Investigation of High Nitrate Concentrations in Groundwater near Fort Macleod, Alberta

Final Report

Prepared for:

Oldman Watershed Council
100, 5401 - 1st Avenue South
Lethbridge, AB T1J 4V6
(403) 382-4239

Prepared by:

Joan Rodvang, M.Sc., P. Geol.,
LandWise Inc.
Lethbridge, AB., Ph.: 403-320-0407
Email: Landys@telusplanet.net

Laura Good, M.Sc. Candidate
Geoscience
University of Calgary,

Dr. M. Cathryn Ryan, Ph.D., P.Eng, P.Geol.
Professor, Geoscience
University of Calgary, Ph. 403-220-2793

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Routine chemical analysis of groundwater samples was conducted by the Alberta Centre for Toxicology (ACFT). Robert Rippin, Environmental Health Officer with Alberta Health Services, assisted with numerous aspects of this project, including field data collection, conducting an initial tour of the study area, provision of background information, assistance with landowner contacts, and submission of samples to ACFT. Robert also supplied photos to the photo plates.

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The Groundwater Information Centre (GIC) managed by Alberta Environment and Sustainable Resource Development (ESRD) stores geology and groundwater data recorded by drillers. This database was invaluable for the current investigation. Particular thanks go to the data managers, Jeannette Homeniuk and Dave Cable, for their generous assistance in the use of this data.

The staff of Dollman’s Waterwell Drilling, including Ron Schmidt and Grant Buyers, generously allowed staff from LandWise and Alberta Health Services to accompany them and collect data as part of drawdown tests they conducted in the study area in February, 2013. Geologic descriptions recorded by drillers were instrumental in characterizing the geology of the study area, and in particular, the logs recorded by Dollman’s Waterwell Drilling were uniformly excellent.

Ron McNeil of LandWise Inc. provided technical expertise throughout the study, particularly in the understanding of geology and soils. Ron assisted with geology characterization in the field, and he led a field tour of gravel exposures in the study area. Ron provided several photo plates. Several other people provided their expertise during this field tour, including Greg Hartman from the Alberta Geological Survey, Gerry Osborn from the University of Calgary, and Kansie Fox, Conservation Biologist with the Blood Tribe Land Management.

Mike Iwanyshyn of the Natural Resources Conservation Board assisted with collection of data on confined feeding operations in the study area. Geoff Nash of ESRD provided detailed and meticulous unpublished geologic logs recorded in the study area during dugout and dam testing in the 1970s and 1980s. The MD of Willow Creek provided digital ortho-rectified aerial photography.

Most importantly, this study relied on the cooperation of landowners in the study area, who generously allowed their wells to be sampled, provided land for the installation of piezometer nests, and provided additional information relevant to the investigation. Their outstanding assistance is much appreciated.

EXECUTIVE SUMMARY

LandWise Inc. was commissioned by the Oldman Watershed Council (OWC), with funding from Alberta Health, to determine the source(s) of elevated nitrate in groundwater south of Fort Macleod, Alberta. The investigation has four major objectives.

- Conduct a hydrogeologic assessment to identify affected aquifers, confirm existing data on elevated nitrate, and identify potential sources and contributing factors.
- Develop a methodology that can potentially be used in the future to help determine the cause of elevated nitrate in groundwater at other locations.
- Develop recommendations to: a) protect the aquifer from additional nitrate loading; and b) improve groundwater quality in the area to a state that is suitable for human consumption.
- Share the methodology and results of the study with stakeholders.

The investigation was based on five main components.

1) Historic data recorded by drillers during the installation of water wells was compiled and interpreted, including lithology descriptions at 270 testholes, installation details and screen information for 114 wells, and production tests for 55 wells.

2) Groundwater chemistry analyses for inorganic ions and nitrate were compiled and interpreted for 123 samples collected from 1959 to 1986, and for 97 samples collected from 2002 to 2013.

3) Eighty-six groundwater samples were collected from domestic water-wells and springs for routine chemical analyses from February to September of 2013. Isotopic analyses included $\delta^{18}O$ and $\delta^{2}H$ in water on 46 samples for the determination of relative groundwater age, and $\delta^{15}N$ and $\delta^{18}O$ in nitrate on 26 samples to provide information on nitrate source and denitrification.

4) Eight piezometers were installed in nests at three locations in the study area, and piezometers were developed, tested and sampled.

5) A geographic information system (GIS) was developed for soils, geology and land use in the study area.

Bedrock in the study area is predominantly shale with some sandstone partings. From a major bedrock upland in the southwestern part of the study area, called the Ardenville Bench, ground slopes to the Waterton River in the south and southeast, the Belly River in the east, and the Oldman River in the north. A second upland bench, the McBride Bench, occurs at an elevation of about 30 m lower than the Ardenville Bench (Fig. 1). Glacial till is 20 to 40 m thick immediately west of the study area, and decreases in thickness to less than 5 to 8 m for the majority of the bedrock upland. Till is thin or intermittent on the slopes, so they are called scarps in this report. Till thickness increases to about 12 to 18 m in the plains areas, and to thicknesses of 20 to 40 m in the river valleys.

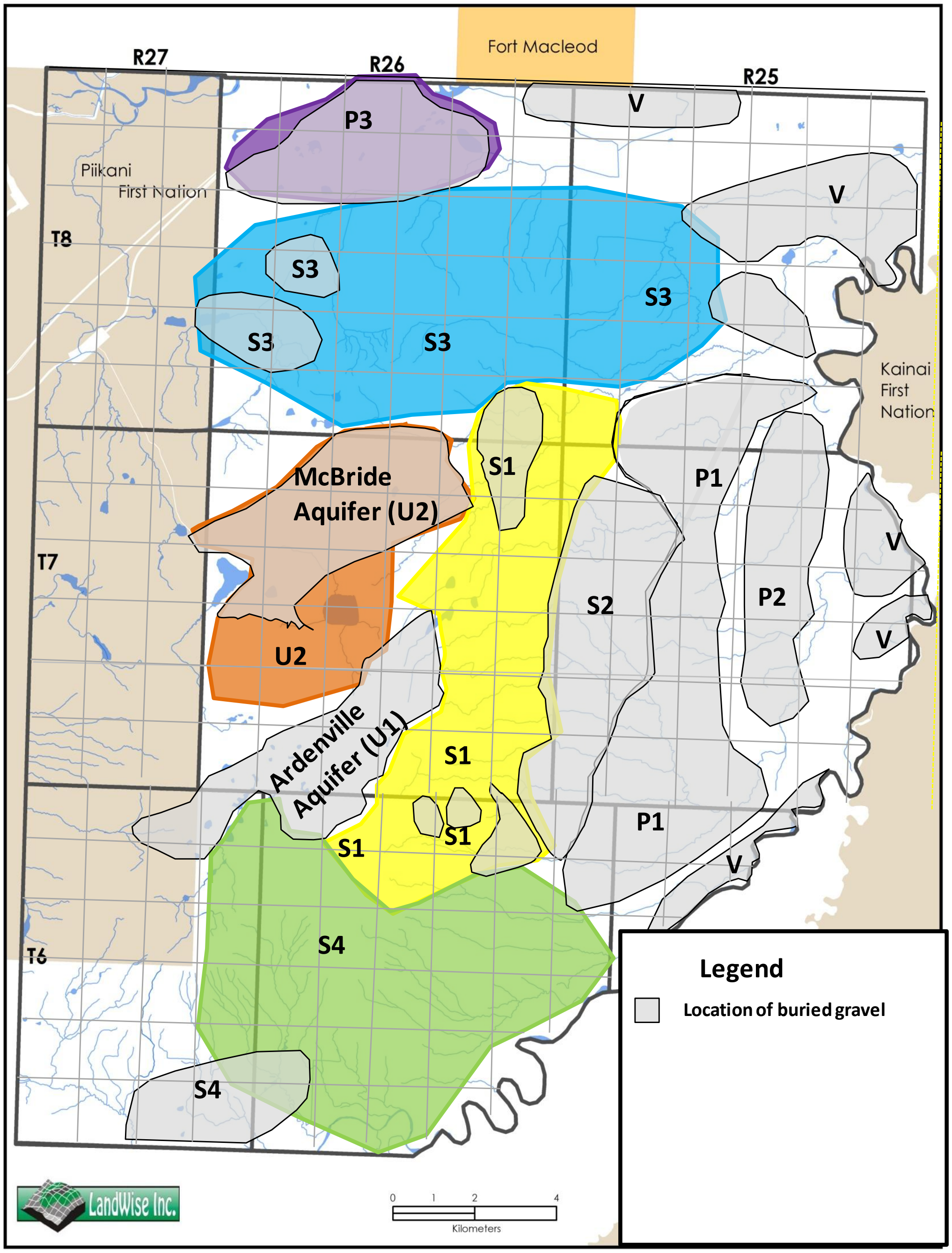

Fig. 1. The study area, showing the locations of preglacial gravel and physiographic areas, including upland benches (U1 and U2), scarps (S), plains gravels (P), and river valley gravels (V).

The study area contains at least six preglacial gravel aquifers between till and bedrock, and smaller areas of productive preglacial gravel are preserved at numerous locations (Fig. 1). Ten physiographic areas were defined. Most areas are centered on the location of major gravels, but gravels are mostly not preserved in scarp areas (S1 to S4) and in the McBride Channel (south of U2 gravels), and most water wells are installed in bedrock at these locations (Fig. 1).

Gravels are generally covered with till on their upslope sides, and pinch out along sloping lands on their downslope sides. Surface drainage channels originate where gravel layers intersect ground surface at the edges of the uplands and along the scarps, and where bedrock comes close to surface along the south and north scarps. Drainage channels have eroded till and are incised into bedrock along the scarps, and they carry groundwater and surface drainage from upland areas to the rivers.

Land use on upland and scarp areas is dominated by native range, hay land or improved pasture, and by non-irrigated annual cropping at lower elevations. The study area contains several confined feeding operations, with the highest density adjacent to the Belly River. Several confined feeding and bedding sites occur on the uplands.

Nitrate distribution was characterized for each physiographic area. NO_3-N concentrations were ≤ 0.5 mg/L in 87 of 239 water wells where chemistry data were available. The majority of wells that did not contain nitrate were deeper than 20 to 30 m (49 wells) or shallower than 6 m (22 wells). Nitrate was not commonly detected at locations underlain by thick till, including the western side of the study area and adjacent to river valleys.

Nitrate source was interpreted for each water-well based on $\delta^{18}O$ (H_2O), chemistry trends with time for wells and springs where repeat samples were available, profiles of NO_3-N concentrations with depth, and land use. Relative ages of groundwater were assessed using $\delta^{18}O$, where values less than -21‰ were indicative of glacial recharge, values less negative than -18‰ were indicative of relatively recent recharge, and values of -18 to -21‰ were considered to be a mixture.

Nitrate interpreted to be derived predominantly from agricultural sources was detected in 48 of 239 water wells and sampled springs. The wells were installed in both bedrock and gravel, and were located in almost all physiographic areas except S4. Most of these wells were installed at depths less than 7 m, but agricultural nitrate was potentially present to depths of 15 to 18 m in upper scarp locations (S1 and S3). Most agricultural nitrate occurred in groundwater with $\delta^{18}O$ values more positive than -18‰, and nitrate concentrations in some wells increased from the early 1980s to 2013. The goal of this study was not to identify specific agricultural sources, but wells with agricultural nitrate most commonly occurred near confined feeding operations or confined feeding and bedding sites. Almost 20% of nitrate detections interpreted to be agricultural exceeded the drinking-water guideline of 10 mg/L NO_3-N.

