# WILLOW CREEK WATERSHED AQUIFER MAPPING AND GROUNDWATER MANAGEMENT PLANNING STUDY TWPS 008 TO 016, RGES 25W4 TO 05W5 NORTH OF FORT MCLEOD, ALBERTA

Submitted To:

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## EXECUTIVE SUMMARY

The Oldman Watershed Council is planning to develop a groundwater management framework for the Oldman River Basin located in south central Alberta. The Oldman River drains into the larger South Saskatchewan River basin and Alberta Environment and Water has placed a moratorium on surface water diversion and use because it is fully allocated. The Willow Creek sub-basin drains into the Oldman River at Fort Mcleod Alberta and therefore is also under moratorium with respect to surface water diversion. As groundwater resources beneath Willow Creek may form part of the water budget in the basin, the Oldman Watershed Council have come to recognize that a conceptual understanding of the subsurface hydrogeology is required. Waterline Resources Inc. was retained to develop the conceptual hydrogeological model within the Willow Creek Watershed as it relates to water supply aquifers and interactions with surface water in Willow Creek. The objective of the project is also to develop a groundwater monitoring plan for key aquifers within the Willow Creek watershed.

Surface water flow in Willow Creek is controlled by the Chain Lakes Reservoir and the Pine Coulee Reservoir. Water supply for the Town of Claresholm and the Town of Granum are extracted from Willow Creek. The Town of Stavely is supplied by groundwater from the Stavely buried valley aquifer which is a confined aquifer situated some 35 m below the ground surface. Overburden deposits in the Willow Creek watershed consist of pre-glacial, glacial, and recent alluvial deposits. Bedrock geology varies from relatively flat lying “layer cake” geologic sequences in the eastern part of the watershed and in the vicinity of Highway 2, to highly complex, thrust faulted and folded geological sequences west of Highway 22 at the western part of the watershed. The following key groups of aquifers were identified:

- Glacial overburden aquifers;
- Glacial and/or pre-glacial buried valley aquifers (e.g, Stavely buried valley aquifer);
- Recent alluvial aquifers in the vicinity of creeks such as Willow Creek;
- Porcupine Hills Formation Aquifers (multiple aquifers with depth); and
- Willow Creek Formation Aquifer.

At present, bedrock aquifers such as the Willow Creek and Porcupine Hills Formation Aquifer(s) are the most important in the watershed from a groundwater use perspective, although buried valley aquifers such as the Stavely buried channel aquifer can be prolific and yield high volumes of groundwater. Alluvial deposits within the Willow Creek valley form an unconfined aquifer which is likely in direct connection with surface water. The Willow Creek alluvial aquifer is of some importance from a water use perspective but and is also highly vulnerable to contamination from surface activities. The greatest number of water wells in the watershed is completed in the Willow Creek Formation.

Average precipitation in the fall and winter (October to February) is generally less than 20 mm or less between 1912 and 2005. The most rain, approximately 70 mm, falls in June.

Precipitation in the Willow Creek Watershed, averaging 413 mm annually (between 1915 and 2005), ranges from 70 mm in June to 20mm fall and winter. Approximately 5% to 15% infiltrates into the ground and recharges aquifers in the subsurface. Although recharge may vary depending on the permeability of surficial geology and ground cover, the water table in unconfined aquifers, and the piezometric (pressure) surface in confined aquifers generally follows topography which is largely defined by the drainage of Willow Creek and groundwater flow therefore occurs from northwest to southeast across the watershed. Leakage through confining layers between aquifers recharges deeper systems and discharge may occur locally to creeks and in topographically lower areas.

The volume of recharge to groundwater systems over the watershed is estimated to be between 54,120,600 and 162,361,800 $m^3$/yr based on an estimated 5% to 15% infiltration from precipitation. The 172 groundwater diversion licenses existing within the watershed account for a groundwater diversion volume of 2,227,908 $m^3$/yr. Groundwater diversion and use for domestic purposes is estimated to be 2,671,250 $m^3$/yr based on the 2,137 households within the watershed. This suggests that there may be a groundwater surplus of between 49,221,442 and 157,462,642 $m^3$/yr. This also suggests that anywhere from 3-9% of the estimated recharge to aquifers may be currently in use.

A fundamental knowledge/data gap, results from the inability to reconcile water wells in the field with Alberta Environment and Water's water well database. The problem arises as a result of the fact that wells are not generally tagged in the field and there is no requirement to record an accurate well location. In most instances, the well location is estimated to the nearest quarter section by the driller which is only accurate to +/- 400 m, making it difficult to reconcile with well ID's in AEW's water well database, AEW's well license approval database, and with water chemistry records. In Waterline's opinion, drillers should be required to apply for AEW well ID number before wells are drilled. In this manner AEW can issue tags which can be affixed to the well casing by the driller so that a tracking system can be established. Although this is a provincial responsibility, the Oldman Watershed Council should promote this practice to drillers operating in the region or to the landowner after the well is drilled, as every well drilled in the watershed is a potential groundwater monitoring point that can help resolve data gaps in developing our understanding of groundwater systems within the watershed.

There is also an immediate need to establish a groundwater monitoring network in key areas. The intent of such a network is to have a series of control points in key aquifers so that the current groundwater conditions can be determined and a long-term water level record can be established. A critical question is whether aquifers in the watershed are being over-exploited and if water levels are stable, increasing or more importantly in decline. Declining water levels in wells indicates that groundwater diversion may be exceeding aquifer recharge and that corrective action may be required to ensure sustainable use of groundwater resources in the region.

Waterline has identified critical areas based on aquifer characteristics, population density, the number of wells completed in aquifers which have been identified, vulnerability of areas, areas where insufficient hydrogeological data exist, and future development areas. The following locations are recommended for establishing an observation well network within the watershed:

- Upstream of Chain Lakes Reservoir – to monitor recharge characteristics high in the watershed within alluvial materials and Alberta Group bedrock;
- Kintz Creek confluence with Willow Creek for monitoring the Porcupine Hills Formation Aquifer(s) and potential communication with surface water resources (recharge/discharge relationship);
- West of Stavely to monitor Stavely buried valley aquifer and underlying Willow Creek Formation aquifer;
- Trout Creek near Willow Creek to monitor interactions between Willow Creek, the Willow Creek alluvial aquifer, the Carmangay buried valley aquifer, and the Willow Creek Formation aquifer;
- Between Claresholm and Granum near Willow Creek to monitor the buried valley aquifer and the Willow Creek Formation aquifer; and
- East of Mud Lake to monitor the Willow Creek alluvial aquifer, Mud Lake buried valley aquifer, and the Willow Creek Formation aquifer.

The groundwater geochemistry transforms from a calcium-magnesium bicarbonate type in the foothills and mountains (Brazeau and Alberta Group aquifer(s)), to a sodium-sulphate, or mixed sodium sulfate-bicarbonate type groundwater in the plains part of the watershed. This is a common geochemical evolution of groundwater as the residence time of groundwater in contact with bedrock increases, and mineral dissolution progresses as groundwater moves from zones of recharge in the upper watershed to zones of discharge in the lower part of the watershed.

The TDS of groundwater appears to increase dramatically from the upper to the lower part of the Willow Creek watershed. Of the 1,504 samples with a measured TDS concentration from the Willow Creek Formation, 1,178 had TDS concentrations greater than the 500 mg/L drinking water criteria for TDS. This change in concentration may coincide with the boundary of the glacial till deposits left by the eastern derived Laurentide ice sheet and western derived Cordilleran glacial deposits from the last ice age. The glacial till to the east of this boundary has high sulphate content likely derived from the higher sulphide mineral content of the granite and gneiss pebbles. Another possibility to explain the higher TDS concentrations could be the result of higher temperature and lower precipitation in the plains region which would result in greater evaporation and thus higher TDS content than in the foothills and mountains to the west.

Continuous long-term, water level and water quality monitoring of aquifer response to natural phenomena such as precipitation events, or human activities such as groundwater pumping and diversion, and contamination is fundamental to developing an understanding of groundwater flow systems and interactions. Such an approach provides an early-warning system for aquifer management and the needed information for future land use planning. Waterline recommends the use of existing wells, or drilling new wells as required, and continuous monitoring of water levels using pressure transducer-data loggers.

Aquifer mapping, and particularly aquifer vulnerability mapping, should be updated once baseline groundwater data are available. Land development and land use planning can then be addressed with some consideration of existing cumulative groundwater impacts. In addition, sustainable development strategies can be established to reduce impacts in sensitive areas through low impact development practices, water conservation, water capture and infiltration measures, establishing communal well systems, and through other measures. Community outreach programs can also be developed in an effort to clarify roles and responsibilities of all users who reside in the watershed.

Managing groundwater resources within the Willow Creek watershed will undoubtedly present challenges but also presents a unique opportunity for innovation and setting the template for the future approach to aquifer management in Alberta. Waterline has developed an approach that we believe will maximize the understanding of aquifers within the Willow Creek watershed so that the data can be integrated into Oldman Watershed Council's future groundwater management framework.

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# 1.0 INTRODUCTION

## 1.1 Report Terminology

The reader is advised that some of the terms used in the enclosed report are of a technical nature, and some may be described in the glossary of terms attached at the back of this report (**Section 11.0**). Waterline has made an effort in the report to indicate when a term has been added to the glossary by placing a superscript "g" ([g]) at the end of the first occurrence of the word so the reader can review the meaning. In addition, a brief description of groundwater and groundwater theory is included in Appendix A.

## 1.2 Background

Waterline Resources Inc. (Waterline) was retained by Oldman Watershed Council (OWC) to complete an aquifer mapping and groundwater management planning[g] study within the Willow Creek watershed based on existing data. The study area is located in Southern Alberta within Townships 008 to 016, Ranges 25W4 to 05W5 (**Figure 1**).


Figure 1 Location map

As is common for some areas in Alberta, groundwater flow is not well understood in the Willow Creek watershed. Although there have been past initiatives to map groundwater resources, mapping is incomplete. In an effort to address this, Alberta Environment and Water (AEW) and Alberta Geological Survey (AGS) are mapping high priority areas that are undergoing rapid growth, such as the Edmonton-Calgary Corridor (AGS, 2011). Their primary objective is to map the groundwater resources of the entire province (GOA, 2010a).

Numerous factors such as climate, population growth, agricultural practices, industrial activities and surface water basin closures to further allocation are placing pressure on groundwater quantity and quality in the South Saskatchewan Region (**Figure 1**). Within this region, areas with high population density have been identified as vulnerable to groundwater overuse. Long-term monitoring is required to demonstrate whether water levels are declining and overuse is indicated.

The Willow Creek watershed has been identified by the OWC as an area of groundwater vulnerability within the South Saskatchewan Region (**Figure 2**). Because there is a lack of groundwater information in this area there is a need to compile, evaluate and present existing information about groundwater resources followed by looking at ways to fill the knowledge gap in order to manage the resource wisely.

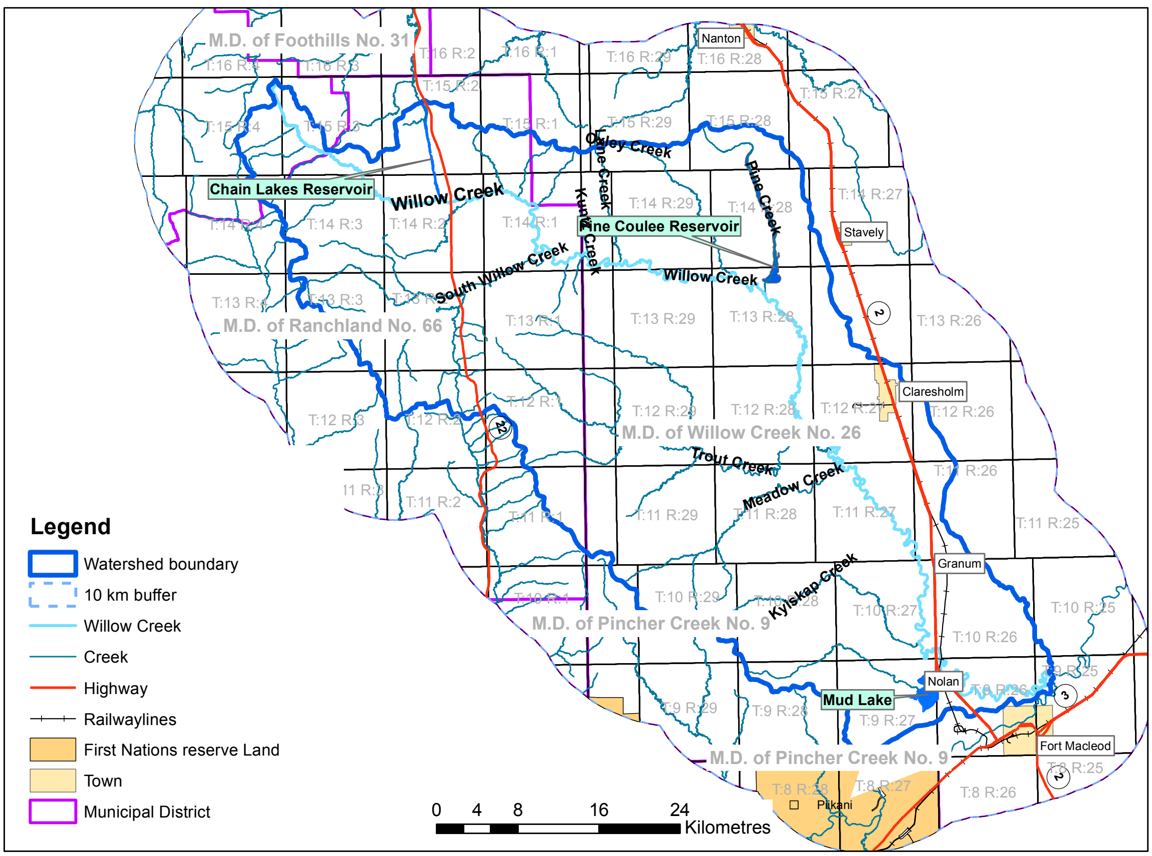



Figure 2 Willow Creek watershed

The Oldman Watershed Council has identified groundwater as a priority to address in the Integrated Watershed Management Plan for the Oldman River basin. As part of the implementation of the South Saskatchewan (River) Regional Plan (GOA, 2010e), the Government of Alberta is working on establishing a land-use change model which includes groundwater and geotechnical data. Municipalities, health agencies and many others also have an interest in understanding groundwater and ensuring it is managed for long term sustainable use.

The Willow Creek watershed encompasses approximately 2,529 $km^2$ comprising all the land area drained by Willow Creek and its tributaries. Approximately 68 per cent of the watershed is located in the Municipal District of Willow Creek (No. 26). The remaining area is divided among the M.D. of Ranchland (No. 66) (30%) and Kananaskis Improvement District (2%).

The watershed area consists of unconsolidated overburden aquifers (e.g., sand and gravel) and consolidated bedrock aquifers (e.g., sandstone). Groundwater is extracted from these aquifers for local domestic, municipal, agricultural, and commercial/industrial water supplies. Although not well developed, an alluvial aquifer appears to exist in the vicinity of Willow Creek, consisting of shallow unconfined fluvial[g] sand, silt and gravel. The alluvial deposits represent approximately 3.5% of the land area of the watershed (95 $km^2$). These alluvial materials are thought to be in direct connection with Willow Creek. Therefore, groundwater withdrawals from these deposits may be considered groundwater directly connected to surface water and would generally be licensed as surface water sources by AEW under the Water Act (Alberta Environment, 2006). Other water wells[g] in the watershed withdraw groundwater from the underlying bedrock, which is a heterogeneous system dominated by sandstone, siltstone and mudstone.

Demand for water in the watershed includes:

- Agriculture – including confined feeding operations (e.g., cattle, swine, poultry) and raising of crops;
- Golf Courses – two exist within the Willow Creek watershed at Claresholm and Granum;
- Oil and Gas activity – mainly in the eastern half of the watershed;
- Timber harvesting;
- Recreation (Chain Lakes and Willow Creek Provincial Parks); and
- Residential – Towns of Claresholm and Granum and rural development.

The Willow Creek watershed falls within the Grassland, Foothills Parkland, and the Rocky Mountain Natural Regions (GOA, 2010a, p.64).

### 1.3 Objective and Scope Of Work

The objective of the study is to compile existing groundwater information to paint a picture of what is currently known and to set the stage for what needs to be done in the near future.

Recommendations are included in this report that will assist in understanding the resource and managing it for long term sustainable use.

The Oldman Watershed Council (OWC) released *Priorities for the Oldman Watershed: Promoting action to maintain and improve our watershed* in January 2012 which outlines eight goals including one for groundwater. The OWC is developing an Integrated Watershed Management Plan for the Oldman River basin which will achieve the eight goals in the *Priorities* document. Goal five is “understand groundwater and how it interacts with surface water” which is followed by three objectives including one that states “research the availability and quality of groundwater and its interaction with surface water”. This study is the first step in meeting that objective.

This study also fulfills one of many outcomes of the Land Use Framework initiative for groundwater in the South Saskatchewan Regional Plan. The Government of Alberta is working on an integrated approach to land management that includes a new cumulative effects[g] management system. Land use impacts on groundwater will have to be an integral part of that system but groundwater information is lacking.

The Government of Alberta has designated the Oldman River Basin as a "Priority Area" in southern Alberta for future establishment of a groundwater management framework[g]. Selection of priority areas is still under review by Cabinet.

The scope of work for the present study is to identify and review available information relating to groundwater supply and quality within the Willow Creek watershed (**Figure 2**) and to provide a description of the hydrologic, geologic, hydrogeological and hydrogeochemical setting. A conceptual hydrogeological model needs to be developed for the watershed and some attempt will be made to develop a groundwater budget based on available data. Recommendations are required for groundwater monitoring sites so that long-term data can be collected from key aquifers within the watershed. This should allow for further groundwater evaluation, planning, and sustainable development of the groundwater resources within the watershed. Major knowledge and data gaps respecting groundwater should also be identified.

The data and the maps found throughout this report are a rough estimate based on limited existing data, as such any interpolation to a local scale especially for planning purposes should be augmented by field investigation to confirm their accuracy. The results presented in this report have not been confirmed by such investigation.

An annotated bibliography of available relevant literature is included in **Section 12.0** of this report.

## 2.0 LAND USE AND WATER MANAGEMENT FRAMEWORKS

In order to place the present study into the proper context, an understanding of Alberta’s Water for Life Strategy and Landuse Framework is required with respect to the Willow Creek watershed.

## 2.1 Water for Life Strategy

In November 2003 after a multi-year drought raised public concern over water, the Government of Alberta announced *Water for Life: Alberta's Strategy for Sustainability*. The strategy has been the vehicle for water management in Alberta ever since. The three goals of Water for Life are:

- Safe, secure drinking water supply;
- Healthy aquatic ecosystems; and
- Reliable, quality water supplies for a sustainable economy.

Water for Life enabled the formation of Watershed Planning and Advisory Councils (WPACs) in each major river basin of the province to report on the state of the watershed, to plan for the future of the watershed and to assist in meeting the other key actions outlined in the Water for Life Action Plan.

The Oldman Watershed Council (OWC) was incorporated as a not-for-profit organization in 2004 as an official WPAC with the merging of two existing groups; the Oldman Basin Water Quality Initiative and the Oldman Basin Advisory Council.

In 2010 the OWC released the first Oldman River State of the Watershed Report (AMEC, 2010) which contains a recommendation to monitor groundwater as an indicator of the health of water resources. A groundwater indicator is needed for the next state of the watershed assessment. However, groundwater information is lacking in the Oldman basin so this study was commissioned as a first step towards addressing that recommendation.

The OWC is currently working on an Integrated Watershed Management Plan that will address the issues identified in the Oldman River State of the Watershed Report. Because groundwater was identified as an information gap it is a priority for the plan. *Priorities for the Oldman Watershed: Promoting action to maintain and improve our watershed* released in January 2012 outlines the eight goals of the plan, including one for groundwater. Goal five is "understand groundwater and how it interacts with surface water" which is followed by three objectives including one that states "research the availability and quality of groundwater and its interaction with surface water". This study is the first step in meeting that objective as well as the state of the watershed recommendation.

Suggested components of a watershed management plan related to groundwater include:

- Identify alluvial aquifers as an important groundwater resource that need to be studied and protected
- Inclusive, integrated and committed stewardship of the river and watershed
- Source water protection – cap and decommission unused groundwater wells;
- Groundwater under the influence of surface water – monitor water quality in alluvial aquifers;
- Alluvial aquifer – conduct groundwater assessments prior to development;

- Groundwater protection - Introduce an inspection system for private septic systems; and
- Mapping – map groundwater areas showing recharge[g] areas and connectivity.

The objectives resulting from these outcomes could be:

- Recommend water quality objectives; and
- Provide decision-making advice within the watershed for federal, provincial and municipal authorities.

## 2.2 Land Use Framework

Alberta's Land Use Framework delineates seven land-use regions where regional land use plans will be developed which will define outcomes for water, air, land, and biodiversity. Monitoring and modelling of these resources will be an important part of managing cumulative effects and achieving these regional outcomes.

The Government of Alberta has started to develop a new land-use system for the province. On December 3, 2008, the Alberta government released an integrated land use planning approach (GOA 2008). This Land-use Framework (LUF) was followed in the Spring of 2009 by the Alberta Land Stewardship Act (ALSA) (GOA 2009). The LUF and ALSA divide the province into seven regions and commit land and resource managers in those regions to taking a cumulative effects approach to land-planning and related management activities. The Land-use Framework identified the South Saskatchewan Regional Plan as an immediate priority (GOA, 2010a).

The availability of potable water within the South Saskatchewan Region will likely become one of the limiting factors to future population and economic growth. The region faces challenges in meeting future water demand because of a combination of history, climate, geographic factors, and patterns of settlement. In dry years, demand for water can exceed the volume of water available in some rivers for extended periods (GOA, 2010a). Water storage in reservoirs during spring freshet, can help meet the water demands of licensed allocations, the aquatic environment and the water-sharing agreement with Saskatchewan (GOA, 2010a).

The provincial Water for Life Strategy (2003) is consistent with Alberta's LUF. Since 2003, Water for Life: Alberta's Strategy for Sustainability, has been the primary guidance document for managing Alberta's water resources. Under the mandate of AEW, this strategy applies to non-saline groundwater defined as possessing a total dissolved solids of 4,000 mg/L or less.

Groundwater Management Frameworks (GMF) are a new tool being considered to integrate the principles of the groundwater protection framework established under the Water for Life Strategy. The future development of a GMF for the sustainable management of groundwater in the Willow Creek watershed is desirable, and the enclosed study represents the first steps toward achieving this goal and aims to help AEW and OWC evaluate whether one is necessary. **Figure 3** shows how a groundwater management framework fits within the overall planning and management policies of the province with respect to water (i.e. Land Use Framework and Water for Life Strategy).

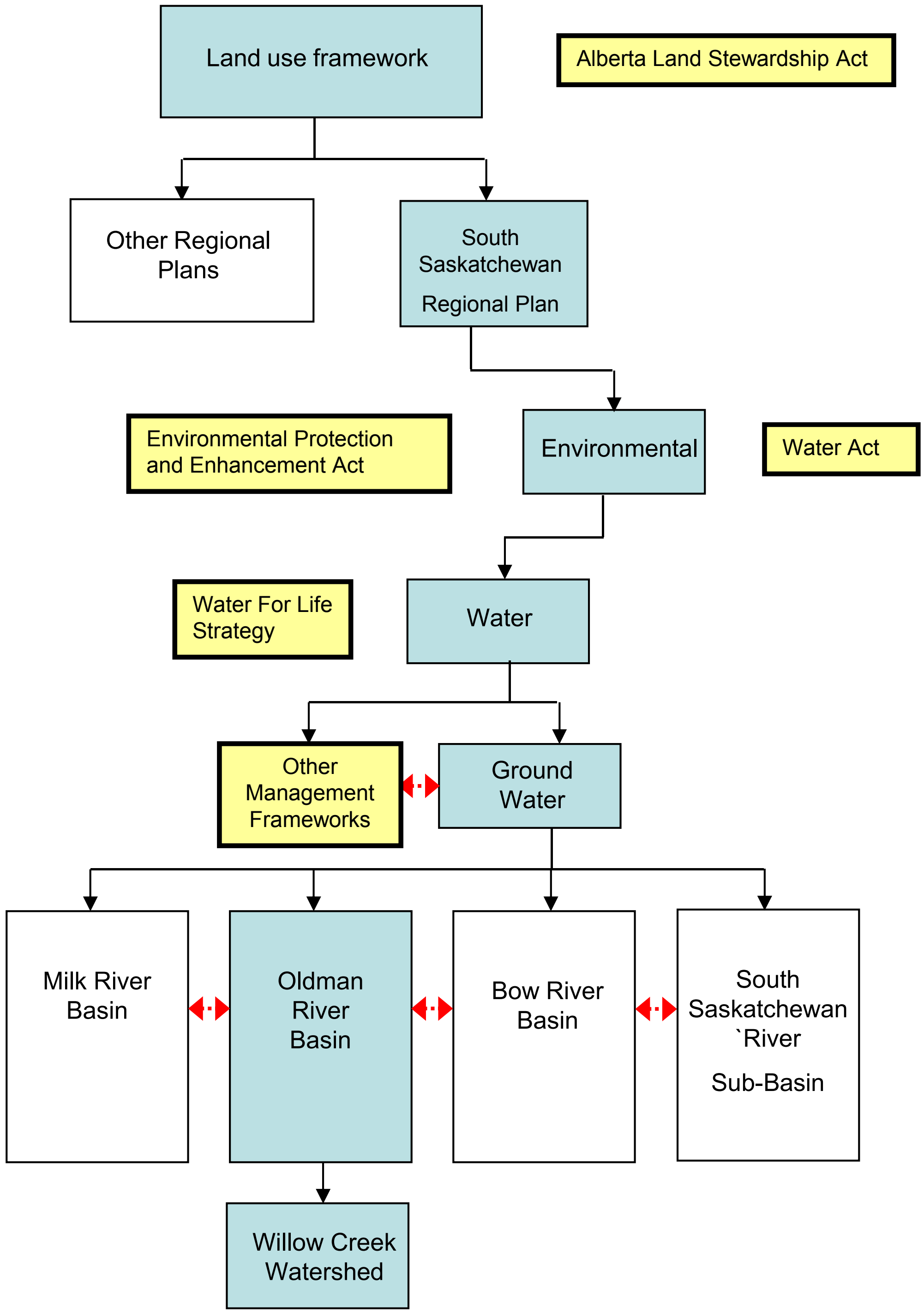



Figure 3 Linkage of Groundwater Management Framework with Land Use Framework and alignment with overall planning and management policies of the province of Alberta

As defined in Water for Life (2003), a GMF needs to be built on the following central themes:

- Groundwater and surface water quality must be recognized as an important aspect of the landscape and preserved while pursuing economic and community development;

- Alberta's water resources must be managed within the carrying-capacity of individual watersheds;
- Managing cumulative effects during growth must consider the potential impacts of all activities (regulated and non-regulated) within a region, rather than solely focusing on the impact of individual projects; and,
- The foundation of the approach to managing cumulative effects is a sound knowledge-base that includes an understanding of the state of the environment, levels of human use and projections of use and prediction of impacts into the future.

A GMF should be based on the principles of performance assessment and an adaptive management system. As new groundwater quality and quantity knowledge is generated in the region, management models will be updated and water management decisions will be adapted accordingly. The framework is therefore considered to be a living document and will be updated as new data become available.

A GMF should be designed to manage existing and planned developments to prevent potential regional-scale cumulative effects on non-saline groundwater resources; this may be done through the following actions:

- Mapping of aquifer vulnerability and risk to identify key areas for monitoring and assessment for potential cumulative effects;
- Identification of regional groundwater quality targets and risk-based thresholds to ensure that groundwater resources are not compromised as a result of area activities;
- Integrated groundwater monitoring and management actions to ensure protection of regional groundwater resources;
- Implementation of site-specific groundwater management plans to ensure protection of regional groundwater resources and development of a culture of shared stewardship and responsibility to achieving regional objectives; and,
- Continued development of the regional groundwater knowledge base to refine the groundwater vulnerability assessment, to establish the range of natural variability with respect to quality and quantity, and to facilitate comparison and assessment of regional monitoring results.

## 2.3 Project Framework

The Water Act governs the diversion of water from surface and groundwater sources by a variety of methods including statutory rights for household purposes, registrations for traditional agriculture uses, and approvals and licenses. As per the Water Act, the household use threshold has been set at 1250 $m^3$/year and does not require a license under the Water Act. In addition, groundwater with Total Dissolved Solids (TDS) concentration in excess of 4,000 mg/L is also exempt from licensing requirements. Any water well planned for a water withdrawal, other than for households purposes and with some exemptions (e.g., fire fighting), requires a licence.

Under the Water Act, agriculture users, who on or before January 1, 1999 submitted an application to Alberta Environment were permitted to divert up to 6,250 $m^3$/year for traditional agricultural purposes. Although not policed, the use is restricted to watering animals or applying pesticides.

With acceptance of the Approved Water Management Plan for the South Saskatchewan River Basin in 2007, the Government of Alberta announced that Alberta Environment would no longer accept new surface water license applications for the Bow, Oldman, and South Saskatchewan sub-basins (i.e Bow, Oldman and South Saskatchewan Water Allocation Orders). This has prompted many communities and municipalities to reassess their water management requirements to meet their water demands. Within the SSRB, the closure of the basin to new surface water applications includes those applications where groundwater is shown to be in direct connection with surface water within a travel time of 4 years or less.

## 3.0 PROJECT BOUNDARIES AND INFORMATION SOURCES

### 3.1 Project Area Boundaries

Two boundaries were identified for this project. The first is the watershed boundary and the second is a buffer zone set to 10 km outside the watershed boundary. This boundary was selected by Waterline in order to use information from geological units and aquifers that extend beyond the watershed boundary. These boundaries were established for the following reasons:

Watershed boundary:

- Used for assessing general statistics on water wells within the watershed; and
- Used to assess groundwater use in the watershed

Buffer zone boundary:

- It is likely that some aquifer boundaries do not coincide with the watershed boundaries; and
- The expanded area will help in the construction of the conceptual hydrogeological model which may ultimately be used in numerical modelling at a later date.
- To ensure that aquifer boundaries, groundwater flow, etc. will match those of future adjacent basin studies

Aquifers are bounded by differences in permeability[g] which are generally controlled by differences in lithology, and structural properties of bedrock units (fractures, faults, folds, etc.). In the case of the Willow Creek watershed, the topography generally slopes from west to east, extending from the Rocky Mountain Foothills to the western edge of the Plains or Prairie physiographic region. Groundwater flow in the shallow unconsolidated overburden aquifers and consolidated bedrock aquifers is essentially from north-west to south-east, paralleling the long axis of the watershed which follows Willow Creek. Locally, groundwater flow may differ in the western half of the watershed where the bedrock geology is highly disturbed and dominated by thrust faulting[g] and folding.

## 3.2 Data Sources and Synthesis

Data collection and compilation for the present study consisted of gathering the available data from a variety of sources that included public domain databases as well as subscribed databases. All data sources are provided in the extended bibliography in Section 12.0 of the enclosed report. The major data sources included the following:

- Alberta Environment and Water (AEW) – Environment management System
    - Groundwater Information Centre - AEW Water Well Record database;
    - AEW Approval database;
    - Snow data;
    - Geographic Information System (GIS) Base data (roads, water bodies, digital elevation model data); and
    - Digital data for the Elbow River alluvial aquifer boundary (produced by ARC and modified by AEW).
- Alberta Research Council (ARC; now Alberta Innovates Technology Futures)
    - Reports and maps
- Alberta Geological Survey (AGS), and Energy Resources and Conservation Board (ERCB)
    - Reports and Maps;
    - Depth to Base of Groundwater Protection Database, and
    - GIS datasets (bedrock geology, aggregate).
- Alberta Sustainable resources Development
    - Land use data interpretation
- Environment Canada
    - Weather data (precipitation); and
    - Stream flow data.
- Geological Survey of Canada (GSC)
    - Reports and publications
- Oldman Watershed Council (OWC)
    - Reports; and
    - Conversations
- University of Calgary
    - Unpublished university theses (maps and cross-sections)
- Municipal Districts (M.D) of Willow Creek and Ranchlands
    - County maps; and
    - Data regarding gravel pits, community wells and confined feeding operations
- Statistics Canada
    - Census 2006 population data
- Information Handling Services (IHS) Accumap database
    - Energy well information (lithology and geophysical logs)

The most important source of data pertaining to the present groundwater resource evaluation is the AEW data base. For the purposes of the present study, AEW provided a copy of the provincial Water Well Database. Using software developed by Dr. David van Everdingen (Mount Pleasant Software) the data were configured in a borehole database to enable synthesis of the data and development of cross-sections. The data were used within an Arc-GIS platform consistent with OWC's and AEW's GIS format. Numerous other licensed software packages were used in the preparation of the report, tables, figures, maps and cross-sections. Appendix A provides a summary of various methods used to process data in this report.

## 3.3 Water Well and Energy Well Databases

Two public well databases were used in this project: the AEW Water Well Record database and the Oil and Gas record database available through IHS Accumap.

### 3.3.1 AEW - Water Well Record Database

The AEW Water Well Record database contains data submitted by water well drillers associated with water wells drilled throughout the province of Alberta.

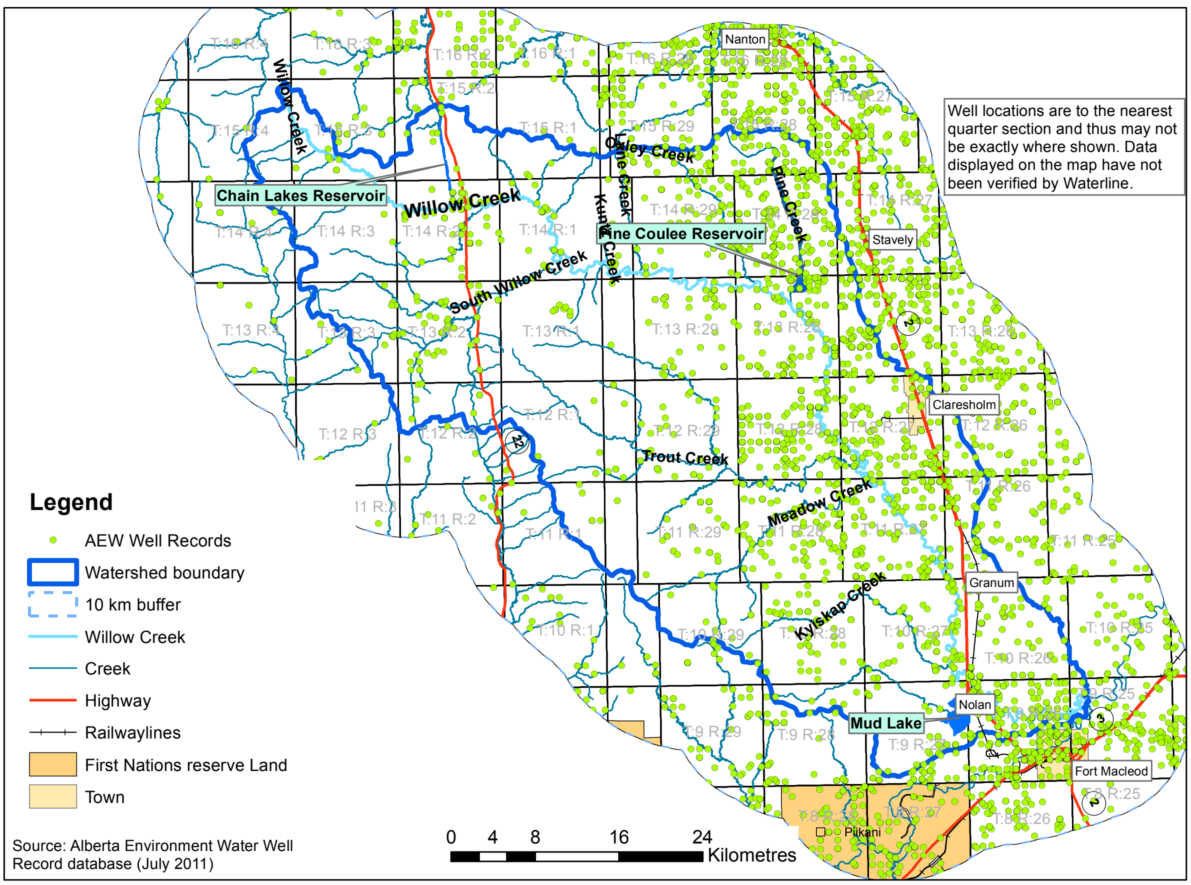



Figure 4 Water well locations

In this database (July 2011 version) there are 4,538 water well records within the Willow Creek watershed and the 10 km buffer zone. Of these, 2,167 water well records lie entirely within the

Willow Creek watershed. **Figure 4** shows the approximate location of wells associated with those records.

The accuracy of the locations of water well records in the database is to the nearest LSD, approximately 400 m.

### 3.3.2 IHS Accumap - Oil ad Gas Database

The IHS Accumap contains information for oil and gas wells drilled by industry and submitted to the Alberta ERCB. Various private companies make these data available through enhanced databases (e.g., IHS Accumap and Geoscout). The IHS Accumap database contained 593 oil and gas well records within the Willow Creek watershed and the 10 km buffer zone (as of Sept 2011). This information was used in the development of the conceptual hydrogeological model for the watershed. **Figure 5** shows the approximate location of the oil and gas well records within the Willow Creek watershed and the buffer zone.

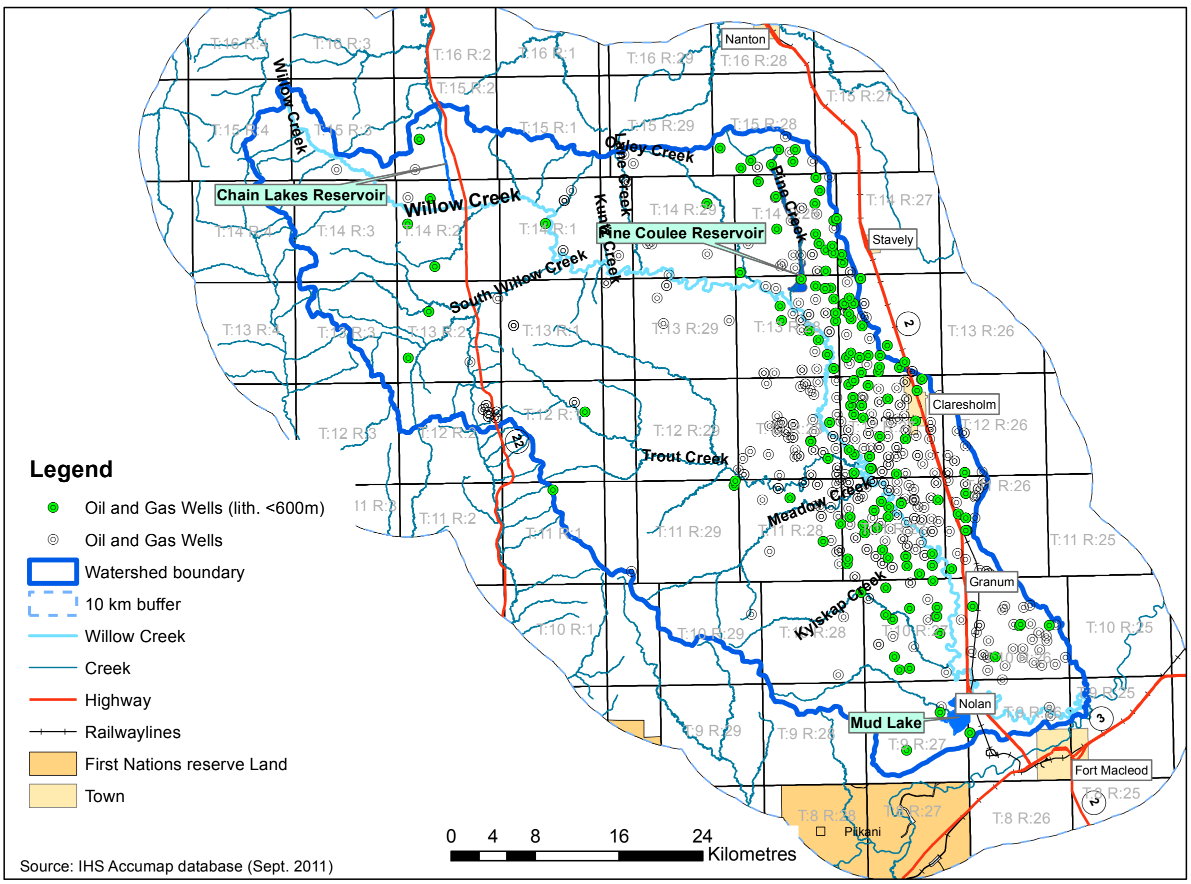



Figure 5 Oil and gas well locations

### 3.3.3 Base of Groundwater Protection

Alberta's Usable Base of Groundwater Protection (BGP) database is provided in ERCB Statistical Series 55 (EUB 1995, and Updated ST55 2007, ERCB 2010). The depth to the base of groundwater protection has been defined by the ERCB as the depth where the TDS concentration of groundwater exceeds 4,000 mg/L (EUB (now ERCB) 1995, ST55 update, 2007). ERCB regulations require that the oil industry place appropriate emphasis on shallow operations and improvement practices that ensure that non-saline groundwater resources are protected. This typically means that surface casings for oil and gas wells are extended to below the BGP.

The Rocky Mountain Foothills and Front Ranges represent the leading edge of the Rocky Mountains and are dominated by intense folding and thrust faulting. This area is defined as the disturbed belt or zone by the Alberta Geological Survey and the depth to the BGP is set to 600 metres below ground surface. Approximately half of the Willow Creek watershed lies within the disturbed belt. In the eastern portion the depth to BGP is mapped as approximately 600 to 1,000 metres below ground level and generally corresponds with the base of the Willow Creek Formation.

### 3.3.4 Methods of Data Compilation

The methods used in compiling geological and hydrogeological data from various databases and sources are described in detail in Appendix A. It should be noted that any data received and compiled by Waterline as part of the present study are assumed to be correct and have not otherwise been verified by Waterline for quality or accuracy. Some of the data have been located in the center of the quarter section (e.g., water wells and chemistry) and exact locations are not known. For the purposes of the enclosed study, maps showing data points may be offset by as much as 400 m. It should be cautioned that there may be a need for further verification of the data used to develop the conceptual model if interpretations and analysis conflict with other information or interpretations not considered as part of the present study. In addition, as new data become available and a more comprehensive understanding of groundwater flow systems is developed within the Willow Creek watershed, the conceptual model presented herein should be updated accordingly.

## 4.0 CONCEPTUAL HYDROGEOLOGICAL MODEL

### 4.1 Background and Setting

### 4.1.1 Political Jurisdictions and Competing Groundwater Interests

The Willow Creek watershed falls within a number of different political jurisdictions as shown in Table 1. The various jurisdictions can have different and conflicting objectives with regard to the sustainable use of groundwater within the watershed. Municipal government bodies, including the Towns of Claresholm and Granum, the MD of Willow Creek, the MD of Ranchlands and the Kananaskis Improvement District, each have land use decision making authority.

The major groundwater users of water in the South Saskatchewan River Basin are municipalities, industry, and agriculture. The largest by far is agricultural irrigation, which accounts for 75 per cent of the volume of all water allocations in the region (GOA, 2010a).

**Table 1 Willow Creek Watershed Political Jurisdictions**

| Entity | Jurisdiction | Watershed Area ($km^2$) | Watershed Area (%) |
|---|---|---|---|
| Willow Creek watershed | MD Willow Creek No.26 | 1730.1 | 68 |
| | MD Ranchlands No.66 | 746.4 | 30 |
| | Kananaskis I.D. | 52.5 | 2 |
| | **Total** | **2,529** | **100** |

### 4.1.2 Population and Groundwater Demand

Almost half of the population of Alberta (45 percent) resides in southern Alberta; the majority in Calgary. Population projections indicate that the population of Alberta will increase considerably over the next 65 years from 3.3 million (2006 Census) to 4 million by 2076.

The population of the Willow Creek watershed, based on the 2006 population census is 14,402. This number includes both the urban dwellers in Claresholm and Granum and the rural population outside the town limits. The breakdown by rural versus urban population is shown in **Table 2**:

**Table 2 Summary Population Statistics (2006 census data)**

| Type | Total Population | Total # Private Dwellings |
|---|---|---|
| Urban | 8,737 | 3,748 |
| Rural | 5,665 | 2,137 |

The breakdown of population by district is shown in Table 3 (AMEC, 2010 and Statistics Canada, 2007a and 2007b). The population in the M.D. of Willow Creek has remained relatively stable from 2001 to 2006 at 5,337 people (Statistics Canada, 2007b). This suggests that groundwater use for domestic purposes may not have increased greatly, although other uses such as agriculture may have increased. The M.D. of Ranchland is home to 86 people (Statistics Canada, 2007a).

**Table 3 Population Comparison (1996 and 2006 census data)**

| District | 1996 Population | 2006 Population | % Change |
|---|---|---|---|
| Town of Claresholm | 3,427 | 3,700 | +8 |
| Town of Granum | 337 | 415 | +23 |
| MD Willow Creek No.26 | 5,106 | 5,337 | +5 |
| MD Ranchland N0.66 | 108 | 86 | -20 |

**Figure 6** shows that the vast majority of the population in the Willow Creek watershed resides in the eastern portion along Highway 2 which runs between Nanton and Fort Macleod. The Towns

of Claresholm and Granum obtain their water supply from the Pine Coulee Reservoir. The population circles in **Figure 6** are for dissemination blocks developed by Statistics Canada for the census. The circle size is dependent on the number of people within the dissemination block.

The only municipality within the Willow Creek watershed that gets its supply from groundwater is the Town of Stavely. The Town operates two wells on either side of Highway 2, south of the center of Town. Both wells are completed in the Stavely buried channel aquifer. These data are discussed in **Section 4.4.4.**

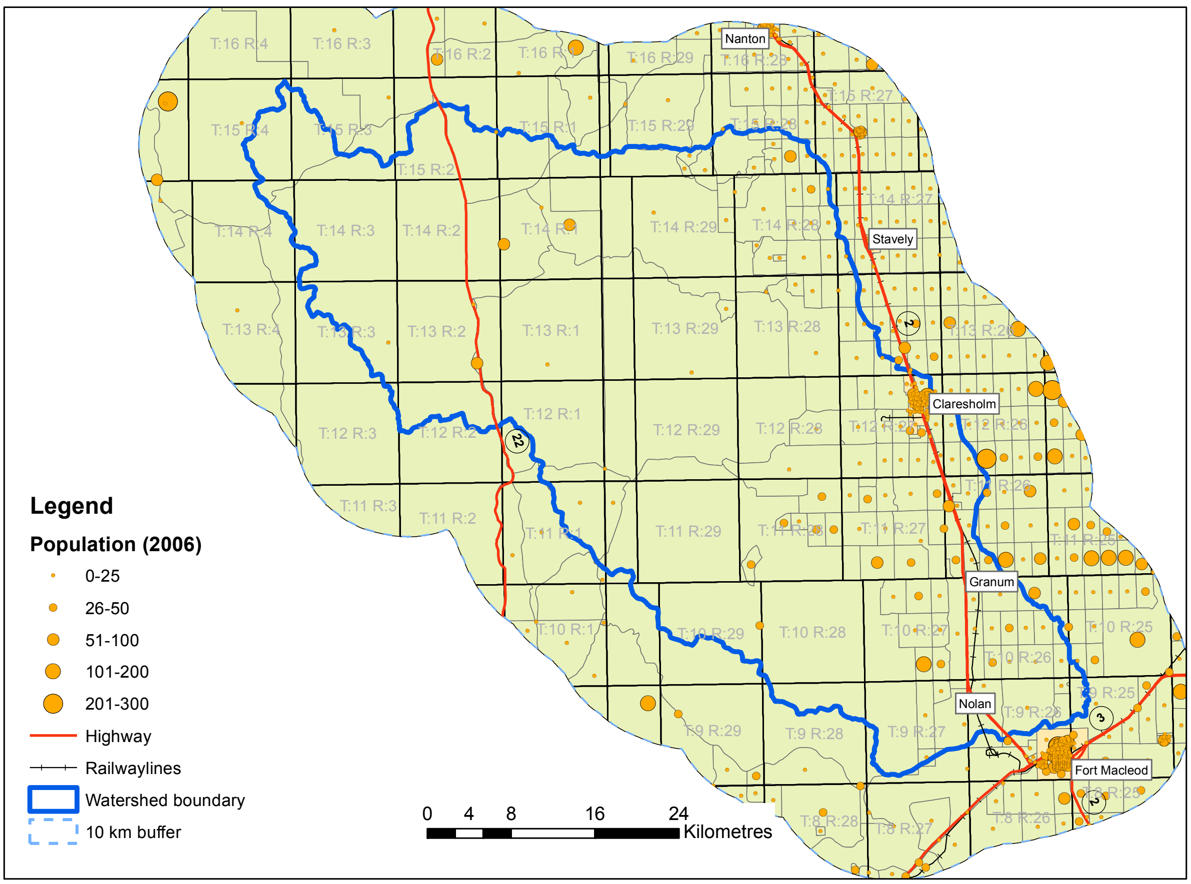



Figure 6 Population distribution

As previously discussed, there are 2,167 water wells within the Willow Creek watershed listed in the AEW water well database (July 2011). Based on population statistics, this results in a ratio of approximately 2.6 people per water well record (5,665 people/2,167 water well records).

As will be shown, groundwater use within the Willow Creek watershed is considerably less than surface water use. However, given the AEW-imposed moratorium on new surface water licences in the South Saskatchewan River Basin, the demand for groundwater resources in the Willow Creek watershed is expected to increase in the future. In addition, over the last several decades an increased number of confined feeding operations has been established resulting in greater groundwater demand for drinking-water supply and for commercial and agricultural use.

### 4.1.3 Land Cover

The classification of land vegetation cover and land use within the Willow Creek watershed was completed by Agriculture and Agri-Food Canada (2009) and is shown in **Figure 7**. This information indicates that the majority of agricultural lands within the Willow Creek watershed are located just to the west of Willow Creek paralleling Highway 2 and extending to the eastern watershed boundary of Willow Creek. West of Willow Creek, the land cover consists of primarily shrubland and grass land with minor agriculture extending toward Highway 2. Further west extending from east of Highway 22 the land cover consists of coniferous and deciduous forest. Land use in the latter area is primarily recreation with some forestry.

