and 64 percent is for irrigation. Groundwater allocations accounted for 16 percent of the total. Most of the Sturgeon basin draws its water from the Capital Region system; however, the balance of the population draws its water from various surface and groundwater sources. Groundwater licenses represent nearly all of municipal water allocations in the Sturgeon basin including (AMEC 2007):

- the City of St Albert (169.6 dam^3),
- Town of Stony Plain (50.1 dam^3),
- Town of Bon Accord (219.6 dam^3),
- Town of Onoway (80 dam^3), and
- Sturgeon County (85.1 dam^3).

Actual water use by residents of the Sturgeon basin residing outside the Capital region was estimated to be 1,239 dam^3 in 2005, consisting of 1,233 dam^3 of groundwater. The estimated municipal water use exceeds licensed use by 134 percent, and results from the large portion of rural and suburban residents that draw water as household users rather than licensed sources.

The population of the Strawberry basin is largely urban. Approximately 94 percent of the population lives in urban municipalities around Edmonton. Total allocations in the basin in 2005 were 440,045 dam^3, and groundwater allocations (2,151 dam^3) accounted for less than 0.5 percent of the total. The industrial sector accounted for 65 percent of the total allocation (281,956 dam^3) and the municipal sector accounted for 32% of total allocations (137,778 dam^3). Municipal groundwater allocations included (AMEC 2007):

- the Village of Warburg (81.4 dam^3),
- Village of New Sarepta (130.8 dam^3), and
- County of Wetaskiwin No.10 (11.1 dam^3).

In the Beaverhill basin, the industrial sector accounted for 90 percent of the total allocation of 515,113 dam^3. Almost all of the allocated water (> 99%) is surface water (514,935 dam^3). The petroleum sector accounted for 7 percent of total allocations in 2005. A total of 5,257 dam^3 was allocated to the agriculture sector, with current actual use estimated to be about 8,624 dam^3. Livestock water use is expected to be about 3,409 dam^3 or 208 percent of that licensed allocation. With actual water use exceeding allocations, farmers are likely using their rights as exempted agricultural users to acquire water for their animal populations (AMEC 2007). In the future, agricultural demand for water in the basin is expected to increase as a result of the expansion of livestock populations. Forty-six active licenses allow withdrawals of 5,448 dam^3 to the "other" sector in the Beaverhill basin, 37 percent of which is expected to be consumed and 63 percent returned. Almost all is surface water (86%) issued for water management for flood control, lake stabilization, and fish, wildlife, and habitat enhancement, and other specified uses. Municipal groundwater allocations included (AMEC 2007):

- Strathcona County (34.5 dam^3), and
- Camrose County (1.2 dam^3).

The White Earth basin is predominantly rural. The commercial sector accounted for 42 percent of the total allocation of 10,808 dam^3. For the commercial sector allocations are primarily for aggregate washing (74%). The agricultural sector accounted for 21 percent of total allocations in 2005. Current agricultural water use is estimated to be about 2,952 dam^3, of which 60 percent is for stockwatering and 40 percent is for irrigation. Groundwater sources account for approximately half of the stockwatering water and less than 1 percent of the irrigation water. In the future, agricultural demand for water in the basin is expected to increase as a result of expansion of livestock populations, whereas irrigation water use is expected to remain constant (AMEC 2007). Municipal groundwater allocations in 2005 included (AMEC 2007):

- the Town of Smoky Lake (555.2 dam^3),
- Village of Clyde (91.3 dam^3),
- Village of Andrew (1.0 dam^3),
- County of Thorhild No.7 (37.0 dam^3),
- Lamont County (6.8 dam^3),
- Westlock County (102.4 dam^3), and
- Village of Warspite (23.4 dam^3).

Under a moderate growth scenario, total future water consumption in the central watersheds is projected to increase substantially (42%), from 173,628 to 245,756 dam^3 by 2025 (AMEC 2007). Much of this anticipated increase was due to bitumen upgrader projects slated. Some of these projects have, however, been recently delayed or cancelled, so that the projection may need to be revisited.