Nitrate interpreted to be derived predominantly from geologic sources was detected in 57 of 239 water wells. Geologic nitrate most commonly occurred in bedrock below 20 m depth, but was also interpreted to occur in gravels buried below till in the P1 area. Geologic nitrate occurred in groundwater with $\delta^{18}O$ values less than -19 to -21‰, indicating groundwater that was a mixture of glacial-aged and more recent recharge. Concentrations were often higher at depth than near ground surface, and concentrations did not change with time since the early 1980s. Approximately 45% of nitrate detections interpreted to be geological exceeded the drinking-water guideline of 10 mg/L NO_3-N, with maximum concentrations most commonly in the range of 15 to 30 mg/L.

Data collected and interpreted for this investigation, in addition to previous investigations, indicate geologic nitrate is associated with oxidized clay-rich glacial deposits over an area that extends from south of Fort Macleod to northeast of Vauxhall. Geologic nitrate has not been reported or documented at other Alberta locations, although the aerial extent of geologic nitrate in the province requires investigation.

Geologic nitrate in southern Alberta most commonly occurs in oxidized till below depths of approximately 5 m, so it is not expected to occur at locations where oxidized till is less than about 6 m deep. Evidence suggests geologic nitrate in buried gravels in the P1 and P2 areas originates via leaching from overlying oxidized till, with the potential for additional input via discharge from oxidized upslope bedrock. Geologic nitrate does not occur in gravels overlain by thick till (including the western side of the study area and the river valleys) because the gravels are separated from oxidized till by low-conductivity unoxidized till that does not contain nitrate.

The source of geologic nitrate in glacial till and bedrock in the Fort Macleod to Vauxhall areas requires additional investigation. Geologic nitrate in oxidized till may be produced via oxidation of organic nitrogen contained in the till, or it may have leached from a near-surface organic source such as a swamp or bog that perhaps once covered this area. Similarly, geologic nitrate in bedrock in the current study area may be the result of oxidation of organic nitrogen in the clay-rich bedrock, or it may have been leached from oxidized till or a near-surface organic source that was subsequently eroded from most upland and scarp locations.

The study area has a complicated geology and topography with a complicated groundwater flow system and the presence of both geologic and agricultural nitrate. Water wells with elevated nitrate were evaluated on a case-by-case basis to establish whether they are impacted by geologic or agricultural nitrate. Existing data were not sufficient to determine nitrate source for 47 of the 239 water wells, most of which were located in the upland Ardenville and McBride aquifers (Fig. 1). The gravels may receive geologic nitrate from upslope bedrock and/or overlying till, or the predominant source may be agricultural. Values of $\delta^{18}O$ (H_2O) were useful to identify groundwater recharged under glacial conditions (where nitrate is exclusively geologic), but groundwater in the majority of wells contained $\delta^{18}O$ values indicative of a mixture of glacial and recent recharge, making source determination difficult.

Three major recommendations arise from the current investigation.

Conduct Additional Research. Research is required in four main areas.

- **Nitrate source in the study area.** Age dates using tritium and tritium-helium are required to provide more information on nitrate source in the study area, particularly for the upland aquifers (Ardenville and McBride), where the current investigation was inconclusive. An on-going Master of Science thesis from the University of Calgary will provide interpretations of ^{13}C and ^{34}S data, which were not discussed in the current report. Groundwater monitoring is also warranted near the Belly River on the east side of the study area, where a relatively high density of CFOs occurs, and groundwater quality data were not available.

- **Extent of Geologic Nitrate in Alberta.** Current research has documented that geologic nitrate occurs in an area spanning from the current study area (south of Fort Macleod) to the Vauxhall area. Geologic nitrate has not been reported or documented at other Alberta locations, although the aerial extent of geologic nitrate in the province requires investigation. Investigations should initially focus on potential occurrence in relatively thick oxidized till. Potential occurrence in gravels and bedrock at other locations could be more easily investigated once the aerial extent of geologic nitrate in till has been documented.
- **Source of Geologic Nitrate.** Additional research is required to determine the source of geologic nitrate in Alberta, and the conditions under which it occurs. The occurrence of geologic nitrate in oxidized glacial deposits in the Picture Butte to Vauxhall area has been well documented in previous research, and the current investigation south of Fort Macleod shows geologic nitrate also occurs to relatively shallow depths in shale bedrock, and in gravels that receive geologic nitrate from overlying oxidized till. Potential sources of geologic nitrate in till and bedrock include in situ oxidation of organic nitrogen, or downward leaching from a previous till or large bog that potentially covered the area at one time. An understanding of the source of geologic nitrate would allow for improved predictions about where it is likely to occur.
- **Tools to Identify Nitrate Source.** In addition to the requirement for increased understanding of the source and aerial extent of geologic nitrate, cost-effective geochemical or isotopic indicators may also potentially be developed to distinguish agricultural from geologic nitrate. The detection of enriched tritium is an important indicator of groundwater that recharged since about the 1960s.

Protect Groundwater Quality

Nitrate interpreted to be derived from agricultural sources was detected in shallow groundwater in bedrock and gravel at many locations in the study area. Landowners should be provided with information about the importance of protecting local groundwater resources, and management practices that protect local groundwater should be encouraged, particularly at locations with relatively high groundwater vulnerability, including upland areas (U1 and U2) and scarp areas (S1, S2, and S3) where till is relatively thin over gravels or bedrock.

Regulatory programs should be reviewed to ensure they include adequate protection for shallow groundwater. Shallow groundwater resources that are not currently used may become important in the future, and contaminated shallow groundwater can impact surface water.

Agricultural sources for nitrate should initially be investigated in most shallow groundwater in Alberta. Geologic nitrate has not been reported or documented at other Alberta locations. Potential agricultural nitrate sources should initially be investigated because they are generally more common and more easily identified than geologic sources, in addition to offering the possibility for improved groundwater quality when management practices are improved. Annual collection of samples from key water wells could provide direct information on how changes in agricultural practices are affecting water quality. Drinking-water treatment will be required at locations where nitrate exceeds drinking water guidelines.

Collect and Manage Groundwater Data in a Publicly Accessible Database

Groundwater quality data should be included in the Groundwater Information Centre (GIC) database of Alberta Environment and Sustainable Resource Development. Groundwater quality cannot be understood in isolation from controlling factors such as well depth, lithology, and installation details, so groundwater quality data should be included with other groundwater data as part of the GIC. The agency in charge of the groundwater database should be staffed with sufficient manpower to allow staff to determine or confirm well depth when samples are submitted for analysis, and to match chemistry samples with existing well logs that include documented lithology and installation details. The GIC database, including groundwater quality data, should continue to be easily accessible to the public.

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INTRODUCTION

Alberta Health Services (AHS) conducted baseline groundwater quality testing in 2008 in an area south of Fort Macleod, Alberta (Township 7 Range 26 W4M). The testing was conducted in response to concerns about wind tower construction over a shallow aquifer in the area. The testing in 2008 indicated that several wells contained nitrate concentrations higher than the Canadian drinking-water guideline of 10 mg L^{-1} NO_3-N (OWC 2012). This finding caused concern because nitrate can cause methemoglobinemia in young children, and has been linked to negative reproductive outcomes and some forms of gastric cancer (Fan and Steinberg 1996), among other concerns reviewed by Ward (2005). A recent discussion document by Health Canada recommends Canadian Water Quality Objectives for NO_3^--N of 10 mg N/L, and 3 mg N/L for nitrite as $NO2^-$-N (Health Canada 2012). A Canadian guideline of 3 mg N/L was recently established for the protection of aquatic life (CCME 2012).

Alberta Environment and Sustainable Resource Development (ESRD) compiled available background data on the hydrogeology of the area (Townships 7 and 8, Ranges 25 and 26) in 2012. Data gaps in the compilation prevented any conclusion being drawn as to the potential source of the nitrate (ESRD 2012).

Hydrogeological Consultants Ltd. (HCL) was commissioned by ESRD to conduct a groundwater evaluation in the area, based on a compilation and interpretation of existing water well data and other available information. In the resulting report, HCL (2012) concluded that two of 34 nitrate samples in surficial deposits exceeded Canadian Health guidelines for nitrate, and “Elevated nitrate + nitrite (as N) and chloride concentrations, when present, can often be attributed to physical conditions at or near the water well, and do not indicate general groundwater conditions” (HCL 2012). Hydrogeological Consultants Ltd. also provided several recommendations for a field investigation to improve the understanding of groundwater in the study area, based on the collection of field data from existing water wells. They also recommended the installation of groundwater monitoring instrumentation to fill major gaps in the geological data, and to provide samples from specific hydrostratigraphic units that may contain the nitrate source(s).

The current investigation was commissioned by the Oldman Watershed Council (OWC), with funding from Alberta Health, to address the need for additional information, particularly the distribution, most probable source(s), and potential fate of nitrate in well water in each hydrostratigraphic unit in the study area south of Fort Macleod. The study is based on a detailed compilation and interpretation of existing information, and a field program that included installation and testing of piezometer nests and the sampling and testing of piezometers and domestic water wells in the study area. Four major objectives of the study were as follows.

- Conduct a hydrogeologic assessment to identify affected aquifers, confirm existing data on elevated nitrate, and identify potential sources and contributing factors.
- Develop recommendations to: a) improve groundwater quality in the area to a state that is suitable for human consumption, and b) protect the aquifer from additional nitrate loading.

- Develop a methodology that can potentially be used in the future to help determine the cause of elevated nitrate in groundwater at other locations.
- Share the methodology and results of the study with stakeholders.

This study was conducted in conjunction with a Master of Science thesis at the University of Calgary. The thesis by Laura Good will focus in more detail on groundwater chemistry and isotopic interpretations.

The study area is located approximately 50 km west of Lethbridge and immediately south of the town of Fort Macleod, in the Foothills and Southern Tributaries Sub-basins of the Oldman Watershed in southern Alberta (Fig. 2). The study area includes most of Townships 6, 7 and 8, Ranges 25 and 26 W4M. The eastern portion of Range 27 was included in the study area, but data were very limited in that area. The study area is bounded by the Oldman River on the north, the Belly River on the northeast, and the Waterton River on the south and southeast (Fig. 2), and it was located between the Piikani First Nation on the west and the Kainai First Nation on the east. The area studied by HCL (2012) is similar to the current study area, but the HCL study area also includes portions of Townships 9 and 10 and Range 24.

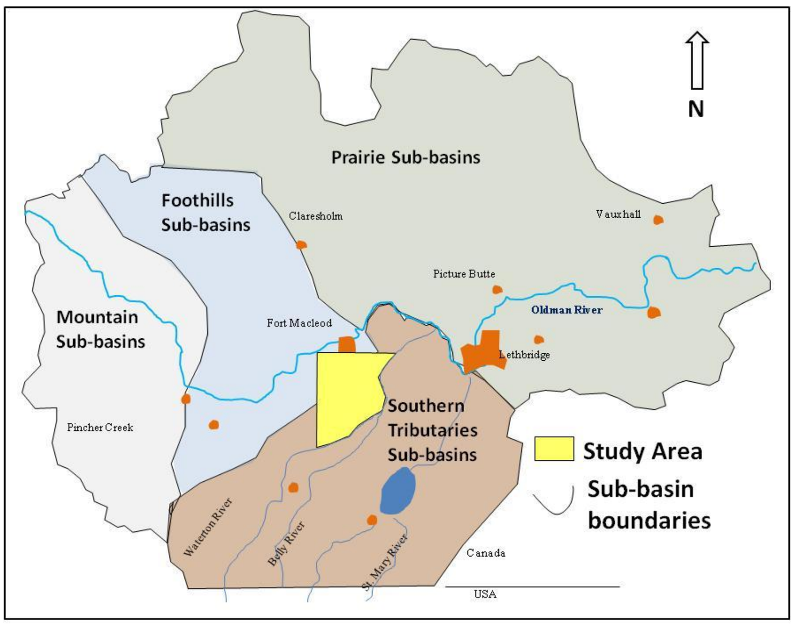

Fig. 2. The study area in the Oldman Watershed.