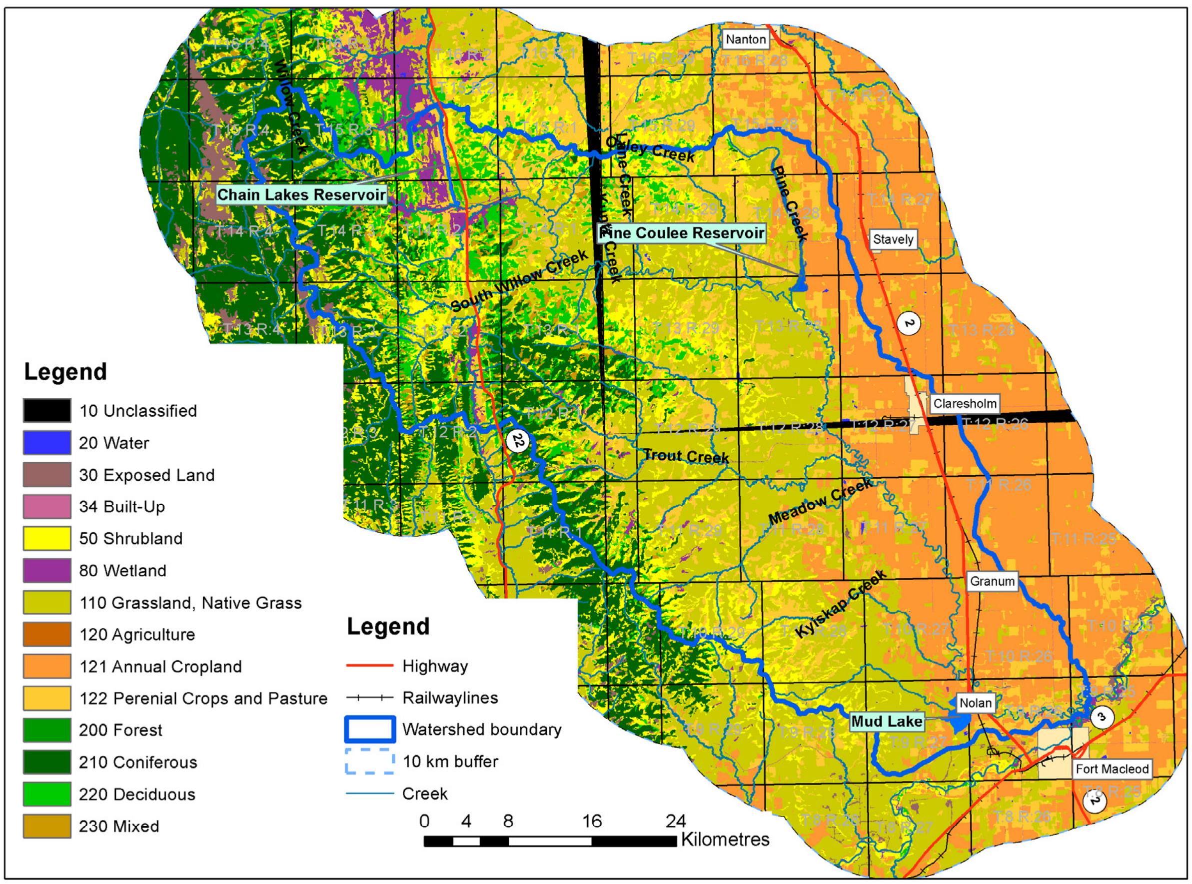



Figure 7 Interpreted land cover (2000)

### 4.1.4 Topography and Physiography

The terrain in the Willow Creek watershed consists of gently undulating to gently rolling uplands, level to gently undulating lowlands, moderately sloping to very steeply sloping escarpments and gullies and level terraces and flats along Willow Creek. The ground elevation in the watershed ranges between 893 metres above mean sea level (mASL) near Fort Macleod and the confluence with the Oldman River and 2,540 mASL in the western most portion of the watershed within the Foothills and Front Ranges (**Figure 8**). The area is well drained by numerous streams, the major one being Willow Creek. The watershed encompasses the following natural regions: Foothills Parkland, Montane and Subalpine (east to west) (GOA, 2012). Willow Creek flows through titled and leased crown land in the west and private and public-owned lands in the east part of the watershed.

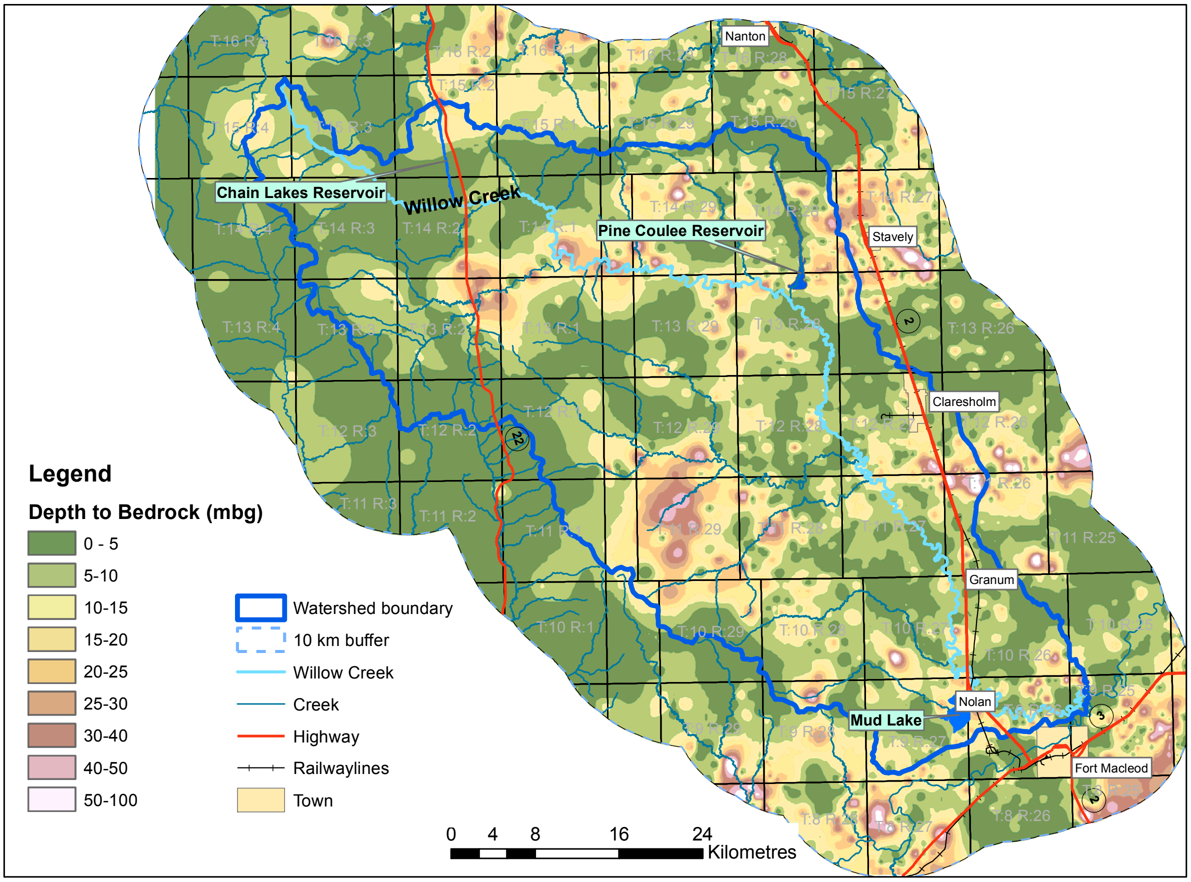



Figure 8 Topography in the Willow Creek watershed

### 4.1.5 Climate

Climate zones are typically defined based on the Köppen classification system (e.g., Strahler and Strahler, 2006). The Köppen classification is based annual temperature and distribution of precipitation throughout the year. The Willow Creek watershed lies within a semi-arid (Köppen climate classification BSk), or humid continental (Köppen climate classification Dfb[g]) zone characterized by long, cool summers, severe winters and no dry season. Note that "humid" denotes that these climates do not meet the criteria to be semi-arid, nor that they necessarily have high humidity. Most places in Southern Alberta that fall under the "humid continental" classification border between semi-arid and humid continental climates.

According to the ecoregion map cited in Strong and Leggatt (1981), the Willow Creek watershed is located in both the Mixed Grass and Foothills Fescue Grassland Natural Regions in the east and in the Foothills Parkland and Montane and Sub-Alpine regions to the west. Increased precipitation and cooler temperatures result in additional moisture availability and influence this vegetation change as well as subsurface recharge to underlying aquifers.

The long-term climate data collected at the Claresholm Waterworks weather station (Climate Station ID: 3031658) which lies in the eastern portion of the watershed are available from 1971 to 2000 (Environment Canada, 2012). The data indicate that the climate in the region can be characterized as follows:

- Daily average temperatures range from -7.8 °C in January, to 17.1 °C in July;
- Non-freezing (i.e. >0 °C) daily average temperatures occur from April to October each year; and
- An average annual precipitation of 428.2 mm of which approximately 75% occurs during the non-freezing months of the year.

Climate change has the potential to drastically alter both the surface water and groundwater flow regime in the Willow Creek watershed. Chen et al. (2006) showed that over the past century, the annual mean minimum and maximum temperatures have increased, albeit at different rates of 1.5 °C and 0.45 °C, respectively. Although Chen et al. (2006) stated that these differing rates are likely the result of different climate forcing mechanisms, they did not speculate on the nature of those mechanisms.

Chen et al. (2006) also noted an increasing number of days with rain and a decreasing precipitation variance. The impact of warming on circulation may explain the increased number of annual precipitation days.

The total annual precipitation as measured at the Claresholm Meadow Creek (Station ID# 3031F5F; the weather station with the longest term record) for the period from 1915 to 2000 is presented in **Figure 9**. A 12 month moving average was applied to the precipitation data and is displayed as a red line on the graph. This indicates that annual precipitation declined to a low in 1935 and then increased to a maximum in 1953. From about 1953 to about 1970 the total annual precipitation decreased and has since then been gradually increasing from 400 to 480 mm/year.

An annual precipitation is of 500 to 550 mm/yr was measured in the northwestern portion of the watershed (Alberta Government, 2012) and 450 to 480 mm/yr in the Prairie section of the watershed. Average precipitation in the fall and winter (October to February) is generally less than 20 mm or less between 1915 and 2000. The most rain, averaging 70 mm over the same time period, falls in June.

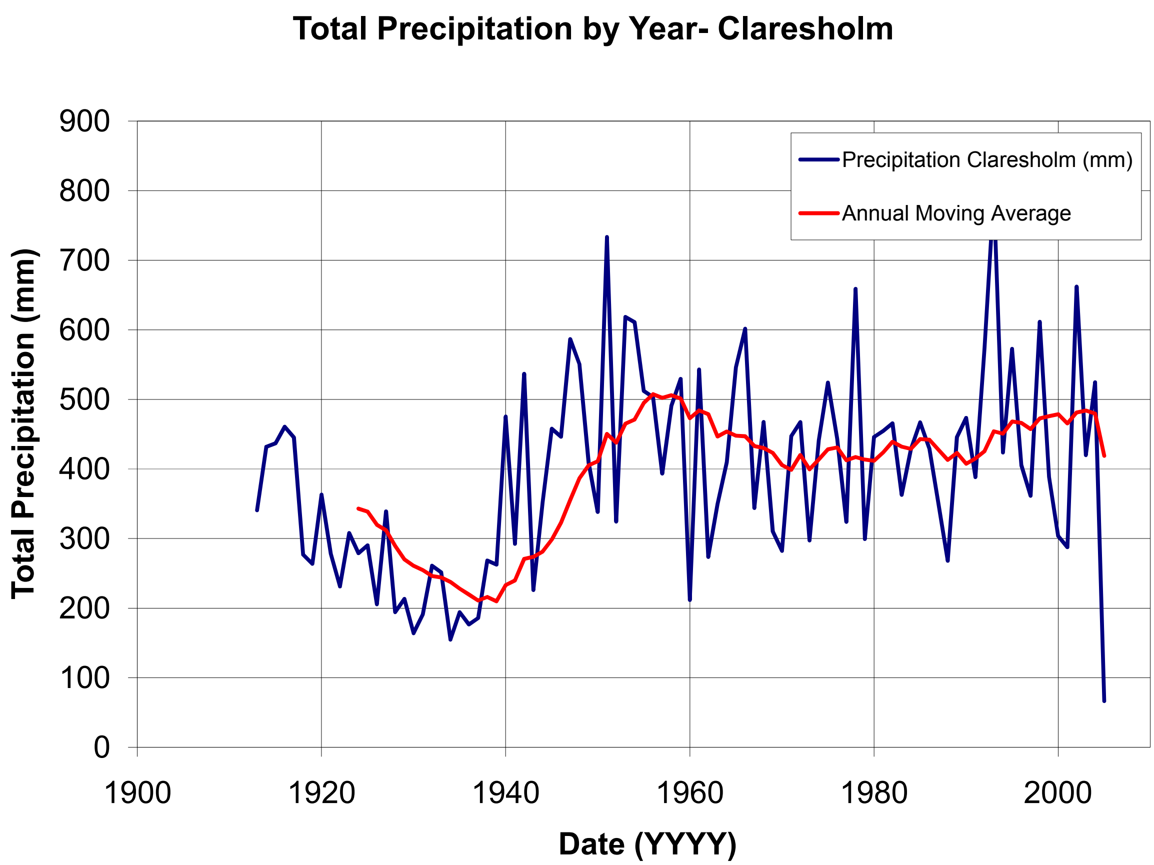



Figure 9 Precipitation graph

According to Ozoray and Lytviak (1974) the potential evaporation in the area exceeds actual precipitation by 1.5 to 3 times. This suggests that the Willow Creek watershed is in a moisture-deficit area and this likely significantly affects recharge to subsurface aquifers.

The climate change scenarios developed by the various climate modelling centres suggest that future precipitation trends may be more erratic and storms may be of greater duration and frequency. Generally warmer temperatures are expected to lead to hotter longer summers which may result in:

- Increasing evapotranspiration[9];
- Less recharge to subsurface aquifers; and
- Lowering of the water table as supply wells continue to be pumped and new wells are brought on line as the population expands.

Changes in temperature and precipitation will alter recharge to groundwater aquifers, causing shifts in water table levels in unconfined aquifers as a first response. In addition, there will be increased lake evaporation which will lower lake levels and creek/river flow. There will likely be an increased demand for irrigation as the population is projected to increase. In addition, supply wells continue to be pumped and new wells brought on line as the population expands This is expected to cause lowering of groundwater levels and reduced groundwater discharge into streams and rivers. The increased evapotranspiration and temperature may also cause increases the soil salinity.

It should also be noted that increased precipitation could increase recharge to aquifers but that would depend on the timing of the increase. Since recharge is mainly derived from snowmelt, increasing temperatures and winter precipitation may be beneficial in terms of aquifer recharge. Conversely, if the precipitation as rainfall is very intense over a short time period most of the water will become part of surface runoff. Our understanding of climate variability and change impacts on groundwater resources remains limited.

In reality it is difficult to accurately predict climate change effects on groundwater systems. Surface water bodies respond quickly, on the order of hours or days, to climate variability. Groundwater systems, on the other hand, have response times on the order of days to millennia depending on hydraulic conductivity[g] of the aquifer(s) and overlying and intervening geology, flow path length, thickness of overlying layers, and other factors.

In Canada, most research on the potential impacts of climate change on the hydrologic cycle has been directed at forecasting the potential impacts on surface water, specifically the links between glacier runoff and river flows. Relatively little research has been undertaken to determine the sensitivity of aquifers to changes in the key climate change variables including but not limited to, precipitation and temperature (van Everdingen, 2006).

## 4.2 Hydrology

Willow Creek flows to the south-east from the headwaters in the Livingstone Range (eastern edge of the Rockies) for a distance of approximately 24 km before flowing into the Chain Lakes Reservoir (**Figure 10**). The flow then continues east, and then south for a distance of 6.4 km where it is joined by South Willow Creek, a tributary which also originates in the Livingstone Range. From this confluence, the water flows east 24 km and along this reach is joined by a number of smaller streams, including Lane, Oxley and Pine creeks, which drain a foothills area to the north. As Willow Creek enters the Mixed Grass Prairie natural sub-region, agricultural activity dominates and the stream flows through level cultivated land.

Willow Creek then flows to the south through the western plains for 48 km receiving water from Trout, Meadow and Kyiskap creeks, all originating in the Porcupine Hills (possibly unglaciated hills between Highway 2 and Highway 22), before emptying into the Oldman River 1.6 km northeast of Fort Macleod (Oldman River Intermunicipal Service Agency, 1998).

Although Willow Creek watershed begins in the mountains, it is shallow and warms up quickly in the summer. Based on 1998 to 2003 temperature data, the median water temperature in Willow Creek was 10.6 °C. This temperature is considerably warmer than the main stem of the Oldman River south of Willow Creek watershed (6.9 °C) (Saffran 2005).

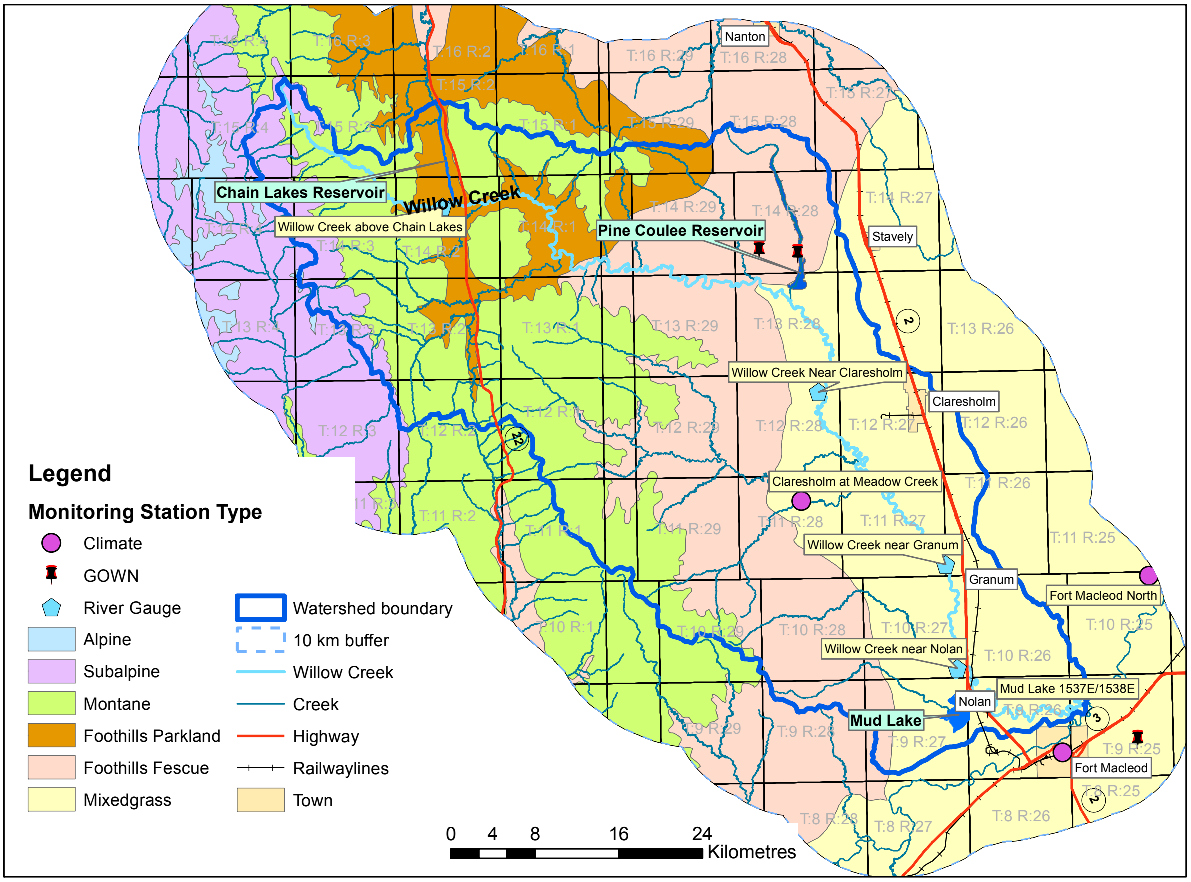



Figure 10 Natural Regions and Creeks in the Willow Creek watershed

Spring snowmelt and precipitation constitute the highest water input to Willow Creek through the year. The highest mean monthly river discharge occurs in June (Environment Canada, 2012).

Two dams are constructed in Willow Creek watershed. The Chain Lakes Dam, completed in 1966, was constructed nearer the headwaters of Willow Creek with a full supply level storage of 15,985 dam$^3$. Water is released periodically to augment the flows in Willow Creek, especially during the summer months.

Pine Coulee Reservoir, further downstream nearer the town of Stavely, was constructed in 1999 on Pine Creek just upstream of the confluence with Willow Creek. It consists of a 450 m wide by 22m high earth fill dam. The reservoir can potentially store 50,600 dam$^3$ of water, retaining water for some 13 km north of the dam on Pine Creek. The Pine Coulee diversion diverts water from Willow Creek to the Pine Coulee reservoir. Because reservoir levels influenced groundwater levels east of the reservoir those groundwater levels are monitored and controlled by pumping water back to the Pine Coulee reservoir (AEW, 2002).

Upstream of the Chain Lakes Reservoir water use is low, allowing natural flow to be recorded there. Flows in Willow Creek near Claresholm and Nolan have been regulated since 1966, after the construction of the Chain Lakes Reservoir. Pine Coulee Reservoir further regulates this flow. Peak flows are recorded in late May and early June; winter flow is very low (AMEC, 2010).

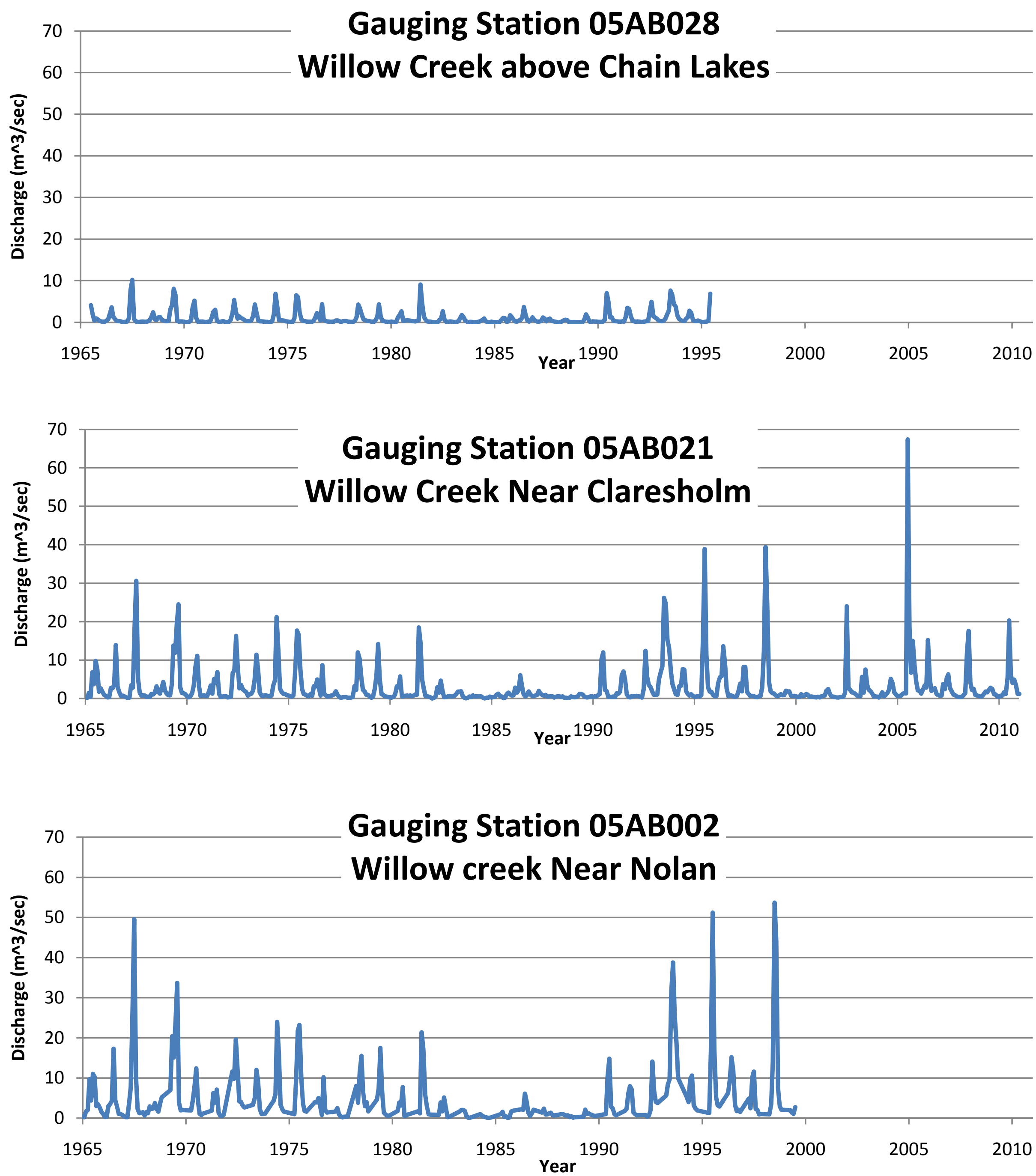



Figure 11 Willow Creek discharge

Discharge from Willow Creek varies from year to year. The 30-year mean discharge as calculated from the data collected from1965 to1995, is approximately 0.9 m3/s at Chain Lakes; 2.8 m3/s at Claresholm; and 3.7 m3/s at Nolan. The maximum flow over the 30-year record was noted at Nolan in June of 1995 at 426 m3/s. Recent peak flows in Willow Creek were measured at Claresholm as high as 694 m3/s during the spring flood event of 2005 (AMEC, 2010). These recorded values are influenced Chain Lake storage and diversions as well as large cumulative diversions by irrigators at the Claresholm and Nolan locations.

Annual discharges in Willow Creek reported at the Chain Lakes, Claresholm and Nolan gauging stations from 1965 to 2010 are plotted on **Figure 11**. The drainage areas extending above each of the stations is noted in **Table 4**. These data were obtained from the Environment Canada website (Environment Canada, 2009).

**Table 4 Willow Creek Gauging Stations Gross Drainage Area**

| Station Name | Station Number | Latitude | Longitude | Drainage Area $km^2$ |
|---|---|---|---|---|
| Willow Creek above Chain Lakes | 05AB028 | 50°11'47" N | 114°12'46" W | 162.0 |
| Willow Creek near Claresholm | 05AB021 | 50°01'06" N | 113°42'53" W | 1180.6 |
| Willow Creek near Nolan | 05AB002 | 49°47'38" N | 113°32'13" W | 2290.0 |

The discharge over the period 1965-1995, the overlap period for the three gauging stations, is plotted on **Figure 12**. This shows that peak flows in Willow Creek occur late May to early June, roughly coinciding with the period of spring snowmelt and runoff. The Nolan station has a higher percentage of its drainage area in the low yielding grassland area (AMEC, 2010).

Based on records from 1965 to 1995, AMEC (2010) constructed trendlines that showed the Willow Creek flows are decreasing by 0.3% per year near Claresholm and by 0.4% near Nolan. The AMEC (2010) report also states that no statistically significant trend is indicated.

The towns of Claresholm and Granum obtain their water from Pine Coulee Reservoir which for the most part ultimately comes from Willow Creek. Claresholm holds two diversion licenses that allows them to divert 1,399,915 $m^3$/yr from Willow Creek. The actual diversion for 2011 was 607,502 $m^3$/yr. The Town of Granum is licensed to divert up to 185,185 $m^3$/yr. During 2011 Granum only diverted 50,169 $m^3$/yr (Town of Granum, Public Works, 2012). It should be noted that Claresholm treats the water before pumping it on to Granum, approximately 15 km to the south. The total licensed amount of water for the towns of Claresholm and Granum from Willow Creek is 1,585,100 $m^3$/yr (0.05 $m^3$/sec). The approximate annual water usage measured over the last year is 657,671 $m^3$/yr. The towns therefore use approximately 41 percent of their total approved diversion volume from Willow Creek.

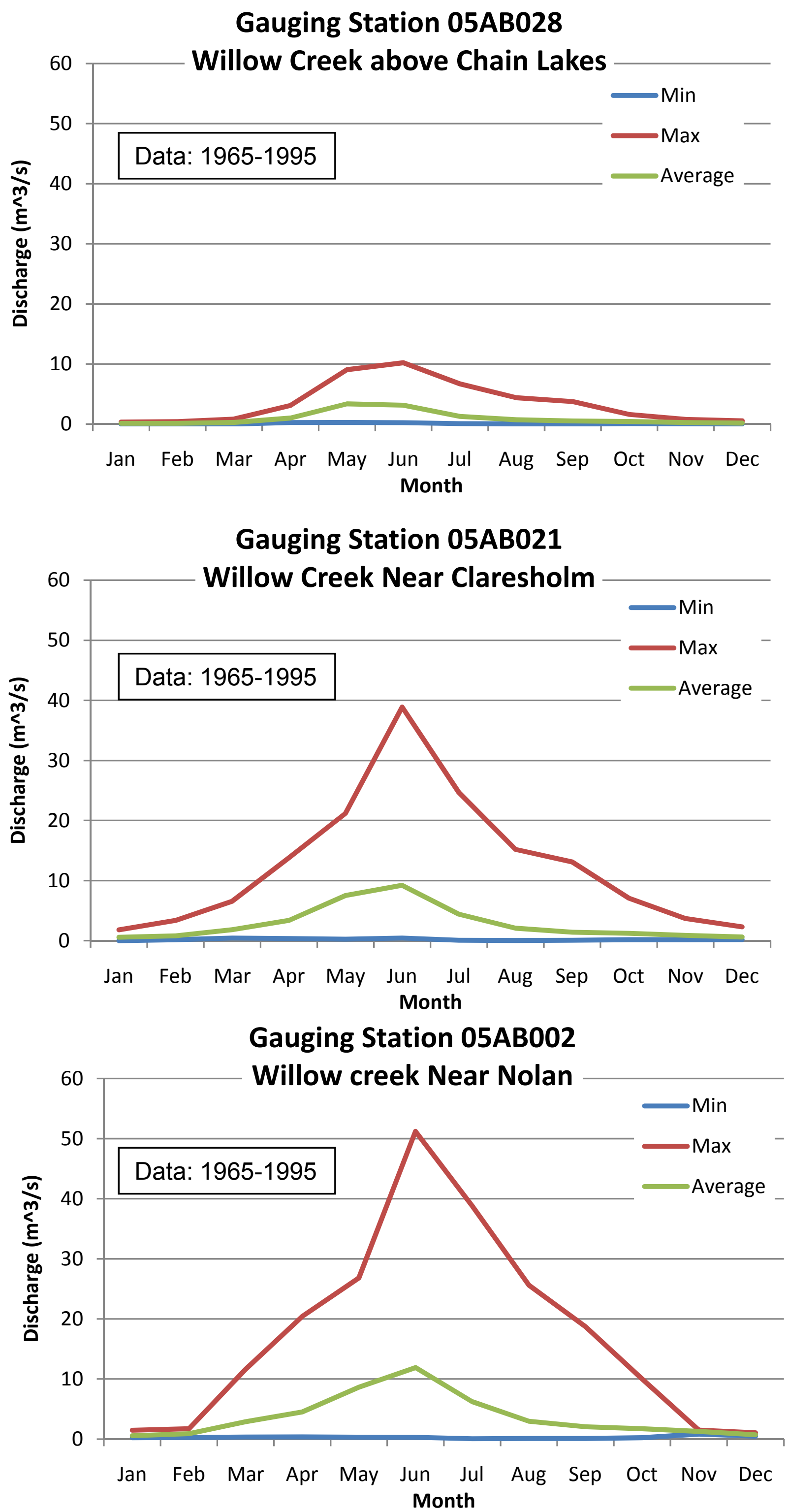



Figure 12 Willow Creek mean discharge

## 4.3 Surficial and Bedrock Geology

### 4.3.1 Unconsolidated Surficial Deposits

The bedrock in the area is covered by a variety of surficial deposits. These have been compiled by Shetsen (2002) from original Geological Survey of Canada authors. Neither surficial soils maps nor soil descriptions are available for the western portion of the watershed, west of the Chain Lakes (**Figure 2**).

### 4.3.2 Regional Geology

A brief description of the regional geology based on the Geological Map of Alberta (Hamilton et al., 2004, 1972) and the structural geology map of the Southern Canadian Cordillera (Wheeler, 1972) was reviewed. As indicated above, the Rocky Mountains and the Foothills together form a complex structure known as the "disturbed belt" in the western portion of the Willow Creek watershed. The geology comprises numerous northwest striking thrust faults that subdivide the disturbed belt into long, narrow structural units. Within these narrow units, the rocks may be folded, block faulted and imbricated[g], with older rocks emplaced or thrust over younger rocks.

The regional stratigraphy[g] in southern Alberta was compiled by Hiebert (1992) and is shown as a stratigraphic column on **Figure 13**. The stratigraphy includes from oldest to youngest:

- Devonian Fairholme Group (limestone and dolomite) and Palliser Formation (limestone and dolomitic limestone); and
- Unconformably overlain by Mississippian Exshaw Formation (shale), Banff Formation (carbonates) and Rundle Group (carbonates).

In most of the Willow Creek watershed, these sequences occur beneath the base of groundwater protection and are unlikely to be of importance with respect to non-saline groundwater.

These are in turn unconformably overlain by the following sequence:

- Jurassic Fernie (shale) and Kootenay Groups (sandstone and shale);
- Cretaceous[g] Blairmore (sandstone) and Alberta Group (shales);
- Upper Cretaceous Brazeau Group consisting of Belly River (sandstone), Bearpaw (shale) and St. Mary River (sandstone) Formations;
- Cretaceous-Tertiary Willow Creek Formation (sandstone);and
- Tertiary (Paleocene) Porcupine Hills and Paskapoo Formations (sandstone and shale).

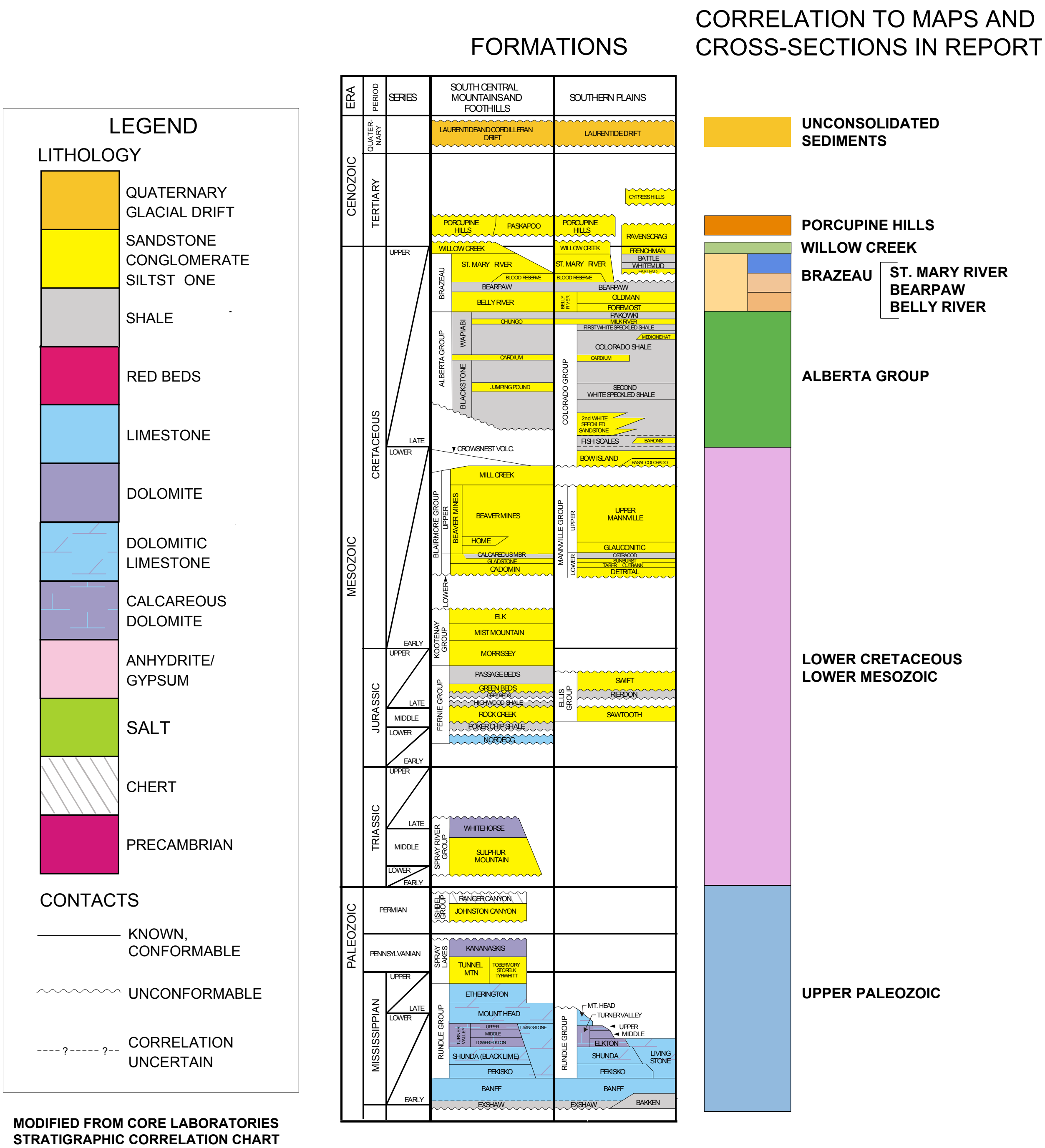



Figure 13 Stratigraphic column

## 4.3.3 Local Geology

**Figure 14** shows the local bedrock outcrop or subcrop[9] based on data from the Alberta Geological Survey. The stratigraphy and descriptions of these formations are presented in more detail in the following subsections. The disturbed zone starts west of Highway 22 where the stratigraphic sequence is repeated in areas as a result of extensive thrust faulting (**Figure 14**).

To the east of the disturbed zone, the bedrock layering dips gently to the west. The near surface bedrock to the east of the disturbed zone is classified primarily as the Porcupine Hills Formation.

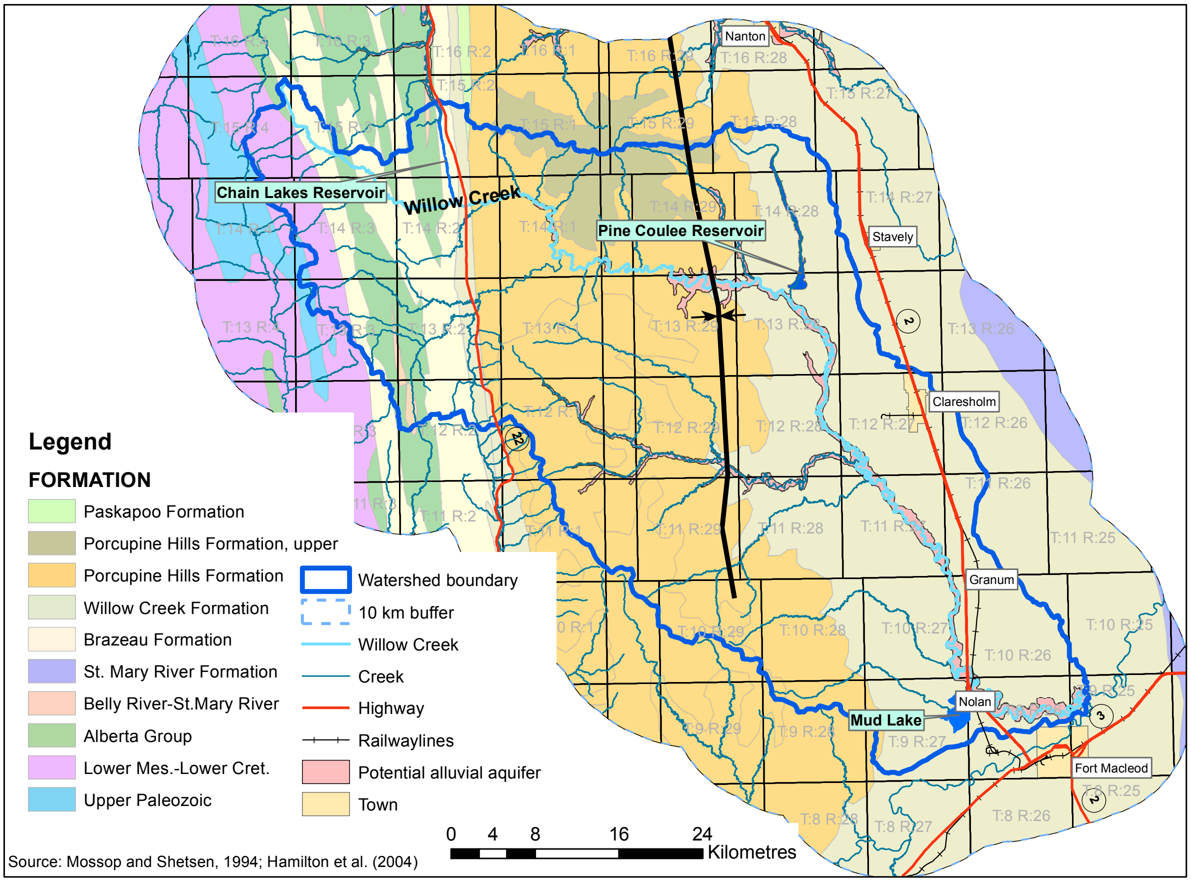



Figure 14 Bedrock geology map

#### 4.3.3.1 Paleozoic Bedrock

Paleozoic bedrock beneath the western part of the watershed consists of Cambrian carbonates, shale and sandstone, Devonian limestone and dolomite, Mississippian shale and carbonate, Jurassic sandstone and shale, and Cretaceous sandstone and shale. Thrust faulting and folding in this part of the watershed is common. The permeability of these rocks has not been tested in the field since very few wells are completed in this region. However, sandstone and limestone units will likely have greater transmissivity because of the greater fracture porosity, karstic features and fracturing relating to faulting and folding.

#### 4.3.3.2 Brazeau Group (Belly River, Bearpaw and St. Mary River Formations)

In southwestern Alberta, the Brazeau Group consists of the Belly River, Bearpaw and St. Mary River formations (oldest to youngest) and is also known as the Belly River-St. Mary River

Succession; it is equivalent to the Brazeau Formation of the central and northern Foothills (Mossop and Shetsen, 1994) .

The Brazeau Group is an Upper Cretaceous non-marine succession of interbedded mudstone, siltstone and fine-grained sandstone with subordinate, but prominent coarser grained sandstone layers. Chert-pebble conglomerate occurs in the lower part of the group. Thin coal beds, coaly shale and numerous thin bentonites occur in the upper part of the group.

The sandstone is grey to greenish grey, and usually has a salt-and-pepper appearance because of the presence of chert and lignitic fragments. The mudstone is greenish grey to dark grey; some organic-rich mudstones are almost black. The buff coloured sandstone generally forms resistant ridges and is characterized by channels and trough cross-bedding.

As can be seen from the geology map (**Figure 14**) the Brazeau Group crops out west of Highway 22. Part of the group is affected by the folding/faulting to the west in the disturbed zone. In the eastern part of the watershed its equivalent, the St. Mary River Formation crops out. To the east, the Brazeau Group extends across the watershed and is thought to be relatively flat-lying and is greater than 600 m thick, based on oil and gas well data.

The Belly River Formation consists of grey thick-bedded sandstone, clayey siltstone and mudstone.

The Bearpaw Formation consists of dark gray blocky silty shale and grey clayey sandstone.

The St. Mary River Formation comprises non-marine sandstone, coarse to fine-grained, pale brown, massive to well-bedded, interbedded with grey carbonaceous shale. It is 500 to 550 m thick and grades into the Edmonton Group to the north. The lower part consists of sandstone, shale and coal seams whereas the upper portion is composed of lenticular sandstones, shales and freshwater limestones (Veilleux, 1993). The upper contact with the Willow Creek Formation, and the basal contact with the Bearpaw Formation is gradational. The St. Mary River Formation does not crop out or subcrop within the watershed, although it is present in the eastern-most portion of the watershed buffer zone.

#### 4.3.3.3 Willow Creek Formation

The Willow Creek Formation consists of multi-coloured shales and light grey sandstones (Hiebert, 1992). Tokarsky (1974) indicates that abundant concretions, fossiliferous limestone, massive cross-bedded grey sandstone (upper part non-marine) are present. The formation is thinner to the north (550 m) and thickens to the south (835 m) (Vielleux, 1993). The Willow Creek Formation crops out along the Oldman River valley outside the Willow Creek Watershed where it can be 300 to 400 m thick.

The Willow Creek Formation occurs in the eastern portion of the Willow Creek watershed where it is thought to be gently dipping to the west on extrapolation of oil and gas well data. (**Figure 14**). It also occurs in the vicinity of Highway 22 where it is strongly folded just within the eastern edge of the disturbed zone.

The Willow Creek Formation is host to the primary bedrock aquifers in the Willow Creek watershed.

#### 4.3.3.4 Porcupine Hills Formation

The Porcupine Hills Formation consists of cross-bedded sandstone and calcareous bentonitic shale (mudstone) and is very similar to the Paskapoo Formation which is situated to the north and described below. Unlike the Paskapoo and deeper sedimentary formations, it is generally devoid of coal beds, suggesting it was deposited in a drier climate. (Sweet, 2011, pers. comm.).

Lerbekmo and Sweet (2000) indicate that the Porcupine Hills Formation is older than the Paskapoo and that the uppermost portion of the Porcupine Hills may be contemporaneous[g] with the lowermost part of the Paskapoo Formation.

#### 4.3.3.5 Paskapoo Formation

The Paskapoo Formation is of Paleocene age. The Paskapoo Formation forms the present day erosional surface or is overlain by tertiary gravel and occurs in outcrops in many places. The Paskapoo Formation consists predominantly of sandstones inter-bedded with siltstone and shale of terrestrial origin. The Paskapoo sandstones are similar in appearance to those of the Brazeau Formation and Porcupine Hills Formation.

The Alberta Geological Survey maps (e.g., Hamilton et al. 2004) show the Paskapoo Formation present in the Willow Creek watershed as a small sliver at the northernmost edge of the watershed in the vicinity of Highway 22. Therefore, no further discussion of the Paskapoo Formation will be presented in this report.

### 4.4 Description of Aquifers and Conceptual Model

An aquifer is defined as a “saturated permeable geologic unit that can transmit significant quantities of water under ordinary hydraulic gradients” (Freeze and Cherry, 1979). If the geologic unit or material is in contact with the atmosphere then it is known as an unconfined or water-table aquifer. Aquifers bounded at the top and bottom by lower permeability layers (clay or shale) are referred to as confined aquifers and water levels referred to as the piezometric surface.

Aquifers beneath the Willow Creek watershed occur in two general settings:

- Surficial unconsolidated sediments (e.g., sand and gravel deposits); and
- Fractured bedrock (e.g. sandstone units in the Porcupine Hills and Willow Creek formations).

The development of a conceptual model for groundwater flow requires a detailed understanding of the inter-connections or “plumbing system” across the watershed. A physical understanding of the structural geology and lithology is the foundation for the development of any conceptual model. Specifically, the geology and hydrogeology information are required and need to be synthesized and integrated so that key aquifers across the Willow Creek watershed can be evaluated. The following information is required:

- Structural geology/stratigraphy across the watershed and extending to the base of groundwater protection
- Aquifer and aquitard properties (e.g., composition, thickness, transmissivity, storativity, hydraulic conductivity, water or piezometric level, hydraulic gradients);
- Aquifer type (e.g., unconfined or confined);
- Recharge and discharge areas;
- Groundwater geochemistry; and
- Information about active wells (number of wells, location, depth, production interval, water levels, pumping rates, etc).

### 4.4.1 Water Well Record Data

Water wells located in rural areas within the Willow Creek watershed are dominantly in use for domestic purposes. The total number of these water well records in the AEW water well record database is 2,167 and various uses are indicated in Table 5.

**Table 5 Proposed Uses For Water Wells**

| Water Well Use | # of Well Records |
|---|---|
| Domestic | 832 |
| Domestic & Stock | 273 |
| Domestic & Industrial | 2 |
| Industrial | 149 |
| Industrial & Stock | 1 |
| Investigation | 147 |
| Irrigation | 4 |
| Monitoring | 5 |
| Municipal | 24 |
| Municipal & Observation | 1 |
| Observation | 39 |
| Other | 10 |
| Standby | 1 |
| Stock | 424 |
| Unknown | 255 |
| **Total** | **2,167** |

The distribution of well records based on the geology encountered at the well screen interval or perforated interval is shown in **Table 6**. This table is based on all well records with associated production intervals and lithology.

**Table 6 Distribution of Well Records by Material at Production Interval**

| Geology Across Screen | # of Well Records |
|---|---|
| Unconsolidated | 161 |
| Unconsolidated/Bedrock | 40 |
| Bedrock | 679 |
| No Lithology/Unknown | 1,284 |

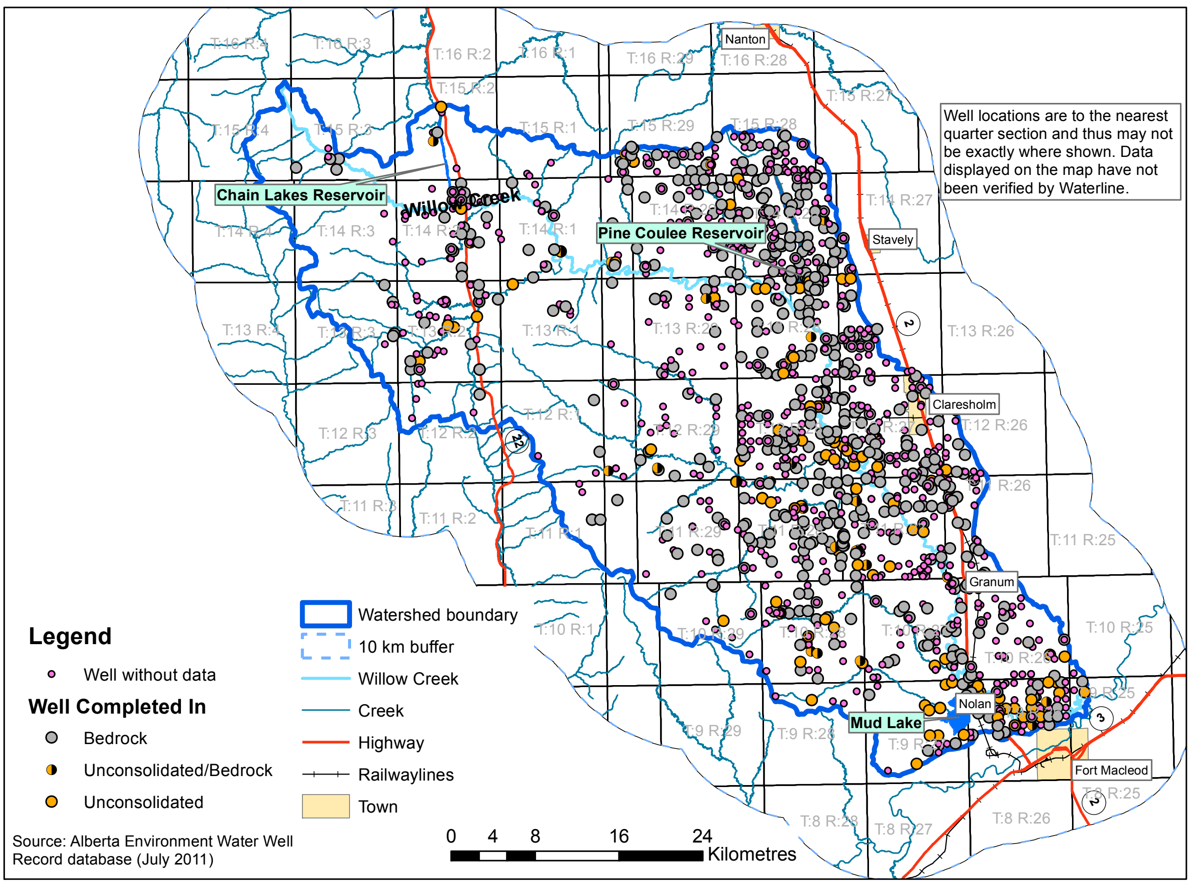



Figure 15 Unconsolidated versus bedrock water well records

The distribution of water well records by material encountered at the production interval is shown in **Figure 15**. Of the 308 water well records located within the area of potential alluvial aquifers, 63 are actually screened in the bedrock below the alluvial materials.

Of the 2,167 well records in the database, 281 were dry and/or abandoned. This is characteristic of fractured-bedrock aquifers where a well can be drilled between fracture zones and effectively isolated from the regional permeability system. As dry wells appear to be evenly distributed throughout the watershed, it suggests that there are no large areas within the watershed in which there is no available groundwater water supply. That is to say, that if a dry well is encountered in one area, a move of 10's to 100's of meters away may prove more successful. A dry well is one that does not produce enough water for the intended use.