4.2.4 Groundwater Vulnerability

The central watersheds are transitional in terms of natural features and intensity of human activity. Foothills change to Boreal Forest and then to Parkland Natural Regions. Landcover changes from forest to predominantly agricultural and urban. The uppermost bedrock geologic unit varies from generally permeable Paskapoo Formation to more heterogeneous Horseshoe Canyon Formation to the Belly River Group, all of which provide potable groundwater through sandstones or fractured coals. The generally more resistant bedrock layers that result in the rolling hills to the west give way to more subdued topography to the east, although a notable exception occurs beneath the Beaver Hills. The buried pre-glacial valleys, also major aquifers, begin in the Modeste and western portions of the Sturgeon and Strawberry watersheds, join with the Beverly Valley, then exit the North Saskatchewan watershed to the northeast. The surfical geology is complex, varying from extensive areas of low permeability but generally thin glaciolacustrine and till deposits to higher permeability eolian deposits. Within the till can be channels of locally-significant high permeability glaciofluvial aquifers.

The central watersheds contribute approximately 8 percent of the entire yield of the North Saskatchewan River. A large proportion of groundwater recharge is expected to occur on topographic highs underlain by more permeable bedrock. The North Saskatchewan River is expected to act as a regional sink for groundwater discharge, but the quantity of yield due to groundwater discharge is unknown. Land-use has changed significantly over the past few decades, but how it may have changed (or will change) regional groundwater recharge and discharge relations is uncertain. How climate change may affect it in the future is also unknown. Overall volume of the groundwater resource is expected to be less than the western basins because thickness of the aquifer intervals decreases to the east. Residence times can also be expected to be more since topographic relief and flow rates are likely less.

On top of the hydrogeologic complexities, development pressures and competing land uses in the central areas are becoming more intensive. Water use is projected to increase by approximately 35 percent by 2025, largely for industrial purposes, and mostly from surface water. Within the Sturgeon basin, water for water management purposes is comparatively large and groundwater licenses represent a considerable portion of municipal water allocations. Agricultural demand for water in the basin is expected to increase mainly as a result of expansion of livestock populations. Within the central basins are areas of major ecological importance like Big Lake, the White Earth Natural Area, the Beaver Hills, and Beaverhill Lake. Meanwhile, basic instream needs have not been established and the contribution of groundwater to surface water, including wetlands, is unknown. Locally-significant groundwater recharge and discharge conditions can be sensitive to land-use changes in perhaps unforeseen ways. An example is the Wagner Natural Area. To protect sensitive wetlands, the connection with the recharge area should be established and recognized within a land-planning framework. With respect to groundwater vulnerability and land-use planning, special attention could be paid to places where units of high permeability bedrock intersect with high permeability surficial deposits, either in topographically high or low settings, which may be areas of focussed recharge or discharge.

Groundwater problems in areas of intensive development include possible changes in recharge and groundwater conditions affecting valuable ecosystems, as well as potential overdraft in local areas of municipal or rural residential supply. In industrial and agricultural areas, other problems could involve deteriorating groundwater quality. A groundwater management framework integrated with a land-use framework that considers cumulative effects would thus appear necessary for most of the Capital Region, including the Beaver Hills and other valued ecosystems, and local municipal groundwater users where declining groundwater levels may be of concern.

A groundwater management framework could be useful not only to encourage water quality protection, but also for integrated water use planning. For example, it could allow opportunity to find beneficial uses or storage of groundwater extracted for mining within a larger community of water users. Consistency of groundwater monitoring and remediation efforts would also be addressed.