Background hydrogeologic information pertinent to the current investigation is summarized in Appendix 1. Appendix 1 includes basic information on: i) isotopic tools used in groundwater investigations, ii) the geology and typical groundwater chemistry and isotopic content of southern Alberta groundwater, and iii) current knowledge regarding the occurrence and potential denitrification of agricultural and geologic nitrate in southern Alberta. Readers who require more information on these relevant background topics are encouraged to read Appendix 1 or portions thereof before reading this report.

METHODS

This investigation was based largely on seven main components.

1. Existing soil, land use and geology data for the study area was assembled into a geographic information system.
2. A large amount of existing data related to previous drilling of domestic water wells in the study area were compiled, interpreted, and used to develop geologic cross-sections and to refine the geographic information system for the study area. Static water-level data and pumping test information were also compiled and interpreted.
3. Historic chemistry data were assembled and interpreted.
4. Groundwater samples were collected from domestic wells for the analysis of chemistry and environmental isotopes.
5. Three piezometer nest locations were selected, and piezometers were installed, tested, and interpreted.
6. A data set was prepared that included historic chemistry data and chemical and isotopic data collected during the 2013 field season. The data set was interpreted to characterize nitrate distribution, source and fate in the study area.
7. Results of this investigation were used to provide recommendations for maintenance or improvement of groundwater quality in the study area. Recommendations were developed to assist in the design of future investigations into nitrate distribution, source and fate.

Collection and Compilation of Historic Data

Routine Chemistry Data

Historic well and chemistry data obtained and interpreted for the current investigation are summarized in Table 1, along with a comparison to the quantity of field data collected during 2013. Well-water chemistry data collected before 1986 are stored in the Groundwater Information Centre database. Well-water chemistry collected after that time was analyzed by the Alberta Centre for Toxicology (ACFT) and stored in their database. Approximately 30% of the routine chemistry samples were collected from water wells during the current investigation, with an additional 30% collected from 2002 to 2013, and the remaining 40% collected from 1970 to 1986 (Table 1). No groundwater chemistry records are available for the 1986 to 2002 time period because they were lost during data transfer from the GIC warehouse to the ACFT warehouse.

Table 1. Data source for groundwater chemistry samples.

Chemistry Samples			Water Wells and Piezometers Installed	
Data Source	**Years of Collection**	**Number of Samples**	**Year**	**Number of Wells Installed**
***GIC**	1959 - 1969	7	1959 - 1969	27
	1970 – 1978	37	1970 – 1978	39
	1979 - 1986	79	1979 - 1989	132
***ACFT**	1986 - 2002	0	1990 - 1999	26
	2002 - 2013	97	2000 - 2013	49
Current Study	Feb – Aug. 2013	86	2013	8 piezometers in 3 nests
Total		**306**		**281**

*GIC is the Groundwater Information Center. ACFT is the Alberta Centre for Toxicology.

A few more than 300 routine groundwater chemistry samples were obtained, including eight samples from piezometers and 24 spring samples. The remaining samples were from wells, but a significant number of the wells were cribbed springs or very shallow wells. Groundwater samples represent 180 different wells or springs (groundwater discharge locations) (Fig. 3), because numerous locations are represented by more than one sample. Several wells were sampled on more than one date, and the legend in Fig. 3 lists the most recent sample date. The phrase “and before” in the legend indicates that some sample locations may also include earlier sample dates. Chemistry data, including historic data and 2013 data, are contained in Appendix 4.

Well and Lithology Data

The GIC Database, which is maintained by ESRD, contains records of the information recorded by drillers during the installation of water wells in Alberta (ESRD 2012). The following GIC data for the study area were downloaded from the website.

- A record of installation that included at least the depth and year of installation for 273 wells, including 71 wells that were abandoned due to insufficient production. Almost three-quarters of the wells were installed before 1990 (Table 2).
- Lithological descriptions obtained during the drilling of 270 test holes representing 191 different quarter-section locations. Locations are shown in Fig. 3 and all lithological descriptions are contained in Appendix 5.
- Screen or perforation depth information for 114 wells.
- Pump-test data for 55 wells. Wells were usually pumped for a maximum of two hours, while recording water-level drawdown during pumping and recovery. All pump-test data are contained in Appendix 8.
- Measured static level depths for 244 wells (Appendix 9).

Lithology data at a few locations were also obtained from detailed descriptions recorded by Alberta Environment staff during the excavation of dugouts in the 1970s and 1980s.

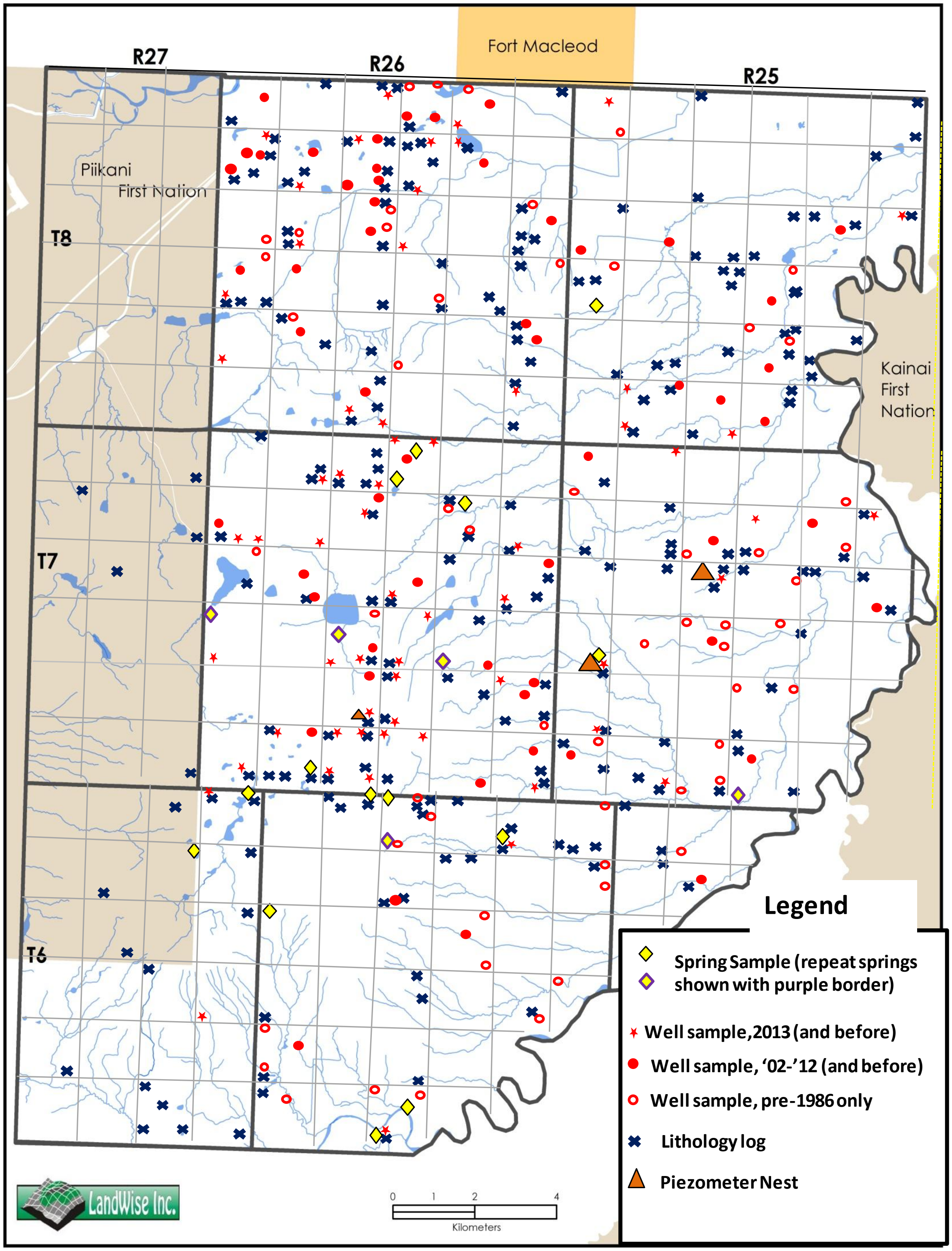

Fig. 3. The study area, showing the location of water samples and lithology logs.

Field Data Collection

Field Work in February 2013

The team of principal investigators visited the study area on a number of occasions in February, 2013. Dollman's Waterwell Drilling conducted simple drawdown tests in the study area in February of 2013, in preparation for planned seismic work. Joan Rodvang of LandWise Inc. and Robert Rippin of Alberta Health Services accompanied them for three field days, during which time 23 wells were visited. Field data collection included information on well location and conditions around the well head, measurements of total well depth, latitude and longitude from a hand-held global positioning system (GPS) unit, and water levels recorded during one hour of pumping and one hour of recovery on each well. Groundwater samples were collected from 21 water wells and submitted to the ACFT for analysis of routine parameters.

Spring 2013 Water Sample Collection

Sample locations for wells sampled in February were those being tested by Dollman's Waterwell Drilling. Locations for samples collected in May were determined from an analysis of existing chemistry and geology data for the study area. The focus was on shallow wells in representative locations. Sample locations for springs were determined by field surveys of optimal locations. Sample locations were those near the origin of springs, and ideally near roadsides for ease of sampling.

Permission was obtained from each well owner before sampling. Almost 100% of approached well owners agreed to have their well sampled. The following tasks were conducted at each well and spring sampled.

- Total well depth, static level (Plate 1), and the height and diameter of the well casing were measured. Static level measurements, including measurements in 2013 and historic data from the GIC database, are contained in Appendix 9.
- GPS readings were collected for latitude, longitude and elevation.
- Each well or spring was pumped using either a peristaltic pump (for wells shallower than 8 m) or a manual foot valve (for wells deeper than 8 m), until temperature and dissolved oxygen readings were low, stable, and representative of groundwater unaffected by surface air. The pumping rate and drawdown were measured during the entire period of pumping. All down-hole equipment, including pump tubing, foot valves, and chemical parameter probes, were thoroughly cleaned with deionized water before lowering into each well. Bottles were thoroughly rinsed with well or spring water before filling.
- Once temperature and dissolved oxygen readings were low and stable, in situ measurements of the following chemical parameters were collected: temperature, barometric pressure, pH, electrical conductivity (EC), alkalinity, and dissolved oxygen.
- Two samples were collected from each location. A 750 mL sample was submitted to the Alberta Centre for Toxicology for the analysis of major ions, nitrate (NO3-N), nitrite (NO2-N), fluoride (F), iron (Fe), and laboratory alkalinity, pH and EC. A 1-L sample was filtered through 0.45 μ filters on the day of collection, frozen after filtration, and sent to the University of Calgary for isotope analysis.
- Local conditions were described around each sampled well or spring.

Five groundwater springs in the study area were selected for repeat sample collection approximately every two weeks, in order to monitor time trends. Locations are shown in Fig. 3. Springs for repeat analyses were selected based on: i) flowing spring water, rather than stagnant water such as spring-fed dugouts and wetlands; ii) predicted to flow throughout the summer, based on visual observations; iii) representative of different locations in the study area.