### 4.4.2 Regional Hydrogeology

The regional hydrogeology in the Willow Creek area has been described in Ozoray and Lytviak (1974) and Tokarsky (1979).

Well yields differ greatly within the area. The highest expected well yields generally occur in present-day alluvial gravel located adjacent to the major creeks (e.g., Willow Creek), and in sand and gravel beds which occur in pre-glacial and glacial buried valleys mapped in the region and described in the following sections. Bedrock formations are expected to produce generally very low to moderate yields. Exceptions are fractured limestone areas in the mountainous western portion of the area which, as will be shown, do likely not contribute to significant groundwater flow in the Willow Creek watershed.

Well and/or aquifer yield in the Porcupine Hills Formation, or Willow Creek Formation bedrock is proportional to the intensity of fracture development. In contrast, aquifer yield in alluvial or glacio-fluvial aquifers is a function of the grain-size distribution and saturated thickness is generally higher where coarse sand and gravel deposits are present. Other factors such as structural and depositional features that determine the areal extent of aquifers, and topographic location and recharge conditions within the watershed also play a significant role in determining the long-term productivity or yield of aquifers or wells.

#### 4.4.2.1 Well Yield and Aquifer Transmissivity

The available aquifer yield, based on data presented in the reports by Borneuf (1979), Ozoray and Lytviak (1974) and Tokarsky (1979), is presented in **Figure 16**. The highest well yields are found in Quaternary sand and gravel beds which have in some cases exceeded 8 L/s (691 $m^3$/day). The fine lacustrine[g] sand, silt alluvium in the Porcupine Hills (not to be confused with the Porcupine Hills Formation), and parts of the Willow Creek alluvial sediments yield 0.4 to 2 L/s (35 to 173 $m^3$/day).

Individual wells can range from less than 0.1 L/s (9 $m^3$/day) to more than 38 L/s (3,283 $m^3$/day). The highest well yield, in the range of 8 to 38 L/s (691 to 3,283$m^3$/day) and greater, have been recorded in wells completed in Quaternary sand and gravel deposits (**Figure 17**).

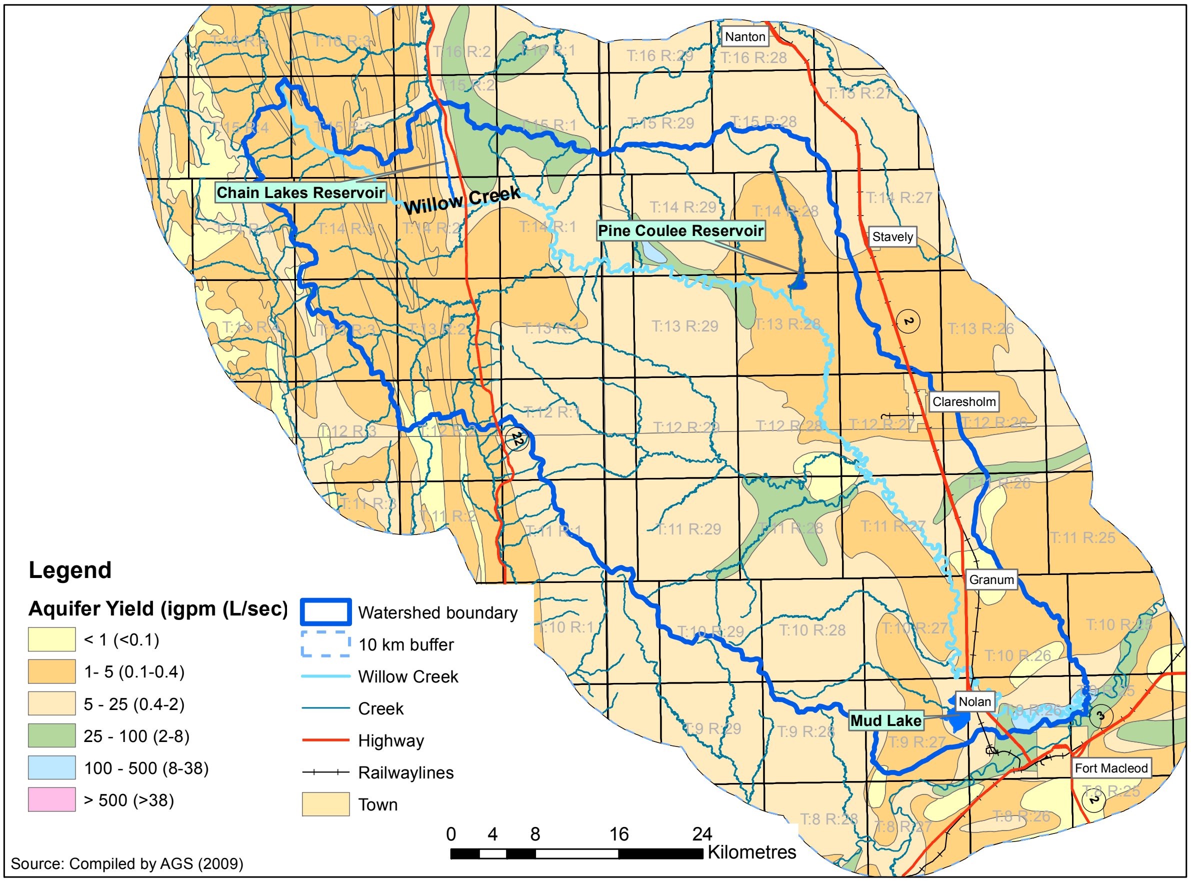



Figure 16 Aquifer yield (based on ARC reports)

The test yields (i.e., pumping rates) from the AEW water well database for water well records within the area were plotted on **Figure 17**. These, in general, are consistent with the data from Borneuf (1979), Ozoray and Lytviak (1974) and Tokarsky (1979).

It should be noted that well yield values in the AEW water well database are based only on measured pumping rate, determined during short-term testing of the well (typically 2 hours), and may not represent an accurate measure of the long-term sustainable rate or safe yield for the well. Nevertheless, the test data can be used to determine the apparent aquifer transmissivity which is an indicator of the ability of the geologic material to transmit groundwater.

Apparent aquifer transmissivity is determined by an iterative calculation that relates the pumping rate during the test to the water level response of the well. The apparent aquifer transmissivity is therefore more representative of the potential long-term productivity of an aquifer than the pumping rate during a test. Appendix A provides the methodology for determining the apparent transmissivity based on individual well tests. Using the location of the water well production interval with respect to the geology (unconsolidated and bedrock materials), the apparent transmissivity values were grouped by formation in **Table 7**:

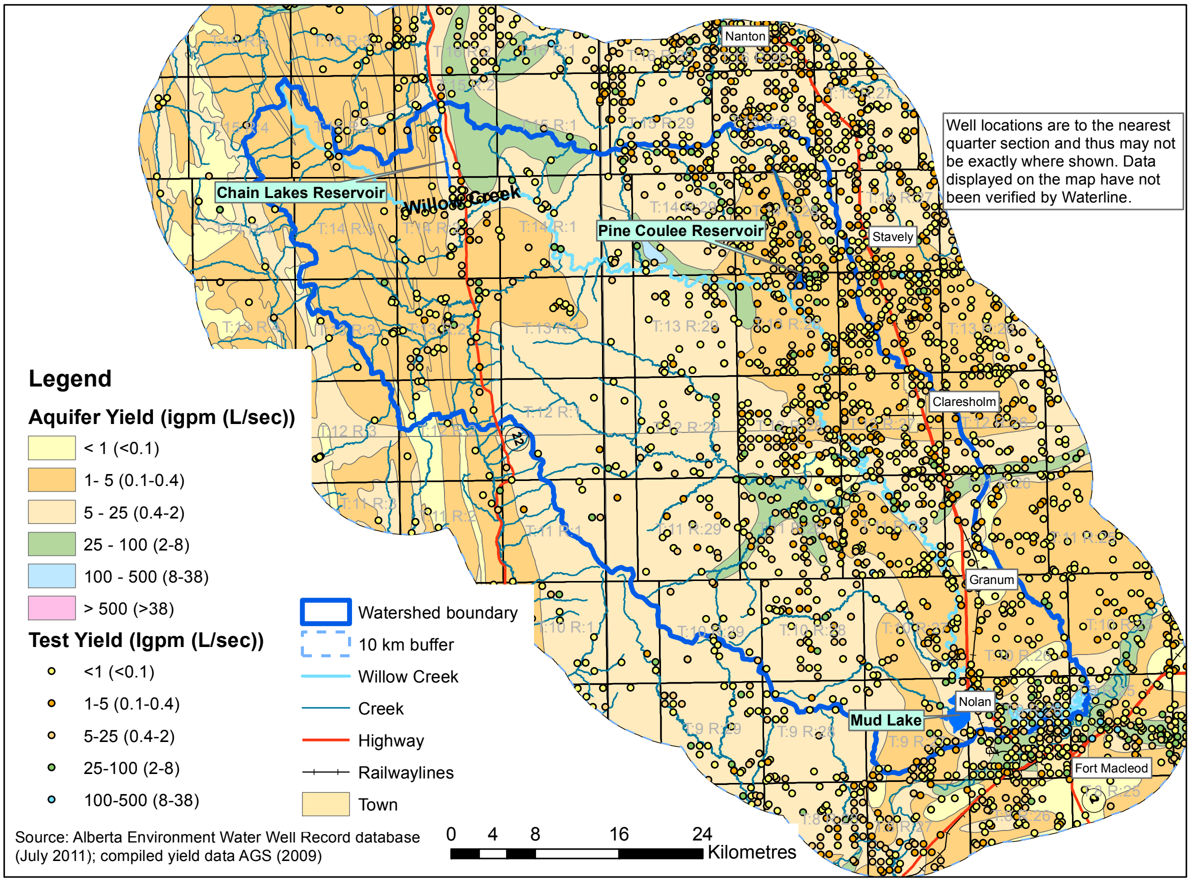



Figure 17 Well yield (based on pumping test rates from AEW database)

**Table 7 Apparent Transmissivity By Formation**

| Formation | Apparent Transmissivity ($m^2$/day) Minimum | Maximum | Geometric Mean[g] | # of Tests |
|---|---|---|---|---|
| Unconsolidated | 0.4 | 98.0 | 34.6 | 56 |
| Upper Porcupine Hills | 0.8 | 9.7 | 16.3 | 18 |
| Porcupine Hills | 0.2 | 97.2 | 14.3 | 115 |
| Willow Creek | 0.1 | 99.2 | 5.3 | 409 |
| St. Mary River | 0.2 | 8.4 | 3.6 | 11 |
| Brazeau | 0.3 | 0.7 | 0.3 | 3 |
| Alberta Group | | 97.1 | 12.2 | 3 |
| Lower Mes.-Lower Cret. | 1.5 | 523.4 | 7.8 | 4 |

Notes: $m^2$/day means metres squared per day, # means number, Mes means Mesosoic Era, Cret. Means Cretaceous Period; Lower Mesozic-Lower Cretaceous not differentiated into formations

The data indicate that the highest apparent transmissivity values occur in water wells with production intervals in the unconsolidated surficial materials and agrees with the regional hydrogeology interpretation by Ozoray and Lytviak (1974) and Tokarsky (1979). The next highest apparent transmissivity values occur in wells with production intervals in the Porcupine Hills Formation. Although the Willow Creek Formation has the same range of transmissivity values as the Porcupine Hills Formation, the geometric mean value is about half that of the Porcupine Hills Formation. The apparent transmissivity values calculated for the Porcupine Hills Formation in the Willow Creek watershed are lower than those calculated for the Elbow River watershed, although a larger number of water well records are present in this formation in the Elbow River watershed (Waterline, 2010).

#### 4.4.2.2 Water Levels and Horizontal Groundwater Flow

Water wells in the AEW water well database generally do not include ground elevation values; these were added by extracting elevations at the well locations from a digital elevation model provided by AEW for this study. **Figure 18** presents a series of water level elevation contour maps within the Willow Creek watershed. The contours are based on water levels measured in wells at the time of well construction or testing (source: AENV water well database, July 2011).

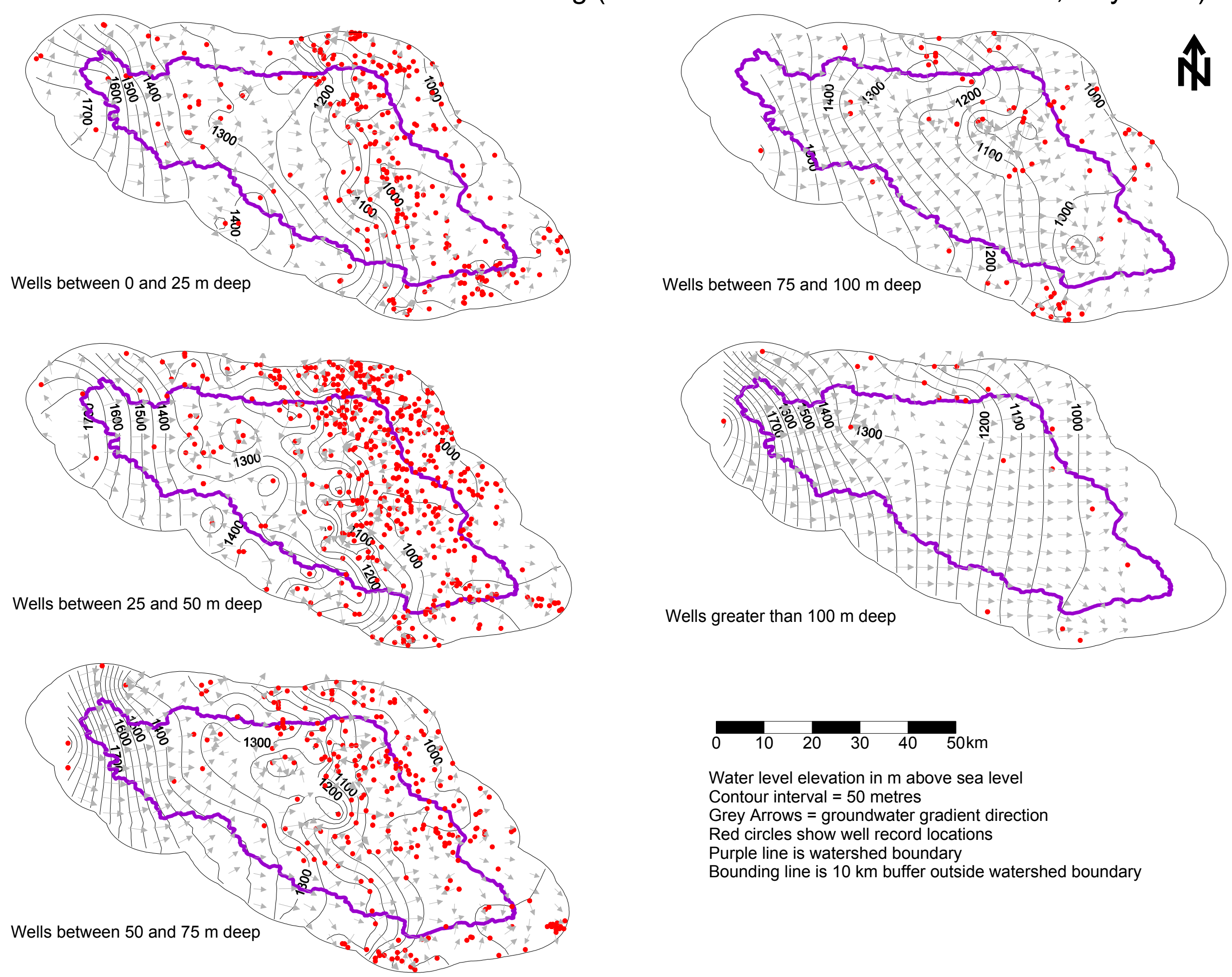



Figure 18 Water level elevation contours in the Willow Creek watershed

The data give a general impression of groundwater flow in the watershed since the water level data were collected when the wells were drilled and can span a long period of time from well to well. For simplicity, the well water level data were grouped according to well depth. The maps depict groundwater elevation at the following depth intervals:

- 0-25 mbGL – includes wells completed in unconsolidated materials;
- 25-50 mbGL, shallow bedrock water wells;
- 50-75 mbGL, intermediate depth bedrock water wells;
- 75-100 mbGL intermediate to deep bedrock water wells; and
- greater than 100 mbGL deep bedrock water wells.

As can be seen, the piezometric contour surfaces for all well depths indicate that horizontal component of groundwater flow generally follows topography and slopes to the east-southeast along the long axis of the watershed. Shallower zones exhibit a more tortuous and local flow path. Although the flow patterns observed may be related to the increased number of data points in the shallow flow systems, it is also likely that shallow aquifers are more directly affected by precipitation and snow melt (recharge) and discharge to the various creeks in the watershed (local, shallow groundwater flow system).

#### 4.4.2.3 Vertical Hydraulic Gradients and Cross-Formational Flow

In general, the contour maps in **Figure 18** indicated that the shallow wells exhibit shallower water levels (or higher groundwater elevation) in comparison to deeper wells at the same location across the watershed. This suggests that groundwater predominantly moves downward (recharging) except in the vicinity of certain reaches within the Willow Creek watershed where groundwater appears to be moving from deeper to shallow zones and discharging to the surface environment.

Springs are discharge zones at the surface and as such are the surface expression of the water table; they are generally, though not always, associated with upward hydraulic gradients. Data associated with springs, extracted from the AEW water well record database, indicate that within the Willow Creek watershed there are records for 90 springs. The majority of these springs occur within the Porcupine Hills Formation which is the first major geological unit east of the disturbed belt and in the vicinity of creeks, although some springs also appear to exist at some distance from creek margins (**Figure 19**). The records indicate that five of the springs exhibited flow rates ranging from 6.5 to 262 $m^3$/day.

Vertical hydraulic gradients (upward or downward component of groundwater flow) were estimated from data provided on driller's logs and using well pairs in the same legal subdivision (LSD) completed at different depths. The methodology is provided in Appendix A. The results are presented in **Figure 20** in the form of a contour map.

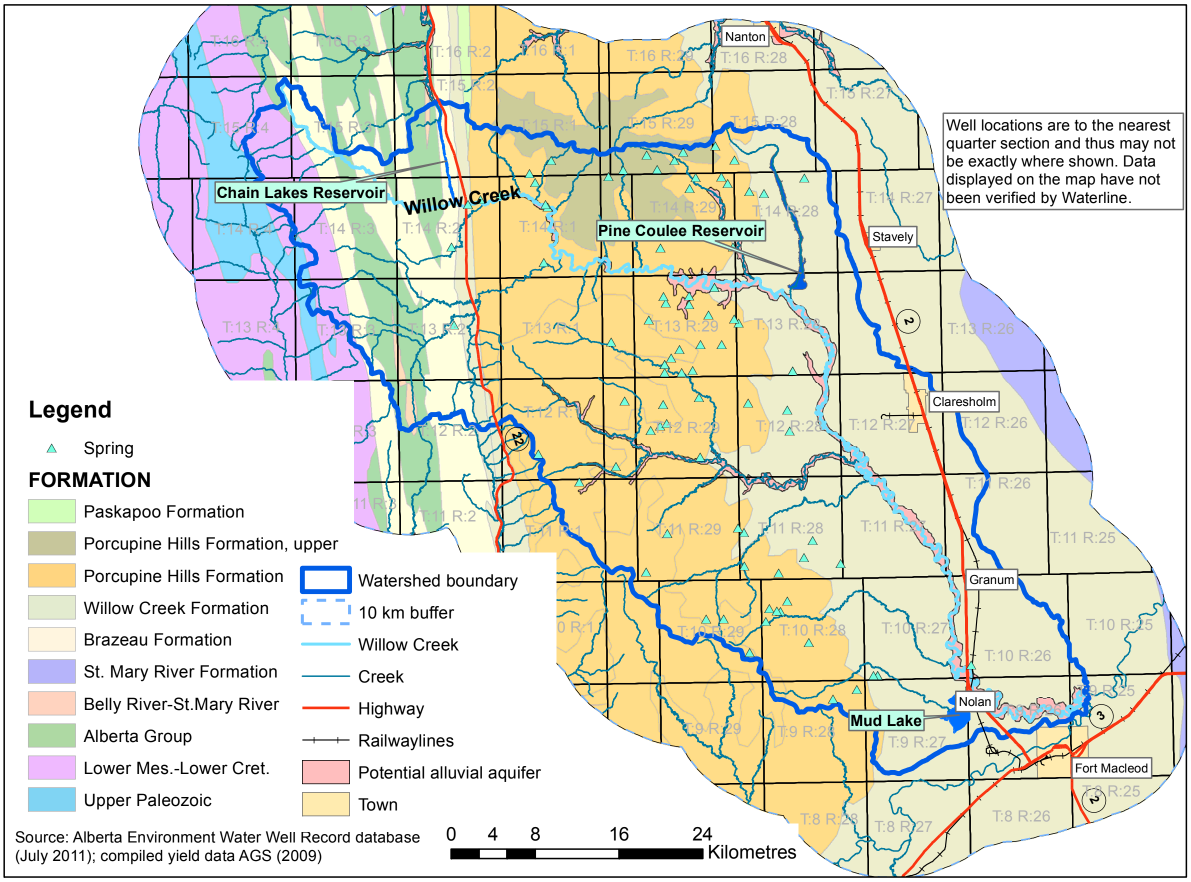



Figure 19 Springs in the Willow Creek watershed

The map agrees with the piezometric data provided in **Figure 18** and indicates that downward vertical gradients (positive values greater than zero or brown colour), indicating recharge conditions prevail across the watershed. Areas coloured in blue indicate upward hydraulic gradients (negative gradients), suggestive of discharging conditions. Where the vertical hydraulic gradients are close to zero (neutral gradient, or where the blue and red meet), they indicate that groundwater flow is essentially horizontal. These gradients were calculated using water wells which generally have maximum depths of less than 100 metres beneath the ground surface.

**Figure 20** also shows the approximate distribution of springs within the Willow Creek watershed and 10 km buffer zone. The locations of recorded springs, coincide with the zones marked as upward gradients (blue zones), but springs can also be found in downward gradient areas (brown zones) (**Figure 20**). As the vertical gradient data represent vertical flow in deeper systems, springs identified in these zones may be more regional in nature and can likely sustain flow for longer periods. Springs occurring in recharge areas (measured downward gradient or red zones) are likely related to local discharges and are topography driven and may be more susceptible to drought. However, these shallow springs are important features as they likely contribute to creek baseflow throughout the year, although they may be ephemeral.

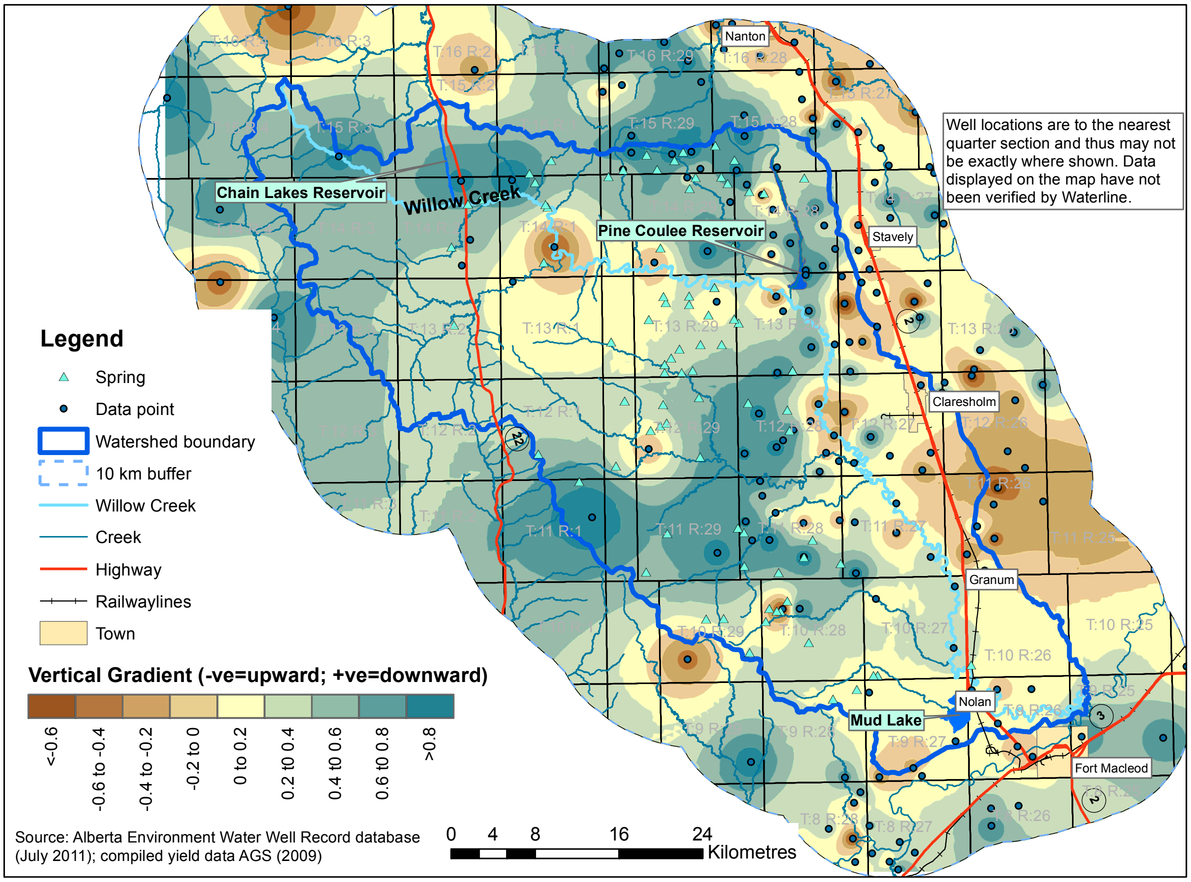



Figure 20 Contour map of vertical hydraulic gradients

### 4.4.3 Hydrogeologic Boundaries and Interconnections

The hydrogeologic boundaries within the Willow Creek watershed consist of the following:

- Surface water boundaries are coincident with topographic highs which direct surface water toward Willow Creek and other creeks;
- The groundwater boundaries are related to:
  - Lithological contacts between the various formations identified in the watershed (e.g., alluvial aquifer, Porcupine Hills, Willow Creek, St Mary's River and Brazeau formations);
  - The formations can then be further subdivided into discrete units based on intervening confining materials such as shales and other low permeability materials that separate conglomerate/sandstone/siltstone/coal which define aquifers within the watershed; and
  - Intensely fractured, faulted, or karstic features may also form important aquifers

It should be noted that watershed boundaries for surface water do not necessarily coincide with the boundaries of aquifers that occur in the subsurface. As indicated above, aquifer boundaries are controlled by the material and structural properties, and observed hydraulics in the system. Within the project the following regional aquifers have been identified:

- Pre-glacial buried valley aquifers (**Figure 22**);
- Unconsolidated Glacial Overburden aquifers (**Figure 21**);
- Willow Creek alluvial aquifer (**Figure 21**);
- Porcupine Hills Formation Aquifers (multiple sandstone units with depth) (**Figure 14**);
- Willow Creek Formation Aquifer (**Figure 14**);
- St Mary River Formation Aquifer (subcrops in the east outside the watershed; present at depth within the watershed; **Figure 14**);and
- The possibly karstic Paleozoic carbonates, although these appear to be outside the watershed.

The following subsections describe individual aquifers occurring within the study area.

#### 4.4.4 Unconsolidated Deposits

The near surface deposits predominantly consist of fluvial sediments deposited by rivers and streams and those deposited by glacial action. The surface materials in the western half of the watershed consist of bedrock and glacial materials (**Figure 21**). Further east, the material consists dominantly of glacial till. Along Willow Creek there are fluvial deposits consisting of gravel and sand (**Figure 21**). Note that the Shetsen (2002) compilation (**Figure 21**) was not continued west of the Chain Lakes.

Based on lithology information presented on well logs, the thickness of surficial deposits or the depth to bedrock, is generally less than 50 m, with an average of approximately 9 m. Pre-glacial valleys within, or in close proximity to, the Willow Creek Watershed were mapped by Geiger (1965) and are shown on **Figure 22**. As is shown, channel thawegs including: the Stavely, Carmangay and Mud pre-glacial valleys are approximately parallel to areas mapped as having thick overburden deposits (**Figure 22)**.

Of particular interest is the location of the Stavely buried valley relative to the Pine Coulee Reservoir. The Stavely buried valley was eroded into the Porcupine Hills Formation during the pre-glacial period. The bedrock valley was subsequently filled with alluvial sand and gravel deposits to a thickness of 6 metres, and then covered by up to 30 metres of glacial till (Smerdon et al. 2005). The sand and gravel deposits at the base of the buried valley form the Stavely Aquifer. It is likely that groundwater flow through the Stavely Aquifer toward the east goes beyond the watershed boundary.

Since the Pine Coulee Reservoir was commissioned in 1998, seepage at the base of the side slopes appears to be causing artificial recharge to the underlying Stavely Aquifer when reservoir levels are greater than 1039 mASL (Smerdon et al., 2005). At present, AEW is mitigating the situation by pumping several dewatering wells and diverting the groundwater back to the Pine Coulee Reservoir (Omni-McCann Consultants, 2008; Klohn-Crippen and Omni McCann, 1999).

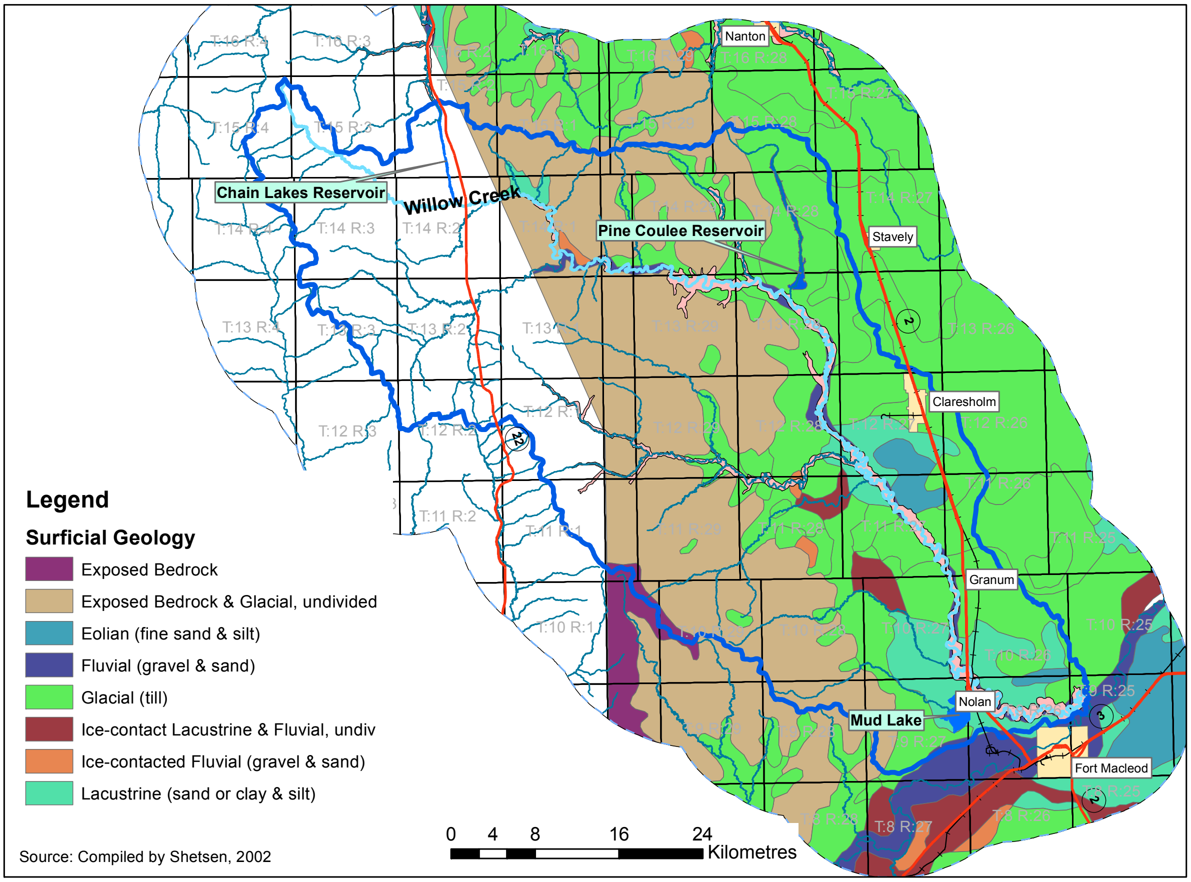



Figure 21 Surficial sediments (Shetsen, 2002)

Water well records within 500 metres of the thalweg[g] of the buried channels are plotted on **Figure 23**. Of the 337 wells with records, 56 are completed in unconsolidated materials, 94 in bedrock; the remainder have no associated Itihology data.

The alluvial sand and gravel materials in the Willow Creek watershed are generally found on the flood plains and terraces of creeks and river beds. The largest sand and gravel deposits are found at the southern edge of the watershed near the Oldman River (**Figure 24**). Large deposits are also found along Willow Creek and some of its tributaries. Some smaller isolated sand and gravel deposits are not laterally extensive and not likely to make good aquifers.

The primary alluvial aquifer within the Willow Creek watershed is associated with sand and gravel deposited along and within Willow Creek. Other smaller deposits related to glacial deposition of sand and gravel materials may be locally important for supplying individual lots or livestock watering but are not expected to be significant in terms of the overall groundwater supply in the watershed.

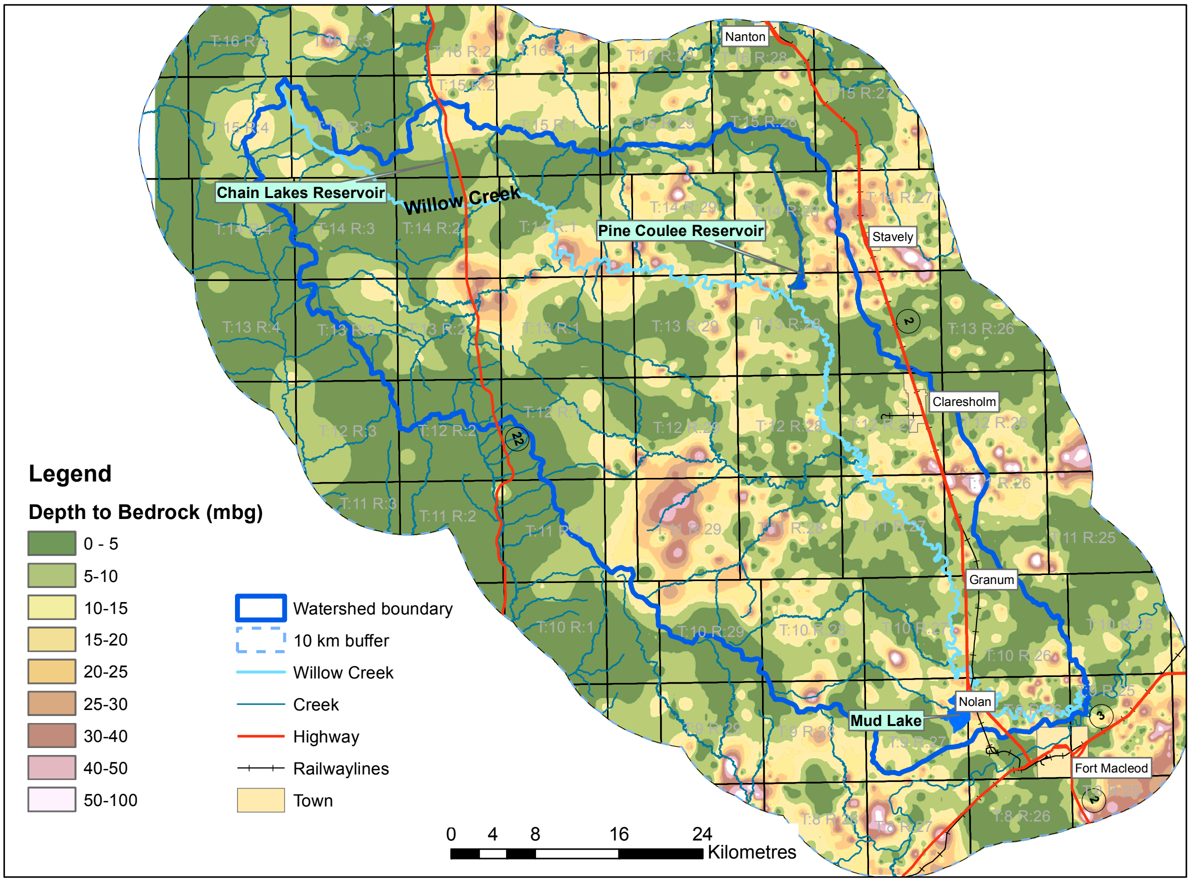



Figure 22 Depth to Bedrock

The alluvial materials extend for over 60 km from west of the Pine Creek confluence in Willow Creek to the south-eastern edge of the watershed at the confluence with the Oldman River (**Figure 25**). The alluvial materials are highly permeable and are thought to be hydraulically connected to Willow Creek. Approximately 308 water well records are present within the area of the Willow Creek Alluvial Aquifer. Of these, 65 wells are completed within alluvial sand and gravel, and 63 wells completed in the underlying bedrock. The remaining well records did not have any associated lithology data.

Waterline was not able to obtain water level monitoring data within the Willow Creek Alluvial Aquifer for the purposes of this study.

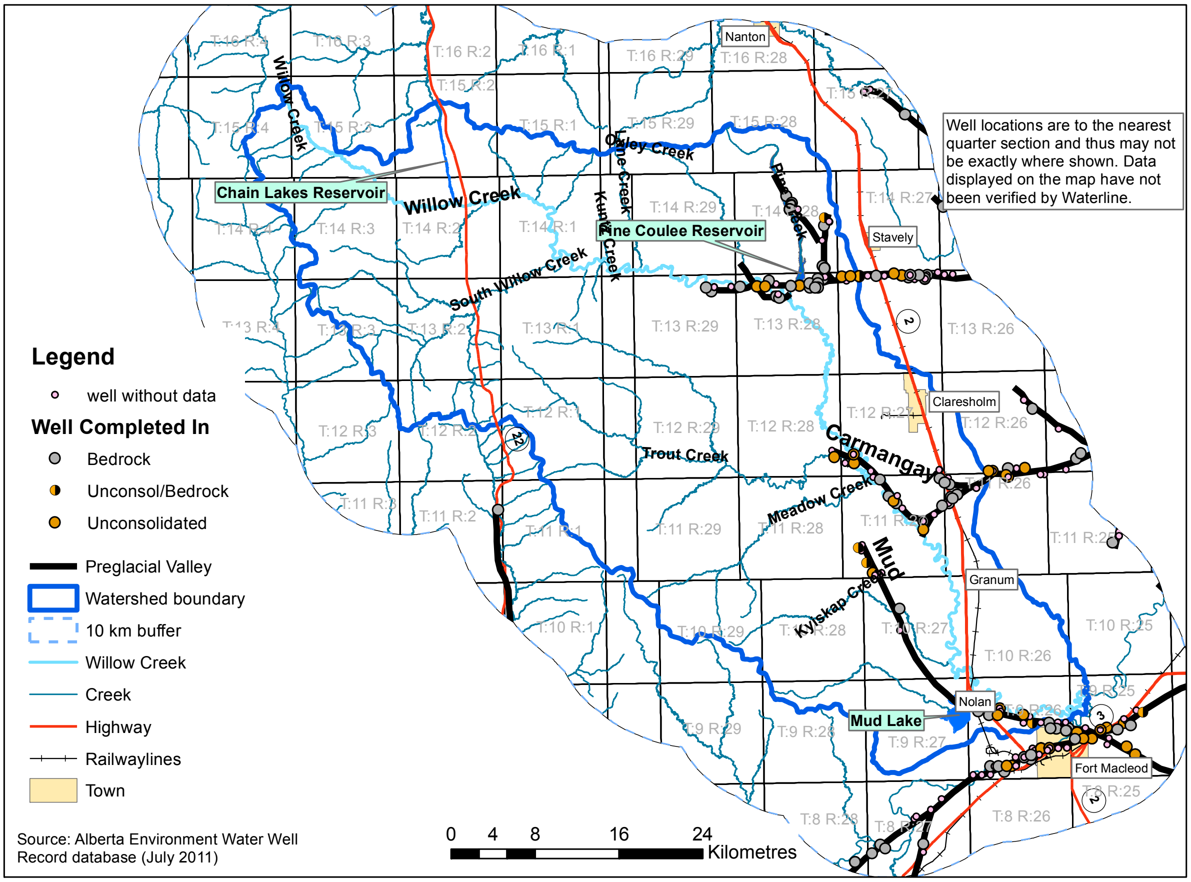



Figure 23 Water wells in the vicinity of buried valleys

It should be noted that the alluvial aquifers such as the Willow Creek Alluvial Aquifer, and other alluvial deposits associated with the various tributary creeks, serve an important recharge function in the watershed and are also vulnerable for the following reasons:

- It is in direct connection with the Willow Creek;
- It provides temporary storage of water from Willow Creek during flood stage and then delayed release of water during low baseflow periods from bank storage;
- It currently supplies water for domestic/agricultural purposes (65 wells listed in AEW database) and will likely be under future pressure resulting from increased development; and
- These deposits are highly susceptible to contamination (septic discharges, feeding operations, agriculture, etc.) because of their coarse-grained nature (high permeability) and unconfined character.

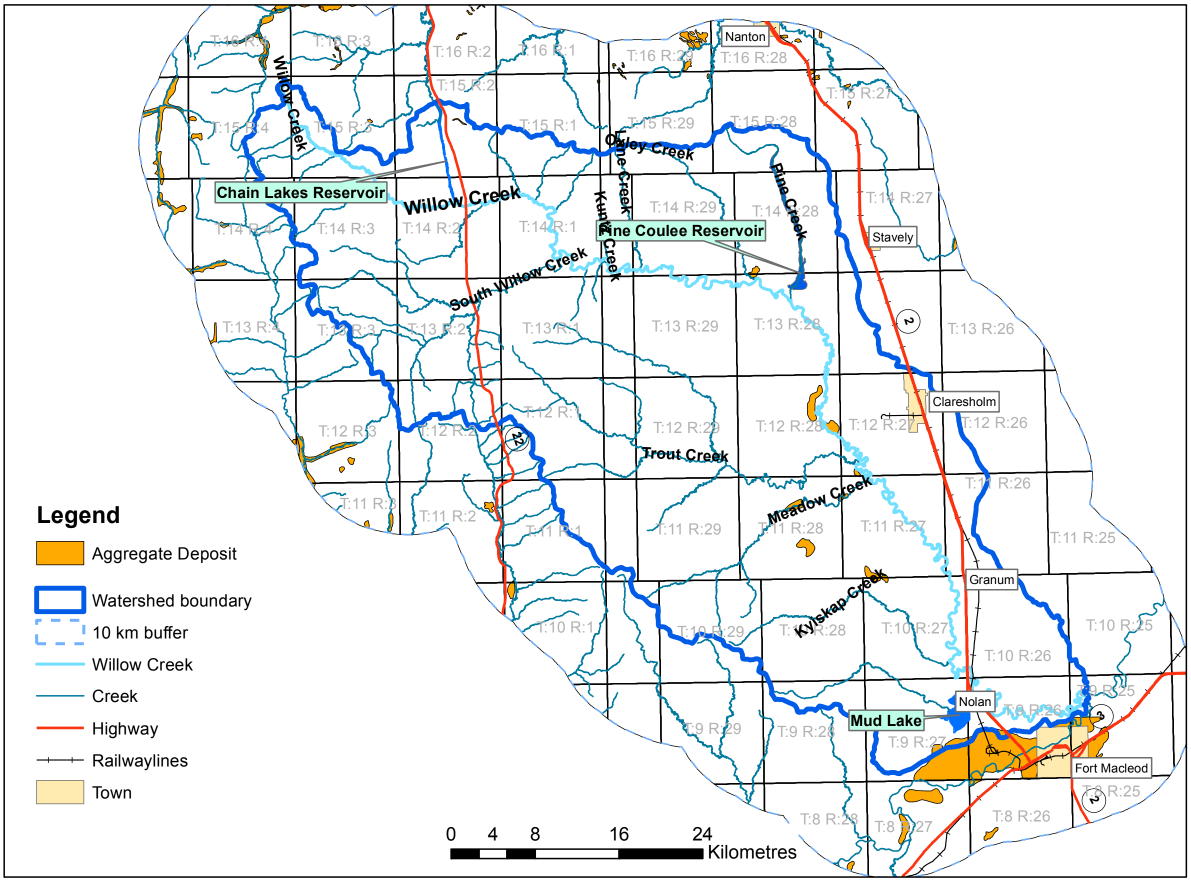



Figure 24 Sand and gravel deposits

Protection of the Willow Creek Alluvial Aquifer is of great importance as it contributes to annual baseflow in Willow Creek which is critical in the winter months, and likely provides recharge to underlying bedrock aquifers. Proper management of the Willow Creek Alluvial Aquifer should be a priority consideration for the watershed because of its high vulnerability, and interaction with Willow Creek.

### 4.4.5 Bedrock Structure and Conceptual Hydrogeological Model

A conceptual model and understanding of the subsurface geology and hydrogeology of the bedrock has been developed for the Willow Creek Watershed using a series of cross sections which integrate numerous datasets. The cross-sections were developed using lithological descriptions and hydrogeological data provided in water well records (AEW water well database, July 2011) and oil and gas well logs (IHS Accumap, October 2011), as well as structural geological studies (e.g., Stockmal et al., 2001). The oil and gas data are based on lithological descriptions and geophysical data (often natural gamma logs) which helps identify formation contacts.

The method of geological interpretation and construction of cross-sections is further discussed in Appendix A and will not be presented here. Full-page versions of the cross-sections can be found in Appendix B. A vertical exaggeration of 40:1 was selected to enable each cross-section to fit on a standard page and also to enhance the appearance of the geologic structure. If the cross-section were plotted with an exaggeration of 1:1 it would have to be printed on paper that is 12 metres in length.

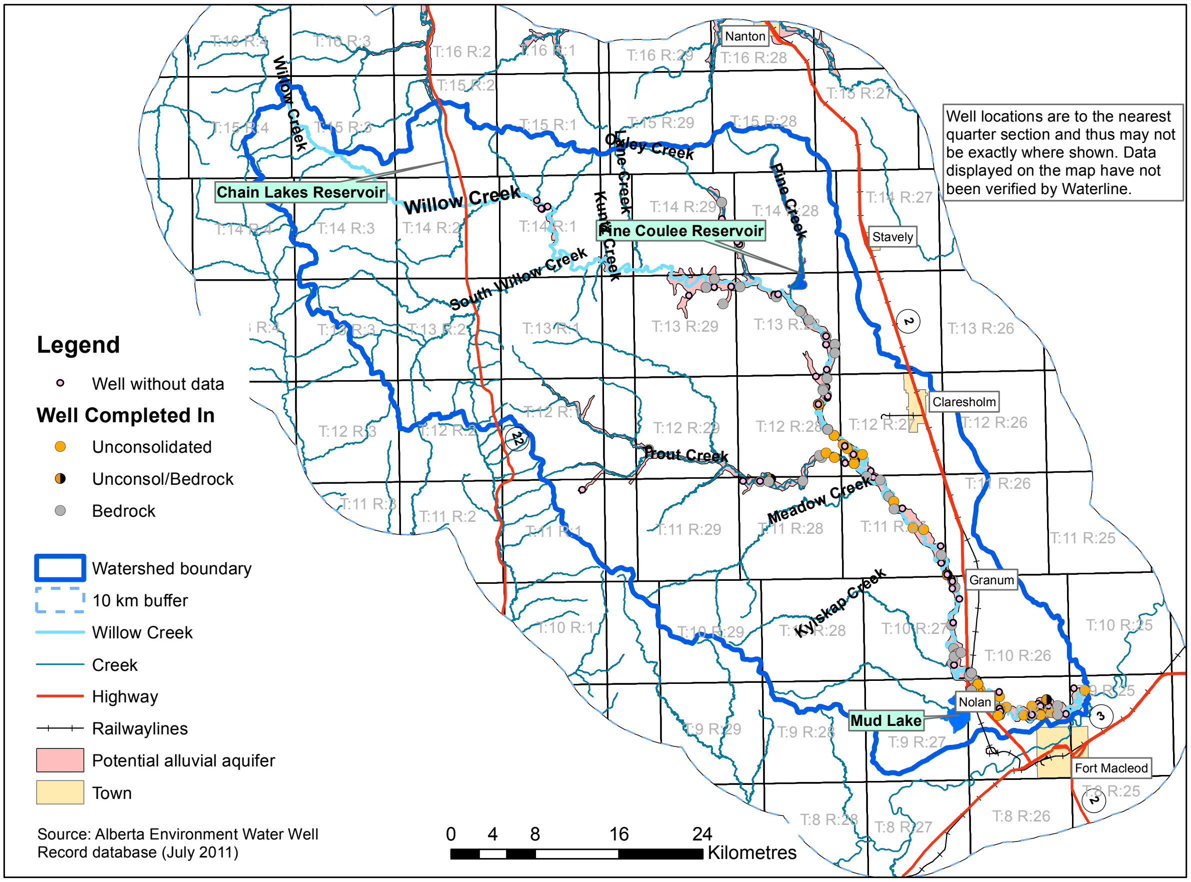



Figure 25 Water wells in the Willow Creek alluvial materials

The hydrogeology in the disturbed belt is complicated and difficult to characterize because of the lack of available information. Groundwater flow is controlled by both the lithology and the faults. Formations are faulted and may be folded. Recharge to active groundwater systems within the disturbed belt may be limited to the small areal exposure of the various formations in the region. Faults and fracture zones perpendicular to the near vertical bedding surfaces will result in interconnections between the various formations. Major northwest-southeast trending thrust faults in the area have been mapped by various authors (e.g., Hiebert, 1992, Dwyer, 1986 and Stockmal et al. 2001).

In order to differentiate between the formations in the cross-sections, estimated lithologic boundaries were drawn as orange dotted lines. The base of groundwater protection (**Section**

**3.3.3**) is shown either as a pink solid or dotted line. The line is solid in the area where the ERCB determined the depth based on water chemistry and formation location, and it is dotted in the disturbed zone where the ERCB set the depth at 600 metres below ground.

As indicated, the structural history in the disturbed zone is complex because of the mountain building process in the Rockies. The stress regime imposed on bedrock formations in this area has resulted in various fracture patterns. Some fractures are orientated along bedding planes, which are sometimes folded, and secondary vertical to sub-vertical fractures related to thrust faulting. The structural dip of thrust faults is oriented to the west with angles of 10 to 15 degrees in the western portion of the section, which thrust older rock over younger rock causing repetition of the stratigraphy. Directionally, these thrust faults dip to the west and away from the Willow Creek watershed, and some also dip to the east toward the watershed. In the bedrock, fractures that are oriented parallel to bedding are thought to be a major control mechanism for lateral groundwater flow (west to east) within aquifers in the watershed. Secondary vertical and sub-vertical fractures are important in terms of understanding the aquifer recharge mechanism. As will be shown, these features are particularly important in the Porcupine Hills and Willow Creek Formations where the layer cake stratigraphy dips at a shallow angle to the west and forms part of the east limb of the Alberta Syncline which underlies more than half of the watershed area (**Figure 26**).