Table 4-4 Summary of Groundwater Conditions and Issues – Central Basins

	Aquifer Potential	Depth to Base of Groundwater Protection	Land-Use	Water Yield	Water Use
	Several buried valley and bedrock aquifers	500 to 200 m	Largely agricultural, locally intense municipal and industrial development; significant natural areas	Approximately 50% of NSR basin	Approximately 86% of NSR basin; of which approximately 6% is groundwater use, largely for agriculture and local municipal
Groundwater Issues	Key questions: • Dynamics of regional and local groundwater recharge, contributions to basin yield, lakes, and wetlands • Effects and timing of agriculture, land-use change, and climate change on groundwater-surface water interactions, including baseflow and wetlands • Need for regional groundwater monitoring and groundwater management plans (overuse and quality) near population and industrial centres				

4.3 Eastern Watersheds

4.3.1 Hydrogeology

Population density is less across the eastern basins (Vermilion, Frog, and Monnery). Elevations range from approximately 800 to 400 masl. Local relief of the North Saskatchewan River Valley ranges between 60 and 90 m. Mean annual temperature is approximately 2°C. Generally across the eastern watersheds, the mean annual precipitation ranges from approximately 400 to 450 mm, of which snowfall is between 35 and 125 mm. Potential evapotranspiration exceeds precipitation from April to October (Currie and Zacharko 1976). Assuming recharge is approximately 1% to 7.5% of annual precipitation (Meyboom 1967) estimated annual recharge varies from approximately 4 to 40 mm. The stratigraphy is summarized below.

Table 4-5 Generalized Stratigraphic Column – Eastern Regions

PERIOD	FORMATION		AQUIFER POTENTIAL
Quaternary	glacial drift		local
Tertiary	Empress Formation		good
Upper Cretaceous	Bearpaw Formation		poor
	Birch Lake Member	Belly River Group	good
	Ribstone Creek Member		
	Lea Park Formation		poor

Groundwater resources are available in the Belly River Group and locally within the drift. The bedrock intervals supplying groundwater are a complex interfingering of sandstones and shales in the lower Belly River Group. The Ribstone Creek and Birch Lake Members of the Belly River Group are relatively widespread and form the major aquifers in the region (Currie and Zacharko 1976). Thicknesses are on the order of 20 m and expected yields range from 140 to 650 m^3/day. Two major buried preglacial valleys are the Vermilion and Vegreville valleys (Figure 26). Sediments in the preglacial valleys can yield 36 to 140 m^3/day or more, depending on lithology and available drawdown.

Below the Belly River Group to the west and directly below the drift to the east is the Lea Park Formation shale, which is a major regional aquitard. The Lea Park Formation limits the depth of groundwater resources in the eastern areas to 150 mbgs or less (Currie and Zacharko 1976). Thin overburden (less than 10 m) directly above the Lea Park Formation is indicated in the area where the North Saskatchewan River exits Alberta. Relatively thicker overburden (approximately 100 to 150 m) is found further north in the Frog Lake area (Andriashek and Fenton 1989). Sand and gravel lenses within the till have been developed for domestic groundwater supplies, as for example at Frog Lake (Currie and Zacharko 1976). Depth to the base of groundwater protection is on the order of 200 mbgs in the Vermilion basin and 100 mbgs or less in the Monnery basin.

Expected groundwater quality is generally good, although sulphate concentrations can be naturally very high in discharge areas. Calcium-magnesium-bicarbonate waters predominate in recharge areas while sodium waters of varying anion types occur in discharge areas. Mineralization commonly ranges between 500 and 1,500 mg/L TDS. Chloride content is generally low, but can be quite high in deeper bedrock wells. The area is largely agricultural and water wells are numerous, particularly in the Vegreville, St. Paul, Vermilion, and Lloydminster areas (Figure 33). In the past, Lloydminster relied on groundwater for its supply (Currie and Zacharko 1976).