Collected samples were filtered, frozen, and sent to University of Calgary for analysis of major ions and isotopes.

Water Analyses

Isotope analyses were conducted at the University of Calgary using a mass spectrometer. Isotopic analyses included ^{18}O and ^{2}H in water, ^{13}C in dissolved inorganic carbon, ^{34}S and ^{18}O in sulphate, and ^{15}N and ^{18}O in nitrate. Detailed isotopic results will be discussed in the forthcoming Masters thesis from the University of Calgary that was conducted in conjunction with this investigation, but the current report includes pertinent results for ^{18}O and ^{2}H in water and ^{15}N and ^{18}O in nitrate.

Water samples were analyzed by ACFT for major ions, nitrate, nitrite, and dissolved iron and fluoride. All chemical analysis results, including historic data and samples collected in 2013, are contained in Appendix 4.

Pesticide Sampling and Analysis

Thirteen water-wells and piezometers were selected for the analysis of 104 pesticides. Selected wells were shallow and in the most vulnerable locations for pesticide contamination, based on land use and geology. Appendix 7 contains all information related to the pesticide analysis, including well locations, sampling and analytical methods, pesticides analyzed, and results. No pesticides were detected, and the results are not discussed further in this report.

Drilling and Piezometer Installation, Development and Sampling

Drilling locations were selected based on the compilation and interpretation of existing data. Eight piezometers were installed at three locations in the study area (Fig. 3). Each location was in a farmyard or former farmyard, at a location with no immediate sources of nitrate or anthropogenic contamination. Drilling and piezometer installation was conducted by Chilako Drilling. Geology at the three locations was described in detail and sediment samples were collected at regular intervals. Piezometer installation details and lithology logs are contained in Appendix 6.

Each piezometer was developed and sampled in August of 2013. The purpose of development is to remove fine particles that may clog piezometer screens, contaminate water samples, and decrease water flow through the screen. Development consisted of alternately pumping with a submersible pump and surging with a Waterra surge block. Surging forced water to move in and out of screens to help remove fine particles. Development continued until pumped water was clean and free of sediment. Groundwater samples were then collected and submitted to the ACFT for analysis.

Hydraulic conductivity tests were conducted on each piezometer in September. A slug in the form of a solid PVC pipe was dropped into each piezometer. Water level readings were recorded until the displaced water level returned to the static level.

Development of a Geographic Information System

Databases used in the geographic information system (GIS) were obtained from government websites, including the following.

- Soils: Agricultural Region of Alberta Soil Information Database (ASIC 2001).
- Bedrock geology: Bedrock Geology of Alberta (Hamilton et al. 2004).
- Surficial geology: Quaternary geology of southern Alberta. (Shetsen 2002).
- Land use: Grassland Vegetation Inventory (ESRD 2011).
- Site types in undeveloped areas: Grassland Vegetation Inventory (ESRD 2011).
- Legal survey and infrastructure data: Available data was downloaded from the Spatial Data Warehouse (2012).
- Surface topography and hydrography: GIS layers prepared by HCL (2012).
- Existing water well data: The Alberta Water Well Information Database (ESRD 2013).

Aerial photography that was flown for the study area in the fall of 2012 was provided by the MD of Willow Creek. The GIS was prepared and completed by Samantha Managh of Honu Consulting in Calgary.

The Grassland Vegetation Inventory (GVI) was simplified to prepare a map distinguishing native rangeland from annual and perennial cropping.

Data Interpretation

Lithology data downloaded from the GIC were used to prepare numerous geologic cross-sections throughout the study area. Cross-sections were required to characterize and understand the complex surficial and bedrock geology and landscape types in the study area. In addition, lithological logs were not available for many of the historic groundwater chemistry samples. Due to the complex nature of the geology and topography in the study area, geologic cross-sections were required to determine the most probable geology of samples without associated lithology recorded during drilling. Once the cross-sections were used to determine the most probable geology for a chemistry sample, chemistry results were interpreted in relation to geology and topography.

Transmissivity values were calculated for all 55 GIC wells where pump test data were available. Transmissivity values were also calculated for 19 pump tests conducted in February of 2013 by Dollman Water Well Drilling. Transmissivity calculations and results are contained in Appendix 8.

Chemistry and isotopic data were interpreted in relation to geology and topography. Geochemical trends were investigated using piper plots, x-y plots, and numerous other investigative tools.

RESULTS AND DISCUSSION

Quality of Historic Data

The location of lithology logs downloaded from the GIC are shown in Figure 3. The vast majority of drill records were accurate and of sufficient detail to provide valuable information on geologic stratification and water-bearing layers. Lithology logs were of sufficient density to provide a relatively detailed characterization of geology for the majority of the study area, although data were more scarce for Tp. 6 Rg. 26 and Tp. 8 Rg. 25 (Fig. 3). The highest density of lithological logs was available for Tp. 7 Rg. 26 and Tp. 8 Rg. 26, with 43 and 48 locations, respectively (Figure 3). Lithology logs are contained in Appendix 5.

Only a few lithologic logs and no groundwater chemistry data are available for the Pikani First Nation to the west of the study area (Figure 3). However, the western boundary of Rg. 26 generally represents the groundwater divide, and the ground surface slopes east and west from that area. Therefore, the eastern boundary of the Piikani First Nation generally forms a close-to-natural western boundary for the study area.

All chemistry data are contained in Appendix 4, sorted by location. The following factors were considered during the interpretation of historic groundwater chemistry data from the GIC and ACFT databases.

- Groundwater chemistry data collected in Alberta from 1986 to 2002 were permanently lost from the ACFT database due to computer malfunction. This significant gap in the record made it more difficult to interpret potential changes in groundwater chemistry with time.
- Many groundwater samples contained in the GIC and ACFT could not easily be matched to well records for the same well. One of the most common problems was poor depth control, because people submitting samples sometimes do not know the depth of the sampled well, in which case an approximate depth or best guess value is generally attached to the sample.
- Many wells lacked well installation details, including screen information. The length of the screened or perforated interval in water wells can vary over a wide range, and this length can have an important effect on groundwater chemistry because it affects which formations the well draws water from. However, the majority of wells were clearly screened in either gravel or bedrock, based on well depth. A significant number of wells were screened across the gravel bedrock interface, but piezometer data provided more information on geochemical changes across the gravel/bedrock interface.
- Some groundwater samples are located in areas without near-by lithology records that can be used to interpret the most probable geology. Geologic cross-sections were a very useful tool for the interpretation of the most probable geology for those samples.
- Wells are generally located only to the centre of the quarter section. This can cause some reduction in the accuracy of matching lithology to chemistry in cases where more than one well occurs in a section. Topography and geology in most quarter sections were uniform enough to prevent this from being a significant problem.

Topography and Land Use

Topography and Soil Zones

Ground surface elevation in the study area is illustrated in Fig. 4. A high-elevation area commonly termed the Ardenville Bench occurs near the southwestern corner of the study area. Ground elevation decreases from 1173 m on the Ardenville Bench, to just higher than 900 m along the Belly River in the northeastern corner of the study area. The upper surface of the Bench is relatively flat-lying, but elevations decrease in scarps and slopes at the edges of the Bench. Topographic slopes are 1.6% on the eastern side of the Bench in Tp. 7 Rg. 26, and 1.75% on the south-facing scarp between the Bench and the southern edge of Tp. 6 Rg. 26. The Ardenville Bench grades more gently to the McBride Bench to the north, but ends in a north-facing scarp with a slope of up to 5.2 % in the southern portion of Tp. 8 Rg. 26 (Fig. 4). Topography also slopes away to the west from the upland benches to topographic lows created by Scott`s Coulee and the northeasterly-trending Oldman River.

The Ardenville Bench and McBride Benches (light green areas on Fig. 5) are in the Black Soil Zone, while the lower elevation area surrounding it is in the Dark Brown Soil Zone. The soil data reflects the higher precipitation and cooler climate that occurs at the high elevations on both Benches.

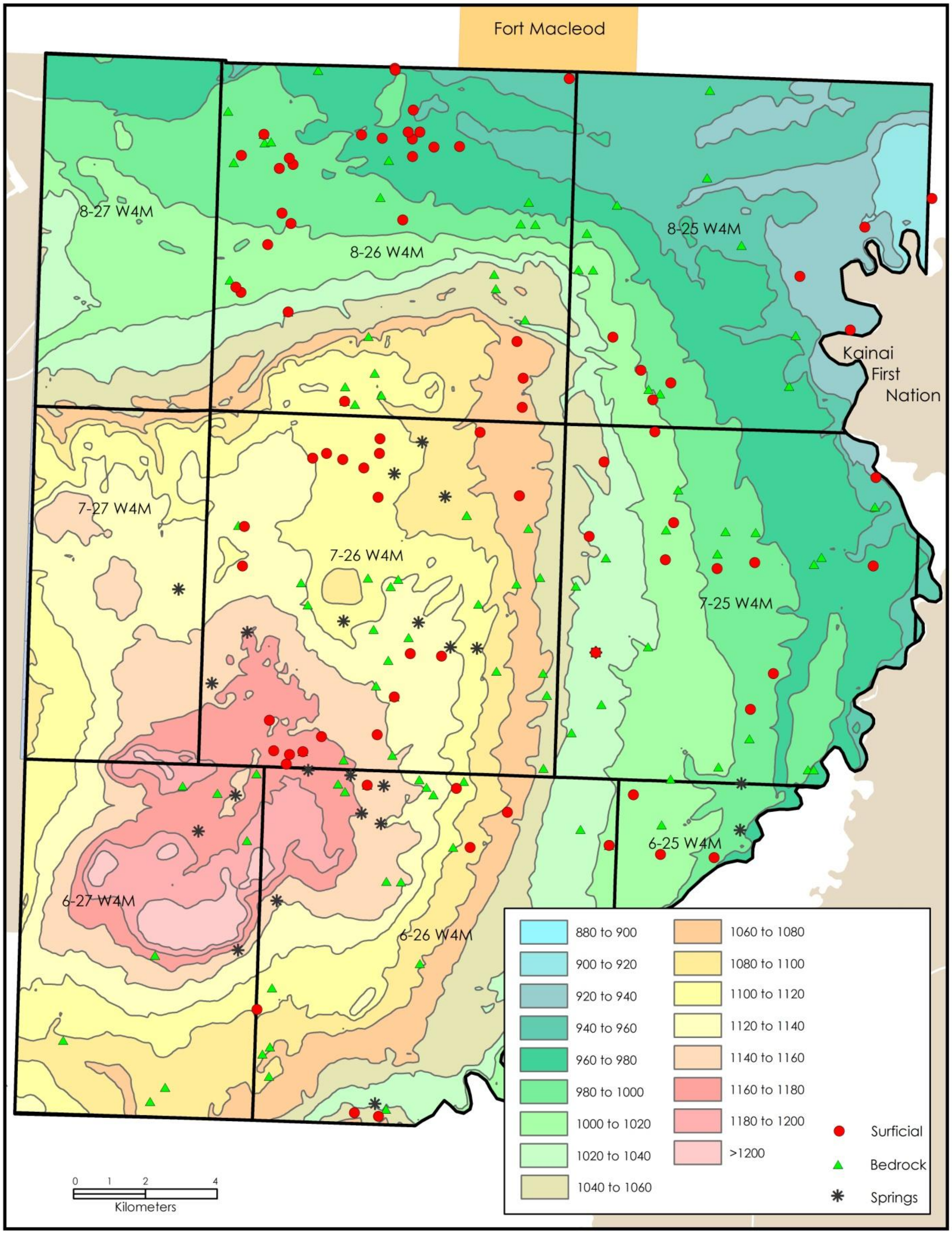

Fig. 4. Ground elevation in the study area.