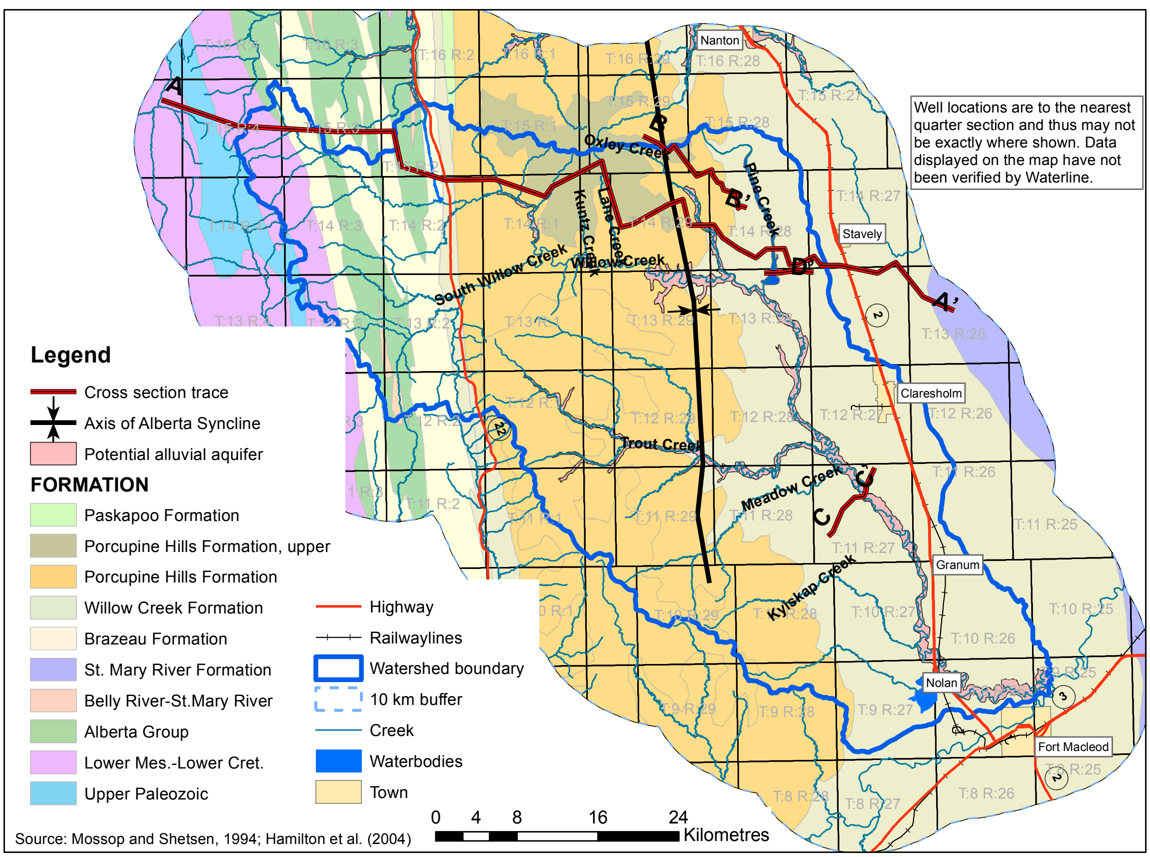



Figure 26 Cross-section location map

**Figure 26** shows the approximate location of four cross-section traces, used to develop the conceptual geological model in the watershed.

**Figure 27** is a west to east cross-section (A-A’ on **Figure 26**) and shows the structural complexity in the upper reaches of the Willow Creek watershed and across the disturbed belt. The stratigraphy/bedding and fracture orientation of Paleozoic and Mesozoic/Cretaceous bedrock in the upper reaches of the watershed suggests that subsurface recharge from snowmelt and precipitation will tend to migrate to the west and away from the Willow Creek Watershed. Therefore, this area may not be important to the overall groundwater flow regime in the watershed. However, surface water from this area, originating as snow melt and precipitation, will tend to follow topography and flow east-southeast along the creeks and valleys and over the Brazeau, Willow Creek and Porcupine Hills formations causing recharge to occur to subsurface aquifers within these formations.

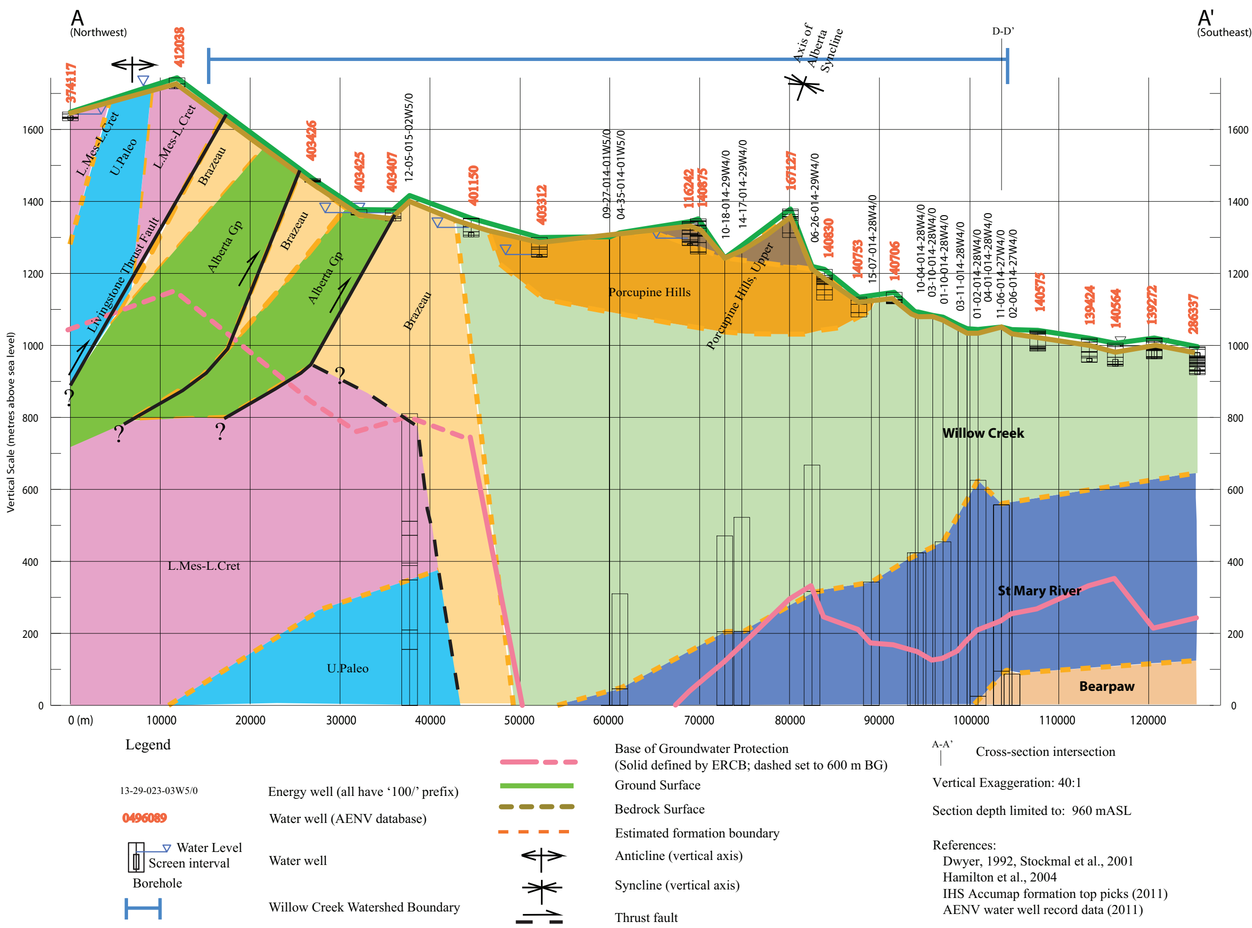



Figure 27 Cross-section A-A’

The web of creeks, exposed fractured bedrock, and associated sand and gravel alluvial and glacial deposits throughout the watershed are therefore considered to be of critical importance to aquifer recharge in the underlying bedrock formations and aquifers.

As can be seen from the cross-section, water supply wells in the region are typically completed within 150 m from ground surface and actually include a very thin zone which appears relatively close to the ground surface. The region of interest from a hydrogeological point of view is the upper 150 m or so of section. Although the depth to BGP may be mapped to be considerably deeper (600 m in some case) it does not necessarily mean that non-saline (potable) groundwater exists at these depths. At this time, however, protection of non-saline zones must be considered using the best available data and, as deeper zones are better defined with respect to water supply development potential, the conceptual model can also be updated.

### 4.4.6 Groundwater/Surface Water Interaction

Understanding groundwater-surface water interactions is of utmost importance to allow for the proper management of both surface water and groundwater resources within the Willow Creek watershed. The circulation of water within the watershed is best explained in terms of the water cycle. **Figure 28** provides a schematic showing a generalized flow path of groundwater in the subsurface.

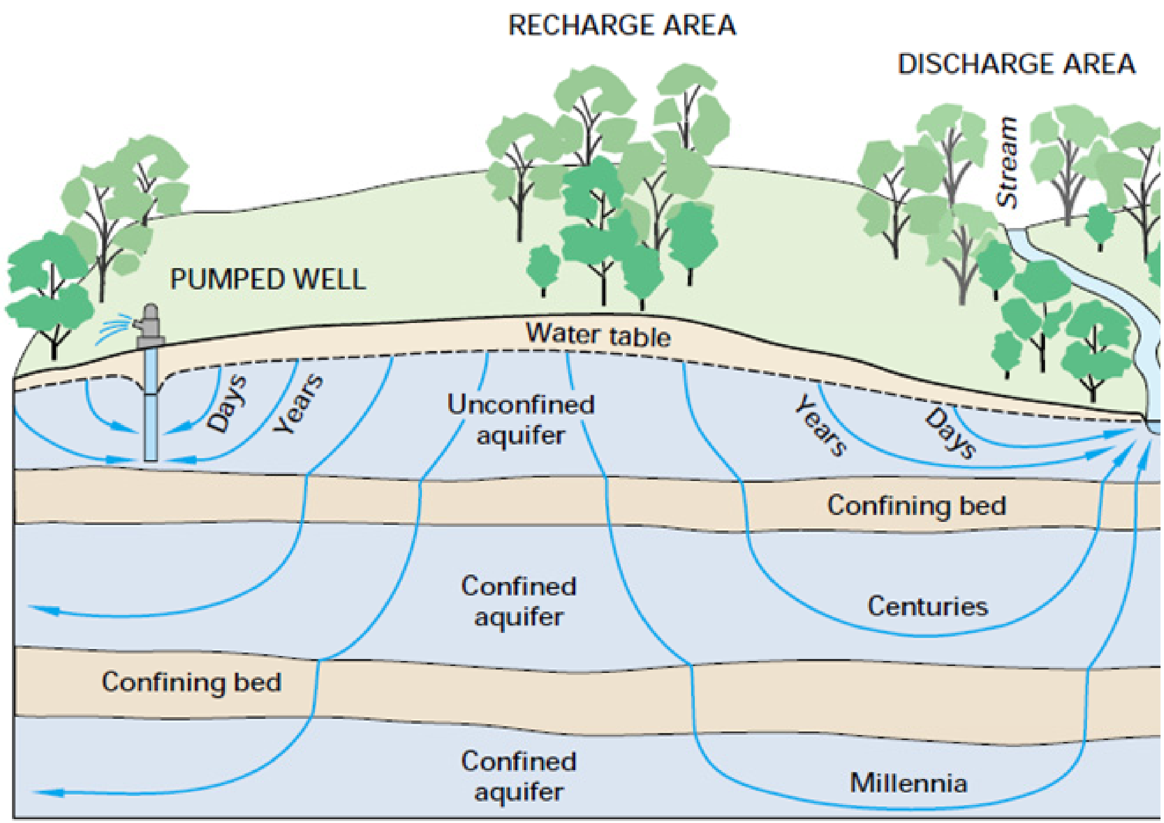



Figure 28 Conceptual groundwater flow paths (from Winter et al., 1998)

Unconfined sand and gravel aquifers that are in direct connection to the surface (e.g., Willow Creek Alluvial Aquifer) can have short flow paths on the order of 10 to 100's of metres in length, with travel times of days to a few years. As water moves down through the strata from above, deeper flow-paths to underlying confined aquifers may be kilometres to 10's of kilometres in length and have travel times of decades to millennia.

To best describe the groundwater flow within the near surface and its interaction with surface water, three cross-sections were constructed (B through D; traces displayed on **Figure 26**). These cross-sections are shorter (than A-A') and have a reduced vertical extent in order to best display the near surface lithology with a vertical exaggeration of 40:1. The reader should note that all sections are not drawn at the same horizontal scale.

**Figure 29** shows a cross-section located at the north boundary of the watershed extending northwest to southeast (**Figure 26**). The section is intended to show the relationship between the Porcupine Hills Formation aquifer(s) and the ground surface.

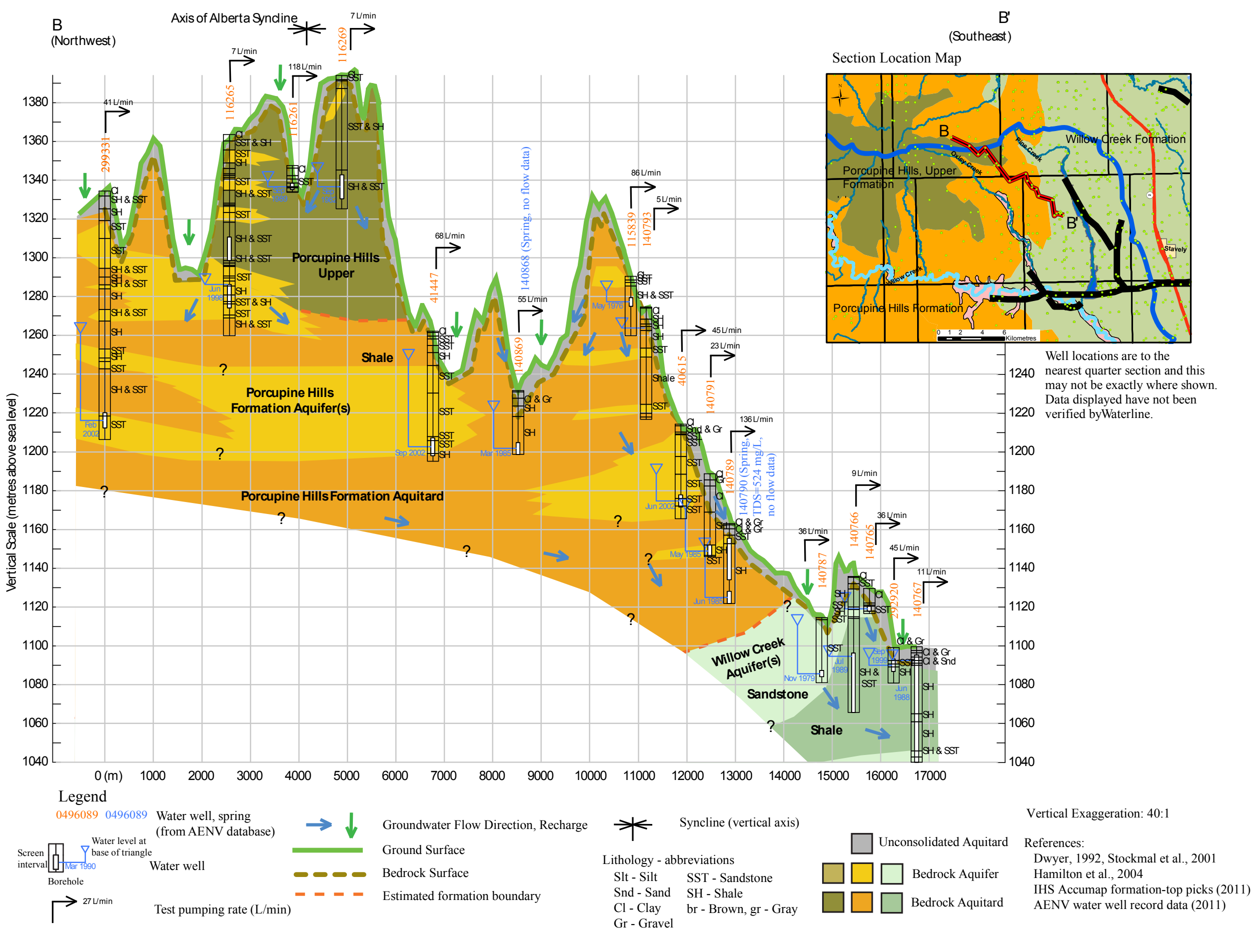



Figure 29 Cross-section B-B'

The cross-section displays recharge into the subsurface (green arrows); anticipated groundwater flow direction arrows (blue); and arrows above the wells showing the yield of the well during pumping tests. This area is characterized by high relief of approximately 300 m over a distance of 12 km. The Porcupine Hills Formation bedrock lies within the Alberta Syncline and thus the bedrock bedding surfaces dip to the east west of the synclinal axis, and to the west east of the axis.

The Porcupine Hills Formation contains aquifer(s) consisting of discontinuous sandstone units likely originally deposited in a fluvial environment. Low permeability strata or aquitards within the Porcupine Hills Formation consist of shale. The unconsolidated materials, where present, consist of glacial till and include more permeable sand and gravel deposits forming aquifer zones, and less permeable clay deposits that form aquitards or barriers to groundwater flow.

Water from precipitation recharges the aquifers through the unconsolidated materials or directly onto exposed bedrock and into the deeper bedrock zones. Although recharge may vary depending on the permeability of surficial geology and ground cover, the water table in unconfined aquifers, and the piezometric (pressure) surface in confined aquifers generally follows topography which is largely defined by the drainage of Willow Creek itself. Groundwater flow therefore occurs from northwest to southeast across the watershed. Leakage through confining layers between aquifers recharges deeper systems and discharge may occur locally to creeks and in topographically lower areas. As groundwater moves through permeable bedrock zones the dominant flow will be horizontal whereas the path of least resistance through lower permeability shale will be in the vertical direction.

Well yields appear to be higher in the Porcupine Hills Formation aquifer(s) in comparison to those completed in the Willow Creek Formation. Two springs are shown on the cross-section. The one spring located further east exhibits a Total Dissolved Solids (TDS) concentration of 524 mg/L which suggests a deeper, more regional source for the discharging groundwater. The Laurentide icesheet formed till deposits which could also be responsible for the high TDS as groundwater moves very slowly through clay till giving it more time to dissolve minerals from the clay (further discussion is provided in **Section 5.3**).

Further to the east groundwater flows from the Porcupine Hills Formation and into the Willow Creek Formation beneath the surficial deposits. The cross-section displayed in **Figure 30** is located northwest of Granum and crosses Willow Creek. As indicated, the top 150 m from the ground surface is actively being developed for surface water and groundwater supply. Groundwater flow arrows are shown to indicate the anticipated flow direction based on water level data and assumed hydraulic gradients.

This area is characterized by relatively low relief of approximately 30 m over 6 km. The sedimentary bedrock consists of gently southwest dipping beds of sandstone and shale within the Willow Creek Formation. The Willow Creek Formation aquifer(s) consists of sandstone beds, and shale with sandstone interbeds. Willow Creek Formation aquitards consists of shale which both overlies and underlies the aquifer. The bedrock is overlain by glacial clay till with sand and gravel alluvial materials adjacent to and beneath creek beds (e.g., Willow Creek).

The shallow groundwater systems are recharged from precipitation and flows down into the glacial till and sand and gravel alluvial aquifer. From the alluvial aquifer flow is directed downward into the bedrock. The groundwater also likely discharges from the sand and gravel alluvial aquifer into the creek when the creek water levels fall below those in the aquifer. Based on water levels measured in numerous wells over many years, regional groundwater flow occurs from west to east across the watershed and generally mimics topography.

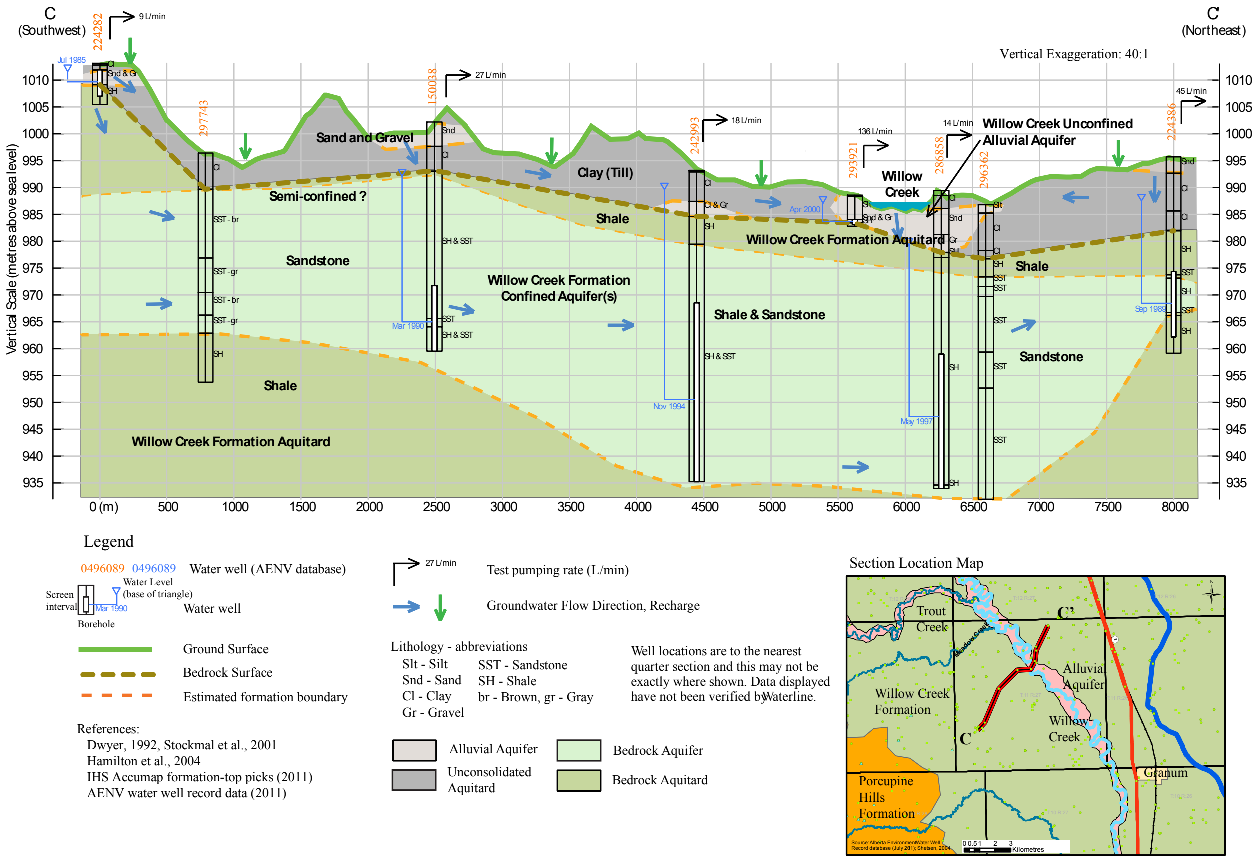



Figure 30 Cross-section C-C'

The highest well yields were noted in the alluvial gravels along Willow Creek (single well yield up to 136 L/min). The well yields in the Willow Creek Formation aquifer are much lower, generally less than 20 L/min. No springs were noted in this area.

As was discussed previously and can be seen in **Figure 30**, the Willow Creek Alluvial Aquifer serves a critical function in the overall water balance of Willow Creek and also is expected to play an important role in the recharge of deeper buried glacial valley and bedrock aquifers.

Groundwater also flows through buried pre-glacial valleys such as the Stavely Buried Valley Aquifer as shown on Cross-section D-D', in **Figure 31**. This section is orientated parallel to the Stavely Buried Valley Aquifer and perpendicular to the length of the Pine Coulee Reservoir as is shown on the inset location map in **Figure 31**. The area is dominated by thick glacial clay till overlying the Stavely Aquifer which is comprised of 3 to 6 m thick sand and gravel. The glacial till provides a approximately 35 m thick confining layer for the sand and gravel of the Stavely Aquifer. In the west, groundwater flow likely occurs down through the glacial till and into the Willow Creek Formation Aquifer. Groundwater flow then occurs laterally through the Willow Creek Formation sandstone units and vertically through the lower permeability shale aquitards.

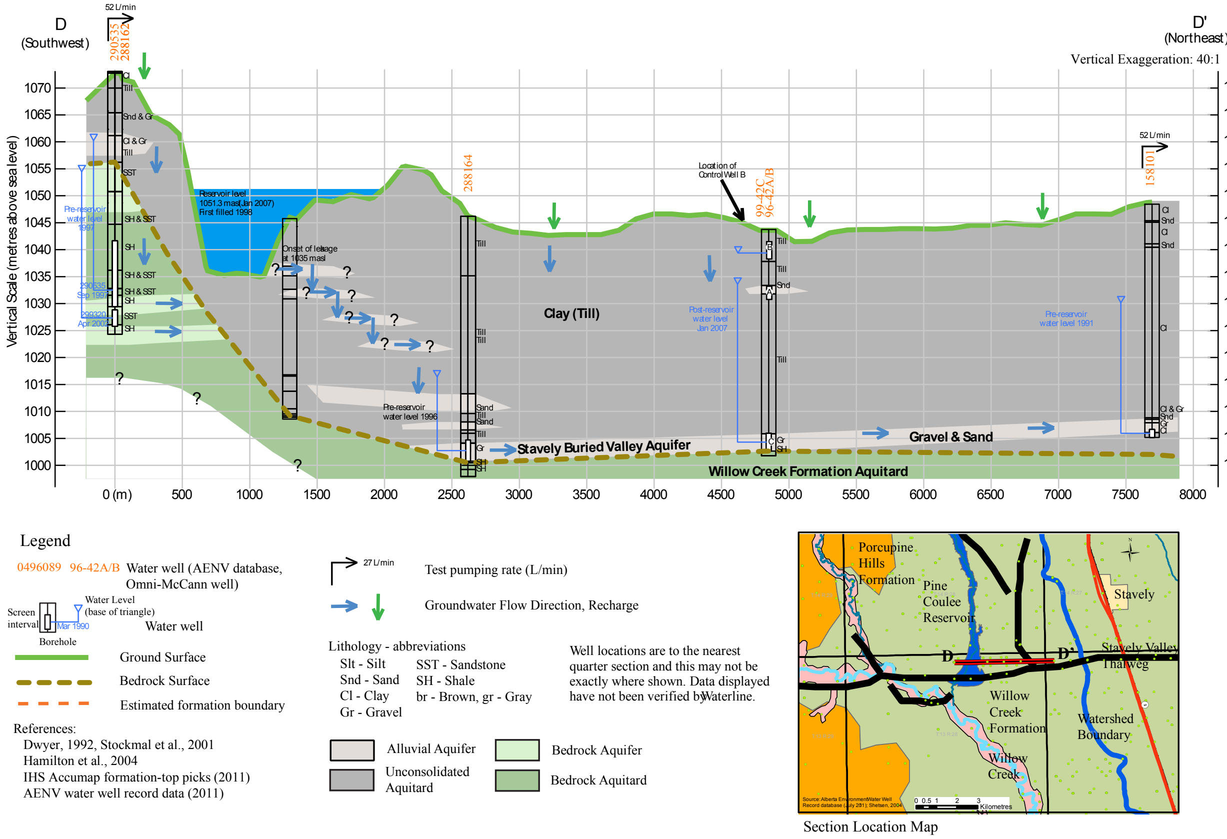



Figure 31 Cross-section D-D’

Following commissioning of the Pine Coulee Reservoir, seepage was noted from the reservoir into the Stavely aquifer. The water levels shown in cross-section D-D’ show water levels measured in wells before and after filling of the reservoir. The groundwater flow is directed from west to east, in that context, however, the water level in well 288164 is lower than expected This is because water level from well 288164 predates the filling of the reservoir whereas the water level in well 99-42C post-dates the filling of reservoir. It is assumed that the leakage occurs through sandstone units cropping out along the side of the reservoir above the 1035 masl level. There may be a direct connection that extends vertiallly to the Stavely Aquifer. There may be a series of discontinuous sandstone units as depicted on **Figure 31** or a vertical fracture system may be more likely. One of a number of wells used by the Alberta Government to control high hydraulic head in the Stavely Aquifer is located in the vicinity of well 99-42C.

## 4.5 Water Diversion and Use

Under Alberta’s Water Act, the commercial/industrial use of surface water and groundwater is regulated through a system of water licences issued by Alberta Environment. Approvals or licensing under the Water Act limits the user to a specific annual water volume based on their specific requirement. In order to comply with the terms and conditions in the license, the user is obligated to report water use and water levels on an annual basis through AEW’s on-line Water Use Reporting (WUR) System. Water Act licences are subject to a priority system based on the principal of first in time, first in right (GOA, 2010a).

The Water Act also provides statutory rights to household users to water. Rural landowners have a right to divert and use up to 1,250 $m^3$/yr of surface water or groundwater for household purposes. In addition, registered traditional agricultural users (restricted to raising animals or applying pesticides to crops) have the right to divert and use up to 6,250 $m^3$/yr of surface or groundwater.

### 4.5.1 Surface water Diversion Information – Willow Creek

The most common use of surface water in the watershed is for irrigation and water management (**Table 8**).

**Table 8 Surface Water Diversion**

| Type of Surface Water Diversion | Maximum Annual Diversion ($m^3$/yr) |
|---|---|
| Agricultural | 11,046,053 |
| Commercial | 19,388,251 |
| Disturbance | - |
| Government Holdback | 144,704 |
| Habitat Enhancement | 41,940 |
| Irrigation | 454,067,115 |
| Management of Fish | 20,970 |
| Management of Wildlife | 24,680 |
| Municipal | 4,955,326 |
| Other Purpose Specified by the Director | 14,668 |
| Recreation | 24,670 |
| Water Management | 60,459,110 |
| Total Licensed Allocation | 550,187,486 |

Surface water license locations plotted on **Figure 32** show that most of the surface water use is in the eastern portion of the watershed where agricultural land use is the most common. The most common use for surface water diverted from Willow Creek is for irrigation purposes.

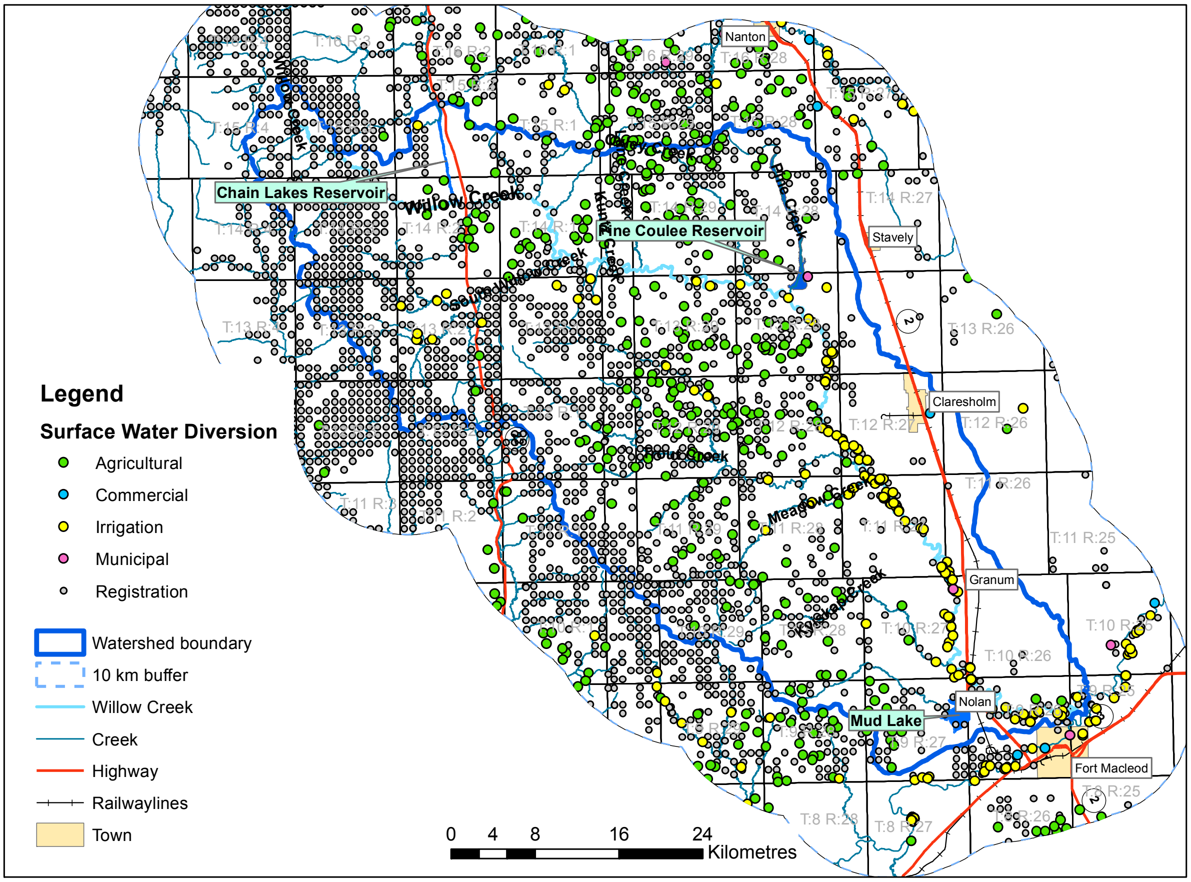



Figure 32 Surface water diversion

### 4.5.2 Groundwater Diversion Information

Groundwater diversion licenses indicate that the most common use of groundwater in the watershed is for agricultural purposes followed by municipal use (**Table 9**).

**Table 9 Groundwater Diversion**

| Type of Groundwater Diversion | Maximum Annual Diversion ($m^3$/year) |
|---|---|
| Agricultural | 1,125,957 |
| Commercial | 252,570 |
| Groundwater Exploration | 10,860 |
| Irrigation | 126,440 |
| Management of Fish | 1,230 |
| Municipal | 701,474 |
| Recreation | 9,377 |
| Total Licensed Allocation | 2,227,908 |

Groundwater diversion license locations are presented on **Figure 33**.

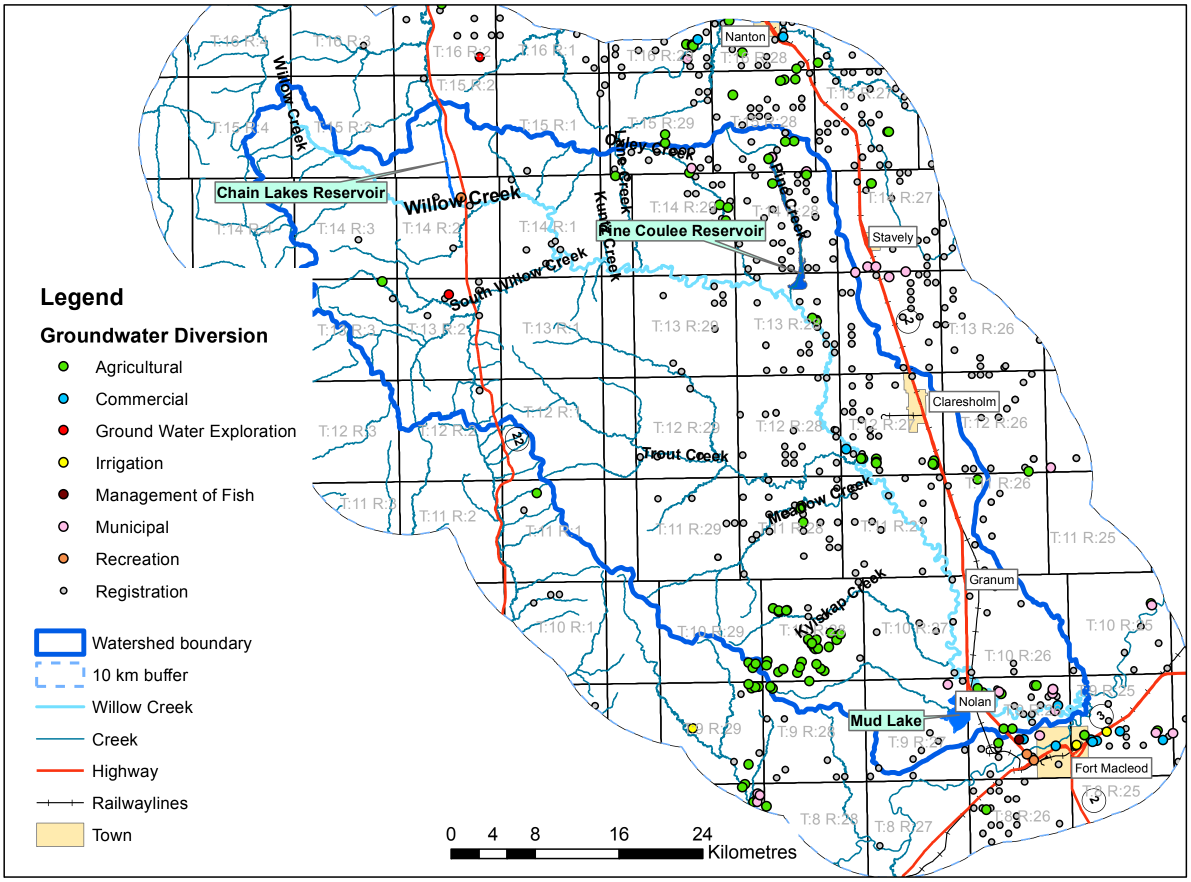



Figure 33 Groundwater diversion

The maximum approved groundwater diversions are shown in
**Table** 10 and have been subdivided by formation. It should be noted that the information included in the license approval often does not include the associated water well (e.g., by AEW Well ID) or formation/aquifer name. Waterline was able to cross-reference the license approval location to the nearest water well(s) and assign a formation into which the well was most likely completed. However, it was not possible to assign the diversion volume to unconsolidated aquifers because depths were usually not provided in the approval. Based on this assessment the most commonly used aquifers are situated in the Willow Creek Formation followed by the Porcupine Hills Formation aquifer(s).

**Table 10 Groundwater Diversion by Formation**

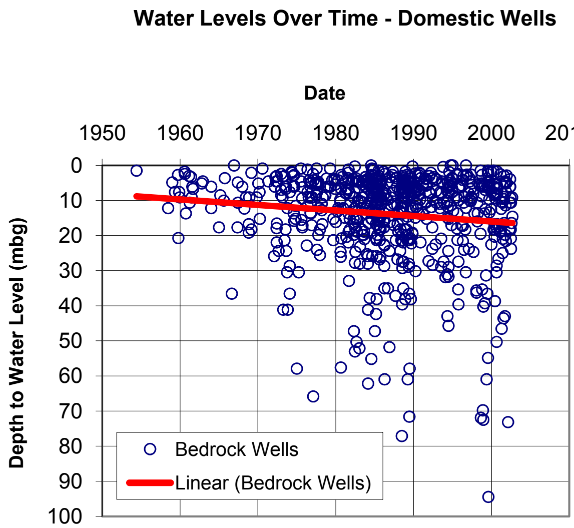
| Formation | Porcupine Hills Formation, upper | Porcupine Hills Formation | Willow Creek Formation | St. Mary River Formation | Brazeau Formation | Alberta Group |
|---|---|---|---|---|---|---|
| **Type of Diversion** | **Maximum Diversion Allowed ($m^3$/year)** | | | | | |
| Agricultural | 2,838 | 152,186 | 958,233 | 8,630 | 1,230 | 2,840 |
| Commercial | - | - | 252,570 | - | - | - |
| Groundwater Exploration | - | 4,813 | 2,715 | - | 3,332 | - |
| Irrigation | - | 53,040 | 73,400 | - | - | - |
| Management of Fish | - | - | 1,230 | - | - | - |
| Municipal | - | 31,826 | 669,648 | - | - | - |
| Recreation | - | - | 9,377 | - | - | - |
| **Total** | 2,838 | 241,865 | 1,967,173 | 8,630 | 4,562 | 2,840 |
| **# Diversion Licenses** | 2 | 63 | 103 | 1 | 2 | 1 |

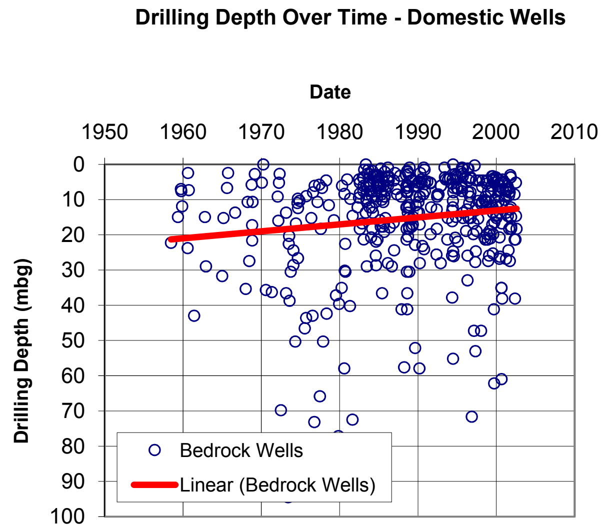
Note: # means number

### 4.5.3 Water Level Monitoring

#### 4.5.3.1 Trends in Water Levels and Well/Drilling Depths

There has been no widespread long term monitoring of groundwater levels in the Willow Creek watershed. **Figure 34** was constructed to provide a preliminary assessment of trends regarding the depths to water level encountered in wells plotted against the time that the wells were drilled, and drilling depth plotted against time. The intent is to assess if the overall trend in the watershed is of declining water levels or deepening of supply wells over time as an indicator of groundwater mining or over use. The data show a very weak declining water levels trend over the 50 year record (based on a moving average). Conversely, the depths of wells being drilled in the watershed appear to be shallower over time. This could suggest that previously unexplored shallow aquifers were being exploited between 1950 and 2000. Based on this assessment, no reliable trend can be established to assess whether groundwater resources in the region are being depleted.




| Formation | Drilling Depth Average | Drilling Depth Std Dev | Water Level Average | Water Level Std Dev | Trendline Trend | Trendline Est. Change (m) |
|---|---|---|---|---|---|---|
| Unconsolidated | 28 | 20 | 12 | 10 | increasing depth to water | 10 |
| Paskapoo Formation | 49 | | | | Too few data points | |
| Porcupine Hills Formation | 40 | 30 | 21 | 18 | increasing depth to water | 17 |
| Porcupine Hills Formation, upper | 47 | 34 | 31 | 22 | increasing depth to water | 17 |
| Willow Creek Formation | 35 | 28 | 11 | 10 | slight increase in depth to water | 2 |
| St. Mary River Formation | 45 | 28 | 14 | 16 | slightly decreasing depth to water | -5 |
| Brazeau Formation | 29 | 22 | 9 | 6 | slightly increasing depth to water | 5 |
| Alberta Group | 16 | 16 | 10 | 15 | slightly increasing depth to water | 2 |
| Lower Mesozoic-Lower Cretaceous | 40 | 39 | 14 | 10 | Too few data points | |

Note: mbg = metres below ground level
Criteria: domestic water wells

Figure 34 Water levels and drilling depths over time

The water level data were also plotted based on the assumed completion formation (**Figure 35**). The graphs indicate a declining trend over time in the shallow unconsolidated sediments, the Porcupine Hills Formation, Alberta Group and Brazeau Formation. Increased groundwater use and less available recharge may be the cause. This is especially true for the Porcupine Hills, Alberta Group, and Brazeau Formation aquifers that occur at higher elevations in the watershed where smaller catchment area is available for capturing recharge. The Willow Creek Formation, and the St. Mary River Formation data suggest that water levels are either not changing significantly or could even be on the rise. As both the Willow Creek Formation and the St. Mary River Formation are found lower in the watershed (**Figure 26**), recharge is occurring from a larger area and groundwater extraction likely does not exceed recharge.

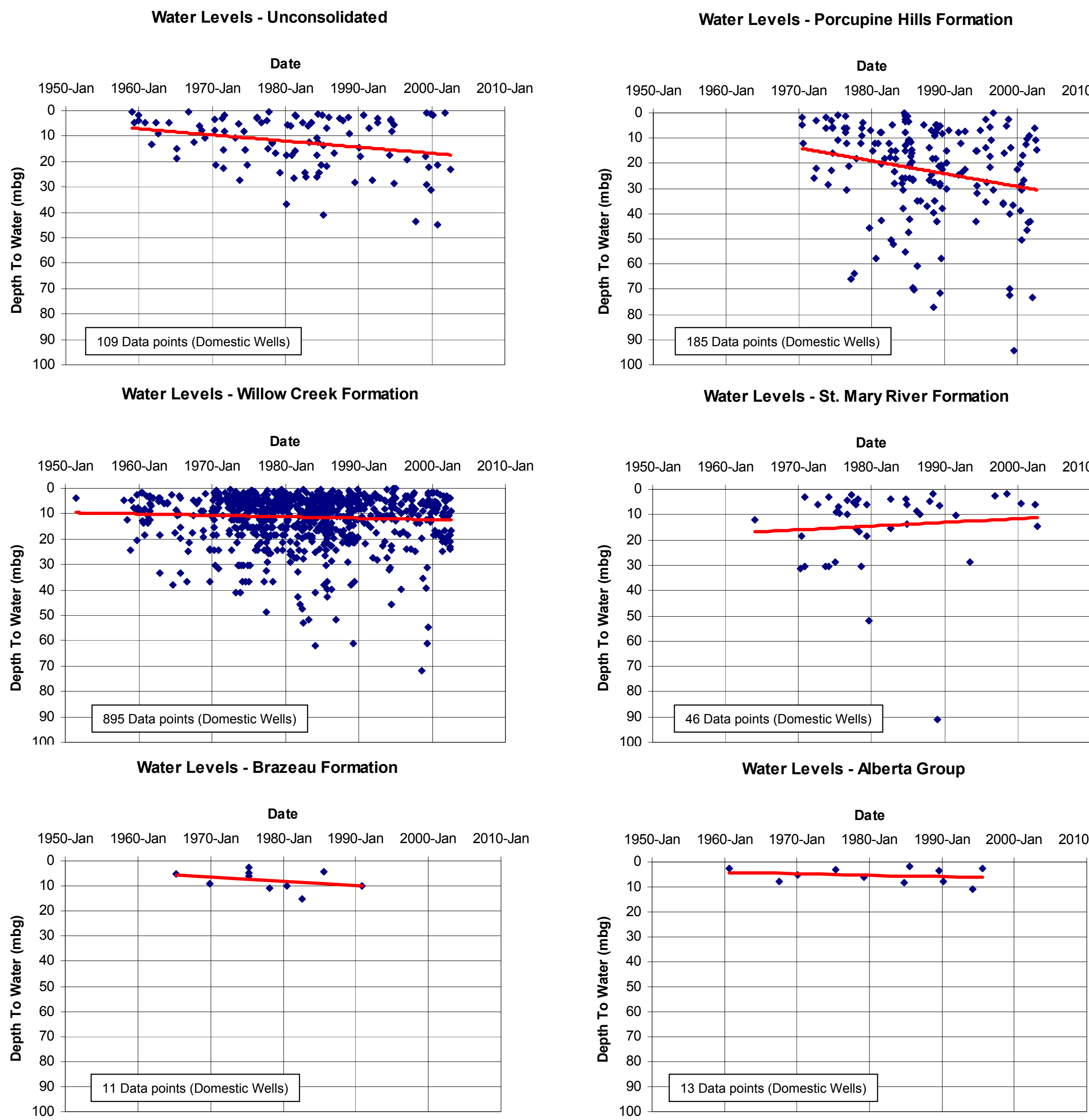



Figure 35 Water levels over time by formation

#### 4.5.3.2 AEW Government Observation Well Network (GOWN)

The watershed and buffer zone contain three sets of observation wells that are part of the AEW GOWN. These include one well at Mud Lake, one at Orton, and two wells west of Stavely (**Figure 36**). At one point the two wells at Stavely were turned over to the farmer since his wells had gone dry. Therefore, no further water level record is available for these wells.

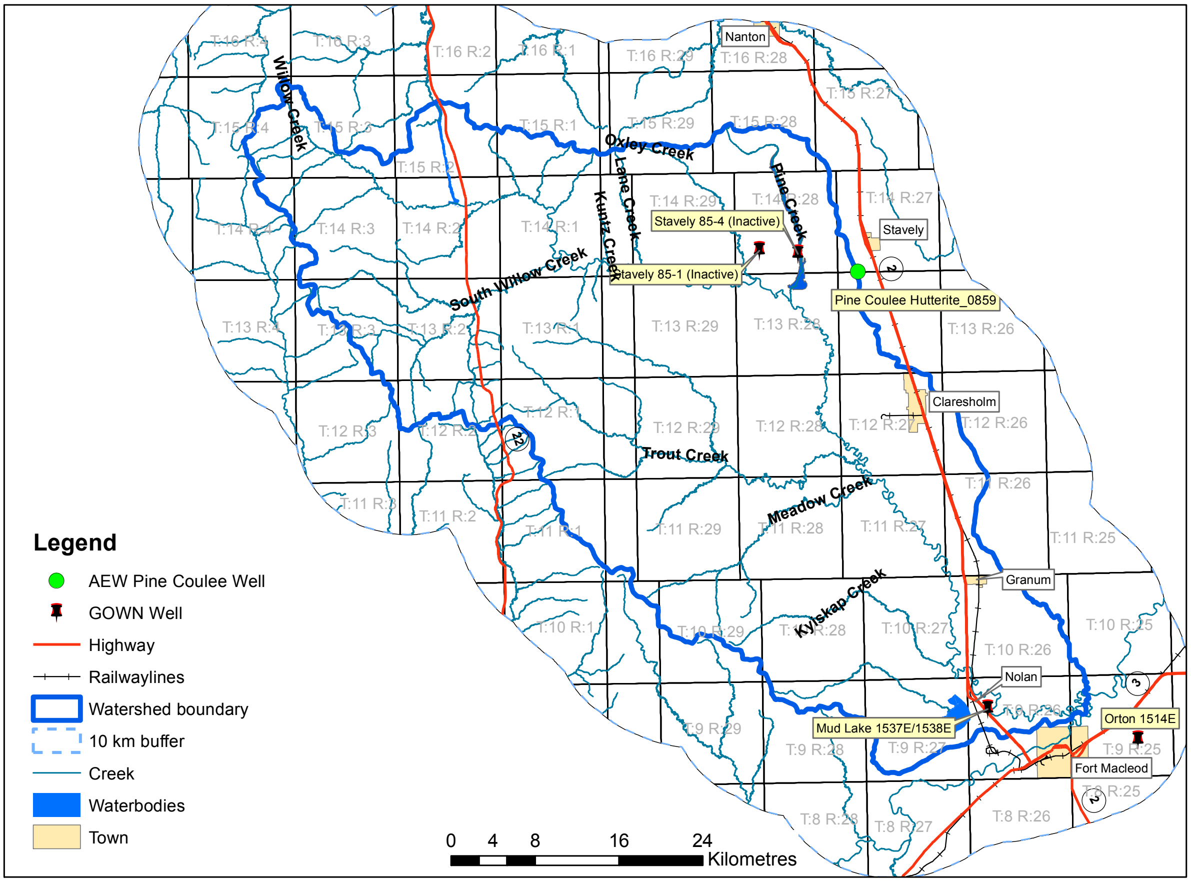



Figure 36 Location of GOWN wells in watershed

A summary of background information for the GOWN wells in the Willow Creek watershed is provided in **Table 11**.

In addition, in the past, AEW monitored a large number of wells in and around the Pine Coulee reservoir. Many of these wells were drilled for the purposes of assessing the effects of groundwater mounding in the area of the reservoir including the Stavely buried valley aquifer. Therefore, these wells do not provide data on natural background conditions in key bedrock aquifers.

The hydrographs for the GOWN wells within the watershed and buffer are shown on **Figure 37**. The Mud Lake well (GOWN #112), located in the south-eastern part of the Willow Creek watershed, and shows consistent water levels from 1977 until January 1998. From 1998 to 2001, there appears to be a decline of the water level to a maximum of about 2.5 m followed by a slow rise of water levels to 2007. This is thought to coincide with drought conditions in Southern Alberta.