4.3.2 Land Use

The Vermilion watershed is located mostly in the Parkland Natural Region (Figure 3). It includes several towns, the Minburn Provincial Grazing Reserve, and Vermilion Provincial Park. Water bodies cover 5 percent of the watershed. The majority of the watershed is classified in various land uses related to agricultural production: cropland (51%), grassland (46%) and forage (1%). Only about 0.2 percent of the watershed is forested. About 4 percent of the land area has been affected by various forms of disturbance including linear development and well sites, which affect about 1% of the watershed. Livestock densities in the Vermilion watershed are moderate with higher densities indicated in the north-central portions (North Saskatchewan Watershed Alliance 2005).

PFRA Land Classification shows wetlands covering 0.2% of the land area; however, an inventory completed by Ducks Unlimited found approximately 6%. The Holden Drainage District, the oldest in Alberta, drains approximately 12,000 acres in the southwest portion of this watershed and the southeast part of the Beaverhill watershed into the Vermilion River (North Saskatchewan Watershed Alliance 2005).

The Frog watershed is located in the Dry Mixedwood Natural Subregion with a small portion near the North Saskatchewan River overlapping in the Central Parkland Natural Subregion. The Rannach and St. Paul Provincial Grazing Reserves lie in the watershed. Whitney Lakes Provincial Park provides recreational opportunities and camping is a popular summertime activity in the St. Paul Grazing Reserve, particularly around Lac Bellevue and Perch Lake. Water bodies including lakes, rivers, streams, wetlands, and dugouts cover 7 percent of the watershed. Agricultural land uses within the watershed are classified as grassland (41%), cropland (28%), and forage (1%). About 18 percent of the Frog watershed is covered with trees. About 15 percent of the land area has been disturbed by various land uses including linear development (2%). Well sites affect about 1 percent of the watershed. Livestock densities are moderate to low in the northeast with higher densities near St. Paul. A Ducks Unlimited inventory found a total of 7.6 percent of the area is covered by wetlands (North Saskatchewan Watershed Alliance 2005).

The Monnery watershed lies mostly in the Central Parkland Natural Subregion (Figure 3). Agriculture is the primary activity in the watershed, although oil and gas operations are also prevalent. Water bodies cover 6 to 7 percent of the watershed. In terms of agricultural production, land-use is classified as follows: grassland (43%), cropland (36%), and forage (0.3%). About 6.5 percent of the watershed is covered with trees. There are no parks or protected areas. About 9 percent of the land area has been disturbed. Livestock densities are moderate (North Saskatchewan Watershed Alliance 2005).

4.3.3 Water Use

Estimated total water use in the eastern watersheds in 2005 was 28,077 dam^3, or 12 percent of total use of the larger North Saskatchewan River basin. Forty-three percent of the water was used for petroleum purpose and 13 percent of the water used was groundwater (Figure 35). The groundwater was used mostly for agricultural (73%) and municipal (18%) purposes. Under a moderate growth scenario, future water consumption is projected to increase from 23,285 to 28,077 dam^3 by 2025 (i.e., 38% increase) largely as a result of municipal, agricultural, and “other” growth (AMEC 2007).

In the Vermilion basin in 2005 the agricultural sector accounted for 39 percent of the total allocation of 4,060 dam^3. The “other” sector accounted for 31 percent of total allocations and municipal for 26 percent. Fifty-five active licenses allow withdrawals of 3,252 dam^3 to the “other” sector, only 4 percent of which is expected to be returned. All is surface water. These allocations were issued for water management mainly for habitat enhancement. As of December 2005, a total of 1,660 dam^3 had been allocated to the agriculture sector in the Vermilion basin. Water allocated to agriculture accounted for 39 percent of all allocations. Groundwater accounted for 59 percent of agricultural allocations. Seventy-five active municipal water licenses allow maximum withdrawals of 2,659 dam^3. Groundwater licenses account for 94% of the total municipal water allocations, including (AMEC 2007):

- the Town of Vermilion (1,312.8 dam^3),
- Town of Two Hills (213.4 dam^3),
- Village of Mannville (142.3 dam^3),
- Village of Kitscoty (184.9 dam^3),
- Village of Marwayne (127.1 dam^3),
- Village of Willingdon (150.5 dam^3),
- Village of Innisfree (27.1 dam^3),
- Village of Dewberry (16.4 dam^3),
- County of Vermilion River (65.7 dam^3)
- County of Two Hills No.21 (69.0 dam^3), and
- Village of Lavoy (38.2 dam^3).