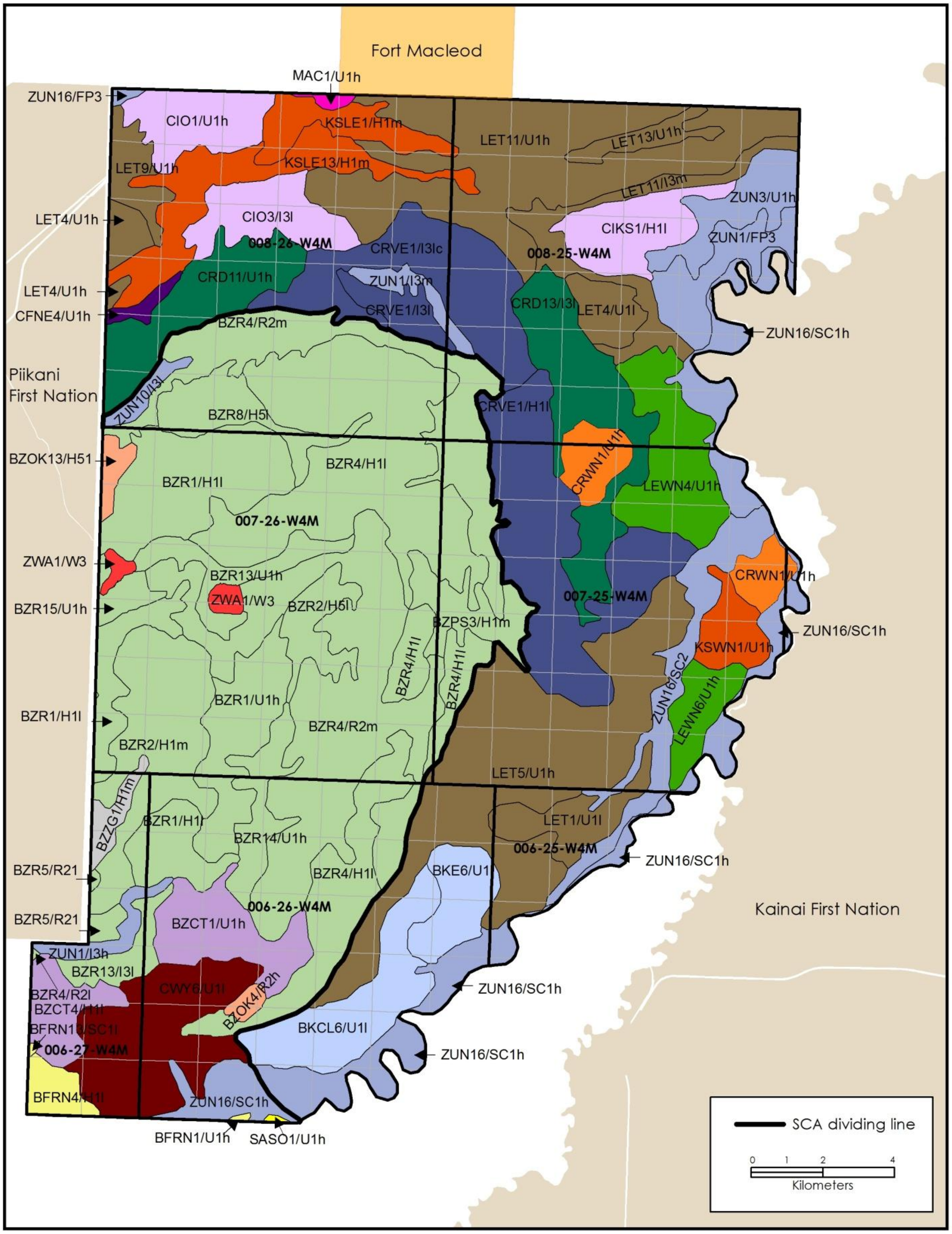

Fig. 5. Soil zone boundary and Soil Landscape Model polygons. (ASIC 2001).

Land Use

An overview of land use can be observed on aerial photography flown in the fall of 2012 (Fig. 6). Land use is dominated by native range, hay land or improved pasture, and annual cropping. Land use is more clearly illustrated in Fig. 7, which was prepared from the Grassland Vegetation Inventory.

- Native range and tame pasture are the dominant land uses on the Ardenville Bench, upland and scarp areas, due to soil and topographic limitations. This area contains some relatively small areas of non-irrigated cropland, and several winter bedding and feeding areas for livestock.
- Native range is the predominant land use on the Piikani First Nation west of the study area, although this area is not shown on Figs 6 or 7.
- Non-irrigated cropland is the dominant land use in the plains areas of Tp. 7 Rg. 25, Tp 8 Rg. 25, and Tp. 6 Rg. 26.
- Irrigation is limited mainly to sections near the Waterton and Belly rivers.
- Locations noted as rural or developed include two Hutterite colonies, farmsteads, and CFOs. Locations of registered CFOs were obtained from the Natural Resources Conservation Board (NRCB) public website. Other potential agricultural sources of nitrate listed in Table 3 were observed during field work in the study area, and from air photo interpretation. Most of the permitted CFOs in Tp. 6, Rg. 26 and Tp. 7, Rg. 25 are associated with the two Hutterite colonies, one near the Waterton River at the south and the other near the Belly River at the east.

Table 3. Confined feeding operations in the study area.

Location (Tp. – Rg.)	Permits Registered with Natural Resources Conservation Board			Other Operations Not Registered with the Natural Resources Conservation Boards
	*Approvals	*Authorizations	*Registrations	
6-26	5 for 1 location			
7-25	1	12 for 1 location		1 swine operation; 1 unknown livestock species
7-26				2 swine operations; 3feeding and bedding areas; 2 abandoned barns for hogs and cattle
8-25	7 for 3 locations	2 for 1location	6 for 2 locations	1 feedlot; 3 dairy; 1 swine operation
8-26	1		1	1 piggery; 1 poultry; 1 dairy

- *Note: Approvals are for relatively large confined feeding operations (CFOs), and registrations are for smaller CFOs. Authorizations are for manure collection or storage areas.

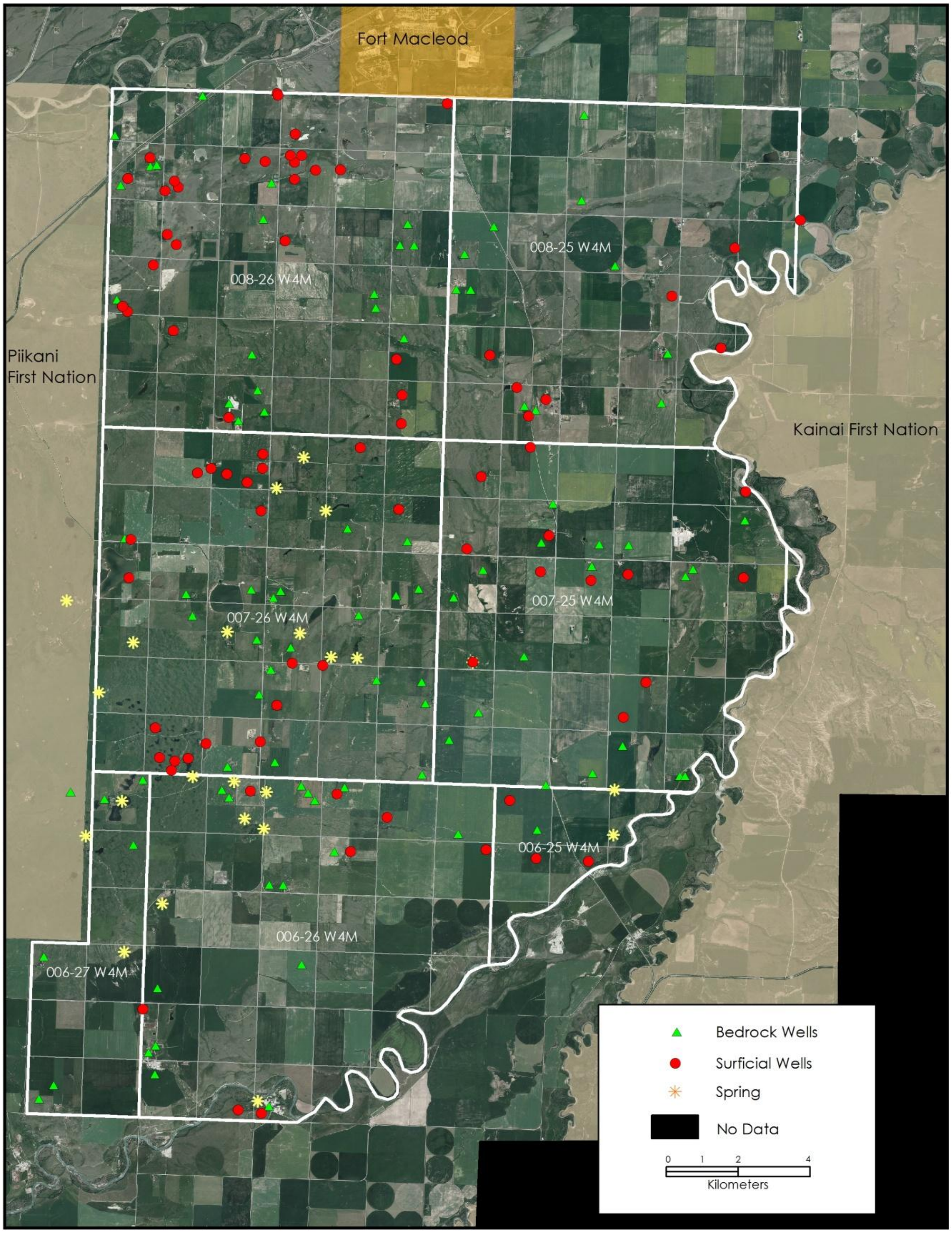

Fig. 6. Orthophotography of the study area. (Courtesy of the M.D. of Willow Creek).