**Table 11 GOWN Well Details**

| **GOWN #** | **111** | **112** | **209** | **210** |
|---|---|---|---|---|
| **Well Name** | **Orton 1514E 0111** | **Mud Lake 1537E 0112** | **Stavely 85-1 0209** | **Stavely 85-4 0210** |
| Location | 01-15-09-25W4 | 15-19-09-27W4 | 06-08-14-28W4 | 02-10-14-28W4 |
| Longitude | -113.3013159 | -113.5107222 | -113.7916149 | -113.7405028 |
| Latitude | 49.72972382 | 49.75702778 | 50.15557771 | 50.15201907 |
| Status Details | Active | Active | Transferred | Transferred |
| In Use Since (WL) | 1985-Jan-11 | 1977-May-11 | 1986-May-27 | 1986-Mar-03 |
| End of Available Data | WL Recent / WQ Nov 2008 | WL Recent | WL Feb 14 1989 / WQ Oct 1993 | WL Nov 5 1998 / WQ Aug 1990 |
| Elevation Casing Top (mASL) | 947.587 | 944 | 1075 | 1075 |
| Depth (m) | 50.3 | 36.58 | 22.9 | 33.3 |
| Production (m to m) | 44.5 - 50 | 27.4 - 33.53 | 17.0 - 22.9 | 24.3 - 33.3 |
| Lithology | Sand & Gravel | Gravel | Sandstone | Sandstone |
| Formation | Channel | Channel | Bedrock | Bedrock |
| Aquifer | Lethbridge Valley | Mud Valley | Porcupine Hills | Porcupine Hills |

The Orton well (GOWN #111) is located outside the Willow Creek watershed and within 10 km of Fort Macleod (**Figure 37**). The hydrograph clearly shows influence from the surrounding wells. According to the AEW Water Well database there are many wells in the vicinity of similar depth to that of the observation well. The hydrograph shows significant and rapid decreasing of water level during the growing season. Recovering of the water level is rapid and complete. Its water levels fluctuate over a slightly wider range than GOWN #112 - about 4 m during the same time period with annual fluctuation on the order of about 2 to 3 m.

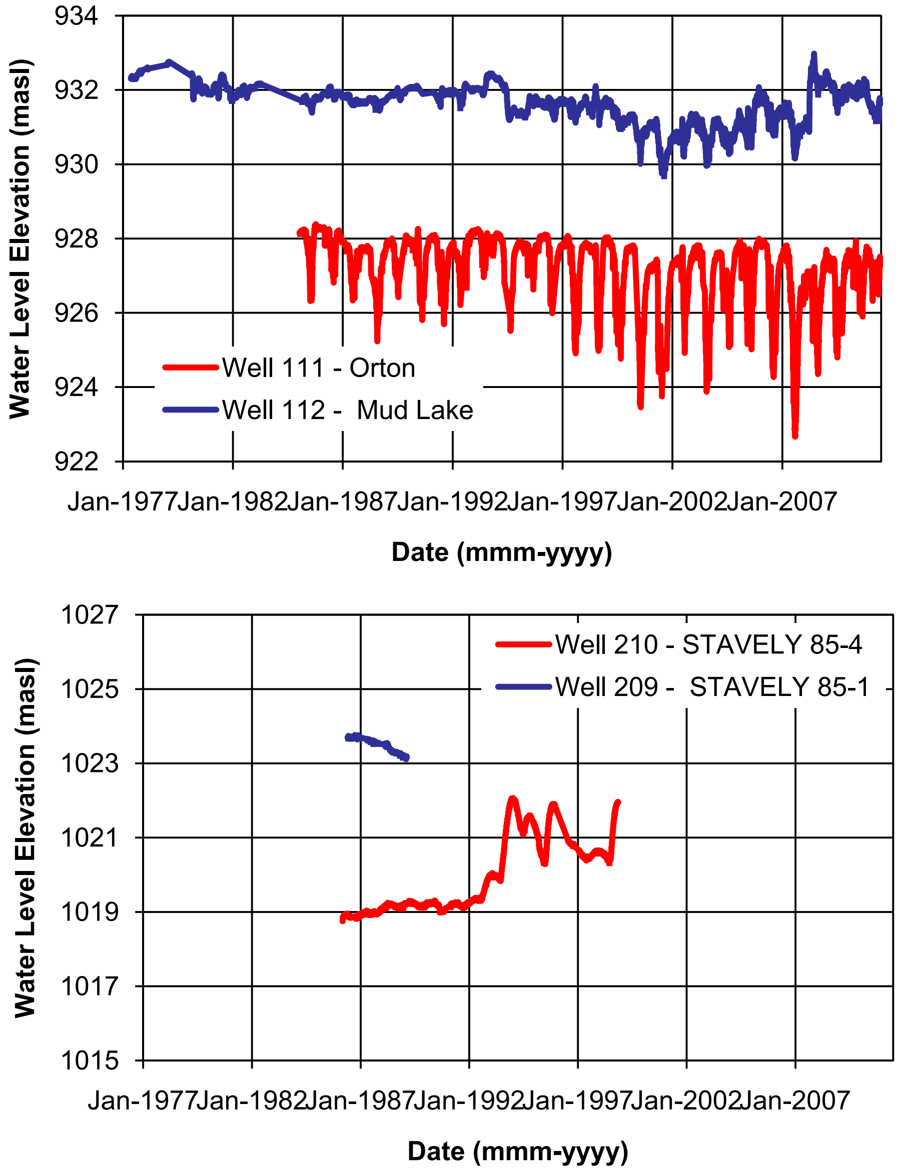
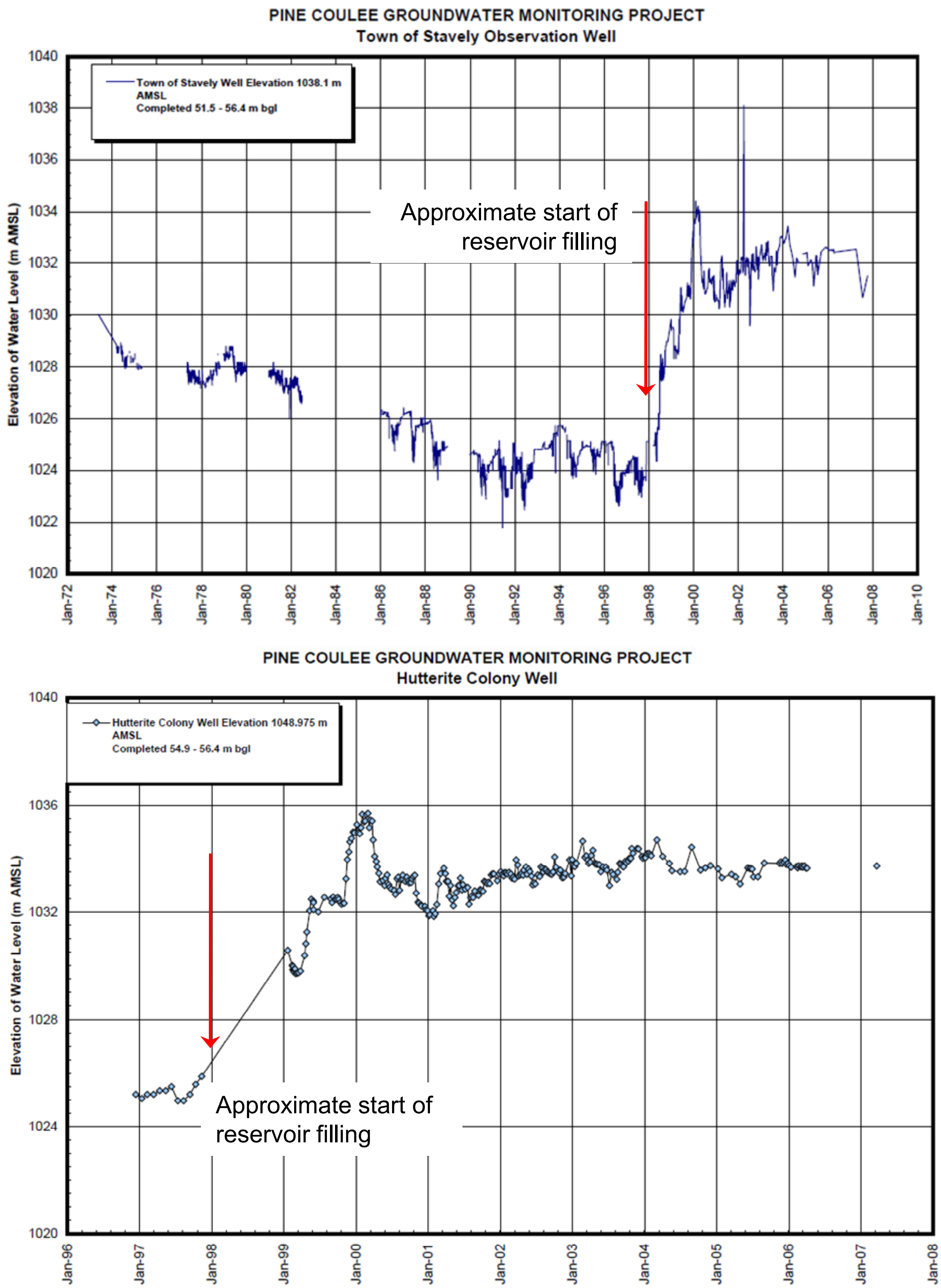



Figure 37 Hydrographs of GOWN wells in watershed

#### 4.5.3.3 Town of Stavely and Pine Coulee Hutterite Colony Wells

Water level monitoring data from the Town of Stavely well, and the Hutterite Colony well (GOWN #859) are shown in **Figure 38**. The data were taken from the Omni-McCann (2008) report.




Source: Omni McCann, 2008

Figure 38 Hydrograph of Stavely Town well and Hutterite Colony well

The Town of Stavely well shows approximately 7 m of decline in water level within the Stavely buried-valley aquifer prior to the filling of the Pine Coulee reservoir in 1998. After the filling of the reservoir started, water levels in the Stavely Aquifer recovered by over 9 m as a result of leakage into the aquifer from the reservoir side slopes. Pumping from control wells has maintained the water level in the Stavely Aquifer below 1036 mASL. The Pine Coulee Hutterite Colony well located some distance down-gradient of the Reservoir shows a very similar response.

#### 4.5.3.4 Water Use Reporting (WUR) Data

AEW operates an on-line reporting system for approval holders to enter water level and groundwater usage data. Although the Alberta water-well-record Well ID is not stored with the approvals, it was possible to associate a number of the wells with reported water levels in the AEW system. The locations of the approvals are show in **Figure 39**. The hydrographs for these approvals/wells are shown in **Figure 40** and the trends are summarized below.

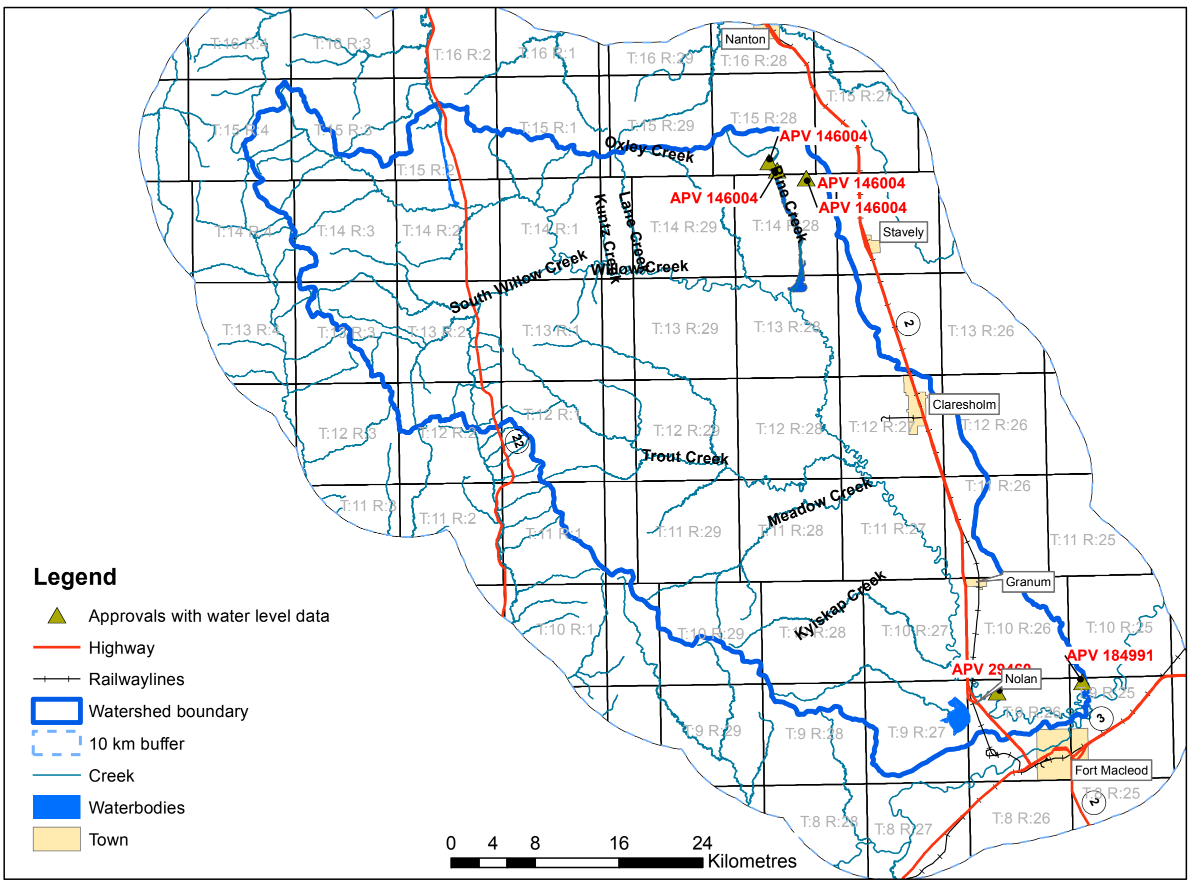



Figure 39 Location of approvals with water level monitoring data

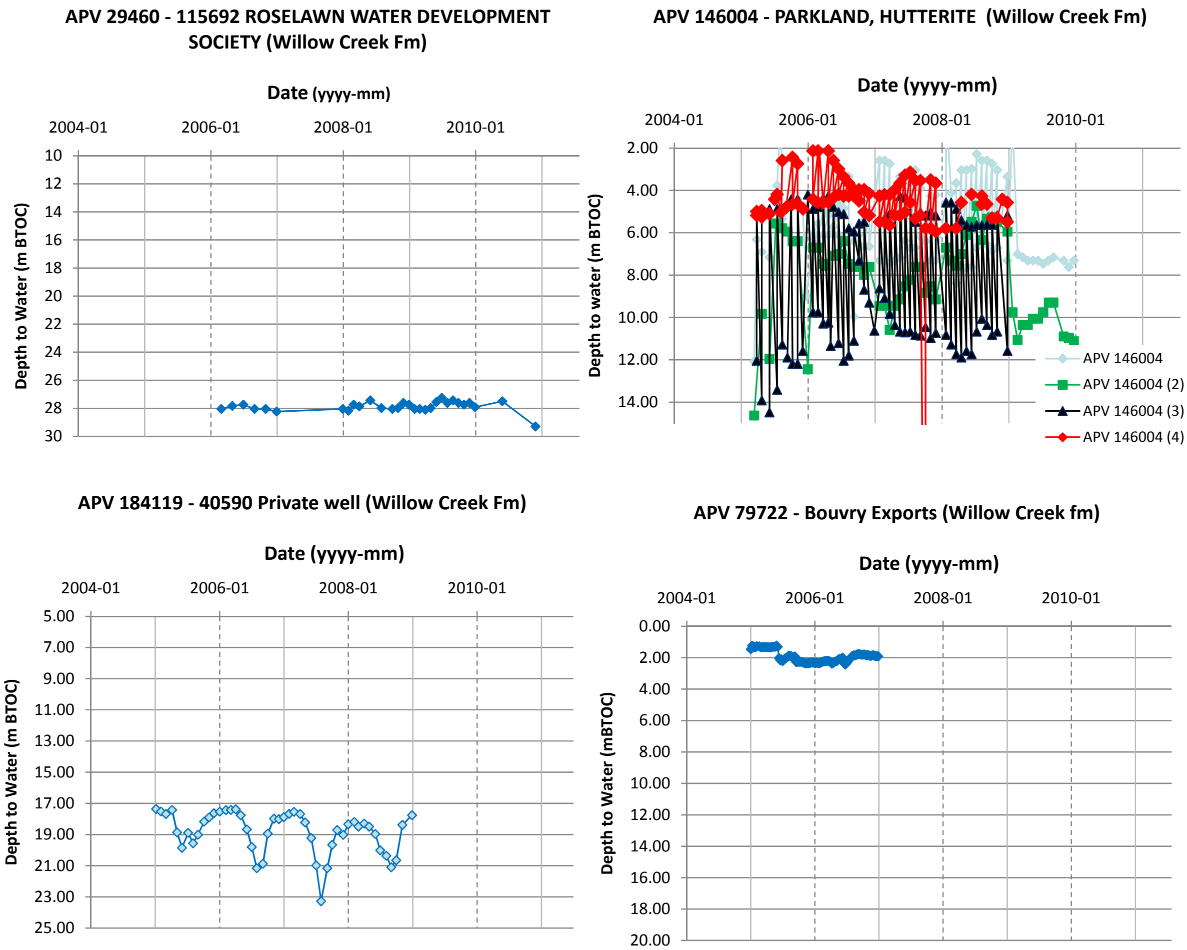



Figure 40 Hydrograph for Approvals

**<u>APV29460 - Roselawn Water Development Society</u>**. This well is completed within the Willow Creek Formation. The hydrograph for this well shows water level data from 2006 to 2011. The water level over this period has remained stable at about 28 m bTOC and more recently shows an almost two metre drop.

**<u>APV 146004 - Parkland Hutterite Community</u>**. Four water supply wells are in use, all of which are completed in Willow Creek Formation bedrock. The water levels in the hydrographs are strongly influenced by pumping as they show fluctuations of up to 9 m over each pumping cycle. The wells appear to have recovered once pumping ceased however two of the wells show a marked decline in water level beginning in February of 2009.

**<u>APV 184911 – Unknown Well.</u>** No well record could be reconciled to this AEW license and the completion depth is unknown. The hydrograph shows water level data from January 2005 to January 2009. Annual fluctuations are observed seasonally and an overall slight decline trend is indicated over the 5 year period.

**APV 79722 - Bouvry Exports.** No well record could be reconciled to this AEW license and the completion depth is unknown. The hydrograph shows water level data from January 2005 to January 2007. In the first 6 months of monitoring, the water level shows a 0.6 m drop but appeared to stabilize thereafter.

To summarize, these data, show both seasonal effects (APV 184911) and the effects of pumping (APV 146004). In order to monitor groundwater levels in an area it is best to use wells that are not influenced by short time period pumping.

## 4.6 Groundwater Budget

Developing a groundwater budget for the Willow Creek watershed is challenging since there are very few data available to verify the budget estimate. At present, insufficient data exist to assess groundwater use and water levels in discrete aquifers and therefore a regional approach has been taken.

The following discussion focuses on groundwater withdrawal from key aquifers within the watershed.

### 4.6.1 Groundwater Input and Aquifer Recharge

Recharge to bedrock aquifers within the Willow Creek watershed is not known with certainty at this time.

Establishing an actual value for aquifer recharge is of secondary importance at this time, as there are insufficient data to allow for an accurate assessment. It is more important to confirm that recharge is in fact occurring. Monitoring of water levels in wells completed in key aquifers has provided preliminary data to help determine if aquifers are currently being sufficiently recharged or over-exploited.

It is evident that the network of creeks that extend over bedrock exposures and associated alluvial gravels adjacent to the creeks are an important recharge mechanism to subsurface aquifers. **Section 4.5.3** discusses water level data from wells completed in the various overburden and bedrock aquifers, and indicates that water levels in bedrock aquifers in the mid to upper part of the watershed may exhibit a slight declining trend. This suggests either, that land development, and increased groundwater diversion in those areas may be stressing the system beyond its recharge capacity or drought in the late 1990's and early 2000's may be affecting water levels. Bedrock and overburden aquifers, including the Stavely Aquifer located at a lower elevation in the watershed appear to have stabilized water levels. The Stavley Aquifer is quite clearly influenced by artificial recharge from the Pine Coulee Reservoir.

Bedrock aquifers within the Willow Creek Formation and the St Mary River Formation lower in the watershed and further to the east outside the watershed appear to also have stabilized water levels indicating that aquifer recharge equals or exceeds groundwater use in that area. Although additional monitoring is required to confirm these trends, despite the slight declining water level in the mid-upper part of the watershed, no significant shortages of groundwater are indicated at this time.

In terms of potential recharge over the entire watershed, some approximations can be made. The average annual precipitation for the watershed, based on the last 12 years of record is approximately 428 mm. Therefore, an average of 1,082,412,000 $m^3$/yr of precipitation in the form of rain and snow falls onto the 2,529 $km^2$ area of the Willow Creek watershed each year. Assuming 5% to 15% infiltrates into the subsurface soils and bedrock in the form of recharge to underlying aquifers, this means that between 54,120,600 $m^3$/yr and 162,361,800 $m^3$/yr of water may recharge the underlying aquifers in an average year.

### 4.6.2 Groundwater Output

Groundwater diversion and use from the aquifers within the Willow Creek watershed includes the following:

- Licensed groundwater diversion. A total 172 licenses with approved groundwater diversion of 2,227,908 $m^3$/yr. It is not known whether the full licence allocation is being diverted.
- Although the actual groundwater that is being diverted for household use in the watershed is not being measured, under the Water Act every landowner has the statutory right to divert and used up to 1,250 $m^3$/year (AEW 1999). Therefore, for the purposes of the present calculation, groundwater diverted for domestic use within the Willow Creek watershed is estimated to be approximately 2,671,250 $m^3$/yr (2,137 households x 1,250 $m^3$/year).
- The result is a total groundwater extraction is 4,899,158 $m^3$/yr.

### 4.6.3 Water Balance

In order to achieve sustainable groundwater use, aquifer recharge should be greater than or equal to groundwater discharge (human extraction activities as well as supporting plant growth in discharge areas). That is to say, that the total diversion of groundwater should not exceed aquifer recharge, otherwise aquifer mining or dewatering will occur.

Based on the above assessment, the difference between the estimated recharge of between 54,120,600 $m^3$/yr and 162,361,800 $m^3$/yr, and the estimated groundwater extraction of 4,899,158 $m^3$/yr suggests a surplus of groundwater of between 49,221,442 $m^3$/yr and 157,462,642 $m^3$/yr. This indicates that 3-9% of groundwater recharge may be currently in use. It should be cautioned that this is a very crude estimate and should not be used for development planning purposes. A more detailed assessment is required of specific aquifers within localized areas where a higher density of groundwater diversion is occurring. Future studies need to focus on groundwater monitoring of water levels and quality in order to assess if water levels are declining over time or water quality is being degraded. The establishment of a groundwater monitoring network is necessary in order to better understand the interconnections between aquifers and surface water resources and to provide an early warning system in the event of adverse impact. If negative impacts are realized, then mitigation can quickly be implemented and groundwater resources managed in a sustainable manner for future generations.

# 5.0 WATER QUALITY ASSESSMENT

## 5.1 Willow Creek Surface Water Quality

A surface water quality study was conducted by Saffran (2005) in the Oldman River basin which noted the following about Willow Creek water quality:

- The pesticide MCPA exceeding the aquatic life guidelines was detected;
- Sodium concentrations were about 10 times less than in the Oldman River main stem;
- Giardia and Cryptosporidium counts were the highest in the Oldman River at Fort Macleod and in Willow Creek near the confluence with the Oldman River.

Saffran (2005) noted that the western portion of the basin is associated with numerous intensive livestock operations.

## 5.2 Geochemistry of Spring Water

The AEW water well record database contains analytical data from springs sampled across the watershed. Sixty-one of the spring records had associated chemical analyses dating from the late 1960’s to the mid 1980’s. The locations of springs are shown on **Figure 19**. The water chemistry data indicate the TDS concentration ranged from 250 to 1,078 mg/L.

A Piper tri-linear diagram is used to display the major ion chemistry of water samples. This diagram also allows the classification of groundwater samples according to major ion composition. The Piper plot of the spring water major-ion chemistry (**Figure 41**) indicates there are two groups with respect to the major ion compositions of the spring waters. Those from areas underlain by the Porcupine Hills Formation are typically of the $Ca+Mg/HCO_3$ type, whereas those underlain by the Willow Creek Formation are of the $Na/HCO_3$ type. The differences in major ion composition may be attributed to a process of cation exchange, whereby Ca+Mg are sorbed to, and the Na is concomitantly released from clay minerals present in the unconsolidated materials and bedrock through which the groundwater has moved. The most likely explanation is that the springs discharging in the area underlain by the Willow Creek Formation have encountered more clay-rich sediments than those discharging in the area of the Porcupine Hills Formation bedrock.

In addition, the springs with low TDS concentrations are likely sourced locally; whereas the groundwater in spring samples exhibiting high TDS concentrations originates either from a deeper, more regional source or was influenced by travelling through the glacial till originating from the Laurentide ice sheet. Four water samples were collected in May of 1975 from springs in the northwestern portion of the watershed and another 8 were collected in that area just outside the watershed. All of these samples indicated the presence of mercury at concentrations greater than the method detection limit and ranged from 0.1 to 0.3 mg/L. No sample verification or quality assurance data are available, nor was there a reason given in the database for the collection of these samples.

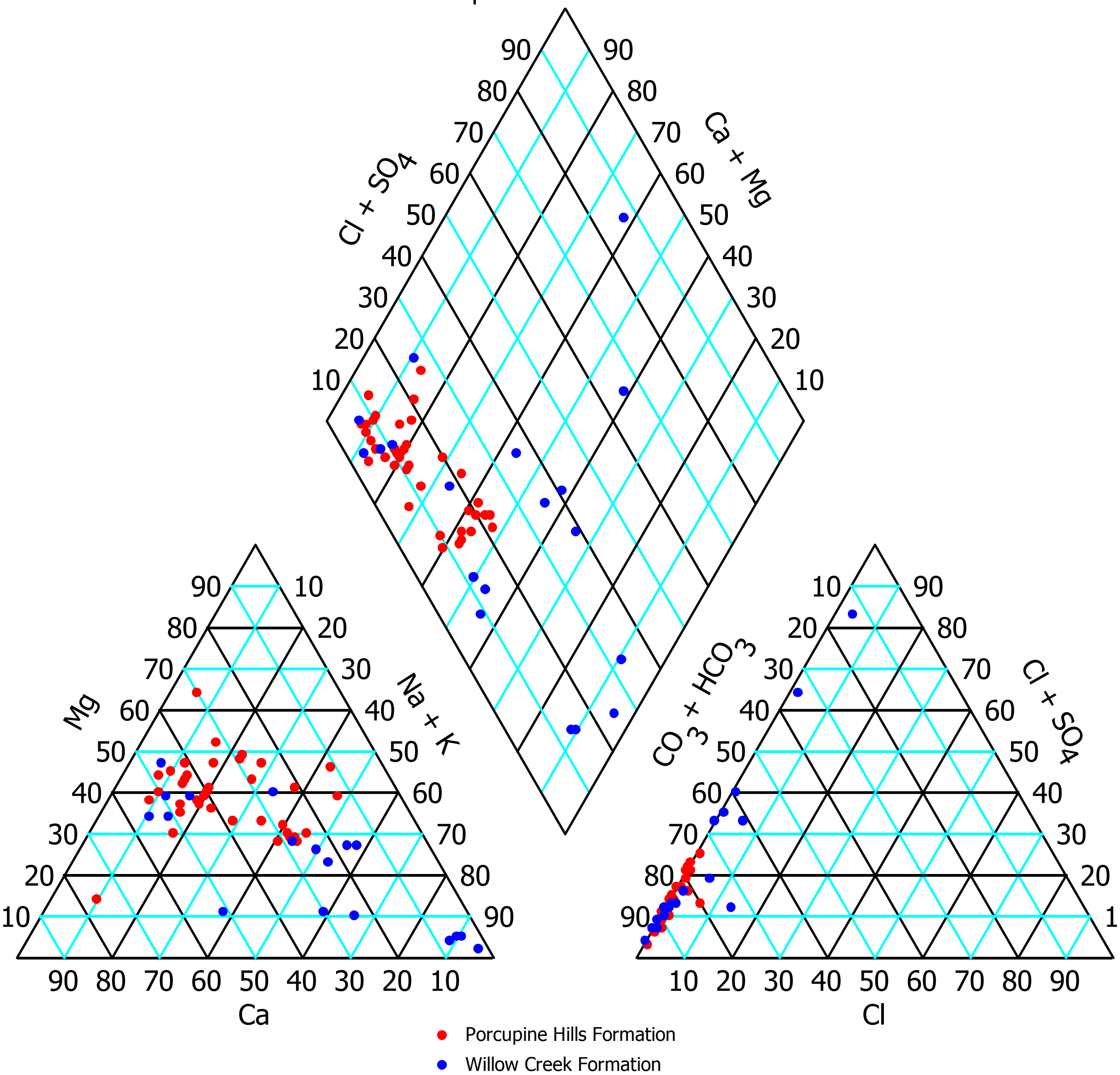



Figure 41 Spring water quality – Piper diagram

## 5.3 Groundwater Geochemistry

Considerable groundwater water quality data are available in the AEW water well database. Based on these data, the TDS of groundwater ranges from 130 to more than 13,000 mg/L.

**Figure 42** and **Figure 43** show piper plots of groundwater samples collected from wells completed in the various geologic formations present within the Willow Creek watershed. The Piper plots show that the greatest number of groundwater samples were collected within the Willow Creek Formation aquifer(s) and the Porcupine Hills Formation aquifer(s).

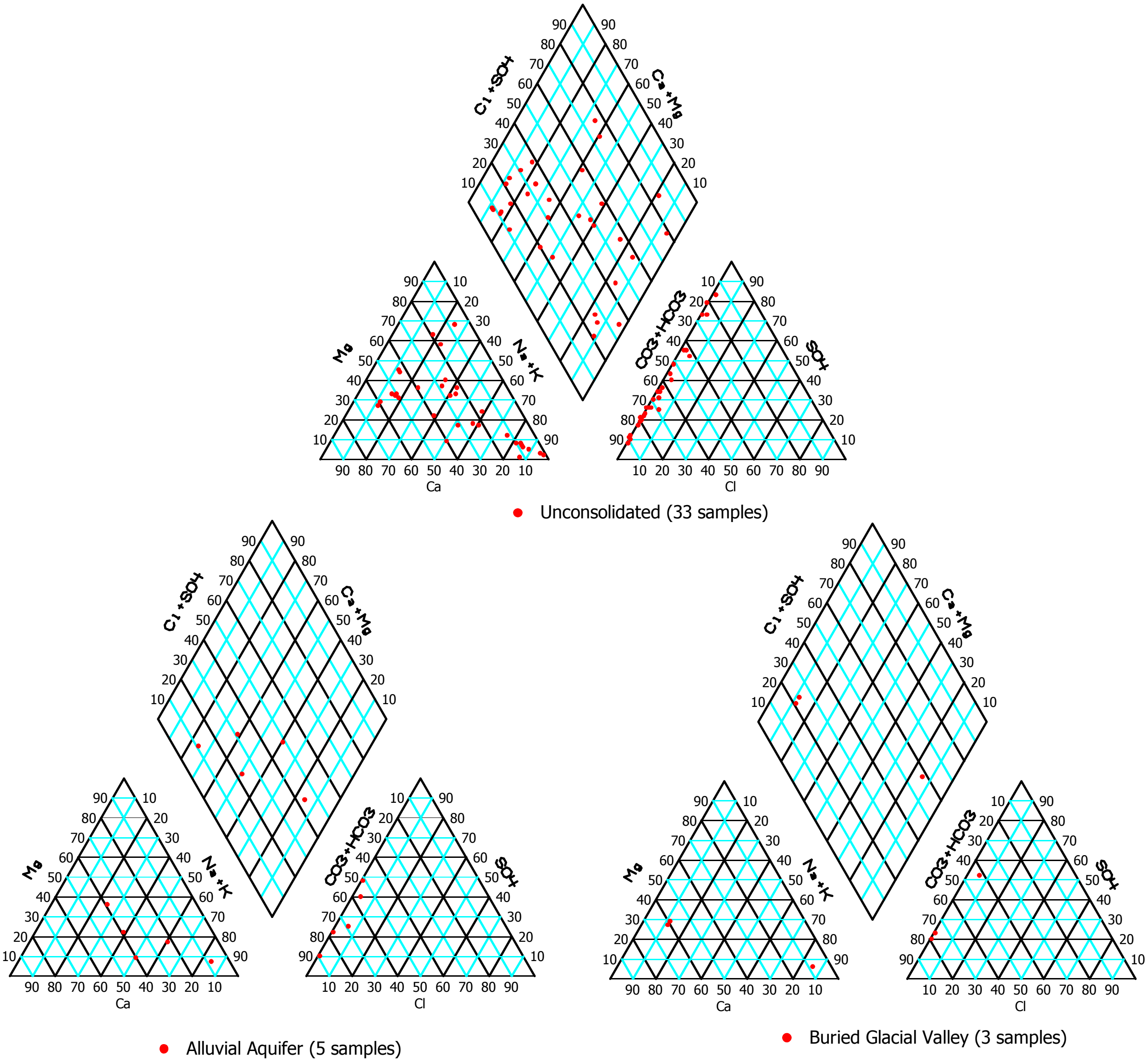



Figure 42 Groundwater quality – Piper Diagrams for unconsolidated materials

This is consistent with the greatest number of wells having been completed in the Willow Creek and Porcupine Hills Formations.

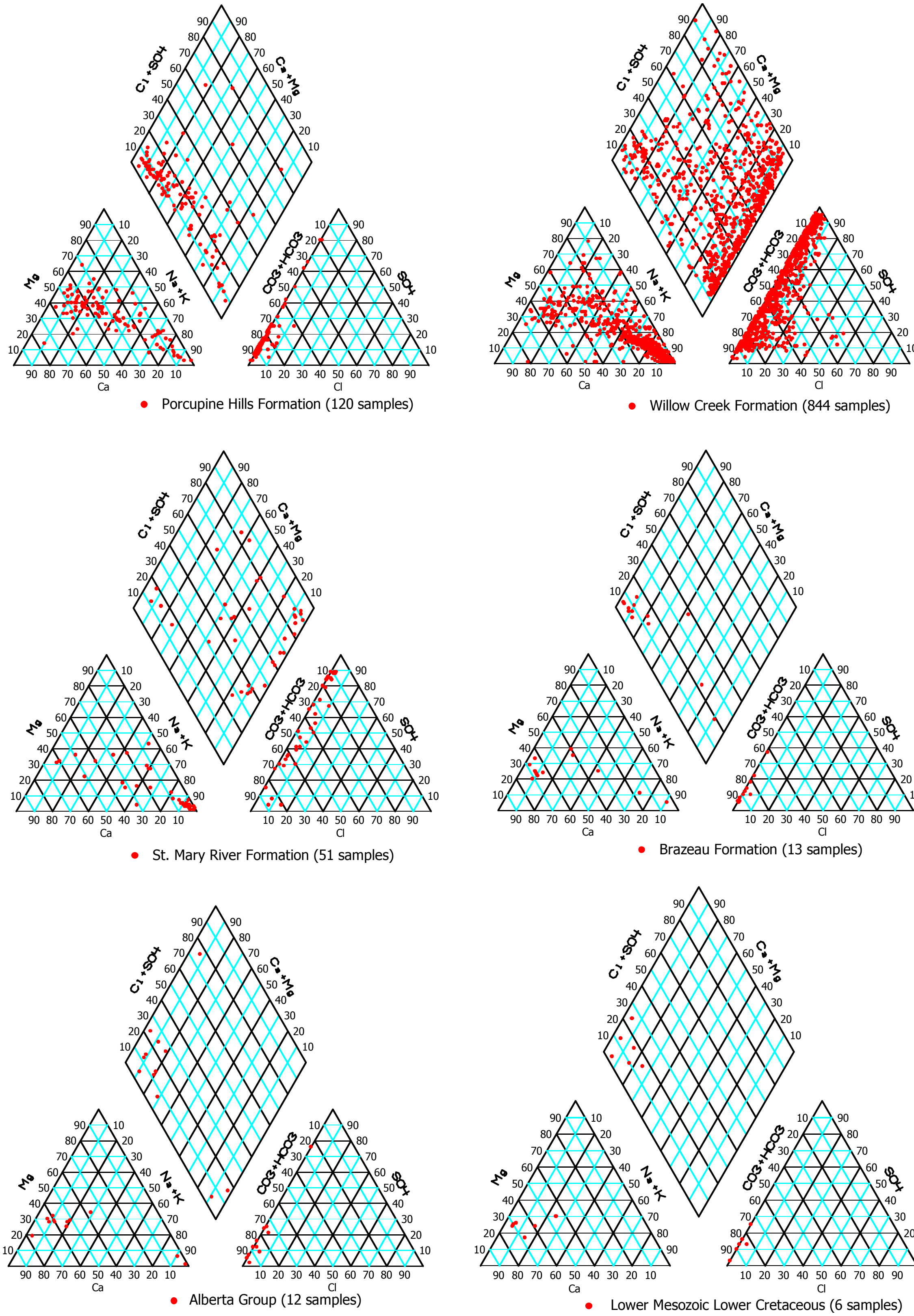



Figure 43 Groundwater quality – Piper Diagrams for bedrock

Piper diagrams (**Figure 42** and **Figure 43**) show that $HCO_3$ and $SO_4$ are the dominant anions, whereas Ca+Mg and Na are the dominant cations and are sometimes replaced by Mg. The data indicate that the geochemistry of groundwater has changed as water moves through the watershed from the upper reaches in the Brazeau Formation and Alberta Group bedrock, to the Porcupine Hills, the Willow Creek, and the St Mary River Formations at the lower reaches of the watershed**. Table 12** summarizes the geochemical differences that are observed.

The groundwater geochemistry has clearly transformed from a calcium-magnesium bicarbonate type in the foothills and mountains (Brazeau and Alberta Group aquifer(s)), to a sodium-sulphate, or mixed sodium sulfate-bicarbonate type groundwater in the plains part of the watershed. This is a common geochemical evolution of groundwater as the residence time of groundwater in contact with bedrock increases, and mineral dissolution progresses as groundwater moves from zones of recharge in the upper watershed to zones of discharge in the lower part of the watershed. Dissolution of carbonate and sulfate minerals in the aquifer matrices and recharge areas, as well as active cation exchange processes along the groundwater flow path are known to modify the concentration of dissolved ions in groundwater.

Several water quality contour plots have been generated to further show the geochemical distribution of groundwater across the watershed and its implication to the conceptual hydrogeological model.

**Table 12 Summary of Groundwater Geochemistry Data by Formation**

| Unit | Number of Samples | TDS Range (mg/L) | Dominant Groundwater Type |
|---|---|---|---|
| Unconsolidated | 33 | 214 to 3,250 | Ca+Mg-Na/$HCO_3$-$SO_4$ |
| Alluvial Aquifer | 5 | 299 to 1,316 | Na-Ca+Mg/ $HCO_3$-$SO_4$ |
| Glacial Buried Channel Aquifer | 3 | 214 to 1,114 | Ca+Mg-Na/$HCO_3$-$SO_4$ |
| Brazeau Group | 13 | 130 to 874 | Ca-Mg/$HCO_3$-$SO_4$ |
| Alberta Group | 12 | 172 to 2,374 | Ca+Mg-Na/$HCO_3$-$SO_4$ |
| Porcupine Hills | 120 | 250 to 2,104 | Ca+Mg-Na/$HCO_3$-$SO_4$ |
| Willow Creek | 844 | 211 to 13,600 | Na-Ca+Mg/$HCO_3$-$SO_4$-Cl |
| St Mary River | 51 | 408 to 4,935 | Na-Ca+Mg/ $SO_4$-Cl $HCO_3$ |

Table 12 Continued

| Unit | Major Cation Concentration<br>Ca Range (mg/L) | Mg Range (mg/L) | K Range (mg/L) | Na Range (mg/L) |
|---|---|---|---|---|
| Unconsolidated | 4 to 300 | 1 to 225 | 0.4 to 17 | 10 to 980 |
| Alluvial Aquifer | 38 to 54 | 5 to 29 | 1.6 to 5 | 37 to 421 |
| Glacial Buried Channel Aquifer | 33 to 53 | 11 to 15 | 0.4 to 1 | 10 to 371 |
| Brazeau Group | 14 to 104 | 5.9 to 47 | 0.4 to 6 | 3.8 to 295 |
| Alberta Group | 2.1 to 456 | 0.3 to 125 | 0 to 6 | 7.5 to 360 |
| Porcupine Hills | 2 to 334 | 2 to 132 | 0.3 to 55 | 3.8 to 626 |
| Willow Creek | 1 to 1560 | 0.5 to 1,568 | 0 to 438 | 2 to 3,239 |
| St Mary River | 3 to 440 | 1 to 325 | 0.8 to 13 | 11 to 1,181 |

| Unit | Major Anion Concentration<br>Cl Range (mg/L) | $SO_4$ Range (mg/L) | $HCO_3$ Range (mg/L) | $CO_3$ Range (mg/L) |
|---|---|---|---|---|
| Unconsolidated | 2 to 61 | 18 to 1,843 | 198 to 795 | 0 |
| Alluvial Aquifer | 2 to 30 | 31 to 385 | 252 to 698 | 0 |
| Glacial Buried Channel Aquifer | 2 to 44 | 40.1 to 451 | 204 to 471 | 0 |
| Brazeau Group | 1 to 8 | 5 to 287 | 120 to 706 | 0 |
| Alberta Group | 1 to 24 | 5 to 1,348 | 200 to 1,037 | 0 |
| Porcupine Hills | 0.7 to 75 | 3.3 to 1,202 | 185 to 651 | 0 |
| Willow Creek | 1 to 751 | 0.1 to 9,183 | 34 to 2,161 | 0 |
| St Mary River | 2 to 87 | 10 to 3,105 | 193 to 788 | 0 |

**Note:** Ca means Calcium, Na means Sodium, Mg means Magnesium, K means Potassium, $HCO_3$ means Bicarbonate, $CO_3$ means Carbonate, $SO_4$ means Sulphate, Cl means Chloride

**Figure 44** is a contour plot of the TDS in mg/L across the watershed. As can be seen, the TDS of groundwater appears to increase dramatically from the upper to the lower part of the Willow Creek watershed.

Of the 1,504 samples with a measured TDS concentration from the Willow Creek Formation (data from the AEW water well database), 1,178 had TDS concentrations greater than 500 mg/L (drinking water criteria for TDS; Health Canada, 2010); all occur in the upper 100 m of the subsurface and there does not seem to be any correlation with depth. Of 844 water samples with chloride concentrations, 20 samples exhibit concentrations ranging from 257 to 751 mg/L (CCME drinking water criteria for Chloride is 250 mg/L). The highest Potassium concentrations for the Willow Creek and Porcupine Hills Formation are likely to be either anomalous or in error.

Grasby et al. (2008) concluded in their study of the Paskapoo Formation that a significant change in TDS concentrations occurs across a north-south boundary along the middle of the Paskapoo Formation outcrop belt. They suggested that the groundwater chemistry change coincides with the boundary of the glacial till deposits left by the eastern derived Laurentide ice sheet and western derived Cordilleran glacial deposits from the last ice age. The glacial till to the east of this boundary has high sulphate content likely derived from the higher sulphide mineral content of the granite and gneiss pebbles. The Cordilleran deposits are dominated by carbonate and quartzite which have low sulphide content. Another possibility to explain the higher TDS concentrations could be the result of higher temperature and lower precipitation in the plains region which would result in greater evaporation and thus higher TDS content than in the foothills and mountains to the west.

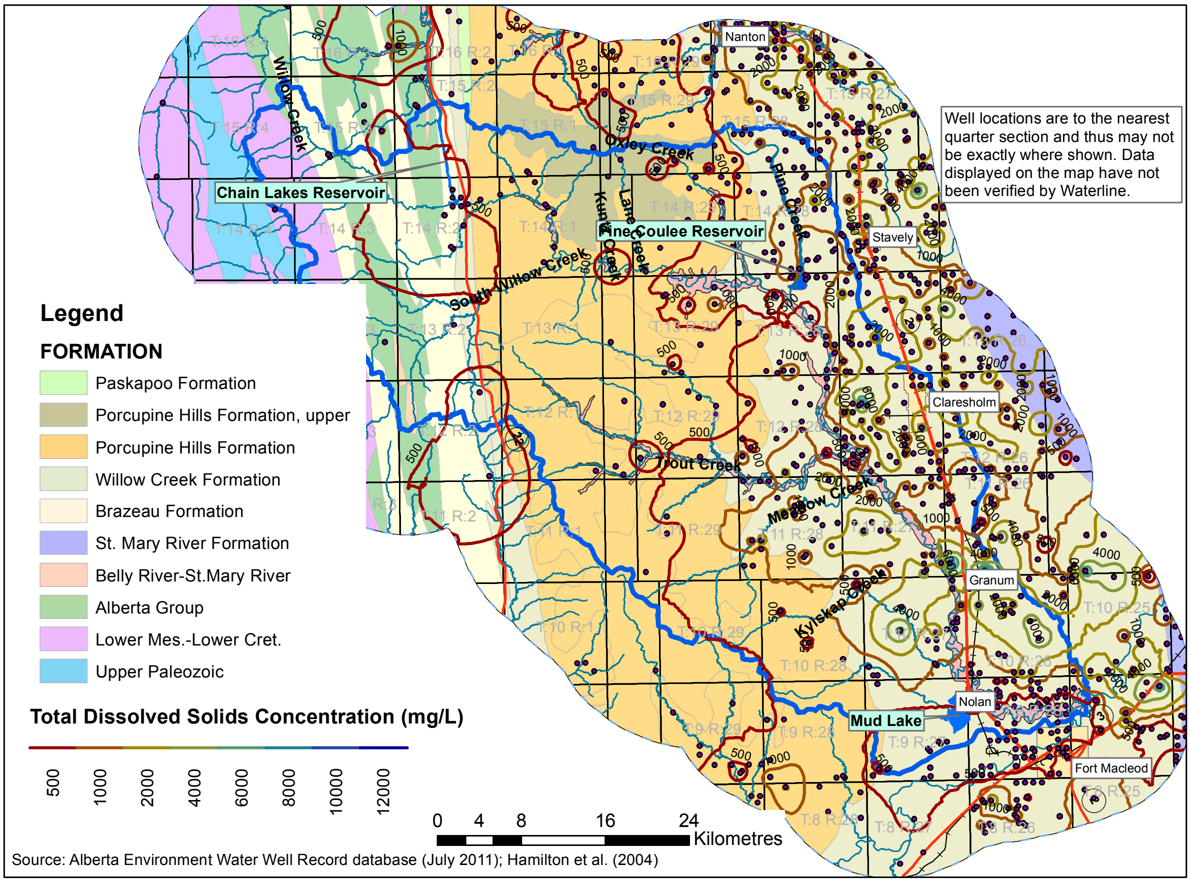



Figure 44 Total Dissolved Solids in the Willow Creek watershed

Contours of the calcium concentration in groundwater are shown in **Figure 45**. These show isolated locations where concentrations are greater than 100 mg/L (the lowest contour interval shown). Note that the drinking water criterion for calcium is 200 mg/L (Health Canada, 2010). There is an unexplained high calcium concentration in groundwater on the southwest edge of the watershed.

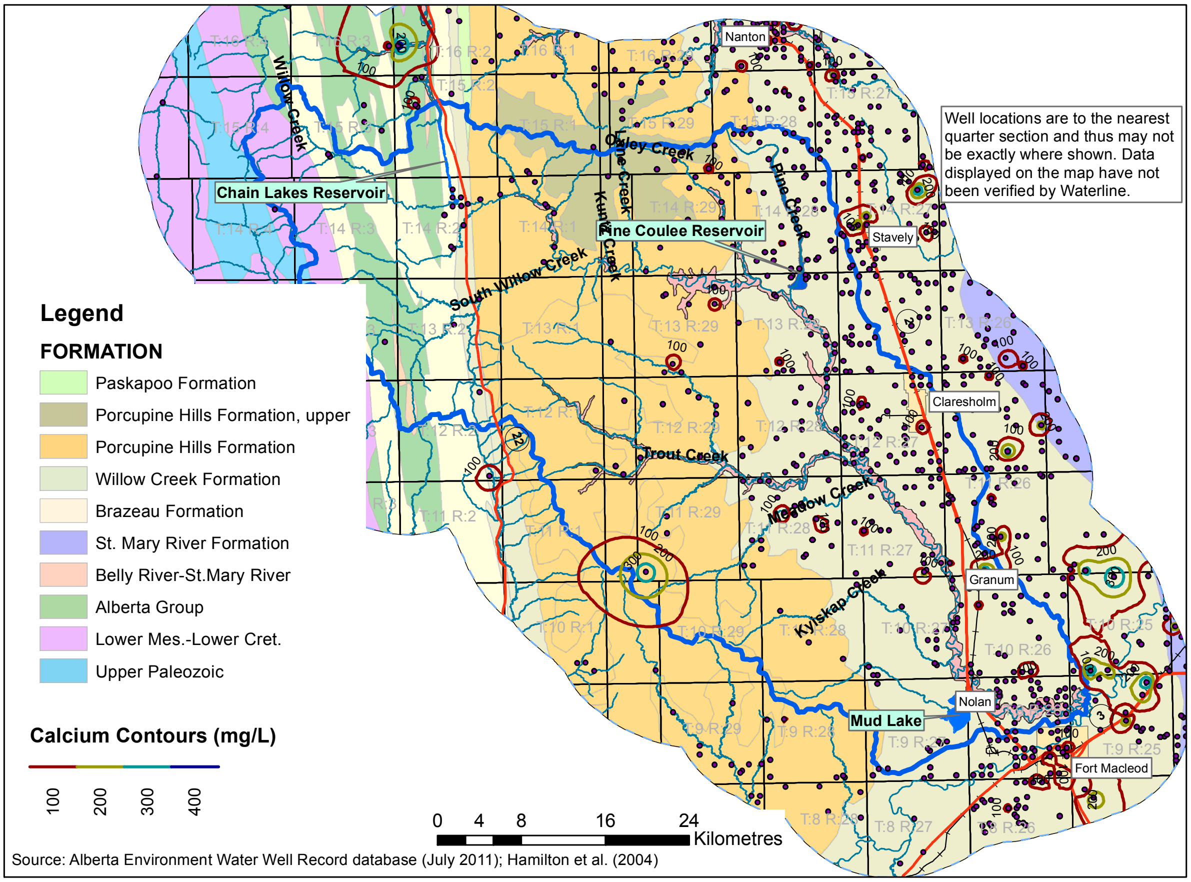



Figure 45 Calcium in the Willow Creek watershed

Contours of sodium concentration in groundwater are shown on **Figure 46** and present a different picture. The highest concentrations of sodium in groundwater occur in the eastern portion of the watershed, almost exclusively within the area of the Willow Creek Formation. Note that the drinking water criterion for sodium is 200 mg/L (Health Canada, 2010).