Estimated actual water use was 558 dam^3 in 2005, corresponding to withdrawals of 2,715 dam^3 and returns of 2,157 dam^3, of which 510 dam^3 was use of groundwater.

In the Frog basin in 2005 the industrial and petroleum sector each accounted for 37 percent and 34 percent of the total allocation of 32,914 dam^3. Eleven water licenses allocate 11,307 dam^3 of water to the petroleum sector, mostly for injection. More than 99% of petroleum allocations are for surface water. Two surface water licenses allocate 12,039 dam^3 of water to the industrial sector (the Canadian Salt Company), which is expected to consume 1,204 dam^3. Municipal allocation was 8 percent. Groundwater licenses accounted for 30 percent of total municipal water allocations, including (AMEC 2007):

- the Village of Myrnam (48.1 dam^3),
- Village of Vilna (152.2 dam^3),
- Village of Derwent (16 dam^3),
- County of St. Paul No.19 (144.1 dam^3),
- County of Two Hills No.21 (14.8 dam^3),
- Smoky Lake County (1.2 dam^3),
- County of Vermilion River (73.0 dam^3), and
- Fishing Lake Metis Settlement (292.0 dam^3).

Agricultural allocation in the Frog basin was 4 percent. Groundwater accounted for 44 percent of agricultural allocations.

In the Monnery basin in 2005, the municipal sector accounted for 49 percent of the total allocation, or 11,175 dam^3 of 23,136 dam^3. The petroleum sector accounted for 43 percent of total allocations. Two surface water licenses allocate 9,955 dam^3 of water to the petroleum sector, all of which is expected to be consumed. The municipal allocation was largely surface water for the City of Lloydminster. Groundwater licenses accounted for less than 1% of the total municipal water allocations (21 dam^3 allocated to the County of Vermilion River). A total of 920 dam^3 had been allocated to the agriculture sector, which accounts for 4% of all allocations. Groundwater accounted for 41% of agricultural allocations.

4.3.4 Groundwater Vulnerability

In the eastern watersheds, groundwater use is proportionately higher than the central watersheds. A number of agricultural and municipal users are dependent on groundwater. At the same time, the aquifers thin like a wedge to the east as the depth to the Lea Park shale becomes less. In addition, the Beverly Valley has left the North Saskatchewan River basin. Smaller lakes and wetlands appear to cover a relatively larger proportion of the eastern watersheds. Ecologically, the Central Parkland Subregion, unique to North America, stretches across most of the eastern watersheds. Challenges to wetlands may present themselves in terms of increased use of groundwater for municipal or agricultural use (e.g., irrigation or stockwatering) but little is known of the possible linkages between groundwater extraction or quality and important wetlands. Potential degree of wetland sensitivity to changing groundwater conditions as a result of land-use change or climate change is also unknown. Some of the larger population centres, where density and type of water supply wells (agricultural, municipal, and petroleum) and land-use activity are relatively high (e.g., Lloydminster) would benefit from a local groundwater management framework.