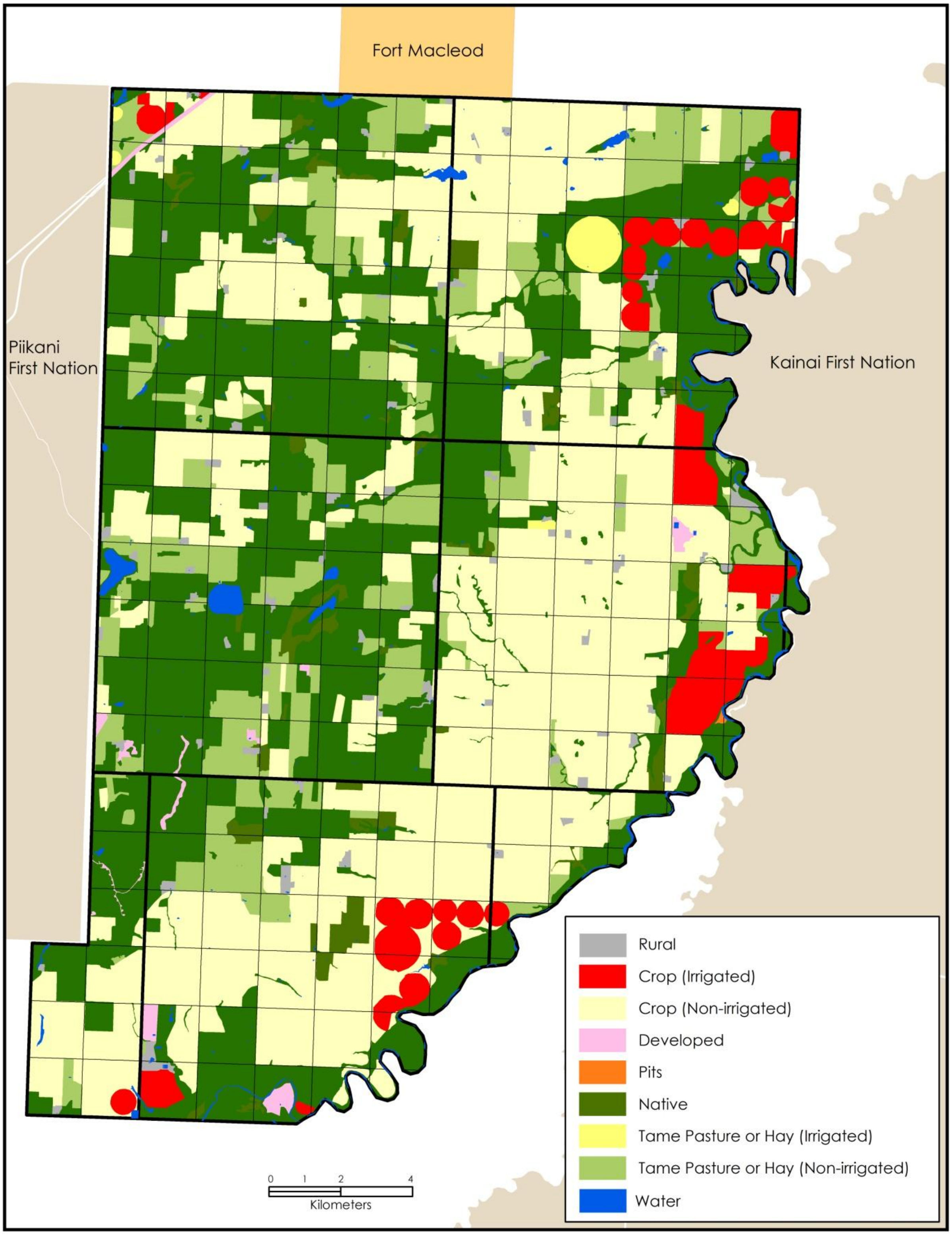

Fig. 7. Land use in the study area.

Geology and Aquifers

Bedrock Geology

Surface topography in the study area is controlled by bedrock, as evident from a comparison of the topography of the bedrock surface (Fig. 8) with ground surface topography (Fig. 4). Existing bedrock geology maps indicate that most of the study area is underlain by bedrock of the Willow Creek Formation. The overlying Porcupine Hills Formation is preserved at high elevations below the Ardenville Bench and Upland (Fig. 9). Both bedrock formations were deposited in freshwater lakes and rivers during the late Cretaceous to early Tertiary Period, approximately 70 million years ago (Robertson and Hendry 1982).

The Willow Creek Formation is composed of soft medium-grained, gray argillaceous sandstone interbedded with gray, maroon, light brick red-weathering shales with some thin gray fossiliferous limestone beds and calcareous concretions in shale. Toward the top of this formation massive cross-bedded buff-weathering gray sandstone occurs and grades into the overlying Porcupine Hills Formation. The Porcupine Hills Formation consists mainly of medium- to coarse-grained, buff weathering, crossbedded, light gray, ledge-forming sandstone interbedded with gray friable silty shale (Hamilton et al. 2004).

The compilation of 270 lithological logs recorded by drillers in the study area (Appendix 5) indicates bedrock lithology in the study area is mainly shale, even in the upland area that is mapped as the Porcupine Hills Formation by Hamilton et al. (2004). For example, sandstone was recorded for a total of approximately 1,050 m in 340 lines of description, compared to a total of approximately 6,275 m of shale described in 860 lines of description. This crude measure suggests that shale was roughly six times more prevalent than sandstone in the study area. Most observed bedrock outcrops were shale. Near-surface shale bedrock is shown along a road cut in Plate 2. Plate 3 shows gravel over shale bedrock along the Belly River valley in Tp. 8 Rg. 25.

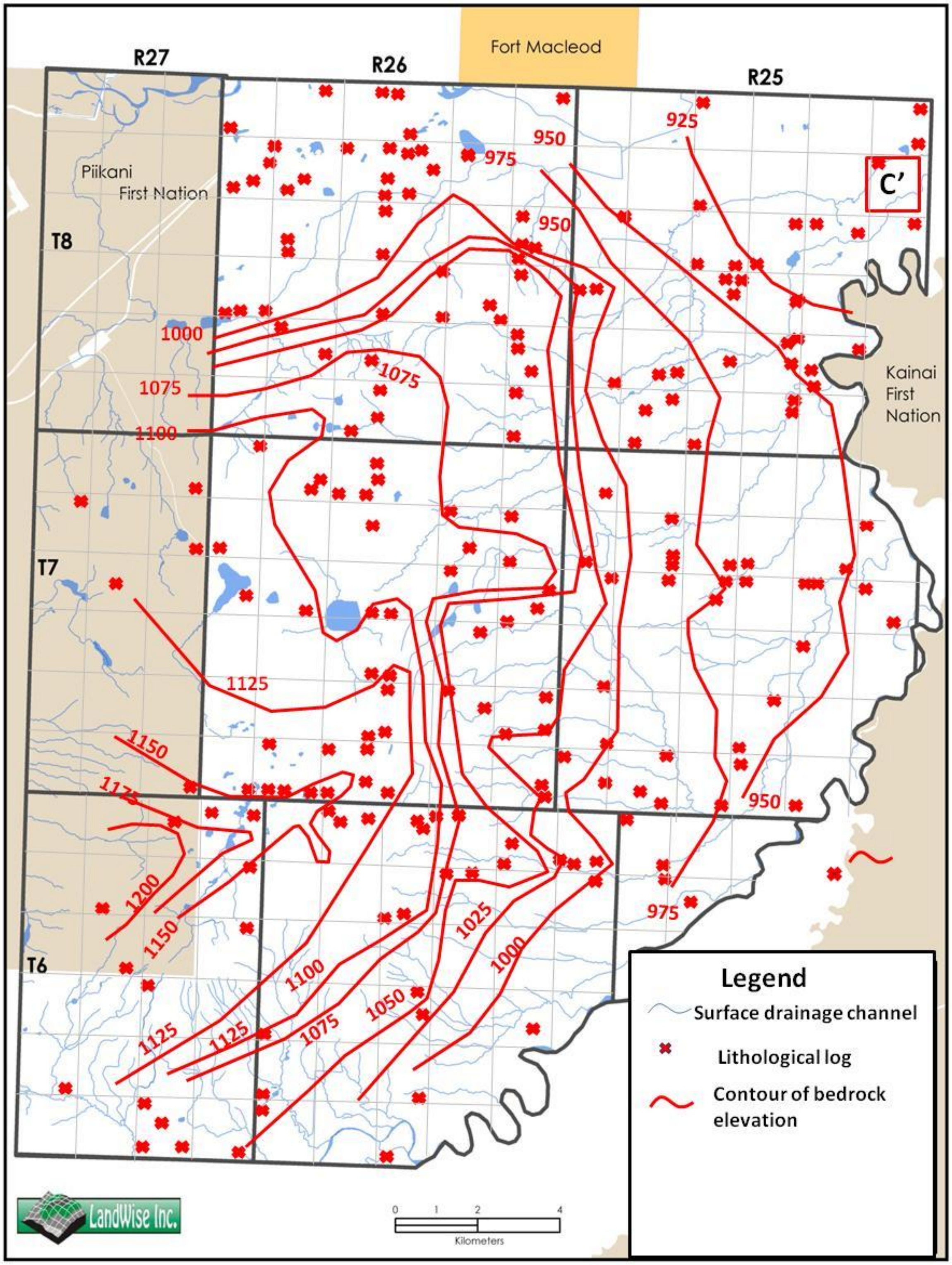

Fig. 8. Elevation of the bedrock surface.

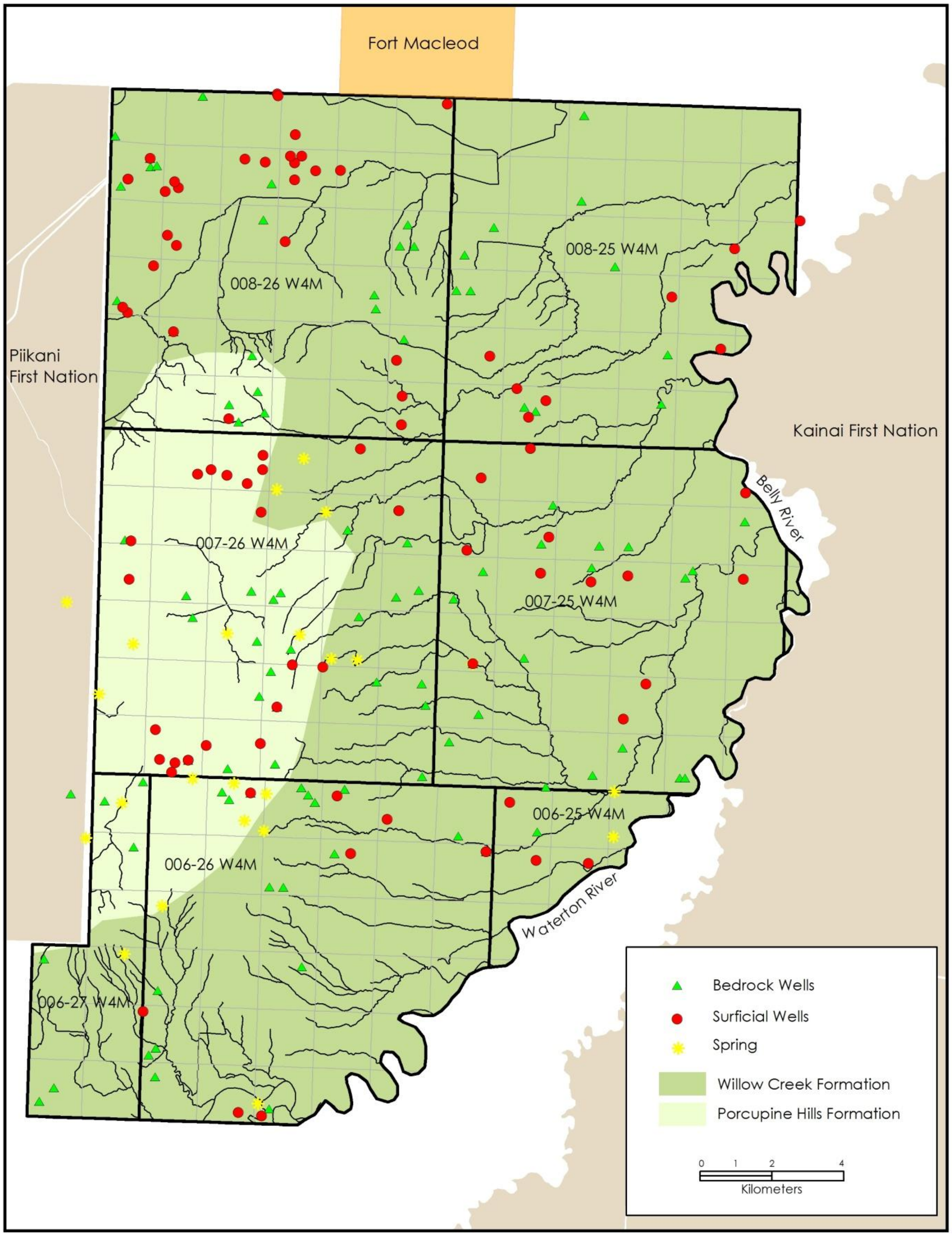

Fig. 9. Subcropping bedrock formations. From Hamilton et al. (2004).