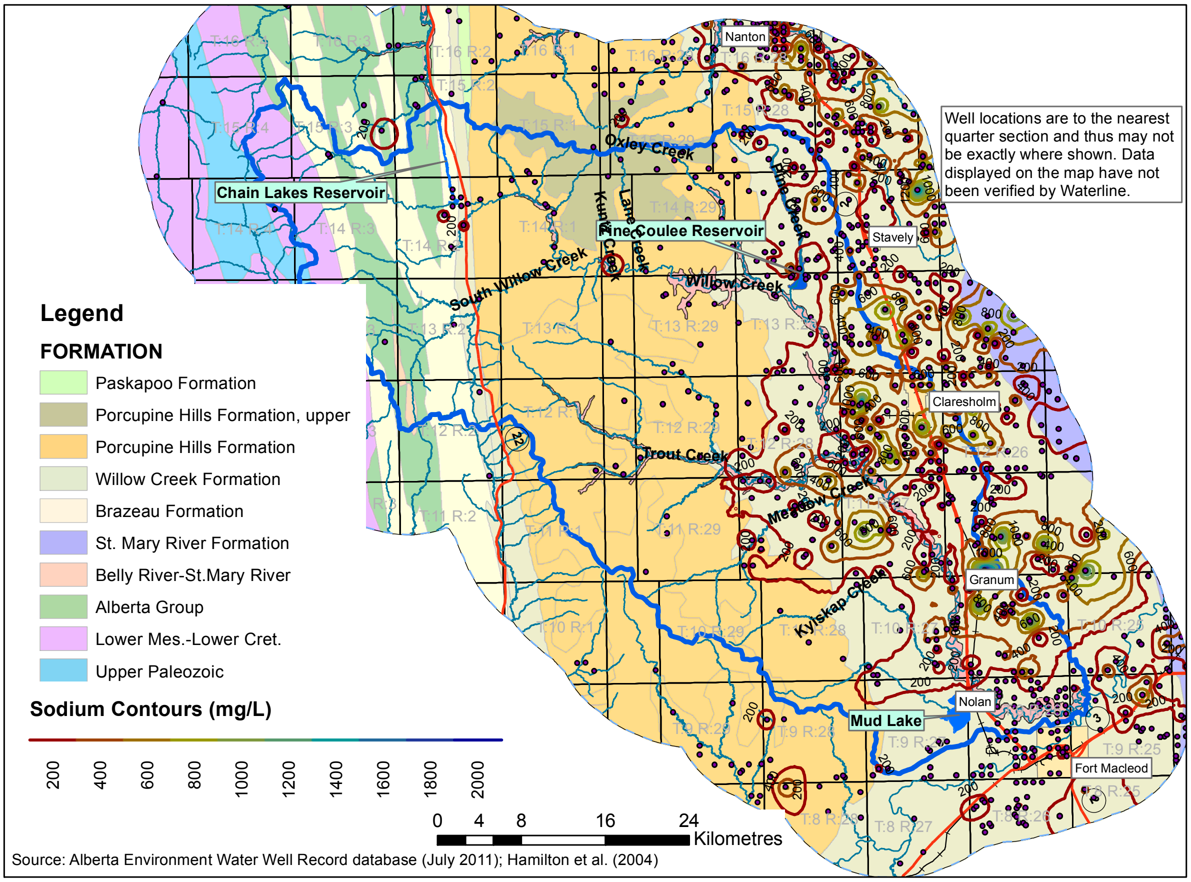



Figure 46 Sodium in the Willow Creek watershed

Sulphate concentration contours presented on **Figure 47** show a similar pattern to the sodium concentration contours. Sulphate concentration in groundwater is highest in the eastern portion of the watershed in wells completed into the Willow Creek Formation. These data agreed with the distribution of TDS and indicates that the groundwater in this area is high in sodium and sulphate This is likely to be a natural occurrence that results from the presence of glacial till in this area which tends to be elevated in those constituents. It should be noted that the north-south orientated boundary of the Cordilleran ice sheet lies just west of Highway 2 in this area. And that of the Laurentide ice sheet lies further to the south and west indicating some overlap between the two (Stalker, 1958). Note the drinking water criterion for sulphate is 500 mg/L (Health Canada, 2010).

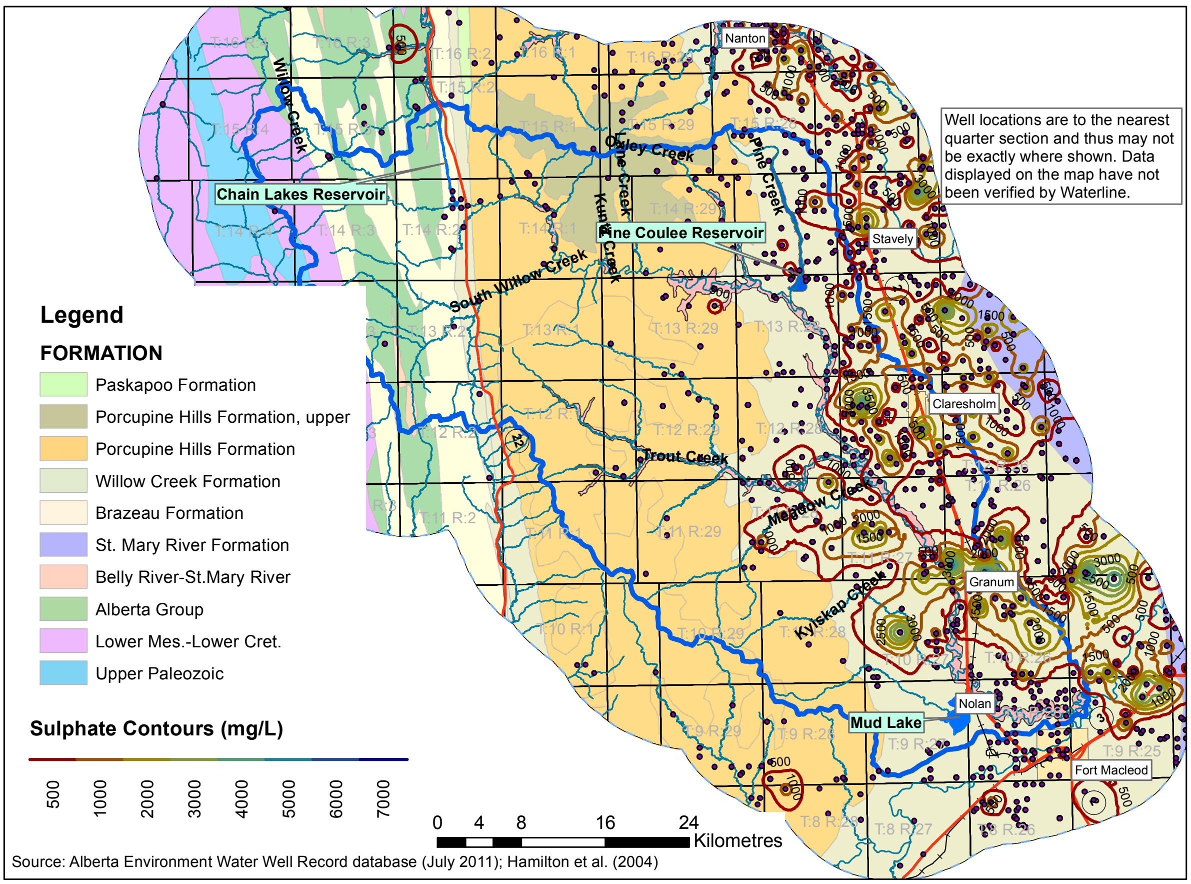



Figure 47 Sulphate in the Willow Creek watershed

Chloride concentration contours presented on **Figure 48** show higher concentrations in the eastern portion of the watershed. There is generally no correlation between high chloride concentrations and either higher sodium or calcium concentrations. The chloride ion could originate from manure if it is in the shallow subsurface. Note the drinking water criterion for chloride is 250 mg/L (Health Canada, 2010).

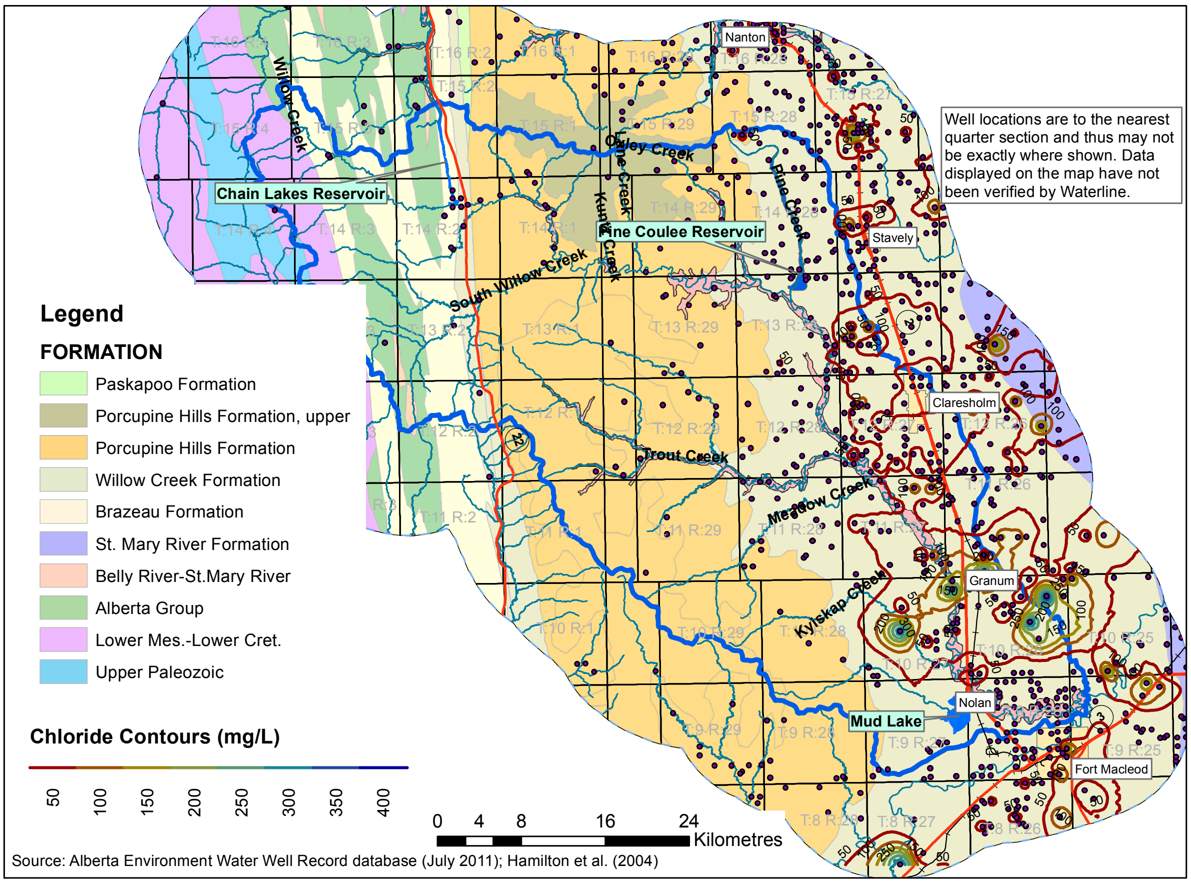



Figure 48 Chloride in the Willow Creek watershed

**Figure 49** shows nitrate (as nitrogen) concentrations in groundwater samples collected from supply wells within the watershed. The highest concentrations of nitrate occur in isolated wells rather than on a regional basis. Note that these samples were collected over a long time period and so any conclusions provided are preliminary. As indicated previously, any interpolation at the local scale, especially for planning purposes, should be augmented by field investigation to confirm its accuracy. There appear to be several water wells in which the nitrate (as nitrogen) concentrations are greater than 10 mg/L. The drinking water criterion for nitrate (reported as nitrogen) is 10 mg/L (Health Canada, 2010). For example, one of these locations is to the west of Claresholm in the vicinity of the Claresholm sewage lagoons.

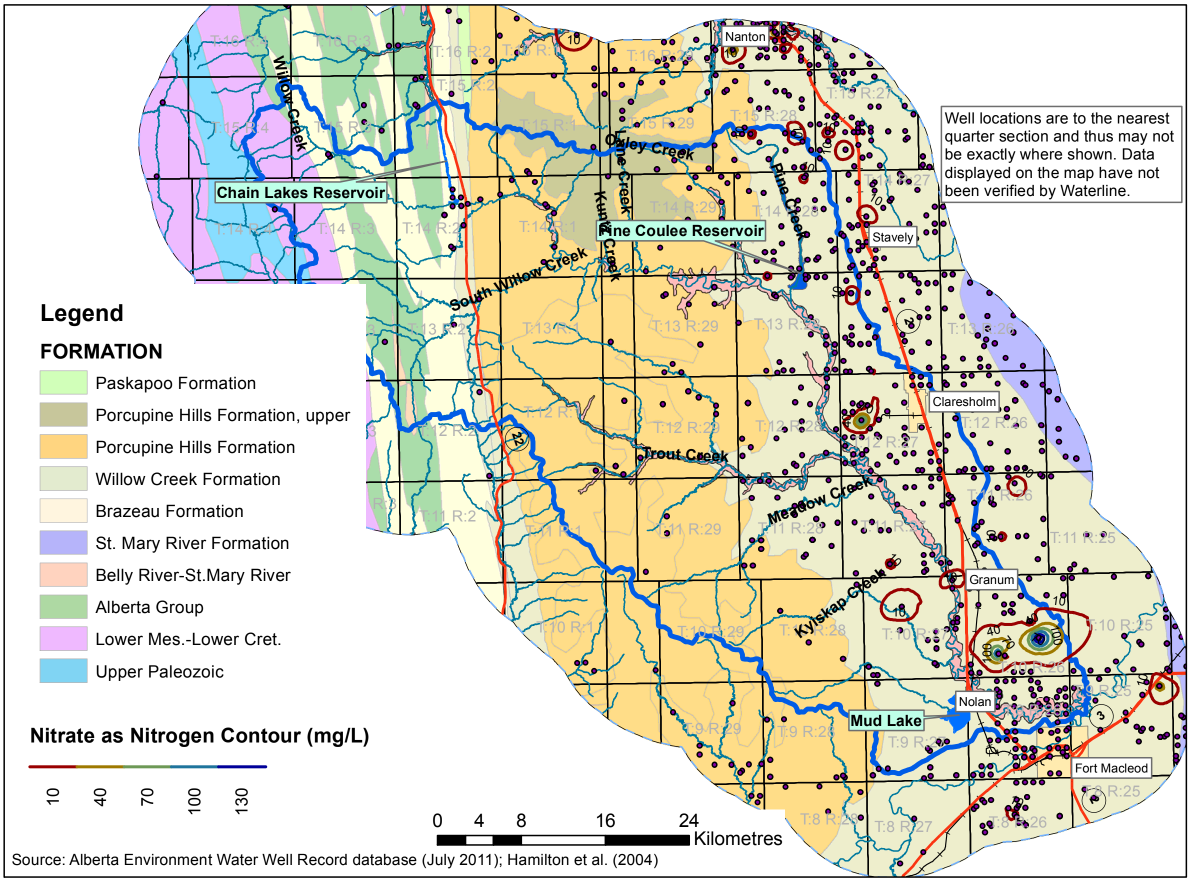



Figure 49 Nitrate in the Willow Creek watershed

## 6.0 Aquifer Protection and Vulnerability

Protection of the Willow Creek watershed groundwater supply is critical to maintaining a safe and reliable water supply. Aquifer protection strategies need to incorporate a thorough understanding of the interactions of the aquifer with potential sources of contamination at the surface and in the subsurface. Although not part of the present scope of work, an inventory of all potential sources of contamination should be carried out and become part of the Willow Creek watershed aquifer management plan.

Potential contaminants[9] can originate from a variety of sources including, but not limited to, the following:

- Domestic or industrial use of fertilizers and pesticides,
- Fuel-supply dispensing facilities (underground and above-ground storage tanks),
- Landfill operations,
- Confined feeding operations,
- Runoff from agricultural operations (stables, composting),

- Storm-water management,
- Septic fields,
- Historical spills, and
- Industrial operations.

The Willow Creek watershed contains a large number of confined feeding operations, The majority of these operations are in the eastern portion of the watershed in the vicinity of Willow Creek (**Figure 50**).

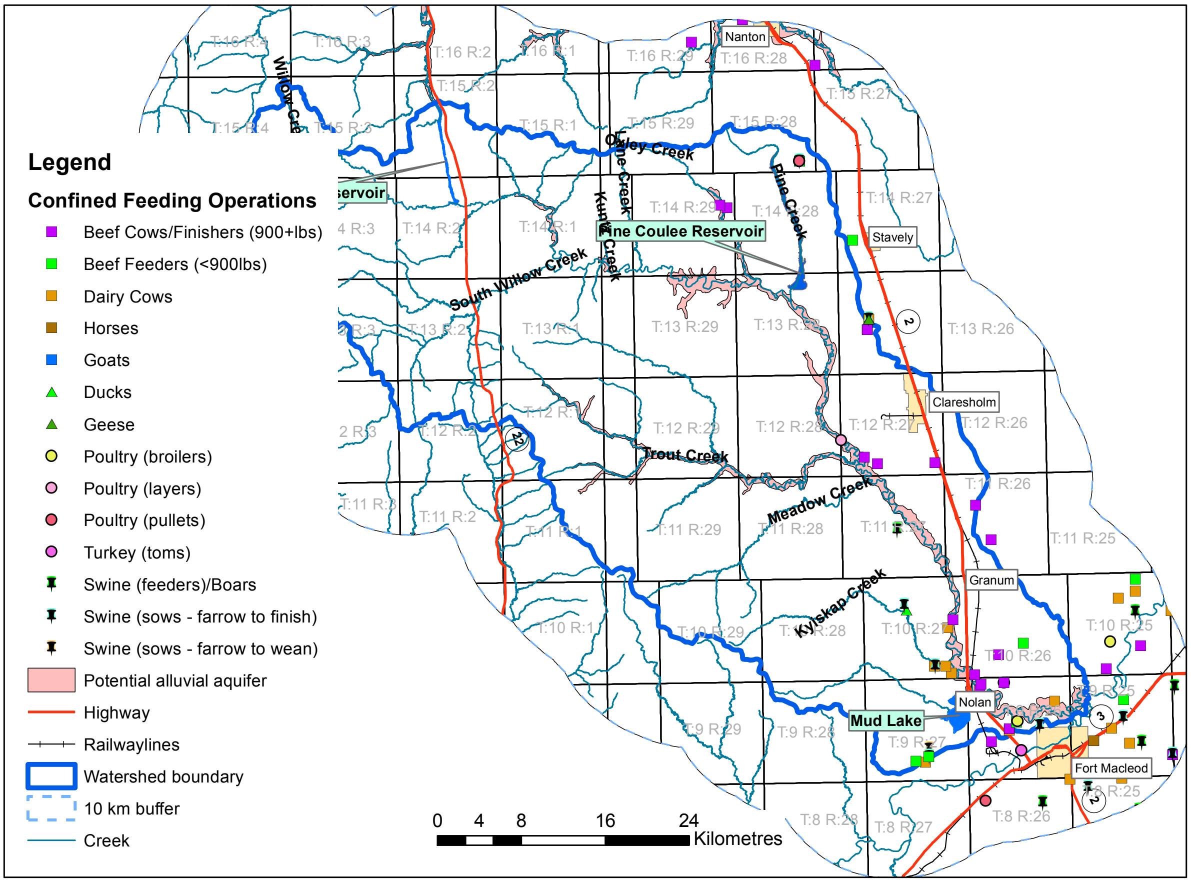



Figure 50 Confined feeding operations in the Willow Creek watershed

Public input, which has been summarized in GOA (2010b&c) lists water quality concerns in the South Saskatchewan River Basin as including contamination from agricultural runoff (especially manure) and impacts from oil and gas activity on groundwater quality. Various participants called for action to conserve and provide stewardship over the region's water resources by:

- Developing a consistent definition of headwaters or source waters and their locations;
- Protecting watersheds;
- Conducting an inventory of groundwater supply, quality and demand;

- Transferring information from the mapping of aquifers currently underway into the South Saskatchewan Regional Plan as soon as possible;
- Developing an overall water conservation plan;
- Designating some areas of the region as no-growth zones or delimiting the type of development in order to protect water sources; and
- Determining flood risk and limiting development in flood zones.

Aquifers occurring near ground surface are much more susceptible to surface sources of contamination than are aquifers overlain by thick aquitards (Dash and Rodvang, 2001). However, if the overlying deposits are fractured, then aquifer contamination can more easily result. The slow movement of groundwater means that aquifer contamination often takes many years or even decades to be recognized, and many more years and great expense to remediate once contamination is apparent (Cherry 1987). The prevention of groundwater contamination is therefore crucial to preserve the quality of this valuable finite groundwater resource. The most effective solution to groundwater contamination problems is prevention (Cherry 1987).

Dash and Rodvang (2001) prepared a groundwater vulnerability map, based on a modified aquifer vulnerability index, for central and eastern Alberta (agricultural area or “White Area”) which was modified by AEW in 2010 for the Green Area and subdivided into the basins. A portion of these data were used in the preparation of **Figure 51**. This shows that the areas most vulnerable to contamination are the alluvial aquifer materials near rivers.

The vulnerability map provides a general ranking, based on potential contaminant travel times, that is an approximate relative risk of contamination to shallow groundwater on a regional scale. The map cannot be used as the sole source of information related to the location of new activities which may impact shallow groundwater quality. Site-specific knowledge or monitoring data must be collected to confirm geological and groundwater conditions.

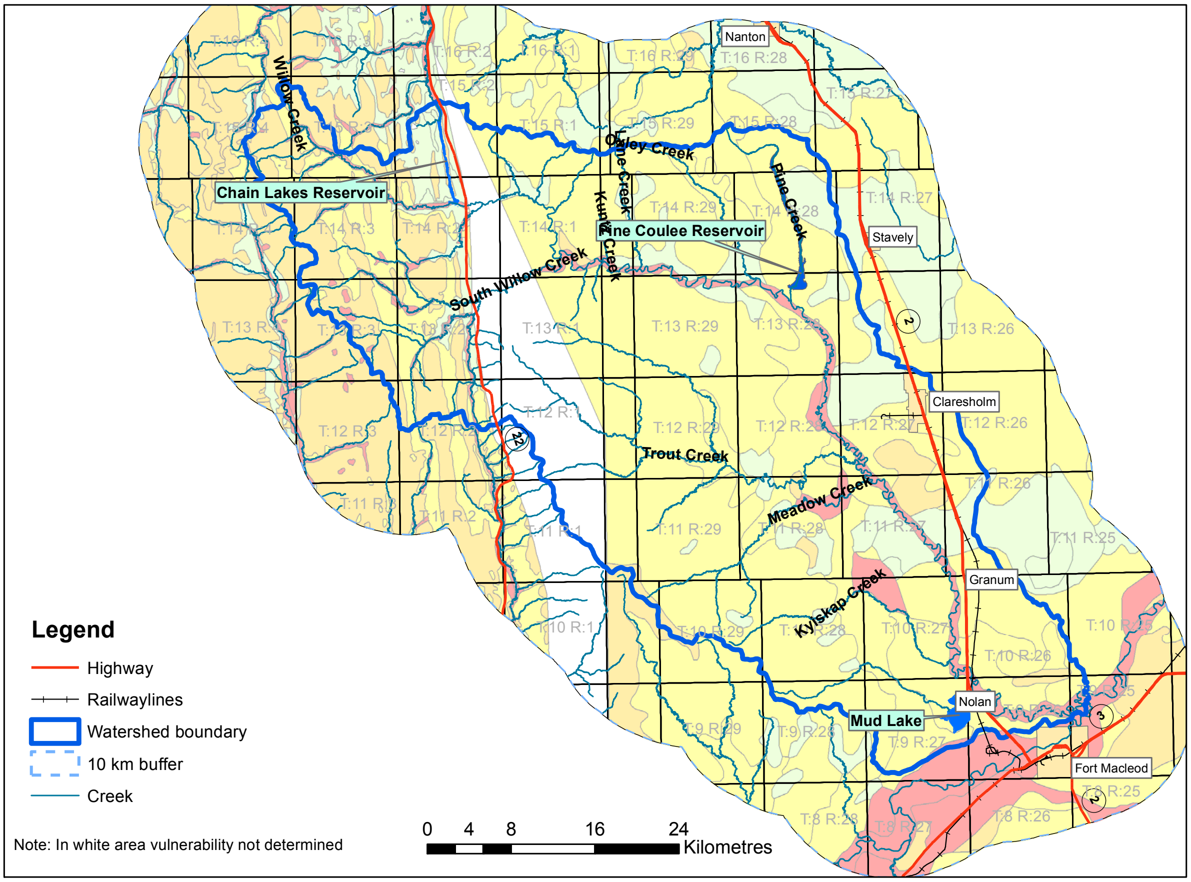



Figure 51 Vulnerability

Nitrate values have been plotted over the vulnerability map in **Figure 52**. Elevated nitrate concentrations are indicated along lower reach of the Willow Creek valley within the watershed and also to the east outside the watershed boundary where land is being used for agricultural purposes.

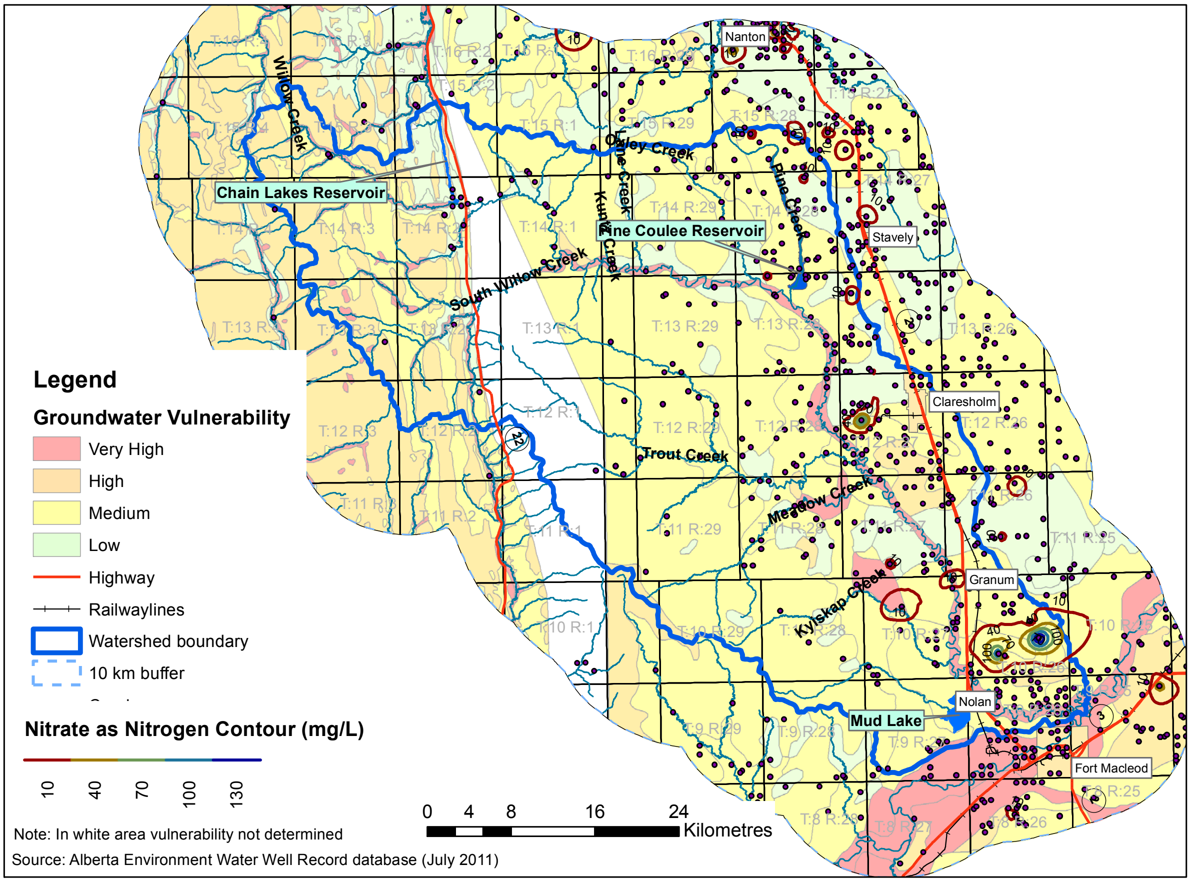



Figure 52 Nitrate and Vulnerability

## 7.0 KNOWLEDGE AND DATA GAPS

There is a considerable amount of hydrogeolgical data that have been collected in the past, and are continuing to be collected at present, within the Willow Creek watershed. The following lists data or information that are being collected, but not necessarily being compiled in a way that is useful to hydrogeologists conducting local or regional scale assessments such as the present Willow Creek watershed study:

### 7.1.1 Water Well ID's, GPS Location and Tagging System

**Knowledge/Data Gap:**

Water well drillers continue to drill wells for private landowners and others, and based on Waterline's extensive experience in Alberta, they may or may not submit their driller report and associated test data to AEW for compilation into the water well database. Furthermore, well records are often submitted with the location of water wells estimated to the nearest quarter section which is insufficient in Waterline's view. Drillers should be required to use a handheld

Global Positioning System (GPS) to obtain well coordinates to at least 10 m accuracy. Some drillers have started to do this. Finally, a water well tagging system is required so that the AEW Identification Number (ID) is clearly shown on the well and it can be reconciled at any future date with the well record in the AEW database. This will also enable reconciliation with AEW licence approval database and WUR system, when further testing or assessment is completed. The following recommendations are presented for consideration by AEW to address this very critical issue.

**Recommendation:**

There is an opportunity to capture very important groundwater data at a minimal cost but some changes need to be made to direct landowners, drillers, and groundwater professionals in this regard. In Waterline's opinion, a self-policing system is possible with minor changes to existing AEW guidelines and regulations. For instance, drillers should be required to apply for an AEW well ID number before any water well is drilled. This could be done electronically, allowing the tracking of a well even before it is drilled. The system should be universally applied to water wells but consideration should also be given to other types of monitoring wells that are drilled above the base of groundwater protection (e.g., environmental monitoring wells, wells used for remediation, seismic holes, etc.). The rationale for this is that any activity occurring in the subsurface that has the potential to affect the quality or quantity of non-saline groundwater resources needs to be controlled or regulated. It also provides hydrogeologists with the needed data to assess and properly manage the groundwater resources. Waterline understands that extending the requirements beyond water wells would create some challenges. However; it should be noted that what is at stake is the protection of groundwater resources for future Albertans and therefore immediate action is required.

Well tags should be made mandatory with well ID's and GPS location inscribed on the tag and firmly affixed to the well. In addition, an electronic photo can be taken by the driller and submitted to AEW as a permanent record and proof that the well was tagged. In this manner, any further work, such as testing of or sampling from a particular well, can be tracked with the well ID (or to a known GPS location if the tag is damaged) and a database of historical water levels and water chemistry data can be established over time.

Enforcement is accomplished if the driller fails to submit a well log with appropriate information because the well ID has been linked to the driller from the outset. Self policing by the Alberta Water Well Driller's Association is therefore possible and disciplinary action can be initiated which could involve revocation of a driller's license if he/she fails to comply. In Waterline's view, this proactive approach is required immediately, as every well completed in the Willow Creek watershed is a potential monitoring point from which conceptual hydrogeological models can be developed and sustainable groundwater management can be accomplished. Although the present Government Observation Well Network (GOWN) system in Alberta is useful, there is potentially an abundance of essentially free, and very valuable, groundwater data that is not being captured in any way that is useful. Although this is a provincial responsibility, the Oldman Watershed Council should promote this practice to drillers operating in the region or to the landowner after the well is drilled, as every well drilled in the watershed is a potential groundwater monitoring point that can help resolve data gaps in developing our understanding of groundwater systems within the watershed.

### 7.1.2 Reconciliation of Water Act Approval Records to AEW Water Well Database

**Knowledge/Data Gap:**

Approximately 172 Water Act licenses have been issued for diversion of groundwater within the Willow Creek watershed (AEW, 2011). Upon inspection of the licensing data provided by AEW, well licenses cannot always be reconciled to a specific AEW well ID. This is a result of timing because AEW well ID's are only issued after the Driller's report has been entered into the AEW Water Well database. By the time drilling and testing has been completed, application under the Water Act has often already been made to AEW and the cross-referencing is lost.

**Recommendation:**

The solution to this problem has already been addressed in the recommendation for Data Gap #1. If drillers are issued an AEW Well ID prior to drilling a well, all paper work including reports and applications made by groundwater professionals on behalf of their clients should include the proper AEW Well ID which are then directly linked to the water well record.

### 7.1.3 Capturing Landowner Water Level and Water Quality Data

**Knowledge/Data Gap:**

Energy companies building pipelines, drilling conventional oil and gas wells, conducting seismic programs or undertaking other oil and gas related activities often complete pre- and post-testing of domestic wells. This is also the case for land developers proposing large residential or commercial developments where there would be a public concern relating to potential impacts to existing water wells. Water well testing is done as part of stakeholder engagement or community relations work which, in the case of energy companies, may be required under directive from the ERCB. At this time, the only regulatory requirement for such test work to be submitted to AEW is under ERCB Directive 35 relating to coal bed methane (CBM) development in the province of Alberta. However, energy companies conducting activities other than CBM development (e.g., seismic programs), or land development companies are under no obligation to submit the data to ERCB or AEW.

Since about 2005, Waterline has completed several thousands of domestic well tests for energy companies and land developers across Alberta, and only those tests that relate to CBM activities are being captured by AEW. This is also the case for the Willow Creek watershed area. Based on this experience, Waterline has identified numerous problems in attempting to reconcile field-verified water wells with those listed in the AEW database. If a property has been sold to a new owner and the wells are not tagged it is often impossible to reconcile the groundwater data being collected with the information provided in the AEW database. If a well test was commissioned by an oil company, a report will be issued to the landowner and also remains in company files, but it is not accessible for consideration as part of regional groundwater management initiatives such as the present study.

**Recommendation:**

The purpose of the present study and AEW's philosophy and mandate is clearly stated in the Water for Life Strategy, Land Use Framework, and SSRP. It is therefore imperative that any groundwater data collected by private or public companies and individuals be submitted to AEW for consideration so that it can be used to aid in the protection of groundwater resources belonging to all Albertans. Waterline understands that legal issues surrounding the Privacy Act may come into play when dealing with privately owned water wells. However, the protection of a public resource is at stake and therefore serious consideration needs to be given to requiring that any new test work completed on water wells be submitted to AEW as part of its mandate to protect groundwater resources in Alberta.

### 7.1.4 Chemical Analysis by Local Health Units

**Knowledge/Data Gap:**

Another disconnect exists in the database between the well ID and water quality samples collected by landowners or local health units without attempting to reconcile each sample with a water well listed in the AEW Water Well database. If the well cannot be reconciled to an AEW Well ID, then another ID is created and the chemistry is logged into the water well database giving the appearance that another well may exist. Since the early 1990's these data have been collected but not entered into the water well database because of privacy issues.

**Recommendation:**

Again, if all water wells were tagged and GPS coordinates measured, it should be possible to exactly reconcile the wells listed in the AEW database with those found in the field. Given the current apparent willingness by Alberta Health to publicly provide water quality data on a go-forward basis, it would be useful to gain access to these data even if the location is made less accurate to protect the privacy of individuals.

### 7.1.5 Conceptual Model Development and the Need for Groundwater Monitoring

**Knowledge/Data Gap:**

The development of an accurate conceptual model is contingent on available geological and hydrogeological data. The geology within the Willow Creek watershed is relatively well understood owing to the considerable amount of historical mapping that has been completed, the presence of numerous wells and boreholes, and a number of energy well logs. However, there is a lack of readily accessible groundwater monitoring data. This includes the following data:

- Water level monitoring throughout the watershed as indicated above and the limited existence of GOWN wells;

- Transmissivity and storativity/specific yield data are needed to understand groundwater flow in various aquifers across the watershed;
- Quantitative studies of groundwater/surface-water interaction are needed to better understand the interconnections between the shallow bedrock and the alluvial aquifers.

As stated previously, the actual measure of recharge is made difficult as a result of the variability of physical parameters that affect infiltration of rainwater and snowmelt (vegetation cover, soil cover, bedrock type, slope of the land, precipitation, snow pack, temperature, etc.). Empirical estimates can be made but monitoring of groundwater level fluctuations on a seasonal basis and over many years is the best method to verify whether our estimates are correct.

**Recommendation:**

As stated above, there is an opportunity to obtain high quality groundwater monitoring data from existing and new wells being drilled, if AEW provides a clear directive and guidance to water well drilling contractors, municipal planning departments involved in approving new developments, oil companies involved in conducting tests for oil and gas activities other than CBM, landowners, and groundwater professionals. This alone could capture a significant amount of groundwater data with very little added expense and without the need for drilling and testing new wells by AEW as part of the GOWN system. Notwithstanding the success of such an initiative, in the sort term, expansion of the Alberta Groundwater Observation Well Network is recommended for key areas within the Willow Creek watershed. Specific well locations are presented in **Section 8.0** of this report.

### 7.1.6 Promoting Groundwater Stewardship

**Knowledge Gap:**

Based on Waterline's experience in conducting thousands of field verification surveys, interviews with landowners, and testing and sampling of domestic water wells, there is a fundamental misunderstanding about groundwater and its interrelationship with the land. The Alberta Water Act protects water being used for household purposes by providing a statutory right to divert and use up to 1,250 $m^3$/yr for household purposes (Water Act, Section 21, 1999), with no monitoring requirements. A "right" to divert and use groundwater can only be realized if the water exists. Therefore, common sense dictates that all water users need to consider practices that help to conserve groundwater resources and promotes sustainable groundwater use. Although licensed users are more likely to cause adverse impact because larger volumes are being pumped, cumulative diversion by smaller unlicensed users can also have a negative impact. The allocated licensed groundwater diversion amounts are of the same magnitude as the calculated potential domestic use (**Section 4.6.3**).

Despite the large volume of literature that is available over the internet or through the various publications issued by special interest groups, municipal, provincial, and federal regulatory agencies, there still remains a fundamental misunderstanding regarding individual responsibilities with respect to the management of groundwater resources in Alberta (Summers, 2010).

**Recommendation:**

Waterline has observed that community outreach and public education programs are useful to encourage groundwater stewardship and participation in groundwater protection by all groundwater users in the watershed. Waterline has been involved in the development of effective strategies for promoting groundwater stewardship at the landowner level. These programs can be as simple as posting message boards along major highways or in sensitive areas where people can take the opportunity to learn more about their drinking water and the flow of groundwater in aquifers occurring beneath their feet. To this end, AEW initiated the Working Well program in 2006 to promote stewardship and better understanding of wells and groundwater (refer to: http://environment.alberta.ca/01317.html). Some consideration should be given to implementing such a strategy tailored specifically to the Willow Creek watershed.

## 8.0 PROPOSED MONITORING PLAN AND MANAGEMENT ACTIONS

The objectives of a groundwater monitoring plan/program are to:

- Identify any long-term geochemical trends and potential cumulative effects from current and future development in the Willow Creek watershed;
- Increase our understanding of background conditions;
- Detect any potential large scale groundwater quality and quantity effects;
- Provide appropriate baseline coverage (in areas of no anthropogenic effects) in each of the key aquifers for use in future development planning;
- Gain a better understanding of the background variability in the region;
- Gain further understanding of aquifer interactions and how the groundwater system is connected to surface environments;
- Verify and refine the regional conceptual hydrogeologic model;
- Identify high-risk areas that may require additional monitoring;
- Provide information to better understand the natural groundwater discharge and constituent flux to the rivers and local tributaries (i.e. loading to the system);
- Verify and refine local and regional conceptual hydrogeologic model which will serve as input data to numerical groundwater flow and transport models;
- Calibrate/verify predictive surface water and groundwater flow and contaminant transport models; and,
- Refine targets for indicator parameters for key aquifers in the Willow Creek watershed region through an adaptive management process.

The development of a monitoring plan is driven by pressures on the Willow Creek watershed in terms of sustainability of water quality and quantity. Population growth and increasing development in the region likely place the greatest pressures on the Willow Creek watershed.

It is likely that the data resulting from implementing the monitoring plan will be used by all stakeholders identified in **Section 4.1.1** of this report. Monitoring goals must be discussed with AEW and the Oldman Watershed Council and other stakeholders in order to gain agreement that will lead to the development of an appropriate groundwater management plan that will lead to sustainable use of the water resources in the watershed.

The first steps toward a monitoring plan were taken in the preparation of this report.

The recommended groundwater monitoring plan will help to establish present conditions in the watershed in terms of groundwater quantity and quality and serve as a baseline for future work. It should be noted that the monitoring system will undoubtedly answer some questions raised herein but will also likely reveal other questions. The intent is to establish a baseline of groundwater information that is available to future users in the watershed to help guide the use of groundwater (and surface water) resources.

## 8.1 Past and Current Initiatives

Alberta Environment established the Government Observation Well Network in 1991. It currently encompasses over 400 wells of which approximately 250 are actively monitored for quality or water levels (the remainder are inactive). Currently there are two active GOWN wells within the Willow Creek watershed buffer zone (**Figure 53**).

A large portion of the Willow Creek watershed, that west of Highway 22, is largely uninhabited with very few water wells. Alberta Environment monitors snow pack thickness at three locations (South Racehorse Creek, Mount Odlum and Lost Creek) outside the watershed and monitors river stage at several locations along Willow Creek (e.g., Chain Lakes reservoir and Claresholm) which is important for assessing recharge.

## 8.2 Proposed Monitoring Locations

Identification of monitoring well locations should consider the following criteria:

- Identified aquifers within the watershed (e.g., alluvial aquifer, buried valley aquifer, Willow Creek Formation, Porcupine Hills Formation Aquifer(s), etc.);
- Population density and number of existing users (Claresholm or Stavely areas);
- Vulnerable areas where the combination of environmental factors and land use are not quite aligned. Industrial or commercial operations have the potential to impact water quality or perhaps unique aquifer conditions (e.g., unconfined aquifer) increase the sensitivity or risk to protecting groundwater quantity or quality and therefore consideration should be given to monitoring these existing areas.
- Areas where insufficient data are available to fully characterize the geology or hydrogeology. A good example is in the western part of the watershed where no baseline information exists and recreational and industrial (timber harvesting) use can potentially impact recharge characteristics and groundwater quality/quantity;

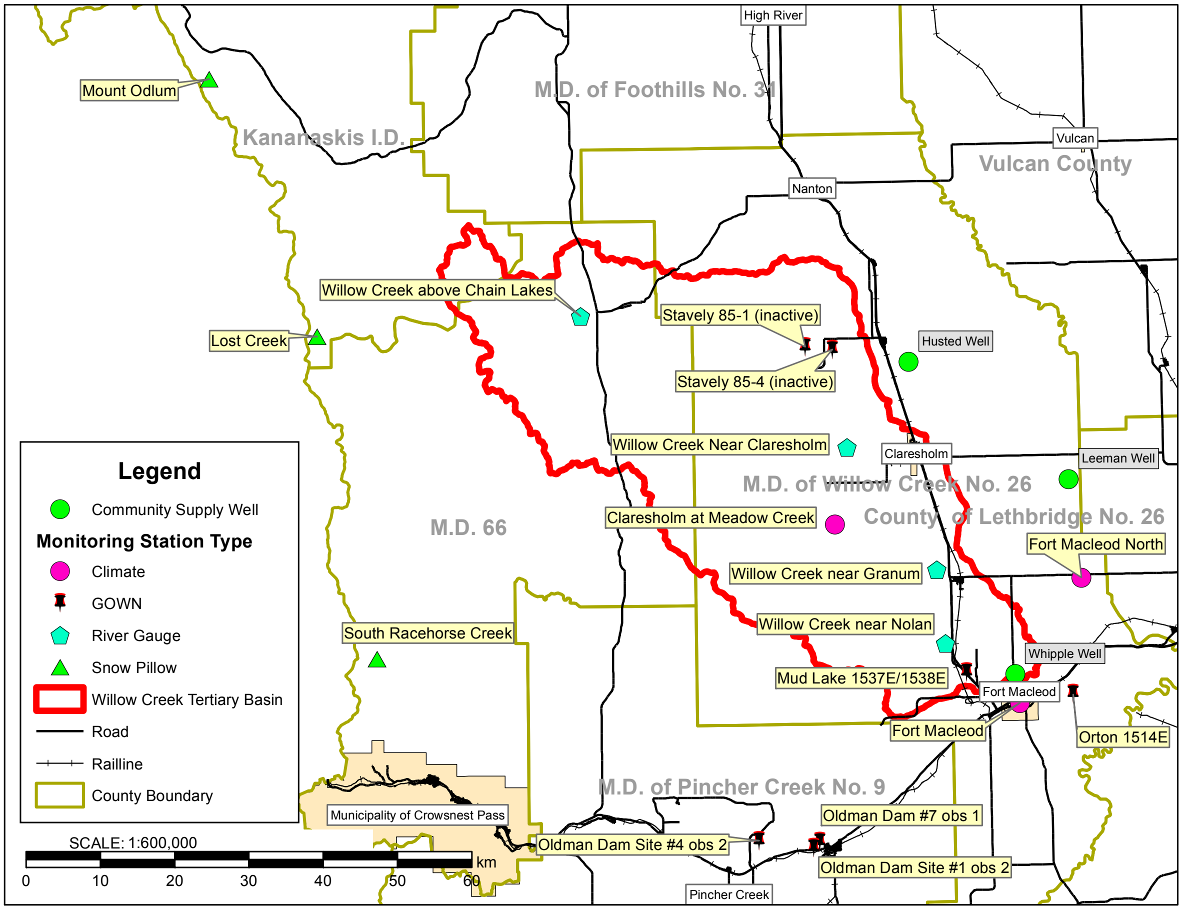



Figure 53 Current AEW monitoring

- Areas where future development is being proposed. The OWC will have to work closely with the subdivision authority or perhaps the ERCB and other regulatory authorities in Alberta to understand future plans within the watershed. Collecting baseline data prior to development will help determine whether additional measures are require to protect groundwater resources in advance of approving such developments.

Based on the above criteria, Waterline has selected six locations within the Willow Creek watershed which are presented in **Table 13**.

**Table 13 Proposed Monitoring Locations**

| Location | | Status | Reason | Comments |
|---|---|---|---|---|
| 1 | Upstream of Chain Lakes Reservoir | No existing monitoring well(s) | Aquifer possibly used for recreation | Alluvial materials; Alberta Group or Brazeau; Future recreational use |
| 2 | In the vicinity of the Kuntz Creek confluence with Willow Creek | No existing wells | Monitor Porcupine Hills Formation | Porcupine Hills Fm |
| 3 | Stavely Aquifer, west of Stavely | Town of Stavely well or Hutterite well (#859) | Monitor quality and quantity in the Stavely aquifer | Stavely buried valley aquifer; Willow Creek Formation |
| 4 | Trout Creek upstream of Willow Creek | No existing wells | Monitor upgradient of Carmangay Valley Aquifer | Alluvial aquifer, buried valley aquifer, Willow Creek Fm |
| 5 | Between Clareshom and Granum near Willow Creek | No existing monitoring wells | Monitor quality and quantity in the Carmangay buried valley | Buried pre-glacial valley materials; Willow Creek Formation |
| 6 | East of Mud Lake | Wells – exist (e.g., GOWN #112 – actively monitored) | Downstream of confined feeding operations | Alluvial aquifer, Mud Lake buried valley aquifer, Willow Creek Formation |

Although identified as an important area for recharge, no locations for monitoring were identified in the upper watershed west of Highway 22. This is because there is a need to initially focus on key areas of groundwater use which are under pressure of development. In addition, monitoring wells in the upper watershed are unlikely to help quantify recharge to the system whereas water levels in areas of groundwater extraction are based on the cumulative recharge and discharge from the system at that location. Thus declines in water levels over time are immediately indicative of discharge exceeding recharge. The monitoring locations are shown on **Figure 54**. The green circles are the locations for the first six proposed monitoring locations. Note that these are locations for monitoring which means that multiple wells could be installed at these locations in order to monitor groundwater at various depths and in various units (e.g., unconsolidated or bedrock aquifers).

To reiterate the previous discussion, there is an opportunity to collect significantly more groundwater-related data than is otherwise possible by installing a few observation wells across the watershed. The monitoring wells and locations being recommended in **Table 13** are presented for discussion purposes at this time. A considerable amount of data exist that could not be obtained as part of the present Waterline study because of timing and budgetary constraints. For instance, land use data should be better integrated into the existing GIS database constructed as part of the present study, as it could assist to refine monitoring well locations based on water quality concerns. Once these data are obtained and integrated into the present study, a final decision on the location of the monitoring well network can be made.

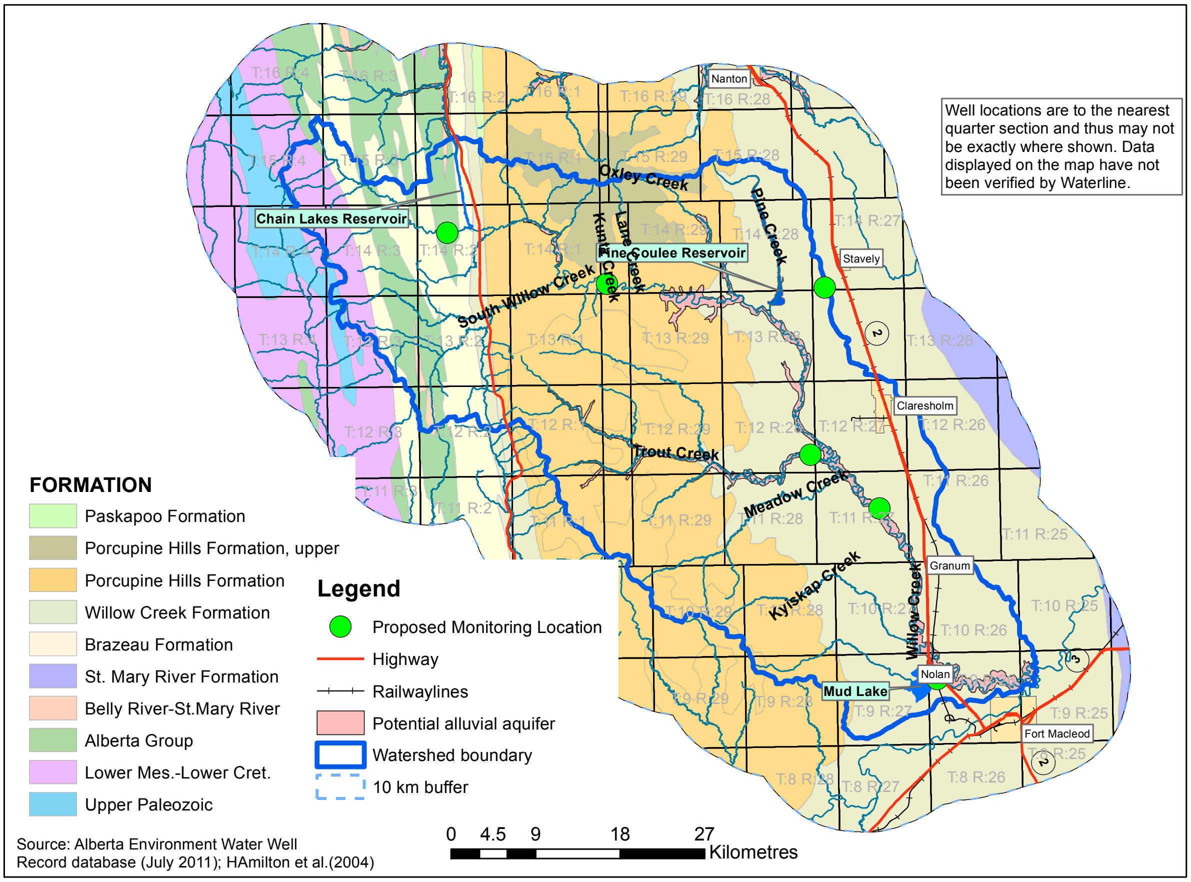



Figure 54 Proposed Monitoring Locations

## 8.3 Process for Determining Water Quality Indicator Parameters

Indicator parameters are commonly used to measure the cause and effect relationship between human activities on the landscape and the environmental response to those activities (AEW 2008). With respect to groundwater, measurement and tracking of indicator trends helps to ensure that quality and quantity conditions are maintained for human and ecosystem needs into the future. Suitable indicators include those that are:

- commonly present in the environment;
- relatively easy and inexpensive to measure;
- sensitive to environmental change; and
- specific to disturbance impacts.