Table 4-6 Summary of Groundwater Conditions and Issues – Eastern Basins

<table>
<tr><th></th><th>Aquifer Potential</th><th>Depth to Base of Groundwater Protection</th><th>Land-Use</th><th>Water Yield</th><th>Water Use</th></tr>
<tr><td></td><td>Few buried valley and bedrock aquifers</td><td>150 m or less</td><td>Largely agricultural, local municipal and industrial development; “duck factory” wetlands and smaller lakes</td><td>Less than 1% of NSR basin</td><td>Approximately 12% of NSR basin; of which approximately 13% is groundwater use, largely for agriculture and local municipal</td></tr>
<tr><td>Groundwater Issues</td><td colspan="5">Key questions:
Dynamics of local groundwater recharge and contributions to surface water
Effects and timing of agriculture, land-use change, and climate change on local groundwater resources
Need for local groundwater management plans (use and quality) near population centres</td></tr>
</table>

5. CHALLENGES AND OPPORTUNITIES

Challenges to groundwater management in the North Saskatchewan River basin arise mainly because of uncertainty. The framework of the hydrogeology is broadly-known in terms of topography and distributions of the main aquifers and aquitards, mainly because of geological and hydrogeological mapping efforts in the 1960s and 1970s. In the decades since the 1970s, however, little work has been done on the dynamics of recharge, discharge, and changes in groundwater storage. Expected well yields can be given in the aquifers, but not in the context of interference with other wells or possible hydraulic continuity with streams or wetlands. Groundwater quality is expected to be generally good, but we have no comprehensive grasp of current groundwater quality, especially in shallow aquifers in areas of combined agricultural, industrial, and municipal activity.

We cannot manage what we do not understand. At the same time, we do not have the resources (or perhaps immediate need) to attempt to understand all the groundwater resources across the basin in one effort. But we must choose priorities. Groundwater recharge in the western watersheds is likely a key to the regional volume of freshwater in the North Saskatchewan watershed as a whole, both quantitatively as baseflow to the North Saskatchewan River and as recharge to the Paskapoo aquifer system, a major water resource that lies beneath at least a third of the basin. An important area of study, therefore, would be to quantify the groundwater recharge in the western watersheds and characterize its flow, storage, and discharge within the Paskapoo aquifer system, including possible connections to the more eastern aquifers. Sensitivities to forestry practices, land-use change, agriculture, and climate change should also be studied for this critical area of the regional watershed.

Consideration should be given to the study of the expected lifespan and risk of casing integrity failure of older conventional oil and gas wells, and possible effects on groundwater resources. Study here should be focused on areas where new energy developments are occurring now or likely to occur (e.g., coalbed methane or carbon sequestration). Study should include a thorough understanding of groundwater flow and chemistry including gas composition and stable isotope ratios, to distinguish between thermogenic and biogenic natural gases.

Detailed study of the possible effects of confined feeding operations and manure-spreading on groundwater resources should be completed. Test sites should be chosen that represent typical groundwater conditions across the watershed where such operations are most frequent. A study of groundwater flow and chemistry at a confined feeding operation located on thin overburden overlying the Paskapoo Formation, or near a buried valley aquifer, for example would be valuable.

In the central basins, a groundwater management framework is warranted to improve land-use planning and management of cumulative effects, especially in areas of dense activity and previously-identified recharge areas around the Capital Region. Tools of analysis of hydrogeology (including mathematical groundwater flow and solute transport models) need to be applied. Special attention should be devoted to quantifying water use (even of unlicensed domestic and agricultural users) and potential industrial and agricultural effects on groundwater quality. Ambient groundwater quality in areas of consistent agricultural and industrial activity has not been characterized systematically since the 1970s. Some substances like chloride and nitrate are relatively conservative in the subsurface and can originate from a number of different human activities. Characterization and tracking of water quality are necessary for setting environmental sustainability objectives within a Cumulative Effects Framework.