Surficial Geology and Physiography

Surficial geology was compiled at a scale of 1:500,000 by Shetsen (2002). The map shows draped moraine and stagnation moraine throughout most of the study area, with fine lacustrine sediments along the Waterton River valley along the southeastern boundary of the study area, and coarse ice-contact fluvial and lacustrine sediments near the Oldman River at the north end of the study area (Fig. 10). Draped moraine is defined as till of even thickness with minor amounts of water-sorted material and local bedrock exposures, up to 5 m thick. Stagnation moraine is defined as till of uneven thickness, including local water-sorted material, up to 30 m thick, with undulating to hummocky topography reflecting variations in till thickness.

The surficial geology map (Shetsen 2002) provides a general representation of geology at ground surface in the study area. A much more detailed investigation based on existing drilling descriptions and drilling for piezometer nests was conducted to understand geology in the study area. The locations of geologic cross-sections are shown in Fig. 11. Geology is illustrated in cross-sectional form in Figs. 12 to 17.

Figure 12 illustrates geology from south to north through the centre of Range 26. The western side of Tp. 7 Rg. 26 is dominated by two major uplands: the Ardenville Bench at the south (labeled U1 in Fig. 12) and the lower-elevation McBride Bench at the north (labeled U2 in Fig. 12). The upland benches are surrounded on all sides by sloping lands (called scarps in this report) that level off to plains, which in turn slope gently to the river valleys. Cross-sections trending from west to east are shown in Figs. 13, 14 and 15, and Figs. 16 and 17 illustrate geology along the eastern plains and the northern plains, respectively. Surficial deposits in the study area are thin relative to topography, with the result that geology at higher elevations is dominated by bedrock (Figs. 12 to 15).

Preglacial Gravels

Sand and gravel deposits occur between glacial till and bedrock in all four physiographic regions (uplands, scarps, plains and river valleys). Major gravel deposits occur on the Ardenville Bench (Figs. 12 to 14) and the McBride Bench (Figs. 12 and 15). They are also preserved in numerous stepped terraces at progressively lower elevations along the steeply-sloping scarp areas (Figs. 13 to 15). Major preglacial gravel layers occur below till at the plains and valley levels in the east (Fig. 16) and north (Fig. 17). An outcrop of gravels in a gravel pit is shown in Plate 4.

The location of preglacial gravels (mostly buried by till) are shown in a gray colour on the plan view map in Fig. 11. Each gravel layer has a distinct location and bottom elevation at the bedrock contact. The gravels were deposited as part of the network of preglacial river valleys that drained east across the Alberta plains from the uplifting Rocky Mountains. Gravels become progressively younger at progressively lower elevations. Each stepped terrace of preglacial gravel represents a later event of progressive river erosion into deeper base levels of the bedrock (Greg Hartman, personal communication[1]).

[1] Greg Hartman, Alberta Geological Survey, Edmonton, Alberta. Field tour, August 2013.

Gravels in a pit on the Bench near the Ardenville Hall were observed to be cemented at lower depths (Plate 5). Such cementation is expected to require at least a million years in an arid to semi-arid climate, suggesting these gravels are much older than preglacial gravels that overlie bedrock on the plains level in the eastern part of the study area.

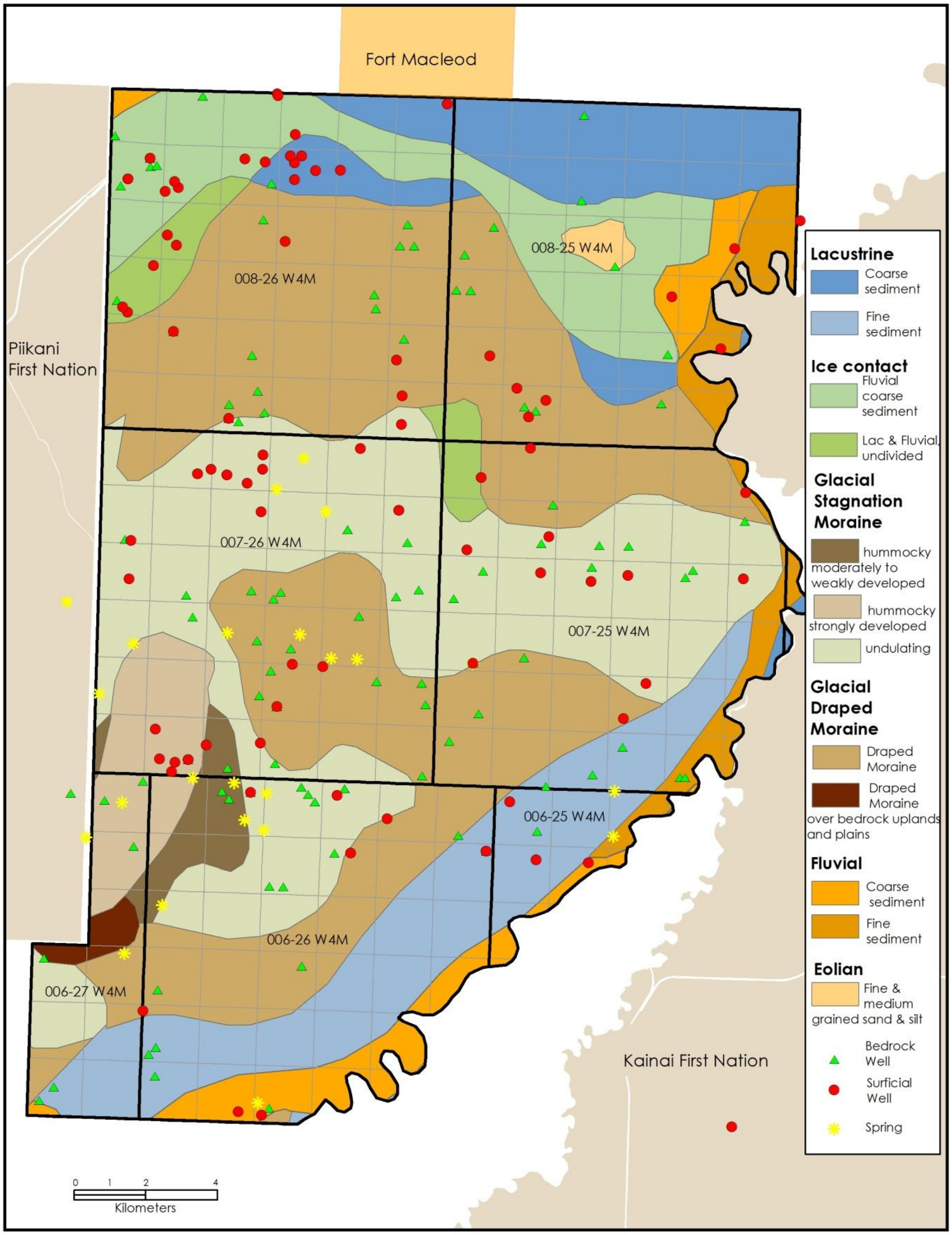

Fig. 10. Surficial geology. (Shetsen 2002).

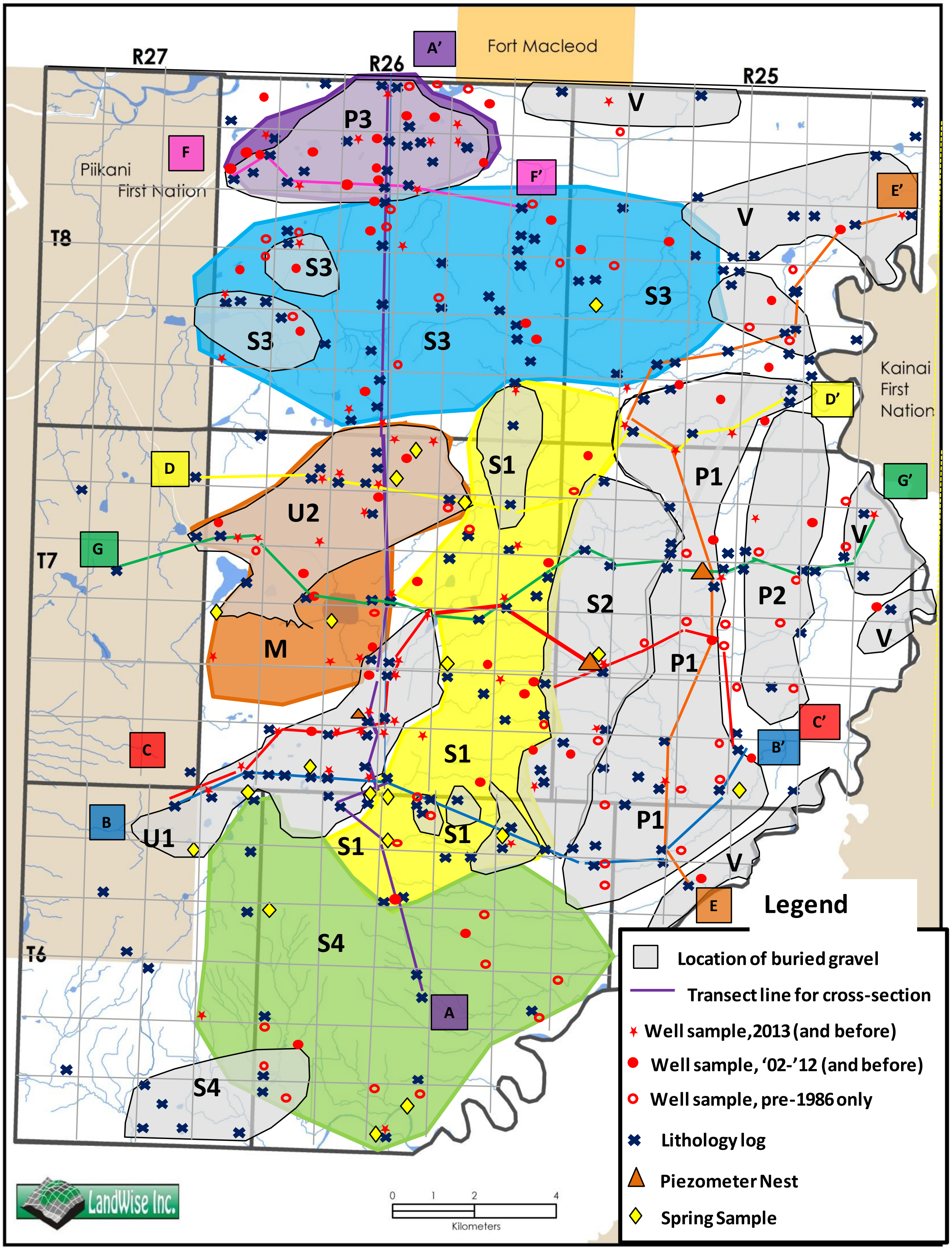

Fig. 11. Location of physiographic areas and transect lines for geologic cross-sections.