Indicators can be grouped as "condition" and "development" indicators. Condition indicators relate to the physical, chemical and biological aspects of the ecosystem, while development indicators relate to anthropogenic activities in a certain area. The indicators would be selected based on land use information

Primary indicators should ultimately be selected to address development issues as well as other human activities. Secondary indicators are intended to support any follow-up investigation required following the exceedance of an established target or identification of an unacceptable trend. If required, a tertiary level of assessment may be required. As such, the tertiary indicators tend to be more expensive and assess conditions from a very high level of refinement and should only be used if required.

A preliminary list of indicator parameters should set out to enable assessment of whether there are contaminant sources within the Willow Creek watershed and whether there is deterioration of groundwater quality. These parameters must act as sentinels to assess changes in the water quality on a regional basis. Other parameters may be more useful on a local scale where contamination is suspected.

Possible parameters for providing regional water quality information could include:

- Total Dissolved Solids;
- Nutrients such as Nitrate, Nitrite;
- All Major anions (e.g., Bicarbonate, Carbonate, Chloride (salt impacts) and Sulfate;
- All Major cations (e.g., Calcium, Magnesium, Potassium and Sodium); and
- Field measurements such as oxidation/reduction potential, pH, Eh.

A parameter such as Total Coliforms would indicate if there was bacteriological activity but this does not necessarily present a health risk. It can also be used as guidance to well owners for determining a schedule for shock chlorination and well maintenance.

Parameters to be measured as a follow-up action when a problem is suspected could include

- Mercury;
- Trace metals such Arsenic; and
- Other indicators indicative of agricultural or anthropological activity such as herbicides/pesticides, pharmaceutical compounds.

## 8.4 Monitoring Frequency

The frequency at which monitoring should be completed is dependent on establishing long term baseline trends, thus there should be sufficient data for this purpose. Typically, baseline data are collected seasonally (2 to 4 times per year) in order to assess which parameters should be used as indicators. In order to be able to establish a statistical trend, a minimum of eight data points are preferred (Gibbons, 1994). Once a baseline is establish, sampling frequency could be reduced. It should be noted that depending on the trends observed, confirmatory sampling may be needed to verify the results. Land development has occurred within the Willow Creek Watershed for over one hundred years. As such it may be difficult to assess natural baseline conditions. The purpose of the monitoring is to aid in assessing changes over time in the condition of the groundwater in the watershed and therefore groundwater monitoring should be initiated early. This is best assessed through monitoring of water levels in water wells on a regular or continuous basis either by hand measurements or, preferably, through the use of pressure transducers-data loggers.

The monitoring process for each location must also be defined in order to estimate cost and time commitments with regard to:

- Who will do the monitoring (e.g., well owners, government, consulting company);
- What is to be monitored and/or sampled (e.g., water levels, water quality);
- Knowledge of aquifer parameters (e.g., transmissivity);
- How is the monitoring to be done (e.g., data loggers/pressure transducers, hand measurements, types of pumps and sampling equipment required);
- Requested laboratory analytical tests (e.g., major ion chemistry);
- Well development and maintenance (e.g., camera surveys of well casing, cleaning, surface casing repairs, pumping test); and
- Data interpretation and reporting.

## 8.5 Establishing Target Water Quality Values

A brief description of the system components used in groundwater management frameworks in the province of Alberta is provided below.

**Target**: A target is a numerically-defined desired condition for a given indicator, and a management tool which is somewhere defined through the integrated process to identify a place between natural conditions (or variability) and an established threshold.

**Threshold**: Value not to be exceeded, such that resource health may be maintained including resources with which the resource interacts (i.e. an exceedance of established or agreed-upon management criterion).

As more data become available for individual monitoring wells, statistical control charting may be used for each selected indicator parameter measured at a regional monitoring well to assess natural variability, and to track quality and quantity (i.e., water levels) conditions at each designated location. The control chart technique is used to determine whether or not an observed value is significantly different from historical values (Gibbons 1994). Once a statistically meaningful set of water quality data are available an upper concentration limit or a lower water level limit is established for each indicator parameter and water level. These limits represent the range of natural variability.

A data point that exceeds the upper concentration limit for a given parameter is an indication that something unusual may be occurring with respect to natural variability in the data. This knowledge should trigger confirmatory sampling followed by mitigative action if the result is verified. Confirmatory sampling is done to ensure that the criteria exceedance is not the result of lab or sampling error. Mitigative actions start with determining the source of contamination or cause of water level decline, and are followed by an assessment of available options.

Analyses of long-term trends in the data may be done using the Mann Kendall[9] test. This is a non-parametric statistical test that assesses the data for an upward or a downward trend. This works well with small data sets containing less than 48 data points that do not show seasonal trends.

Other statistical methods are available; however, the use of any statistical test must be preceded by an assessment of the method for its application and appropriateness to this context.

## 9.0 CONCLUSIONS AND RECOMMENDATIONS

The Willow Creek watershed is located at the eastern edge of the Rocky Mountains and Rocky Mountain Foothills and extends down gradient for over 70 km to the outlet where Willow Creek enters the Oldman River. The watershed has been identified as an area of vulnerability within the South Saskatchewan Region. As part of the implementation of the South Saskatchewan Regional Plan, aquifer mapping was required in order to develop an understanding of groundwater resources in the watershed.

The structural geology within the watershed is complex and ranges from Rocky Mountain thrust-belt and folded terrane in the disturbed zone in the west part of the watershed, to sub-horizontal, “layer cake” geologic sequences to the east of Highway 22. Based on Waterline’s data compilation efforts, the following six groups of aquifers were identified:

- Glacial Overburden aquifers;
- Glacial and/or pre-glacial Buried Valley aquifers;
- Recent Alluvial aquifers;
- Porcupine Hills Formation Aquifers;
- Willow Creek Formation Aquifer; and
- St. Mary River Formation Aquifer (Brazeau Formation Aquifer).

The alluvial aquifers are generally unconfined and are likely in direct contact with the Willow Creek. It is believed that they play an important role in providing the needed baseflow to Willow Creek during low flow, and allow for bank storage which may be important for recharge to underlying bedrock aquifers.

The buried valley aquifers including; the Stavely, Carmangay and Mud; along with the alluvial aquifer around the Willow Creek, are generally long narrow features, and although not laterally extensive in comparison to bedrock aquifers, provide for some of the highest yield wells in the watershed. Buried valley aquifers are generally confined by overlying low permeability glacial materials, although there are zones in hydraulic connection with the ground surface (e.g, Stavely aquifer near Pine Coulee reservoir). In addition, these aquifers provide pathways for groundwater flow out of the basin to the east

In terms of bedrock aquifers, the Porcupine Hills aquifer(s) is situated near the center of the watershed and is relatively well developed. The Willow Creek Formation aquifer(s) is the most extensively used aquifer within the Willow Creek watershed. Groundwater flow is generally directed to the east-southeast along the axis of the watershed. Recharge conditions prevail over the eastern and central portion of the watershed and are thought to be controlled by the abundance of creeks that run over exposed bedrock and various sand and gravel deposits. Deeper flow systems within the St. Mary River Formation likely have a longer flow path and may discharge outside the Willow Creek watershed.

The most common use for groundwater in the watershed is for agricultural purposes, followed by municipal use. Recharge to groundwater systems is estimated to be between 54,120,600 $m^3$/yr and 162,361,800 $m^3$/yr based on estimated 5% to 15% infiltration of precipitation. A total of 172 groundwater diversion licences indicate a cumulative total groundwater volume of 2,227,908 $m^3$/yr has been approved for diversion and the groundwater diversion for domestic purposes is estimated at 2,671,250 $m^3$/yr, based on the existence of 2,137 water wells within the watershed. This suggests that there may be a surplus of groundwater of between 49,221,442 $m^3$/yr and 157,462,642 $m^3$/yr, indicating that anywhere from 3-9% of the estimated recharge to aquifers may be currently in use. It is noted that this is a very crude estimate for discussion purposes only and should not be used for planning purposes.

The groundwater geochemistry transforms from a calcium-magnesium bicarbonate type in the foothills and mountains (Brazeau and Alberta Group aquifer(s)), to a sodium-sulphate, or mixed sodium sulfate-bicarbonate type groundwater in the plains part of the watershed. This is a common geochemical evolution of groundwater as the residence time of groundwater in contact with bedrock increases, and mineral dissolution progresses as groundwater moves from zones of recharge in the upper watershed to zones of discharge in the lower part of the watershed.

The TDS of groundwater appears to increase dramatically from the upper to the lower part of the Willow Creek watershed. Of the 1,504 samples with a measured TDS concentration from the Willow Creek Formation, 1,178 had TDS concentrations greater than the 500 mg/L drinking water criteria for TDS. This change in concentration may coincide with the boundary of the glacial till deposits left by the eastern derived Laurentide ice sheet and western derived Cordilleran glacial deposits from the last ice age. The glacial till to the east of this boundary has high sulphate content likely derived from the higher sulphide mineral content of the granite and gneiss pebbles. Another possibility to explain the higher TDS concentrations could be the result of higher temperature and lower precipitation in the plains region which would result in greater evaporation and thus higher TDS content than in the foothills and mountains to the west.

One of the fundamental knowledge or data gaps identified as part of the present study is related to how groundwater data and wells are identified in the field and compiled by drillers and submitted to AEW. There are over 2,100 water wells within the Willow Creek watershed and over 4,500 water wells within the surrounding buffer zone. These wells potentially represent important data monitoring points but the present system does not allow for the capture of future groundwater data in a single data management system. Therefore, data that may be collected by the landowner, oil and gas companies, land developers, the local health units, and AEW cannot be compiled and integrated such that an accurate conceptual hydrogeological model can be developed.

Field verification of water wells and reconciliation with AEW's water well database is often not possible because of the absence of well tags and no requirement to collect hand-held GPS locations. This creates great difficulty in reconciling water wells found in the field with AEW licenses, and water chemistry data. Drillers should be required to apply for an AEW well ID number before any water well is drilled. This could be done electronically, allowing the tracking of a well even before it is drilled. The system should be universally applied to water wells but consideration should also be given to other types of monitoring wells that are drilled above the base of groundwater protection. In addition, well tags should be made mandatory with inscribed well ID's and GPS locations and firmly affixed to the well. In this manner, any further work such as testing of or sampling from a particular well can be tracked with the well ID (or to a known GPS location if the tag is damaged) and a database of historical water levels and water chemistry data can be established over time. The main point here is that if properly designed, monitoring data will be provided by the users rather than by AEW or other regulatory bodies after supply or observation wells have been installed. Although this is a provincial responsibility, the Oldman Watershed Council should promote this practice to drillers operating in the region or to the landowner after the well is drilled, as every well drilled in the watershed is a potential groundwater monitoring point that can help resolve data gaps in developing our understanding of groundwater systems within the watershed.

The most vulnerable areas, with respect to potential for contamination, within the Willow Creek watershed, are the alluvial aquifers associated with Willow Creek which are largely unconfined and provides a direct connection to Willow Creek. The south-eastern portion of the watershed is under development pressure and the future demand for groundwater will undoubtedly increase.

Aquifer mapping, and particularly aquifer vulnerability mapping, should be updated once additional groundwater monitoring data are available across the watershed. Land use planning and activities can then be fully developed for the Willow Creek watershed and informed decisions by provincial, and municipal officials can then be made on a site-specific, or project by project basis. Mitigative strategies may be established to reduce impacts where possible through low impact development practices, water conservation, capture and infiltration measures, establishing communal well systems, and through other measures.

Our primary recommendation is to revise existing guidelines and regulations to ensure that any future groundwater data collected from existing water wells by users within the watershed can be properly compiled and available for use by groundwater professionals. However, there is an immediate need to establish a groundwater monitoring network in critical areas within the Willow Creek watershed. Continuous long-term monitoring of aquifer response to natural phenomena such as precipitation events, or human activities such as groundwater pumping and diversion, is fundamental to developing an understanding of groundwater systems. In order to understand the plumbing system within the aquifers, it is important to assess the cause and effect relationship of these key elements by implementing a continuous, long-term monitoring program. Such an approach may also provide an early-warning system for aquifer management and the needed information for future land use planning. It would also allow for rapid mitigative responses so that corrective action can be implemented if adverse impacts are identified in order to preserve safe and reliable groundwater supply for future generations.

Critical areas were identified by Waterline based on a number of criteria including; lithology and aquifer characteristics, population density and number of wells completed in the aquifer, sensitive or vulnerable areas, areas where insufficient hydrogeological data are available, and areas of potential for future development. Based on these criteria, Waterline has selected six proposed locations for establishing an observation well network within the watershed:

- Upstream of Chain Lakes reservoir located in the western portion of the watershed. The alluvial aquifer and Alberta Group or Brazeau Formation should be monitored at this location;
- West of Pine Creek confluence with Willow Creek to monitor conditions upgradient of Pine Coulee and start of Stavely buried valley aquifer;
- South-west of Stavely – monitor the Stavely buried valley aquifer;
- Trout Creek upstream of Willow Creek confluence – to monitor start of Carmangay aquifer, alluvial materials and Willow Creek Formation;
- Between Claresholm and Granum along Willow Creek – to monitor the Carmangay buried valley aquifer, alluvial materials and Willow Creek Formation; and
- East of Mud Lake – monitor alluvial aquifer downgradient of confined feeding operations.

Groundwater quantity monitoring is best assessed through monitoring of water levels in water wells at the selected locations on a regular/continuous basis, preferably with pressure transducer-data loggers.

Possible water quality indicator parameters include those commonly present in the environment, easy and inexpensive to measure and sensitive to environmental change and impacts. These could include, total dissolved solids, nutrients, major anions and cations. The locations should be monitored sufficiently to capture seasonal changes (2 to 4 times per year) until baseline is established in order to assess which might be the most useful parameters to use as indicators. The analysis of these water quality data should be through a process of developing targets and thresholds based on the natural variability of the indicator parameters.

Despite the large volume of literature that is available over the internet or through the various publications issued by special interest groups, municipal, provincial, and federal regulatory agencies, there still remains a fundamental misunderstanding regarding individual responsibilities with respect to the management of groundwater resources in Alberta. Groundwater conservation practices need to be encouraged and community outreach programs are needed so that residents understand the importance of groundwater protection measures and the need for participation. Concepts such as best management practices and groundwater conservation measures need to be explained so that all present and future people who live in the Willow Creek watershed adopt sustainable practices to conserve and protect fresh groundwater sources.

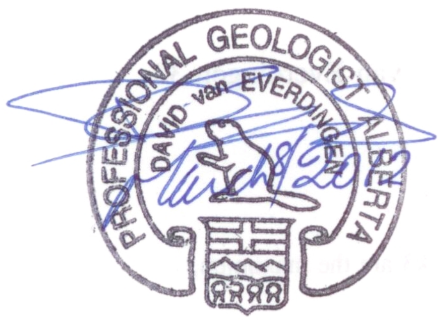
Waterline has developed an approach that we believe will maximize the understanding of aquifers within the Willow Creek watershed so that the data can be integrated into the future groundwater management framework of the OWC. Managing groundwater resources within the Willow Creek watershed will undoubtedly present unique challenges but also presents a unique opportunity for innovation and setting the template for the future approach to aquifer management in Alberta.

## 10.0 CLOSURE

This report and the information included were compiled exclusively for Oldman Watershed Council and presents results of the groundwater data evaluation and monitoring plan development. This work was carried out in accordance with the scope of work for this project and accepted hydrogeological practices. No other warranty, expressed or implied, is made as to the professional services provided to the client. Any use which a third party makes of this report, or any reliance on or decisions to be made based upon it, are the responsibility of such third parties. Waterline accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions based on this report.

Respectfully submitted,

Waterline Resources Inc.
APEGGA Permit To Practice No. P07329

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## 11.0 GLOSSARY OF TERMS

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| Acre-foot | The amount of water that will cover an acre of land one-foot deep. A flow of one cubic meter per second will, in a day, equal seventy acre-feet |
| Alluvial | Applying to the environments, actions, and products of rivers or streams. |
| Aquifer | Any water-saturated body of geological material from which enough water can be drawn at a reasonable cost for the purpose required. An aquifer is only a relative term determined largely by economics and is best illustrated by extreme examples. An aquifer in an arid prairie area required to supply water to a single farm may be adequate if it can supply 1 $m^3$/day. This would not be considered an aquifer by any industry looking for cooling water on the order of 10,000 $m^3$/day. A common usage of the term aquifer is to indicate the water-bearing material in any area from which water is most easily extracted. |
| Aquifer management unit | A hydraulically-connected groundwater system that is defined to facilitate management of the groundwater resources (quality and quantity) at an appropriate scale. |
| Aquitard | A water-saturated sediment or rock whose permeability is so low it cannot transmit any useful amount of water. An aquitard allows some measure of leakage between the aquifer intervals it separates. |
| Baseline concentration | The baseline concentration of a substance in groundwater is the natural concentration of that substance in a particular groundwater zone in the absence of any input from anthropogenic activities and sources. |
| Bedrock | The solid rock that underlies unconsolidated surficial sediments. |
| Block-Faulted | High-angle faulting in which blocks of the crust move vertically up or down relative to each other. Often occurs in areas undergoing horizontal extension. |
| BSk | One of the Köppen climate classifications; a BSk climate usually features hot and dry (often exceptionally hot) summers, cold |

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| | winters and major temperature swings between day and night. The mean monthly temperature for the warmest month ranges from 0.1 to 9.9° C. B = dry (arid and semi-arid) climates. The second letter can be either W: desert - dry winter where the driest winter month has at most 1/10 of the precipitation found in the wettest summer month, or S: Steppe - dry summer where the driest summer month has at most 30 mm of rainfall and has at most 1/3 the precipitation of the wettest winter month. The third letter h: low latitude climate with average annual temperature greater than 18 °C or k: middle latitude with average annual temperature less than 18 °C. |
| Bedrock aquifer | A bedrock unit that has the ability to transmit significant volumes of water to a well completed within it. Typical examples include sandstone and siltstone or significantly fractured intervals. |
| Buried valley | An eroded depression in the unconsolidated sediment or bedrock within which sediments with significant permeability (e.g. sand) or low permeability (e.g. till, clay) have accumulated. |
| Channel | An eroded depression in the soil or bedrock surface within which alluvial deposits accumulate (i.e. gravel, sands, silt, clay). |
| Contaminant | A substance that is present in an environmental medium in excess of natural baseline concentration. |
| Contemporaneous | Formed or existing at the same time |
| Cretaceous | A period of the Mesozoic era thought to have covered the span of time between 140 and 65 million years ago; also, the corresponding system of rocks. |
| Cumulative Effects | The changes to the environment caused by all past, present, and reasonably foreseeable future human activities. |
| Dfb | One of the Köppen climate classifications; a Dfb climate consists of warm to cool summers, severe winters, and no dry season. The mean monthly temperature drops below -3° C in the coolest month, and exceeds 10° C in the warmest month. D = continental/microthermal climate. The second letter can be either w: a dry winter where the driest winter month has at most 1/10 of the precipitation found in the wettest summer month, or |

s: a dry summer where the driest summer month has at most 30 mm of rainfall and has at most 1/3 the precipitation of the wettest winter month, or f: Does not meet either of the above specifications. The third letter a: warmest month averages above 22 °C or b: does not meet the requirements for a, but there still are at least four months above 10 °C.

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| Evapotranspiration | The process by which water is discharged to the atmosphere as a result of evaporation from the soil and surface-water bodies and transpiration by plants. Transpiration is the process by which water passes through living organisms, primarily plants, into the atmosphere. |
| Facies | The aspect or character of the sediment within beds of one and the same age (Pettijohn, 1957) |
| Fault | A break in material in which material on one side of the break has moved relative to that on the other side. In the Foothills and Rocky Mountain Front Ranges Thrust faulting is the most common – Thrust faults are low angle faults in which older material may be 'thrust over' younger material. |
| Fluvial | Produced by the action of a stream or river |
| Geometric mean | A geometric mean, unlike an arithmetic mean, tends to dampen the effect of very high or low values, which might bias the mean if a straight average (arithmetic mean) were calculated. This is helpful when analyzing transmissivity estimates, which may vary over 10 orders of magnitude. A geometric mean is a log (base 10) transformation of data to enable meaningful statistical evaluations. |
| Groundwater | All water beneath the surface of the ground whether in liquid or solid state. |
| Hydraulic Conductivity | The rate of flow of water through a unit cross-section under a unit hydraulic gradient; units are length/time. |
| Hydraulic Gradient | In an aquifer, the rate of change of total head per unit distance of flow at a given location and direction. It has both horizontal and vertical components. |
| Hydrogeology | The science that relates geology, fluid movement (i.e. water) and geochemistry to understand water residing under the |

earth's surface. Groundwater as used here includes all water in the zone of saturation beneath the earth's surface, except water chemically combined in minerals.

Hyporheic — Region beneath and lateral to a stream bed, where there is mixing of shallow groundwater and surface water.

Imbricated — Overlap in a regular pattern, like scales or roof-tiles

Infiltration — The flow or movement of precipitation or surface water through the ground surface into the subsurface. Infiltration is the main factor in recharge of groundwater reserves.

Instream Flow Needs — The amount of water required in a river to sustain a healthy aquatic ecosystem, and/or meet human needs such as recreation, navigation, waste assimilation or aesthetics.

km kilometre

Lacustrine — Fine-grained sedimentary deposits associated with a lake environment and not including shore-line deposits

m — metres

mm — millimetres

$m^2$/day — metres squared per day

$m^3$ — cubic metres

$m^3$/day — cubic metres per day

mg/L — milligrams per litre

Mann Kendall test for trend — The Mann-Kendall, non-parametric statistical test is routinely used to assess trends in groundwater concentration data.

Monitoring Well — A constructed controlled point of access to an aquifer which allows groundwater observations. Small diameter observation wells are often called piezometers.

Overburden — Any loose material which overlies bedrock (often used as a synonym for Quaternary sediments and/or surficial deposits) or

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| | any barren material, consolidated or loose, that overlies an ore body. |
| Permeability | A physical property of the porous medium providing an indication of how easily water will flow through the material. Has dimensions Length$^2$. When measured in cm$^2$, the value of permeability is very small, therefore more practical units are commonly used - darcy (D) or millidarcy (mD). One darcy is equivalent to $9.86923 \times 10^{-9}$ cm². |
| pH | The logarithm of the reciprocal of hydrogen-ion concentration in gram atoms per litre; provides a measure on a scale from 0 to 14 of the acidity or alkalinity of a solution (where 7 is neutral and greater than 7 is more basic and less than 7 is more acidic). |
| Piper tri-linear diagram | A method that permits the major cation and anion compositions of single or multiple samples to be represented on a single graph. This presentation allows groupings or trends in the data to be identified. For a more detailed explanation, please refer to Freeze and Cherry (1979) |
| Receptor | Components within an ecosystem that react to, or are influenced by, stressors. |
| Recharge | The infiltration of water into the soil zone, unsaturated zone and ultimately the saturated zone. This term is commonly combined with other terms to indicate some specific mode of recharge such as recharge well, recharge area, or artificial recharge. |
| Significant Aquifer | A permeable water-bearing horizon of sufficient thickness and lateral extent that can yield useable quantities of water. An aquifer in excess of 5 m thick, 100 m or more in width and extending a lateral distance of 500 m or more may be considered a significant aquifer. |
| Stratigraphy | The geological science concerned with the study of sedimentary rocks in terms of time and space. |
| Stressor | Physical, chemical and biological factors that are either unnatural events or activities, or natural to the system but applied at an excessive or deficient level, which adversely affect the receiving ecosystem. Stressors cause significance changes |

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| | in the ecological components, patterns and processes in natural systems. |
| Strike | The strike line of a bed, fault, or other planar feature is a line representing the intersection of that feature with a horizontal plane. |
| Subcrop | An occurrence of the strata directly beneath an unconformity (e.g., base of unconsolidated materials constituting a weathering surface). |
| Surficial Deposits | See Overburden. |
| Sustainable | A characteristic of an ecosystem that allows it to maintain its structure, functions and integrity over time and/or recover from disasters without human intervention. |
| Target | A management tool, which is somewhere defined through the integrated process to identify a place between natural conditions or variability and a threshold. A target is a numerically defined desired condition for a given indicator. |
| Thalweg | The line defining the lowest points along the length of a river bed or valley. Also the line defining the central (long) axis of a buried channel or valley. |
| Threshold | Value not to be exceeded, such that resource health may be maintained including resources with which the resource interacts (i.e. an exceedance of established natural variability at a given location or an agreed-upon published criterion). |
| Thrust Faulting | A shallow dipping fault in which the hanging wall moves up relative to the footwall. It is caused by horizontal compression. This results in placing older rock over younger rock. |
| Till | A sediment deposited directly by a glacier that is unsorted and consisting of any grain size ranging from clay to boulders. |
| Total Dissolved Solids | Concentration of all substances dissolved in water (solids remaining after evaporation of a water sample). |
| Transmissivity | The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient; a measure of the ease with which groundwater can move through the aquifer: **Apparent Transmissivity**: the value determined from a summary of aquifer test |

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| | data, usually involving only two water-level readings; **Effective Transmissivity**: the value determined from late pumping and/or late recovery water-level data from an aquifer test; and **Aquifer Transmissivity**: the value determined by multiplying the hydraulic conductivity of an aquifer by the thickness of the aquifer. |
| Trend | The relationship between a series of data points (e.g. Mann Kendall test for trend). |
| Water Management Framework | A framework to enable water planning, allocation and management of water resources. |
| Water Management Plan | A plan that provides guidance for water management and sets out clear and strategic directions for how water should be managed. |
| Watershed | The geographic area of land that drains water to a shared destination. The boundary is determined topographically by ridges, or high elevation points. Water flows downhill, so mountains and ridge tops define watershed boundaries. |
| Water Well | A hole in the ground for the purpose of obtaining groundwater; "work type" as defined by AEW includes test hole, chemistry, deepened, well inventory, federal well survey, reconditioned, reconstructed, new, old well-test. |
| Yield | A regional analysis term referring to the rate a properly completed water well could be pumped, if fully penetrating the aquifer: **Apparent Yield**: based mainly on apparent transmissivity, and **Long-Term Yield**: based on effective transmissivity. |
| AENV | Alberta Environment (prior to late-2011) |
| AEW | Alberta Environment and Water |
| AMSL | above mean sea level |
| BGP | Base of Groundwater Protection |
| DEM | Digital Elevation Model |
| GCDWQ | Guidelines for Canadian Drinking Water Quality |
| NPWL | non-pumping water level also often referred to as static water level |
| OWC | Oldman Watershed Council |

# 12.0 ANNOTATED BIBLIOGRAPHY/REFERENCES

## 12.1 Reports and Publications (Willow Creek watershed)

Acres Consulting Services Limited, 1978, Oldman River Basin: Phase II - Water Balance Model, Oldman River Study Management Committee, 65p, plus appendices.

This study investigated the factors that affect the balance of water supply and demand in the Oldman River Basin.

Alberta Energy and Utilities Board (EUB), 2007, Alberta's Base of Groundwater Protection (BGWP) Information, ERCB, Bulletin 2007-10.

Contains the elevation of the base of groundwater protection for each LSD in Alberta. Note areas in the disturbed belt (Foothills and Rocky Mountain Front Ranges) this is set to 600 m below the ground surface; elsewhere it is to some extent dependent on the formation water chemistry. It is currently set to cover all groundwater with a total dissolved solids content of less than 4,000 mg/L.

Alberta Environment, 1986, Willow Creek Basin Storage Site Feasibility Investigations, Alberta Environment, Water Resources Management Services, Planning Division, 15p, plus appendices.

The report outlines the results of feasibility studies carried out for six potential storage projects in the Willow Creek Basin based on physical, economic, environmental and social considerations. The report recommends a 41,000 acre-foot off-stream storage project.

Alberta Environment, 2002, Alberta Environment's Water Management Operations in the Oldman River Basin During the Flood of 2002, Alberta Environment, 203p..

Bill Kuhnke, Team Leader Alberta Environment , 2006, Approved Water Management Plan for the South Saskatchewan River Basin (Alberta), ISBN: 0-7785-4619-5 (Printed), 52p, August 2006, ISBN: 0-7785-4620-9 (On-line) Pub No. I/011, Website: http://www.environment.alberta.ca/documents/SSRB_Plan_Phase2.pdf.

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The hydrogeology and hydrogeochemistry of an aquifer covered by glacial drift has been studied. The study area lies in the western glaciated plains region near Lethbridge, Southern Alberta. South of Lethbridge, the aquifer is confined with flow towards the north. Both unconfined and dry zones occur at and northeast of Lethbridge where flow is towards the northeast. Cluster Analysis (CA) indicates that hydrogeochemical differences between groundwater in the oxidized till and groundwater from all other groups are the most significant. Principal Components Analyses (PCA) revealed two trends in hydrogeochemical evolution: downward transport in the overlying till, and mixing with groundwater from shallow bedrock. The typical Na-SO4-HCO3 groundwater in the aquifer was formed during recharge through a thin till sheet at the Milk River Ridge and was modified along its flowpath by diffusion loading from the overlying aquitard and by mixing. The redox conditions in the aquifer are slightly reducing, sulfate reduction occurs at several locations. Three important changes occurred in the history of the aquifer after the last glaciation 10,000 years B.P. The first change was the weathering of the upper till 10,000-3,000 years B.P. that caused increased concentrations of major ions in the oxidized till. The second important change was the outcropping of the aquifer in the Oldman River valley 2,500-2,000 years B.P. that resulted in groundwater drainage from the aquifer into the valley and dewatered a part of the aquifer. The third major change was the beginning of mining in Lethbridge in 1872 resulting in drainage of groundwater into mining works.

Strahler, A.H. and Strahler, A.N., 2006, Introducing physical geography, Wiley Interscience, Fourth Edition, 728p.

Discussion of climate classification (Koppen) systems

Summer, R.J., 2010, Alberta Water Well Survey, A report prepared for Alberta Environment. (University of Alberta: Edmonton, Canada), 116p.

A study based on approximately 1000 survey questionnaires suggesting that: Survey respondents demonstrated a low level of participation in well maintenance and stewardship practices; most respondents demonstrated a low level of knowledge with regard to the source of their well water and the functioning of their well; Most survey respondents have a false sense of security regarding the risks posed by their well and unjustified confidence in their knowledge of their water supplies.

Thornthwaite, C. W., and J. R. Mather, 1957, Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance, Drexel Institute of Technology. Laboratory of Climatology. Publications in Climatology, v 10 n 3, pg 181-289.

van der Kamp, G. and Maathuis, H., 2011, The Unusual and Large Drawdown Response of Buried-Valley Aquifers to Pumping, Groundwater, doi: 10.1111/j.1745-6584.2011.00833.x, 9p, Website: http://ngwa.org.

The buried-valley aquifers that are common in the glacial deposits of the northern hemisphere are a typical case of the strip aquifers that occur in many parts of the world. Pumping from a narrow strip aquifer leads to much greater drawdown and much more distant drawdown effects then would occur in a sheet aquifer with a similar transmissivity and storage coefficient. Widely used theories for radial flow to wells, such as the Theis equation, are not appropriate for narrow strip aquifers. Previously published theory for flow to wells in semiconfined strip aquifers is reviewed and a practical format of the type curves for pumping-test analysis is described. The drawdown response of strip aquifers to pumping tests is distinctive, especially for observation wells near the pumped well. A case study is presented, based on extensive pumping test experience for the Estevan Valley Aquifer in southern Saskatchewan, Canada. Evaluation of groundwater resources in such buried-valley aquifers needs to take into account the unusually large drawdowns in response to pumping.

van Everdingen, D.A., 2006, Potential Effects Of Climate Change On Groundwater Systems, Climate Change and Water Management, Edmonton, Alberta, 24 slides, April 2-4 2006.

General discussion on the effects of climate change on groundwater with some specific examples in the prairies and the City of Calgary

van Everdingen, R.O., 1963, Groundwater flow-diagrams in sections with exaggerated vertical scale, Geological Survey of Canada, Paper 63-27, 22p.

Provides methods for the determination of the distorted angle of bedding and flow directions in a cross- section with a vertical exaggeration

Wagner, G. and Alberta Environment-Water Resources Management Services, 1992, Willow Creek instream flow needs study: Riparian vegetation, wildlife component, Alberta Environment, Water Resources Management Services.

A habitat-based approach was used to develop the riparian vegetation IFN component. IFN were developed based on streamflow characteristics that promote long-term maintenance of riparian vegetation communities alongside Willow Creek, specifically riparian poplar forests, since they are the major vegetation associations; previous studies indicated these forests provide important habitat for wildlife along the creek; they exert a strong influence on other riparian plant species and play an important role in the succession of riparian vegetation communities; they provide important spiritual, cultural and aesthetic contributions; they maintain water quality, livestock and recreation; and they benefit fluvial systems by stabilizing banks, slowing runoff and reducing water temperature as well as providing organic material that supports aquatic life.

Wassenaar, L.I., Hendry, M.J., Aravena, R. and Fritz, P., 1990, Organic Carbon Isotope Geochemistry of Clayey Deposits and Their Associated Porewaters, Southern Alberta, Journal of Hydrology, 120, pg 251-270.

Wheeler, J.O., 1970, Structure of the Southern Cordillera, Geological Association of Canada, Special Paper No. 6, pg 1-39.

General structural geology covering the Front and Main ranges of the Rocky Mountains

Winter, T.C., Harvey, J.W., Franke, O.L. and Alley, W.M., 1998, Ground Water and Surface Water A Single Resource, U.S. Geological Survey, Circular 1139, 87p. General information about the interaction of groundwater and surface water resources

### 12.3 Maps

Alberta Environment, 2005, Water Management Operations Southern Alberta Major Headworks Systems & Irrigation Districts, Alberta Environment - Water Management Operations Lethbridge Geomatics Department, 1:350,000.

Alberta Environment, 2005, Water Management Operations - Major Headworks Systems, Alberta Environment Water Management Operations Lethbridge Geomatics Department, 1:500,000.

Hume, G.S., Shaw, G., Douglas, R.J.W., 1949, Langford Creek, West of Fifth Meridian, Alberta, Geological Survey of Canada, "A" Series Map, 981A, 1:63,360, Website: http://apps1.gdr.nrcan.gc.ca/mirage/full_result_e.php?id=106805.

Located in Alberta in 082J/01NE; 082J/01SE. Surficial geology

Jackson, L.E., 1998, Surficial geology, Langford Creek, Alberta, Geological Survey of Canada, "A" Series Map, 1927A, 1:50,000, Website: http://apps1.gdr.nrcan.gc.ca/mirage/full_result_e.php?id=209704.

Located in 082J/01. Surficial geology and geomorphology

Jackson, L.E. Jr., 1998, Surficial Geology - Granum, Geological Survey of Canada, "A" Series Map, Map 1929A, 1:50,000, Website: http://apps1.gdr.nrcan.gc.ca/mirage/full_result_e.php?id=209694.

Located in 082H/13. Surficial geology/geomorphology

Leavings Water Co-op, 2011, Leavings Water Coop Map, Website: http://www.mdwillowcreek.com/html/leavings.html.

The Leavings Water Co-op Ltd. was formed in 2010 to create a water supply for the residents in this dry Southern Alberta area where many haul water or use well, dug out or irrigation water as their supply. The Municipal District of Willow Creek in their wisdom enlarged the water line that was run from Claresholm to Granum. This line will provide one half to three quarters of a gal / minute which is adequate for residential and domestic use. Tying into this treated town system will provide users with much better water than tying into the Aquifer, which may have limited life because of potential contamination from drilling activity or ground water leaching. The Co-op Board has contacted the Provincial and Federal Governments to request funding. We are waiting for a response from them. A rough estimate of costs has been received from an engineering firm. The Board has solicited memberships at $500 per tie-in to help cover the initial costs. To date we have 134 memberships. More memberships are available. The Board is still looking to purchase water rights to make this needed potable water a reality.

McMechan, M., 1997, Granum (82H/13), Alberta Geology (Preliminary), Geological Survey of Canada, Open File, 3445, 1:50,000, Website: http://apps1.gdr.nrcan.gc.ca/mirage/full_result_e.php?id=211644.

Located in 082H/13. Stratigraphy and surficial geology/geomorphology

Norris, D.K., 1958, Livingstone River, West of Fifth Meridian, Alberta, Geological Survey of Canada, Preliminary Map, 5-1958, 1:63,360, Website: http://apps1.gdr.nrcan.gc.ca/mirage/full_result_e.php?id=108558.

Located in Alberta 082J/01NW; 082J/01SW. regional and structural geology

Norris, D.K., 1993, Geology, Langford Creek (West Half), West of Fifth Meridian, Alberta, Geological Survey of Canada, "A" Series Map, 1837A, 1:50,000, Website: http://apps1.gdr.nrcan.gc.ca/mirage/full_result_e.php?id=192424.

Located in Alberta 082J/01SW; 082J/01NW showing stratigraphy, structural geology and stratigraphic correlations

SSRB, 2009, South Saskatchewan River Basin Watersheds, The Partners FOR the Saskatchewan River Basin, Website: http://www.saskriverbasin.ca/page.php?page_id=70.

This report is aimed at satisfying, at least in part, the goal that persons who are making decisions and recommendations concerning the waters and associated resources within the Saskatchewan River Basin do so with an understanding of and an appreciation for the entire basin. One of the objectives is to examine the overall condition of the basin by assembling existing information so that it can be reviewed by groups throughout the basin. This will contribute to integrated water resources management in the basin. The report pays particular attention to hydrology, water use, water quality, and biodiversity aspects of the basin. The report uses currently available data and information. No new data were obtained for this report although some of the interpretations of existing data are new. To the extent possible, information from all basin jurisdictions is brought to a common language and terminology.

Stalker, A.M., 1957, Title Surficial Geology, High River, West of Fourth Meridian, Alberta, Geological Survey of Canada, Preliminary Map, 14-1957, 1:253,440, Website: http://apps1.gdr.nrcan.gc.ca/mirage/full_result_e.php?id=108467.

Located in West half 82I (082I/03; 082I/04; 082I/05; 082I/06; 082I/11; 082I/12; 082I/13; 082I/14). Regional geology, surficial geology and geomorphology

Stalker. A.M., 1958, Surficial Geology - Fort Macleod, Geological Survey of Canada, Map 21-1958, 1:253,440.

West half 82H. Surficial Geology

Stockmal, G.S., 1996, Geology, Maycroft (East Half), Alberta (preliminary), Geological Survey of Canada, Open File, 3275, 1:25,000, Website: http://apps1.gdr.nrcan.gc.ca/mirage/full_result_e.php?id=208495.

Located in 082G/16SE; 082G/16NE. Structural geology and stratigraphy

Stockmal, G.S. and Lebel, D., 2003, Blairmore (East Half - 82G/9E), Geological Survey of Canada, Open File, 1653, 1:50,000, Website: http://apps1.gdr.nrcan.gc.ca/mirage/full_result_e.php?id=214510.

Located in 082G/09. Regional and structural geology

Stockmal, G.S. and MacKay, P., 1994, The Triangle Zone and Foothills Structures Adjacent to the Oldman River, Southern Alberta: A Reappraisal Based on Seismic Data and New Structural and Stratigraphic Observations, Geological Survey of Canada, Open File 2937.

Willow Creek, M.D. of, 2011, The Municipal District of Willow Creek No.26, Willow Creek M.D. 26, 1:102,000, Website: http://www.mdwillowcreek.com.

Land ownership map for the MD of Willow Creek

## 12.4 On-line Resources

Agriculture and rural development department of Alberta, 2008, Farm Water supply requirements, Last viewed: 2011-Jan-29, Website: www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex1349.

Contains references to the amounts of water required for various types of livestock

Agriculture and rural development department of Alberta, 2010, Agricultural Region of Alberta Soil Inventory Database, Last viewed: 2012-Jan-03, Website: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sag3249?opendocument.

Database of soil types and models for the White zone in Alberta

Alberta Environment, 2006, Approved Water Management Plan for the South Saskatchewan River Basin (Alberta), Website: http://environment.alberta.ca/documents/SSRB_Plan_Phase2.pdf.

Alberta Environment, 2008, River Flow and Levels in Oldman River Sub Basin, Government of Alberta, Website: http://www.environment.alberta.ca/apps/basins/Map.aspx?Basin=10&DataType=1.

Alberta Environment, 2011, Groundwater Information Centre Water Well Records Database, Website: http://www.envinfo.gov.ab.ca/GroundWater/.

Water well drilling records for the province of Alberta - contain construction details, lithology encountered, chemistry and pumping test records for those wells whose data have been submitted by the driller.

Alberta Geological Survey, 2011, Provincial Groundwater Inventory Program, Website: http://www.ags.gov.ab.ca/groundwater/groundwater-inventory.html.

Background information on the provincial groundwater inventory program. Last updated Nov 22, 2011 (viewed Jan 3, 2012)

Energy Resources and Conservation Board (ERCB), 2007, Base of Groundwater Protection Query Tool. , Last viewed: 25-Sep-2011, Website: https://www3.eub.gov.ab.ca/Eub//COM/BGP/UI/BGP-Main.aspx#.

Base of Groundwater Protection (BGWP) elevations are available for all Dominion Land Survey locations in Alberta, at the legal subdivision (LSD) level, with exception of the mountainous region (disturbed belt) and the very northeast corner of Alberta. The BGWP within the mountainous region is set at 600 metres below ground level.

Environment Canada, 2012, Archived Hydrometric Data, Last viewed: 2012-Jan-09, Website: http://www.wsc.ec.gc.ca/hydat/H2O/index_e.cfm?cname=main_e.cfm (Real time data are available at: http://scitech.pyr.ec.gc.ca/waterweb/formnav.asp?lang=0).

Weather data (precipitation, temperature, etc.) for weather stations in the province. Note some stations include long histories of data that can be downloaded

Government of Alberta, 2012, Forest Management Plans, Sustainable Resource Development, Last viewed: 2012-Jan-04, Website: http://www.srd.alberta.ca/LandsForests/ForestManagement/ForestManagementPlans.

Government of Alberta, 2012, Agro-Atlas of Alberta: Maps, Agriculture and Rural Development, Last viewed: 2012-Jan-10, Website: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sag7019.

Maps of Alberta showing precipitation and temperature maxima and minima throughout the province

National Resources Energy Board, 2011, Confined Feeding Operations - Applications and Decisions, Last viewed: 2012-Jan-05, Website: http://www.nrcb.gov.ab.ca/application/notices.aspx.

Listing of confined feeding operations. Note spatial dataset available from MD of Willow Creek

Statistics Canada, 2007a, Ranchland No. 66, Alberta (Code4815045) (table). 2006 Community Profiles. 2006 Census. Statistics Canada Catalogue no. 92-591-XWE. Ottawa., Last viewed 2011-Jul-19, Website: http://www12.statcan.ca/census-recensement/2006/dp-pd/prof/92-591/index.cfm?Lang=E. Released March 13, 2007.

Statistics Canada, 2007b, Willow Creek No. 26, Alberta (Code4803018) (table). 2006 Community Profiles. 2006 Census. Statistics Canada Catalogue no. 92-591-XWE. Ottawa., Last Viewed: 2011-Jul-19, Website: http://www12.statcan.ca/census-recensement/2006/dp-pd/prof/92-591/index.cfm?Lang=E. Released March 13, 2007.

## 12.5 Spatial Data (Willow Creek watershed)

Agriculture and Agri-Food Canada, 2009, Land Cover for Agricultural Regions - Circa 2000, Agriculture and Agri- Food Canada, Website: http://www4.agr.gc.ca/AAFC-AAC/display-afficher.do?id=1226330737632&lang=eng.

A thematic land cover classification representative of Circa 2000 conditions for agricultural regions of Canada. Land cover is derived from Landsat5-TM and/or 7-ETM+ multi-spectral imagery by inputting imagery and ground reference training data into a Decision-Tree or Supervised image classification process. Covering approximately 370,000,000 hectares of mapped area.

Alberta Environment, 2009, Groundwater Vulnerability map, prepared by the Groundwater Policy Section, Water Policy Branch, Alberta Environment, contact person Guha, S..

The groundwater vulnerability map prepared for the South Saskatchewan Region (SSR) provides a high level overview of the sensitivity of shallow groundwater quality to potential impacts by surface activities. The SSR groundwater vulnerability mapping was conducted based on the work originally done by Prairie Farm Rehabilitation Administration (PFRA, now Agriculture and Agri-Food Canada) and Alberta Agriculture and Rural Development (Dash and Rodvan, 2001). The final groundwater vulnerability is ranked as Low, Medium, High and Very High providing relative risk to groundwater quality from land-based activities. The HEMS Groundwater Vulnerability Map was used to cover a major part of central and eastern Alberta (the agricultural area or "White Area"). Different surficial geologic units were ranked (by the HEMS team) for the vulnerability of shallow groundwater from contamination. Vulnerabilty ranking for the Bayrock and Reimchen surficial geology were originally assigned by PFRA (Dash and Rodvang, 2001) based on professional experience.

Alberta Environment, 2010, Base Data from Alberta Environment.

Base Data from Alberta Environment as part of this project included Culture points, Groundwater diversion, Surface water diversion, Cutlines, Hydrography, Pipelines, Powerlines, Raillines, Roads, ATS Township Index grid, Legal subdivisions, Quarter sections

Alberta Geological Survey, 2009, Compilation of Alberta Research Council's Hydrogeology Maps (GIS data, polygon features), Alberta Geological Survey, Website: http://www.ags.gov.ab.ca/publications/DIG/ZIP/DIG_2009_0003.zip.

Between 1971 and 1983, the Alberta Research Council created a series of hydrogeological maps of Alberta. The geologists examined the sediment types present and used existing water well information to assign yield values to distinct zones within the mapped areas. Alberta Geological Survey compiled the shapefiles for the yield polygons, digitized by the Prairie Farm Rehabilitation Agency, and then digitized the remaining linework for the remaining map areas.

AltaLIS, 2010, Alberta Boundary Data, downloaded October 2010, Website: http://www.altalis.com/products_base.html.

Boundary data included: Forest reserve, Wildland parks, Green and white areas, NTS 1:20,000 grid, Natural areas, Land use framework, Integrated resource plan, Forest protection areas, Forest land use, Crown Reserve, Exploration restricted areas, Forest management units, Eastern slopes land use and Fish management zones.

Edwards, D. and Budney, H., 2007, Alberta Sand and Gravel Deposits with Aggregate Potential (GIS data, polygon features), Alberta Geological Survey, Vector data, Website: http://www.ags.gov.ab.ca/publications/DIG/ZIP/DIG_2004_0034.zip.

This AGS GIS dataset is a result of the compilation of all existing Alberta Geological Survey sand and gravel geology and resource data into digital format and has been developed by AGS to provide information on sand and gravel deposits with aggregate potential to support the sustainable development of Alberta's earth mineral resources. The data sources include AGS maps and reports produced between 1976 and 2002.

Hamilton, W.N., Langenberg, C.W. and Price, M., 2004, Bedrock geology of Alberta, Alberta Geological Survey, Website: http://www.ags.gov.ab.ca/publications/DIG/ZIP/DIG_2004_0033.zip.

This data set comprises the bedrock geology of Alberta in geographic information systems (GIS) format. The GIS coverage was originally prepared by digitizing Map 027, 1972, Alberta Geological Survey, Alberta Research Council. Revisions since 1972 have incorporated new mapping data from work by the Alberta Geological Survey and the Geological Survey of Canada, and by the Canadian Society of Petroleum Geologists through the contribution of its membership to the Geological Atlas of the Western Canada Sedimentary Basin. The coverage shows the formation and geologic age of the bedrock subcrop, as well as the nature of the contacts between formations.

Lemay, T. and Guha, S., 2009, Compilation of Alberta Groundwater Information from Existing Maps and Data Sources, ERCB/AGS, Open File Report 2009-02, Website: http://www.ags.gov.ab.ca/publications/DIG/ZIP/DIG_2009_0003.zip.

Between 1971 and 1983, the Alberta Research Council created a series of hydrogeological maps of Alberta. The geologists examined the sediment types present and used existing water well information to assign yield values to distinct zones within the mapped areas. They also looked at the materials, generally to a depth of 305 metres (1000 feet) below ground surface, and added the yields of the sediments encountered within this interval to arrive at a yield value for the whole. Alberta Geological Survey compiled the shapefiles for the yield polygons, digitized by the Prairie Farm Rehabilitation Agency, and then digitized the remaining linework for the remaining map areas. Afterwards, we created a geodatabase of the yield polygons for the entire province and assigned yield values to the polygons based on the original maps. We also assigned the most likely formation name, age and lithology to the yield polygon.

MD Willow Creek, 2011, Spatial Data from the MD of Willow Creek.

Data included county map background, location of gravel operations and location of confined feeding operations.

Shetsen, I., 2002, Quaternary Geology of Southern Alberta - Deposits (GIS Data, polygon features), Alberta Geological Survey, Vector data, Website: http://www.ags.gov.ab.ca/publications/DIG/ZIP/DIG_2007_0012.zip.

To provide the base data for the surficial geology and an interpretation of Quaternary Geology in the area, the AGS GIS data set incorporating polygon features from AGS Map 207, 'Quaternary Geology, Southern Alberta'

# APPENDIX A

# BACKGROUND INFORMATION

Methodology

# METHODOLOGY

This section of the report provides details on the methodology used in preparation of the various datasets used in this report:

1. Introduction to basic groundwater theory

2. Classification of water-well records by lithology at completion interval

3. Determination of apparent transmissivity from pumping test data in the Alberta Environment & Water (AEW) water-well-record database

4. Construction of cross-sections

5. Vertical exaggeration in cross-sections

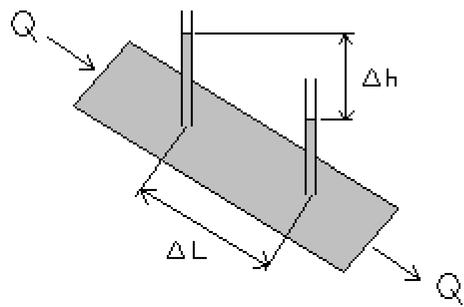
6. Determination of hydraulic gradient based on data in the AEW water-well-record database

## GENERAL THEORY OF GROUNDWATER MOVEMENT

Groundwater is water that has entered (recharged) the ground after falling as precipitation on the ground. Groundwater flows through pore spaces and fractures in both unconsolidated and consolidated materials. This flow is driven by physical gradients – such as pressure, gravity, density and temperature. The rate of flow is dependent on the material properties (e.g., permeability) through which the fluid flows.

### 1.1. Darcy's Law

Darcy's law is an empirical law based on experimental observation of flow through a porous medium (i.e., sand). This law relates the rate of flow to flow through a unit cross-sectional area under a unit gradient through a constant of proportionality.




The fluid in the figure above flows from the upper left to the lower right driven be gravity as a result of the difference in elevation between the ends of the sand filled tube. The flow rate is denoted by Q and has units of $L^3/T$. The magnitude of the potential gradient, i, is the difference in head, h, between the two manometers divided by the distance, L between the two manometers.

$$i = \frac{dh}{dL}$$

The specific discharge, $\upsilon = \frac{Q}{A}$ (where, Q is the flow rate and A is the cross-sectional area through which the fluid flows) is directly proportional to the negative of the change in head, Δh and inversely proportional to the distance between monitoring points, ΔL (refer to the figure above).

Based on the above relationships, the French engineer, Darcy, came up with the following empirical formula,

$$Q = -KiA \, ,$$

where K, the constant of proportionality, referred to as the hydraulic conductivity, is related to both the material properties and the fluid properties.

### 1.2. Hydraulic Conductivity

Hydraulic conductivity, K, provides a measure of the relative ease with which a fluid passes through a material. It incorporates the properties of the fluid and those of the porous medium through which the fluid passes,

$$K = \frac{k\rho\vec{g}}{\mu},$$

where g is acceleration due to gravity, k is the intrinsic permeability, a property of the medium through which the fluid passes and based on the square of the particle diameter and the grain size distribution for porous media. In fractured media the permeability is proportional to the square of the fracture aperture (it has units of length squared).

The fluid properties that are part of the constant, K, include the fluid viscosity, $\mu$, and the fluid density, $\rho$.