Potential effects of land-use activity or change in recharge areas on hydraulically-connected discharge areas need to be identified and quantified for land-use management purposes. Protection of discharge-dependent ecosystems could be identified as an environmental objective within the Land-use Framework. The relationships between groundwater flow and ecologically-important areas like Big Lake, the Wagner Natural Area, and the Beaver Hills should be investigated, quantified, and monitored. Other such lower profile but locally-valued wetland features should also be identified and characterized in terms of hydrogeology and ecology. Education and outreach programs should be considered to bring attention to such areas. The real cost of replacing a disappeared wetland (i.e., in terms of benefits to society like water treatment and carbon sequestration) should be incorporated in land-use decision-making. In the future, it is expected that economic valuation of water and the ecohydrological services it provides will be a very powerful organizing principle for land- and water-use management (e.g., Olewiler 2004).

To the east, population pressures are less but water resources too are less abundant. At the same time, the eastern areas are proportionately more dependent on groundwater use both for municipal and agricultural purposes. The combined effects of groundwater use, agricultural use, land-use change, and climate change on the wetlands and unique ecosystems of the Central Parkland are unknown. The time-scale of effects is also unknown. By 2025, water use is expected to increase by almost 40 percent in the eastern watersheds.

By studying such priority areas as outlined above, groundwater monitoring networks can be expanded and strengthened as necessary. Monitoring networks and indices for assessing ecosystem health need to be developed and implemented in the case of groundwater contributions to streams or wetlands. In many areas, industrial activities have groundwater monitoring wells already installed at their facilities to monitor background conditions as well as to permit early detection of contaminants. Industrial users could be approached to share stratigraphic, groundwater level, and groundwater quality data, especially of their background wells. Springs are another excellent, low-cost opportunity to measure and monitor the health of a watershed, and sometimes a unique ecosystem. They should be incorporated in monitoring networks and data compared to historical measurements from the 1970s or earlier if available. Any networks thus developed need to be maintained over time and the data gathered need to be digitized, centralized, and easily accessible.

Because of its critical role in defining our present and future economic and environmental well-being, Alberta's water resources require effective governance. The Alberta government should take strong leadership to align all ministries and programs that have effects on water resources. These ministries include the agricultural, energy, environment, forestry, infrastructure, sustainable resources, transportation, and other departments. All must work in concert if water is to be objectively managed.

Otherwise, water may need to have its own ministry. In 1970, President Richard Nixon created the EPA as "a strong, independent agency" from a number of smaller arms of different federal agencies. Prior to the EPA, the federal government was not structured to comprehensively establish and enforce federal environmental protection laws. The President was reluctant to propose setting up a new independent agency, but he was eventually convinced by all "the arguments against placing environmental protection activities under the jurisdiction of one or another of the existing departments and agencies." These arguments were: (1) the primary mission of each existing department would bias any decisions it made on a government-wide basis concerning the environment; and (2) the same factors might raise questions about the objectivity of any existing department as a standard-setting body for other agencies and departments (Lewis 1985). A lesson can perhaps be learnt from the establishment of the EPA.

6. SUMMARY AND CONCLUSIONS

The North Saskatchewan River basin has a diversity of hydrogeologic conditions. Groundwater resources appear relatively abundant in bedrock and drift aquifers across the basin. The volume of fresh groundwater is expected to far exceed the volume of fresh surface water. Conceptually, we know that the groundwater is recharged in topographically-elevated areas, flows through rocks of varying permeability, and discharges to low areas of regional to local scale. Quantitatively, however, we have almost no specific information on how much groundwater flows or is stored in these various systems across the basin, even though agriculture, ecosystems, select municipalities, and private users depend substantially on groundwater resources. We expect that future demand on groundwater resources will increase due to population increases and climate change.

To look to groundwater for future environmental and economic needs, the resource needs to be managed responsibly. But to manage responsibly, we must have a better understanding of the physical and chemical hydrogeology of the system and its connections to water availability, water use, land use, and ecosystem functioning within varying scales of both time and space. Valued ecosystems and wetlands within each basin need to be identified and their connection to regional or local groundwater flow established. The sensitivities of the associated groundwater systems to agricultural land-use, groundwater extraction, and land-use change (as the case may be) should be characterized. Key areas of further study include the following.

- The dynamics of regional groundwater recharge in the Rocky Mountains and Foothills should be characterized in terms of contributions to baseflow in the headwaters and to regional flow in the Paskapoo aquifer system, as well as the sensitivities of regional groundwater flow to the effects of forestry practices, land-use change, and climate change in the headwaters.
- Groundwater management frameworks should be developed for basins or local areas having more dense population and competing land use, to establish a consistent and systematic approach to understanding, monitoring, and protecting groundwater resources.

We need to use these studies to build quantitative models of groundwater and surface water interaction across the basin. Evaluation of these models will require more focussed and robust monitoring systems. We should build on existing government and industry wells and we should incorporate springs and ecosystem parameters in our monitoring systems. The development of groundwater models will reveal areas where our knowledge needs strengthening. As key knowledge gaps are filled across the basin, the monitoring systems can be synthesized as building-blocks towards eventual regional monitoring. The gathered data needs to be digitized, centralized, managed, interpreted, and reported on regularly with the purpose of recognizing and managing cumulative land-use or water use effects, and climate change.

Integrated land- and water-use management is necessary for sustainable water supply, water quality, economic welfare, and functioning ecosystems. There is no better time to do this work than now. Future generations would thank us.

7. CLOSURE

We trust that this report satisfies your current requirements and provides suitable documentation for your records. If you have any questions or require further details, please contact the undersigned at any time.

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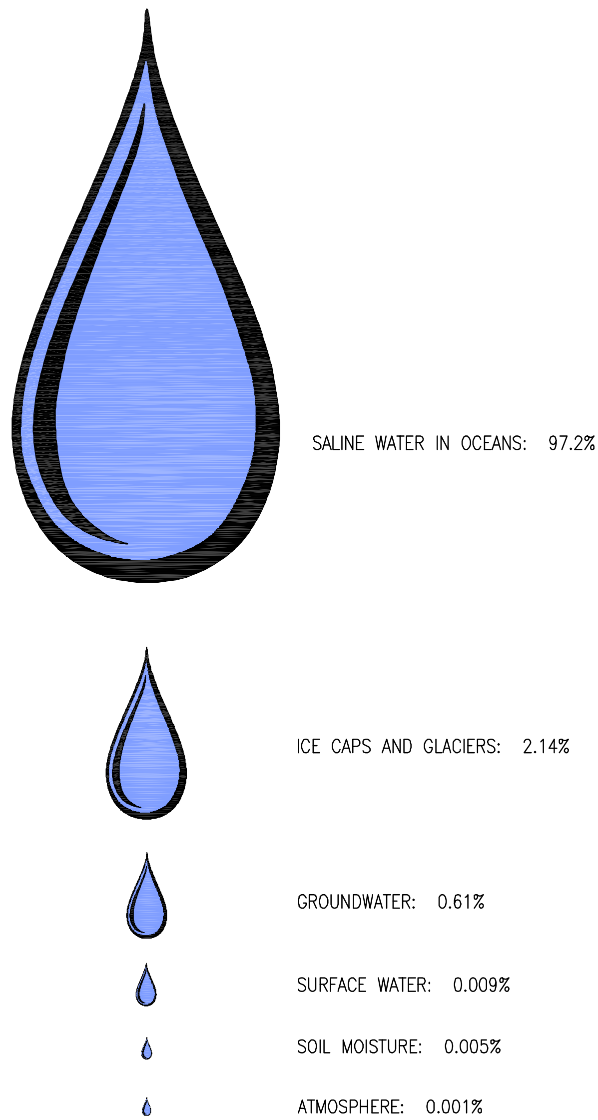

SOURCE: FROM FETTER (2001) PAGE 4

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NORTH SASKATCHEWAN WATERSHED ALLIANCE
OVERVIEW OF GROUNDWATER CONDITIONS

DISTRIBUTION OF THE EARTH'S WATER SUPPLY

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FIGURE: **1**