The hydraulic conductivity of an aquifer may be different in different directions – it is expressed mathematically as a three dimensional tensor. It depends on the variation of the material properties throughout the porous medium.

**Table 1 Ranges of Hydraulic Conductivity Values for Various Materials (from Freeze and Cherry, 1979)**

| Material | Type | K ($m^2$/sec) |
|---|---|---|
| Gravel | Unconsolidated | $10^{-3}$ to 1 |
| Sand | Unconsolidated | $10^{-5}$ to $10^{-2}$ |
| Silt | Unconsolidated | $10^{-7}$ to $10^{-3}$ |
| Clay (glacial till) | Unconsolidated | $10^{-12}$ to $10^{-6}$ |
| Sandstone | Consolidated | $10^{-10}$ to $10^{-6}$ |
| Shale | Consolidated | $10^{-13}$ to $10^{-7}$ |
| Limestone | Consolidated | $10^{-9}$ to $10^{-6}$ |

The hydraulic conductivity is generally estimated in monitoring wells through a slug test. The slug test involves the instantaneous addition or removal of a slug. The slug may be the removal of a volume of water (not the addition of water since that brings up potential external contamination issues) or the removal/addition of a metal or other material bar of known volume.

The test duration is typically of the order of seconds to minutes, although it can last hours in materials with very low hydraulic conductivity. Because the volume of water displaced in the well is quite small (a few litres or so), the radius of influence of the test is also small.

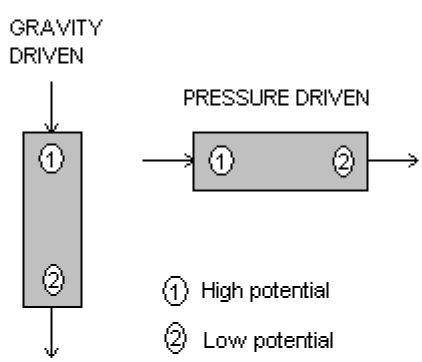
To get an idea of the conductivity of materials over a larger area or volume of formation, a pumping test would be more appropriate. The results of the pumping test are then evaluated to determine the transmissivity, T of the aquifer in which the well is screened. The transmissivity is related to the hydraulic conductivity through the following equation,

$$T = K\,b,$$

where b is the thickness of the aquifer. Thus, a thick aquifer with a low hydraulic conductivity can have the same transmissivity as a thin aquifer with a high hydraulic conductivity.

### 1.3. Fluid Potential

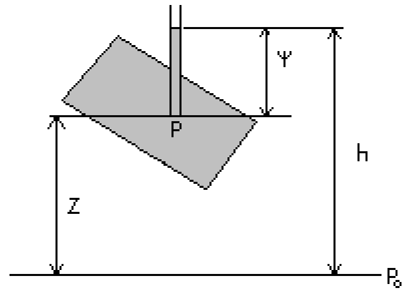
Groundwater flows from areas of high potential to areas of low potential. The potential consists of, elevation and fluid pressure. Refer to the figure below – flow is in the direction of the arrows.




The level to which fluid will rise in a manometer or piezometer is a measure of the total head at the open end, point P (refer to figure below) of the manometer or piezometer. At this point P, the fluid pressure is defined as,

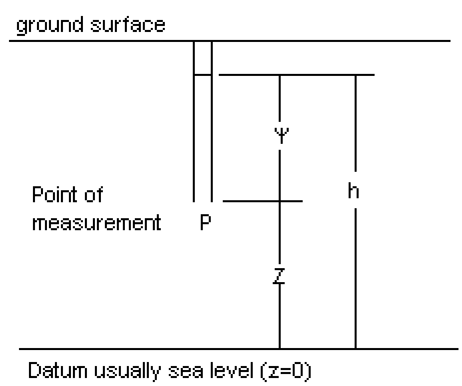
$$p = \rho g(h - Z) + P_0$$

where $P_0$ is the pressure at the datum point (reference elevation, e.g. mean sea level).




The total potential, h or head, at the measurement point, P, which is the open end of the piezometer or the screened interval of the well, consists of Ψ, the pressure head and Z, the elevation head,

$$h = z + \psi$$

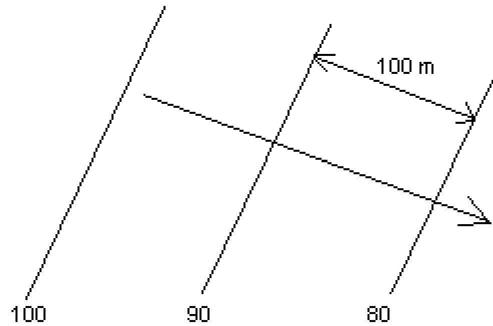



It should be noted that the point to which these data apply is the mid-point of the screen – thus if the well has a long screen the data are an integration over the length of the screen. Thus longer screens give less specific hydraulic information than shorter screens.

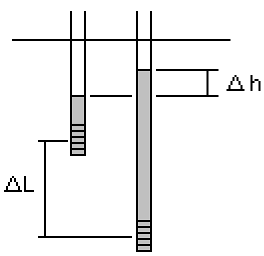
### 1.4. Hydraulic Gradients

Flow direction in porous media is defined by the hydraulic gradient. There is a tendency for environmental investigations to focus only on the horizontal component of flow. In fact, the hydraulic gradient consists of both horizontal and vertical components.

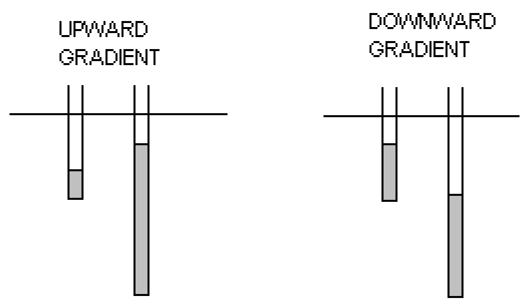
The hydraulic gradient is given by the ratio of the change in head over the distance between two points. The horizontal component of the gradient is usually determined in a direction perpendicular to the equi-potential lines drawn on a map. The map below contains three equi-potential or piezometric contour lines (labeled from left to right 100, 90, 80). These values are the heads along the contour lines. The flow direction is perpendicular to those equi-potential lines and is to the southeast. To determine the horizontal hydraulic gradient take the difference in equi-potential between two of the lines (90-80) and divide that by the distance between those lines (100 metres) to give a horizontal gradient of 0.1.




The vertical gradient is calculated the same way, only now it is the head difference between the centre points of two well screens (Δh) situated as close as possible to each other (horizontally) – such as in a well nest. This is divided by the distance between the centre points of the well screens (ΔL - refer to figure below).




The direction of the vertical gradient (up or down) indicates whether there are local discharge or recharge conditions. The figure below (on the left) shows a water level in the deeper well that is higher than that in the shallow well, indicating an upward gradient exists, this suggests that discharge conditions could exist locally.

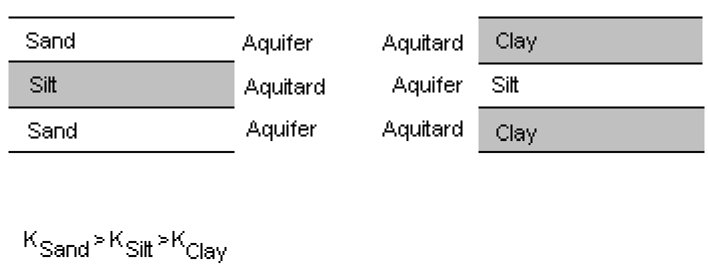


An upward gradient would be expected in areas such as valley floors, at the base of hills or near bodies of water. Downward gradients (the level in the deeper well is deeper than that in the shallow well) are indicative of recharge conditions. These conditions generally exist on topographically high areas.

## 1.5. Aquifer versus Aquitard

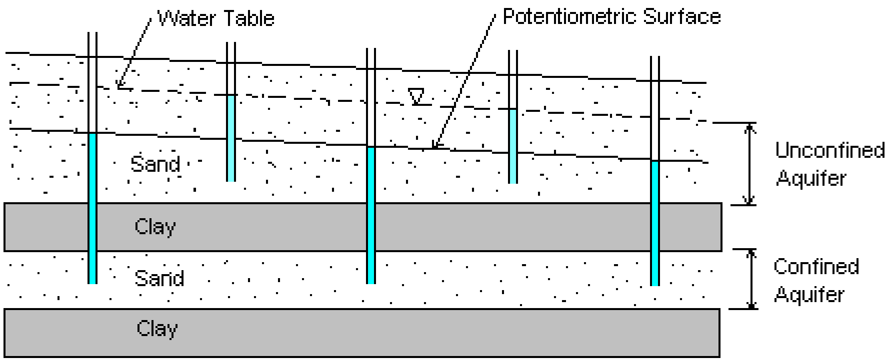
There are numerous definitions of an aquifer; in general though aquifers are defined as materials that yield economic quantities of water; aquitards on the other hand do not. Alberta Environment in their Standards For Landfills (May 2004) states that an “exceptional underlying aquifer” means a hydrostratigraphic unit with a transmissivity of greater than 2.5 x $10^{-3}$ $m^2$/sec yielding water with a total dissolved solids (TDS) concentration not exceeding 4000 mg/L. They also use the concept of Domestic Use Aquifer that is defined as a water-bearing unit capable of a sustained yield of 0.76 L/min and currently used for domestic purposes and/or a total dissolved solids concentration of 4,000 mg/L or less. It can also be defined as an aquifer that is determined by Alberta Environment to be capable of domestic use. From a contamination viewpoint an investigation should look for the presence of an aquitard capable of protecting the groundwater beneath a contaminated aquifer.

A material does not define an aquifer; it is the contrast between different adjacent materials that determines which will be the aquifer and which the aquitard, as demonstrated in the following figure.




## 1.6. Confined versus Unconfined Aquifers

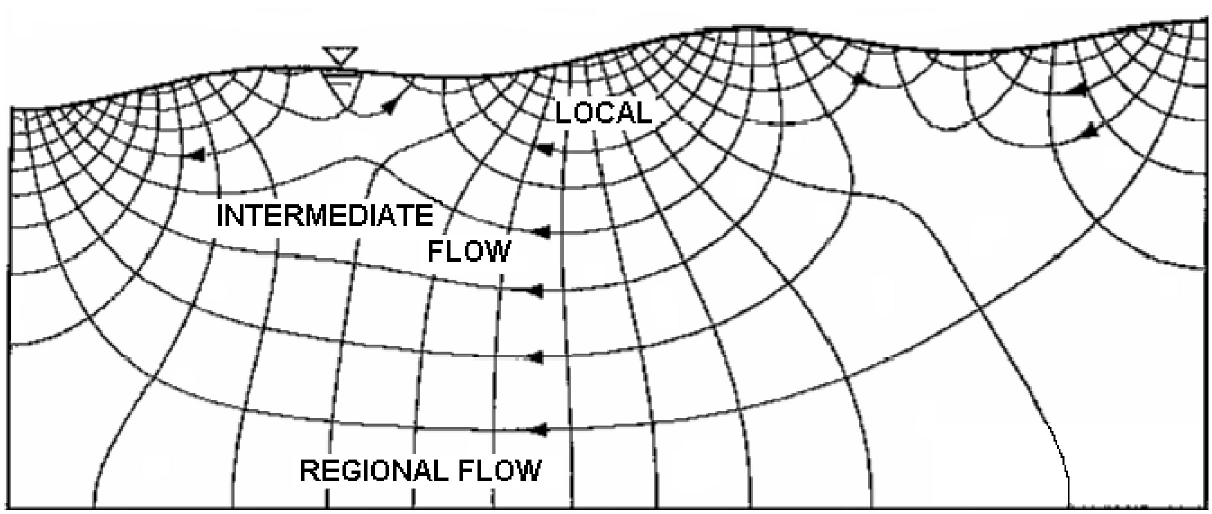
A confined aquifer is one that underlies materials of lower permeability. Generally speaking, in the previous figure on the right-hand side the silt unit would be classed as a confined aquifer because it is confined by the overlying clay layer. An unconfined aquifer lies near the ground surface and generally contains an unsaturated zone near the top.




The water table is a potentiometric surface with zero pressure head; the total head consists of elevation head. To be sure that you are monitoring the water table level – the fluid level in the well must be in the screened interval. For a confined aquifer the head may lie within the aquifer or above it – this is not the same as the water table.

### 1.7. Regional and Local Flow

Groundwater flow occurs everywhere that there are hydraulic gradients. The flow is controlled in the near surface by the local topography. Deeper groundwater flow is controlled by more regional topographic changes. For example, local depressions on a hill slope may act as local discharge (springs or seepage) areas, whereas local topographically higher points act as recharge areas. Regional flow is driven by regional topography  - in Alberta this flow is driven by the higher mountains to the west and the lower Plains to the east. The figure below demonstrates these relationships.



## 1.8. Porous Media versus Fractured Media

Both consolidated and unconsolidated materials contain porosity. This porosity is termed either primary or secondary porosity. The primary porosity is the porosity preserved from deposition through lithification and consists of the original pore spaces.

This type of material can typically be treated as a porous medium implying homogeneous distribution of hydraulic conductivity. From a hydrogeological perspective a porous medium is simpler to deal with.

Secondary porosity is the porosity created through alteration of rock, commonly by processes such as dolomitization, dissolution and fracturing.

Fracturing is a type of secondary porosity produced by the tectonic deformation of rock. Fractures themselves typically do not have much volume, but by joining preexisting pores, they enhance permeability significantly. This material is termed a fractured medium.

Fluids will preferentially flow along fractures over flowing through the matrix pore spaces. Both consolidated and unconsolidated materials can contain fractures. Fracturing is quite common in the glacial tills found in and around Calgary. The fluid flow is still driven by hydraulic head gradients but the direction of flow is controlled to a greater degree by the orientation, continuity and connectivity of the fractures.

## CLASSIFICATION OF WATER-WELL-RECORDS BY LITHOLOGY AT COMPLETION INTERVAL

In order to objectively evaluate the aquifer properties in the surficial deposits and consolidated bedrock aquifers, it is first necessary to select the water well records that have data indicating they were completed in the overburden or in the bedrock. This information is not directly stored in the AEW water-well-record database. These water well records were assigned to unconsolidated or bedrock aquifers by assessing where the completion interval is situated with respect to the lithology as follows:

- Water well records with information of completion interval above the bedrock or total depth less than that of the bedrock were classified as completed in the unconsolidated deposits, whereas those with completion intervals below the top of bedrock were designated as bedrock wells.

- Water well records that had a completion interval extending from above the top of bedrock and into the bedrock were classified as completed in unconsolidated/bedrock.

- Water well records without either lithology information or completion interval were marked as indeterminate since no determination could be made.

## DETERMINATION OF APPARENT TRANSMISSIVITY FROM PUMPING TEST-DATA IN THE ALBERTA ENVIRONMENT WATER-WELL-RECORD DATABASE

Transmissivity is generally defined as the rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. It is a measure of the ease with which groundwater can move through the aquifer. The following are further definitions:

- Apparent transmissivity is determined from a summary of aquifer test data using only two water-level readings;
- Effective transmissivity is determined from late pumping and/or late recovery water-level data from an aquifer test; and
- Aquifer transmissivity is determined by multiplying the hydraulic conductivity of an aquifer by the thickness of the aquifer

Note that hydraulic conductivity of a material is the volume of water that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

The Alberta Environment Groundwater Information Centre Water Well Database contains records sent in by drillers at the time of the well installation. Some of the records contain pumping test data. These data can be used to estimate apparent transmissivity value (e.g., Farvolden, 1959 and Ozoray, 1970). The apparent transmissivity can be calculated assuming the assumptions of the Theis (1935) pumping test analysis are valid and values for the following parameters: discharge rate, discharge time, casing diameter and drawdown at the end of the discharge interval. The apparent transmissivity can be determined through iterative solution of the following equations:

For short-term pumping tests (typically tests of 2-hour duration), and with information available for the pumping rate, length of test, drawdown at end of test and radius of well casing, the following approach is used in calculating the apparent transmissivity, T.

To calculate the apparent transmissivity, a value is required for discharge rate, discharge time, casing diameter and drawdown at the end of the discharge interval. The equations used in the solution are (Hydrogeological Consultants Inc., 1998):

$$u = \frac{r^2 S}{4tT}$$

$$T = \frac{Q\left(-0.5772 - \ln u + u - \frac{u^2}{4} + \frac{u^3}{18}\right)}{4\pi \Delta h}$$

where,

u - well function
r - radius of casing (mm)
S – Storativity (taken as 0.0001)
T – Apparent transmissivity ($m^2$/day)
Q - pumping rate ($m^3$/day)
Δh - drawdown per log cycle (m)
t - time (min)

The apparent transmissivity is calculated by the iterative solution of two equations, since T occurs in both equations.

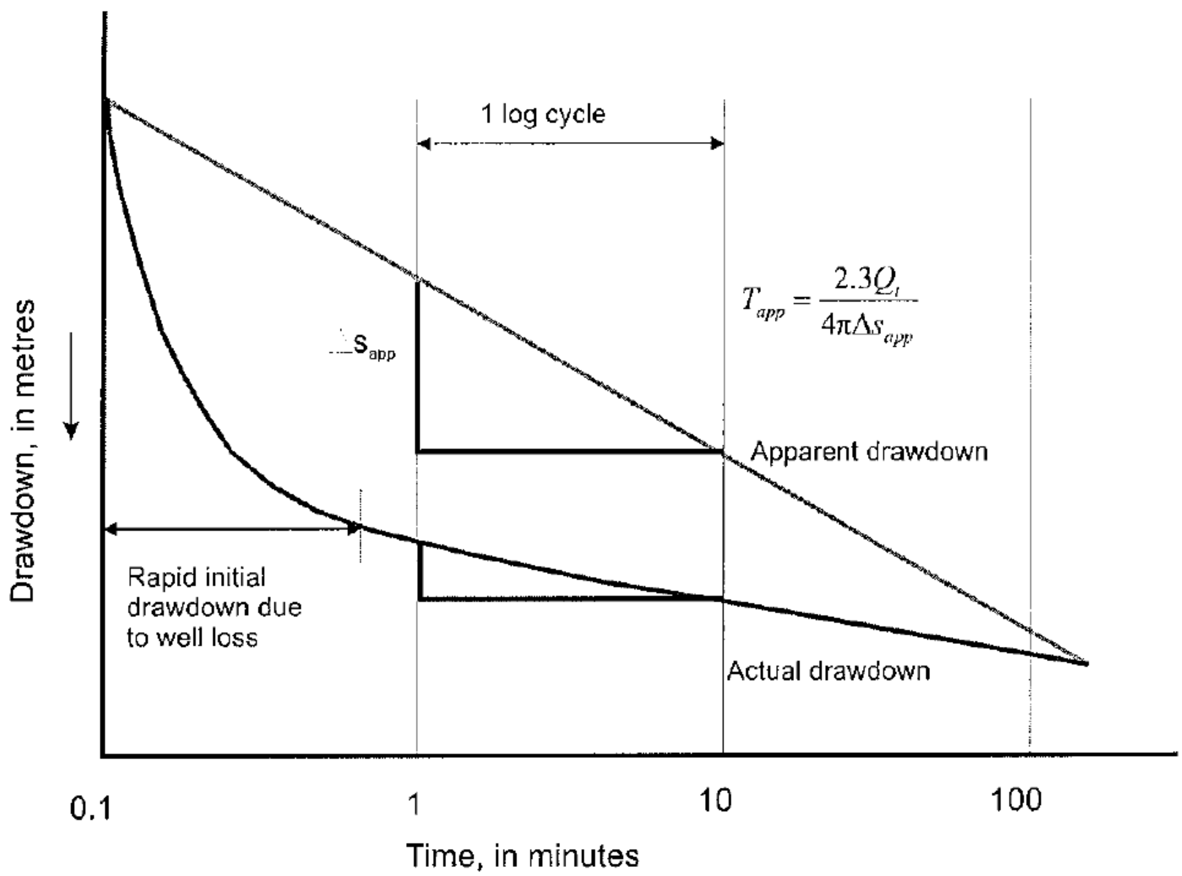



Illustration of Farvolden's apparent transmissivity concept (source: Figure 6 in Maathuis and van der Kamp, 2006))

It should be noted that the pumping tests from which these data come are rarely of more than 2 hours duration which means that the volume of the aquifer that the pumping test influences is quite small, especially in highly permeable materials. Thus these data provide apparent transmissivity estimates that are likely higher than the true transmissivity of the aquifer. Comparison with pumping test analyses for which there is more than just the start and end point data available shows that the apparent transmissivity calculated can be of the order of 3 times higher/lower. They do however provide a first estimate of the transmissivity for the area. These estimates should not be relied upon for specific sites. In such cases, it is always preferable to conduct a long term pumping test (e.g., 24 to 48 hours duration) in order to obtain data that give an estimated transmissivity that is more representative of the aquifer.

## CONSTRUCTION OF CROSS-SECTIONS

The cross-sections prepared for this study (**Figure 27** and **Figure 29** to **Figure 31**) were constructed as follows:

1. Using ESRI's ArcMap, select the water well records within the Willow Creek watershed buffer zone (10km beyond the edge of the watershed boundary). Save the selected water well records to a shapefile.
2. Using the BH_Log borehole data management program and the shapefile produced in the first step, extract the associated borehole data from the AEW water-well-record database (this includes the lithology, well location production intervals, etc).
3. Using IHS Accumap and their database to select oil and gas well records within the 10 km buffer zone. These data are generally exported to an MS Excel file.
4. Import the oil and gas well data into the BH_Log program database.
5. Using the BH_Log program, select those wells with lithology data present and prepare cross-sections. These sections display the lithology in the wells. Note, however that these wells were drilled and logged by different people and thus the descriptions are comparable only with difficulty. For these reason the lithologic descriptions were standardized using a common terminology so that boreholes and their lithology could be more easily compared.
6. Using Adobe Illustrator connect the lithologies in the various wells to provide an interpretation of the subsurface lithology/formations. Other information used in the construction of the cross-sections included the Alberta Geological Survey geology maps (Hamilton et al., 2004), University of Calgary structural geology theses (e.g., Hiebert, 1992) and Geological Survey of Canada reports (e.g., Stockmal et al., 2001).

## VERTICAL EXAGGERATION IN CROSS-SECTIONS

It is important to note that all these cross-sections exhibit a large degree of vertical exaggeration. This is a distortion applied to the cross-section in order to view long sections (covering long stretches of land) while still being able to view the changes in lithology with depth. In a cross section with no vertical exaggeration a unit distance horizontally is the same as a unit distance vertically. In a cross-section with vertical exaggeration of 10 to1 (noted as 10:1) a unit distance vertically translates into 10 units horizontally. So, on paper, for a cross section with a 10:1 vertical exaggeration, 1 cm in the vertical direction may equate to 1 m whereas in the horizontal direction that 1 cm would equate to 10 m.

It is important to note that in cross-sections with vertical exaggeration angles are not preserved. This means that if a lithologic unit or a fault dips at 10 degrees in the ground, on the section, depending on the amount of vertical exaggeration that dip will be much steeper, following this equation:

Tan(angle on section) = Tan(angle in ground) * (vertical exaggeration)

So for our 10:1 example above, the fault dipping at 10 degrees in the ground would dip at 60 degrees on the cross section. The same applies to lithologic boundaries and groundwater flow directions. Keep this in mind when viewing cross-sections with vertical exaggeration. A more complete treatment of the subject can be found in van Everdingen (1963).

## DETERMINATION OF HYDRAULIC GRADIENT BASED ON DATA IN THE AEW WATER-WELL-RECORD DATABASE

In order to determine vertical hydraulic gradients within the Willow Creek watershed the following approach was used:

1. From the Alberta environment water-well-record database search for pairs of wells within each legal subdivision of land within the Willow Creek watershed. These wells should have different production interval elevations in order to be able to calculate the vertical hydraulic gradient.

2. Determine the hydraulic gradient (dh/dl), based on the difference in elevation of the production interval between the two wells (dl) and the difference in static water level elevations between the two wells (dh).

For a recharging area (groundwater moving downward) the hydraulic gradient will be pointing downward (positive value) and for a discharging area (groundwater moving upward) the gradient will be pointing upward (negative value). The calculated values of vertical hydraulic gradient are then contoured over the area of the watershed and plotted on a map.

It should be noted that maps such as these are primarily constructed to give an indication of trends and should not be used for specific locations. The data within the AEW database are too sparse to get true vertical hydraulic gradients (wells need to be in close proximity).

In addition, true vertical gradients should be determined using wells that are in close proximity; the calculations done here are on pairs of wells in the same LSD. This means that the wells could be as far as 400 m apart (a LSD is a quarter mile (400 m) on a side). Another assumption is that the static water level present in the AEW water-well-record database was taken **before** starting the pumping test and after the water levels stabilized following well construction so that it is a true reflection of the water level in the well.

## RECOGNITION OF ALLUVIAL AQUIFERS

(taken from van Everdingen et al. 2009)

Rivers and their alluvial aquifer systems are dynamic and constantly changing. The alluvial aquifer systems provide a valuable source of groundwater to surrounding communities, while the surface alluvial features provide excellent soils for agricultural purposes.

Alluvial aquifers are those that were deposited by a stream or other body of running water in a streambed, on a flood plain, on a delta, or at the base of a mountain. They are usually under and on at least one side of the river and can be highly permeable.

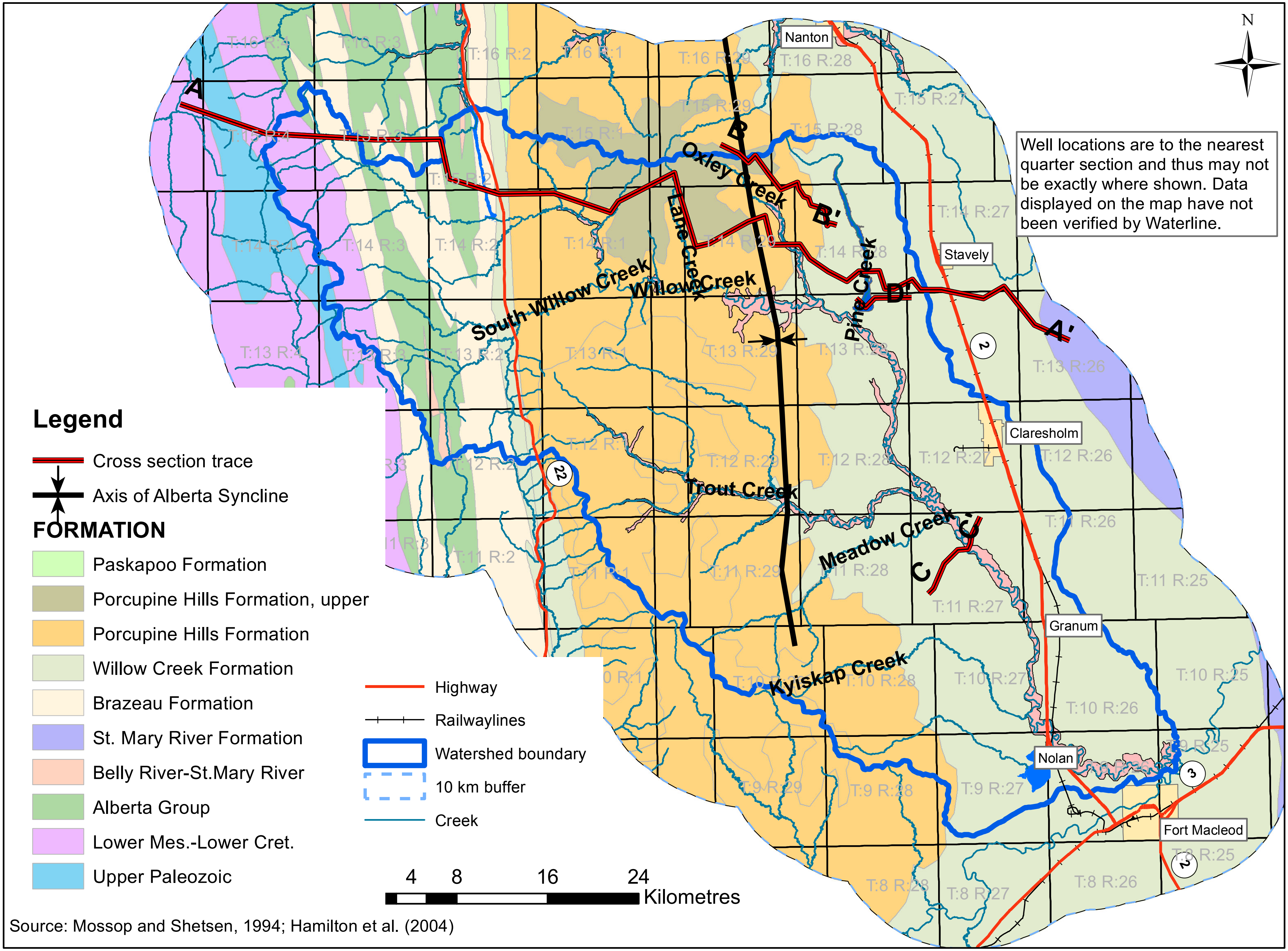
An aquifer is an underground unit or layer that yields water. By this definition the unsaturated portion of the layer above the water table is not part of the aquifer. Alluvial materials were deposited by a river at some time in the past; since that time the river channel may have moved or may have cut down further into the alluvial materials. Thus there may (will) be portions of the alluvial material that are not saturated and thus are not part of the alluvial aquifer. The distinction can only be determined through invasive investigations; such as through drilling boreholes and installing monitoring wells.

This distinction can not generally be made on the basis of remotely sensed data (aerial photographs or satellite imagery). If one makes the assumption that (from a vulnerability viewpoint) contaminants dumped onto the alluvial materials will eventually make their way into the river, even if dumped on unsaturated portion of the alluvium, then a definition of an alluvial aquifer could encompass all those alluvial materials of high permeability that are adjacent to or beneath a body of running water (i.e., including the unsaturated portions). This includes materials both in the flood plain and the older terraces.

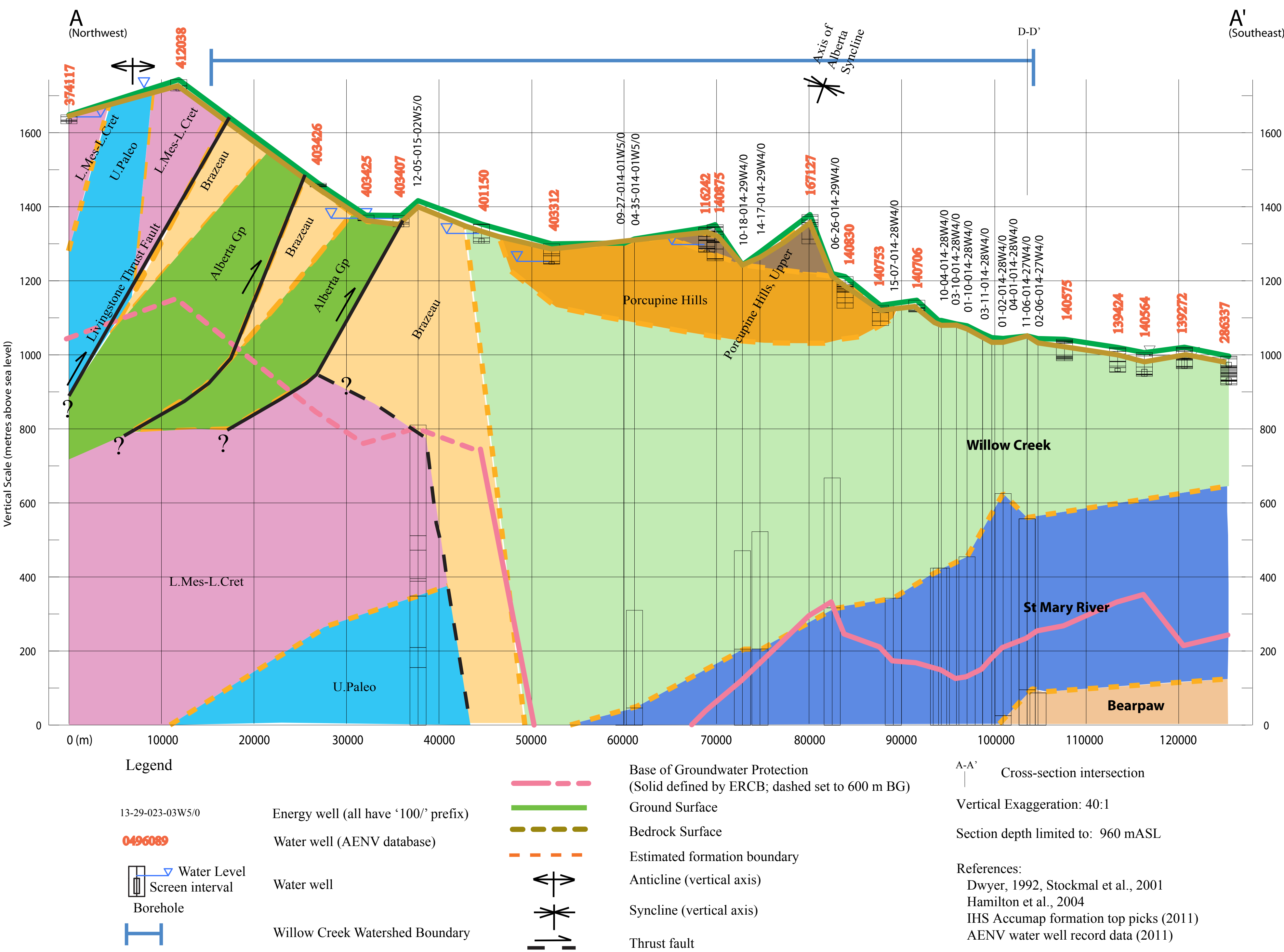
Alluvial aquifers are also recognized by topographic breaks (i.e., alluvial materials fill a river valley and are bounded by outcroppings of material that existed prior to the river (e.g., bedrock).

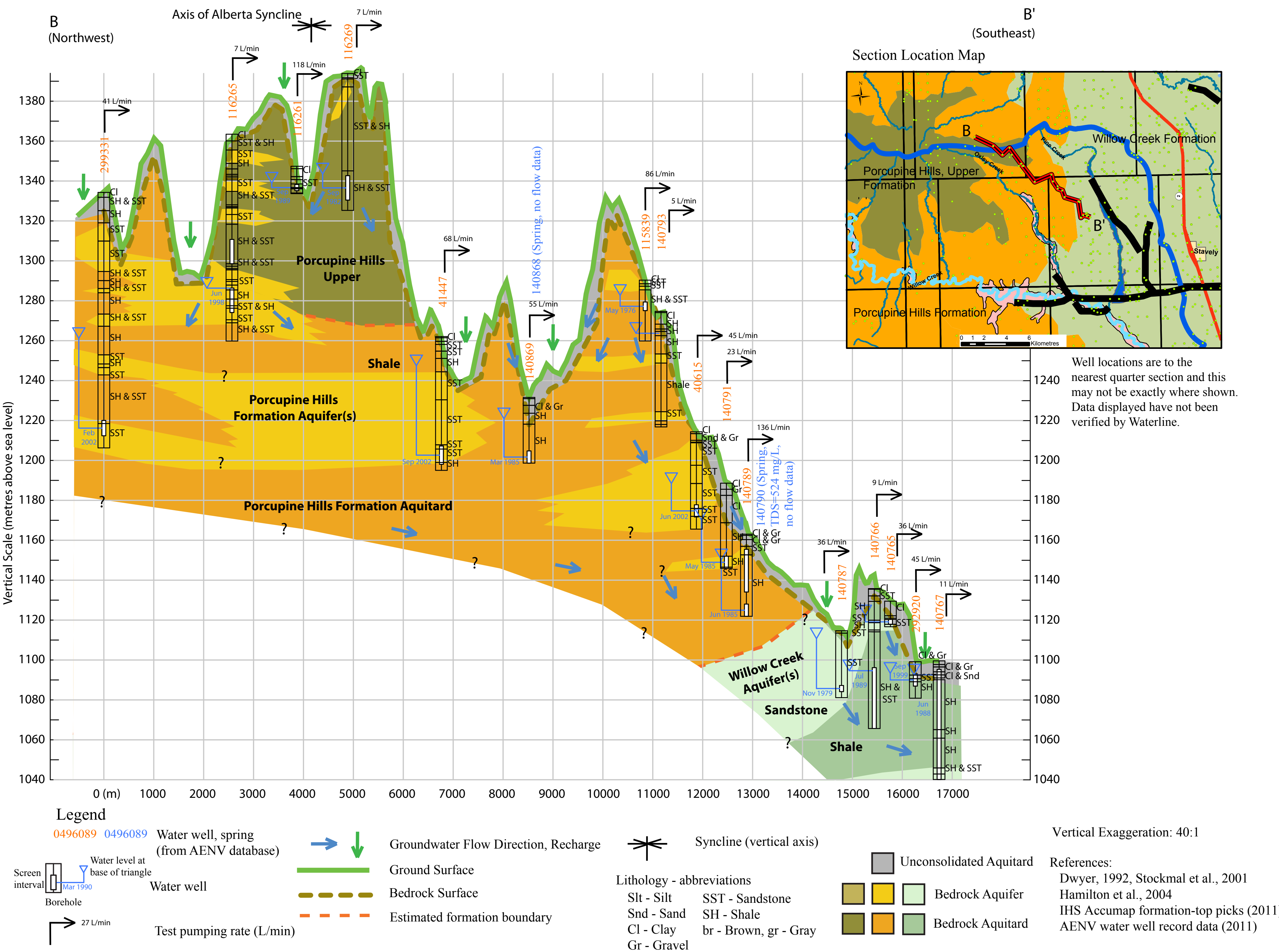
# APPENDIX B

# CROSS-SECTIONS

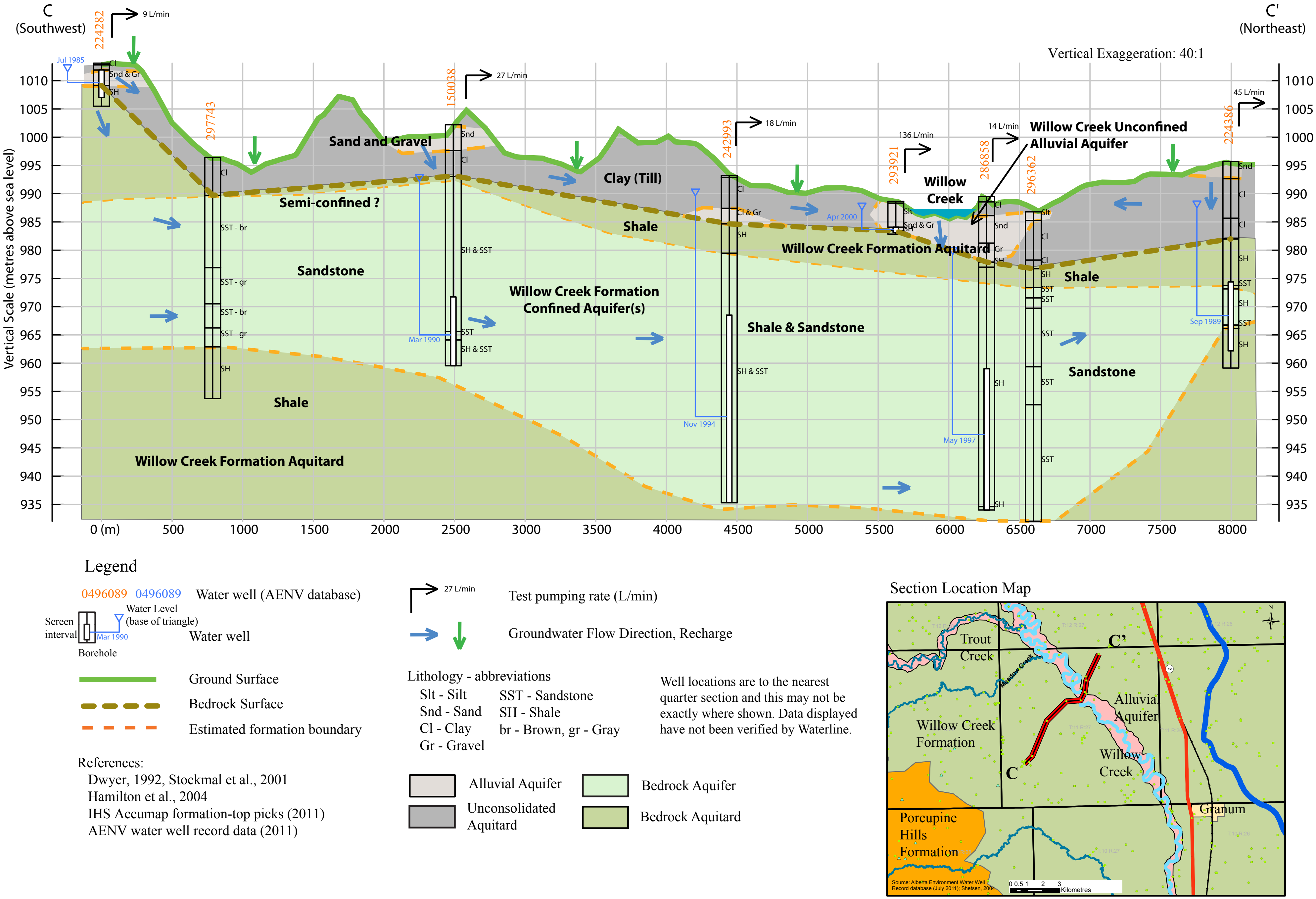


Source: Mossop and Shetsen, 1994; Hamilton et al. (2004)

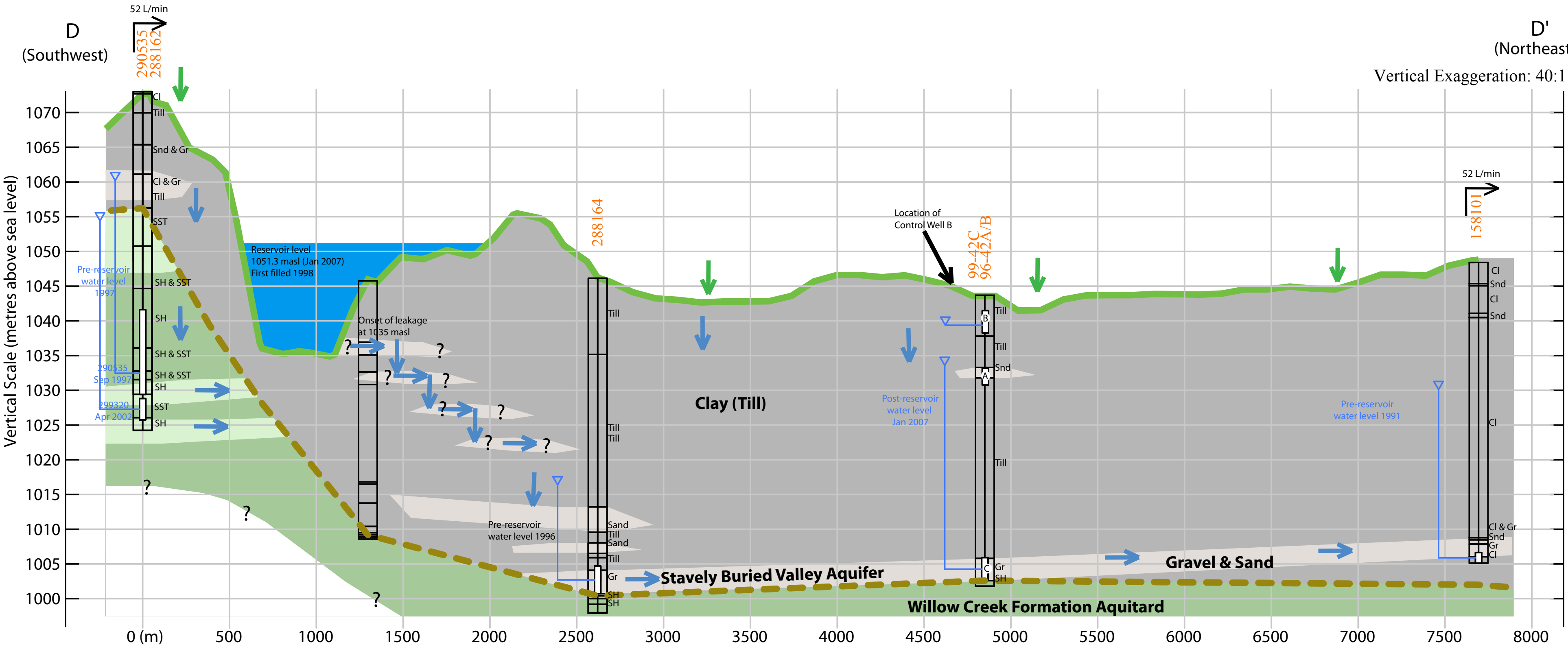

A
(Northwest)
A'
(Southeast)
D-D'
Axis of Alberta Syncline
374117
412038
403426
403425
403407
12-05-015-02W5/0
401150
403312
09-27-014-01W5/0
04-35-014-01W5/0
116242
140875
10-18-014-29W4/0
14-17-014-29W4/0
167127
06-26-014-29W4/0
140830
140753
15-07-014-28W4/0
140706
10-04-014-28W4/0
03-10-014-28W4/0
01-10-014-28W4/0
03-11-014-28W4/0
01-02-014-28W4/0
04-01-014-28W4/0
11-06-014-27W4/0
02-06-014-27W4/0
140575
139424
140564
139272
286337
L.Mes-L.Cret
U.Paleo
L.Mes-L.Cret
Brazeau
Alberta Gp
Brazeau
Alberta Gp
Livingstone Thrust Fault
Brazeau
Porcupine Hills
Porcupine Hills, Upper
Willow Creek
L.Mes-L.Cret
U.Paleo
St Mary River
Bearpaw
Vertical Scale (metres above sea level)
1600
1400
1200
1000
800
600
400
200
0
0 (m)
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
110000
120000
Legend
13-29-023-03W5/0
Energy well (all have '100/' prefix)
0496089
Water well (AENV database)
Water Level
Screen interval
Water well
Borehole
Willow Creek Watershed Boundary
Base of Groundwater Protection
(Solid defined by ERCB; dashed set to 600 m BG)
Ground Surface
Bedrock Surface
Estimated formation boundary
Anticline (vertical axis)
Syncline (vertical axis)
Thrust fault
A-A'
Cross-section intersection
Vertical Exaggeration: 40:1
Section depth limited to: 960 mASL
References:
Dwyer, 1992, Stockmal et al., 2001
Hamilton et al., 2004
IHS Accumap formation top picks (2011)
AENV water well record data (2011)



B
(Northwest)
Axis of Alberta Syncline
B'
(Southeast)
Section Location Map
Willow Creek Formation
Porcupine Hills, Upper Formation
Porcupine Hills Formation
Stavely
Willow Creek
Pine Creek
Kilometres
Well locations are to the nearest quarter section and this may not be exactly where shown. Data displayed have not been verified by Waterline.
Vertical Scale (metres above sea level)
Porcupine Hills Upper
Shale
Porcupine Hills Formation Aquifer(s)
Porcupine Hills Formation Aquitard
Willow Creek Aquifer(s)
Sandstone
Shale
299331
116265
116261
116269
41447
140868 (Spring, no flow data)
140869
115839
140793
40615
140791
140789
140790 (Spring, TDS=524 mg/L, no flow data)
140787
140766
140765
292920
140767
41 L/min
7 L/min
118 L/min
7 L/min
68 L/min
55 L/min
86 L/min
5 L/min
45 L/min
23 L/min
136 L/min
9 L/min
36 L/min
36 L/min
45 L/min
11 L/min
0 (m)
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000
17000
Legend
0496089 0496089 Water well, spring (from AENV database)
Screen interval
Water level at base of triangle
Mar 1990
Borehole
Water well
27 L/min
Test pumping rate (L/min)
Groundwater Flow Direction, Recharge
Ground Surface
Bedrock Surface
Estimated formation boundary
Syncline (vertical axis)
Lithology - abbreviations
Slt - Silt
Snd - Sand
Cl - Clay
Gr - Gravel
SST - Sandstone
SH - Shale
br - Brown, gr - Gray
Unconsolidated Aquitard
Bedrock Aquifer
Bedrock Aquitard
Vertical Exaggeration: 40:1
References:
Dwyer, 1992, Stockmal et al., 2001
Hamilton et al., 2004
IHS Accumap formation-top picks (2011)
AENV water well record data (2011)



C (Southwest)
C' (Northeast)
Vertical Exaggeration: 40:1
Vertical Scale (metres above sea level)
224282
9 L/min
Jul 1985
297743
150038
27 L/min
Mar 1990
242993
18 L/min
Nov 1994
293921
136 L/min
Apr 2000
286858
14 L/min
May 1997
296362
224386
45 L/min
Sep 1989
Sand and Gravel
Clay (Till)
Semi-confined ?
Shale
Sandstone
Willow Creek Formation Confined Aquifer(s)
Shale & Sandstone
Willow Creek
Willow Creek Unconfined Alluvial Aquifer
Willow Creek Formation Aquitard
Sandstone
Shale
Willow Creek Formation Aquitard
0 (m)
Legend
0496089 0496089 Water well (AENV database)
Screen interval
Borehole
Water Level (base of triangle)
Mar 1990
Water well
Ground Surface
Bedrock Surface
Estimated formation boundary
27 L/min Test pumping rate (L/min)
Groundwater Flow Direction, Recharge
Lithology - abbreviations
Slt - Silt
Snd - Sand
Cl - Clay
Gr - Gravel
SST - Sandstone
SH - Shale
br - Brown, gr - Gray
Well locations are to the nearest quarter section and this may not be exactly where shown. Data displayed have not been verified by Waterline.
Alluvial Aquifer
Unconsolidated Aquitard
Bedrock Aquifer
Bedrock Aquitard
References:
Dwyer, 1992, Stockmal et al., 2001
Hamilton et al., 2004
IHS Accumap formation-top picks (2011)
AENV water well record data (2011)
Section Location Map
Trout Creek
Willow Creek Formation
Alluvial Aquifer
Willow Creek
Porcupine Hills Formation
Granum
C
C'
Kilometres




## Legend

0496089 96-42A/B Water well (AENV database, Omni-McCann well)

Screen interval — Water Level (base of triangle) — Mar 1990 — Water well — Borehole

Ground Surface

Bedrock Surface

Estimated formation boundary

27 L/min Test pumping rate (L/min)

Groundwater Flow Direction, Recharge

Lithology - abbreviations

- Slt - Silt
- Snd - Sand
- Cl - Clay
- Gr - Gravel
- SST - Sandstone
- SH - Shale
- br - Brown, gr - Gray

Well locations are to the nearest quarter section and this may not be exactly where shown. Data displayed have not been verified by Waterline.

Alluvial Aquifer

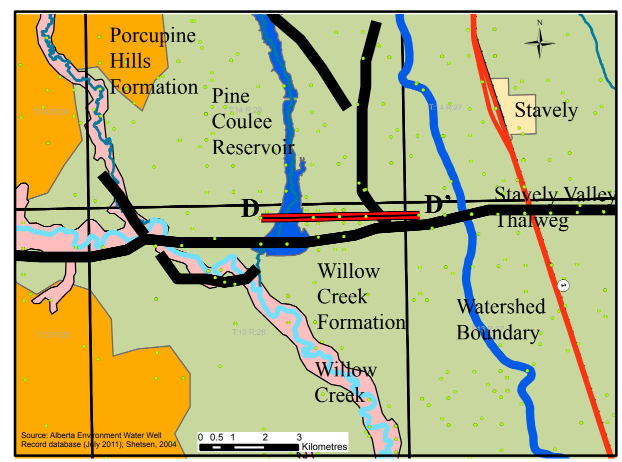
Unconsolidated Aquitard

Bedrock Aquifer

Bedrock Aquitard

References:

Dwyer, 1992, Stockmal et al., 2001
Hamilton et al., 2004
IHS Accumap formation-top picks (2011)
AENV water well record data (2011)




Section Location Map