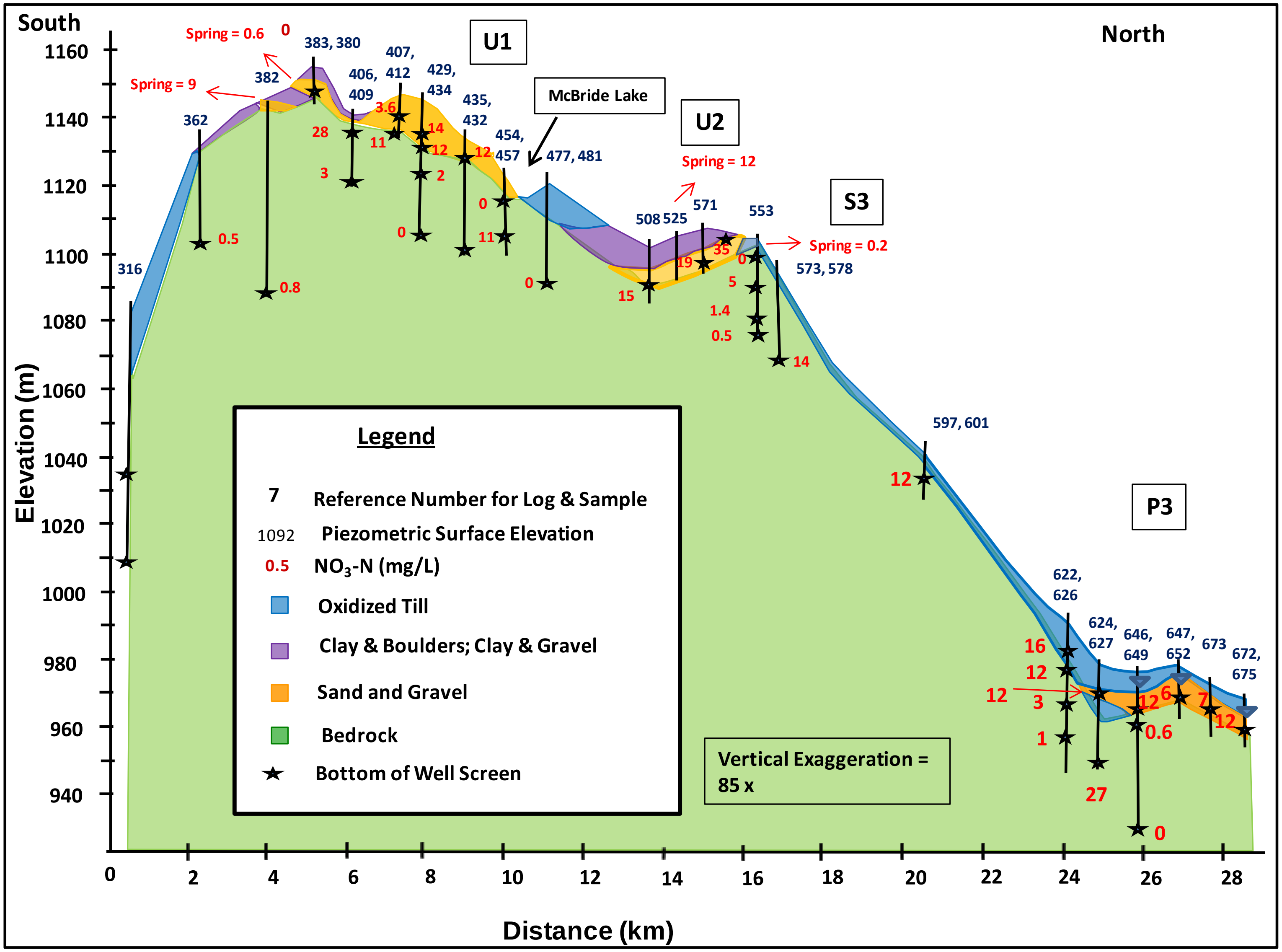

Fig. 12. Geologic cross-section along transect AA'; Rg. 26, south to north (purple line in Fig. 11).

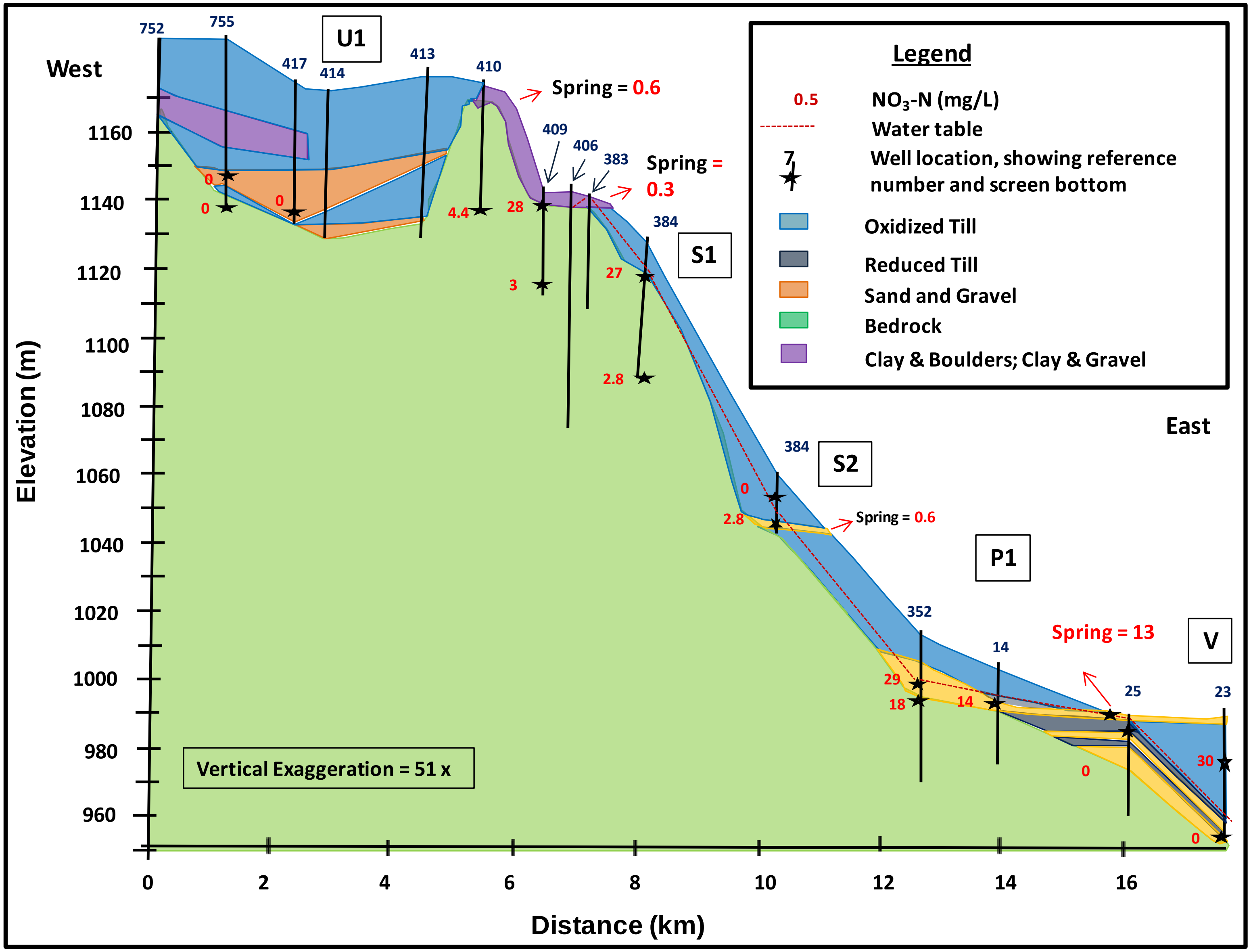

Fig. 13. Geologic cross-section along transect BB'; west to east (blue line in Fig. 11).

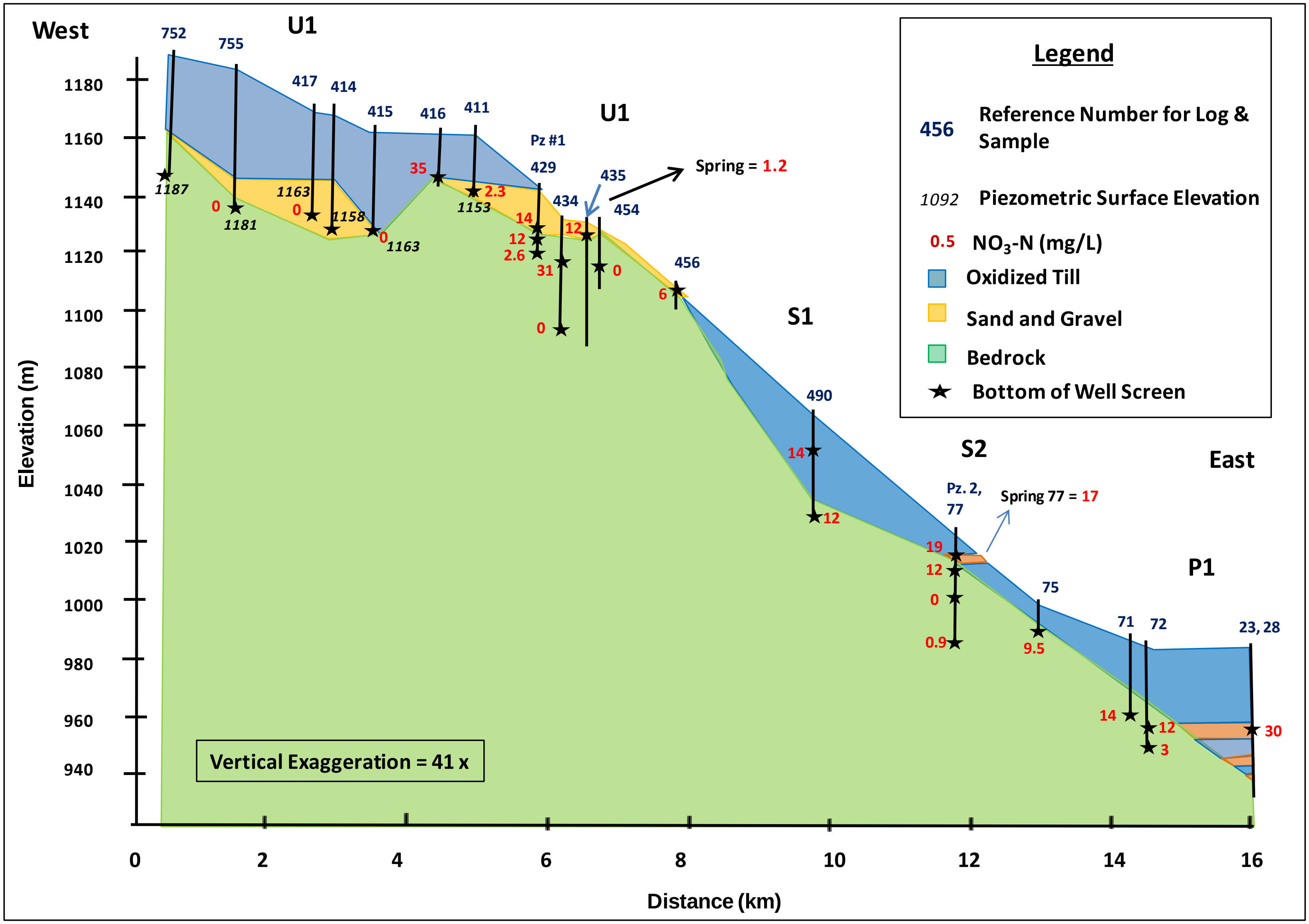

Fig. 14. Geologic cross-section along transect CC'; west to east (red line in Fig. 11).

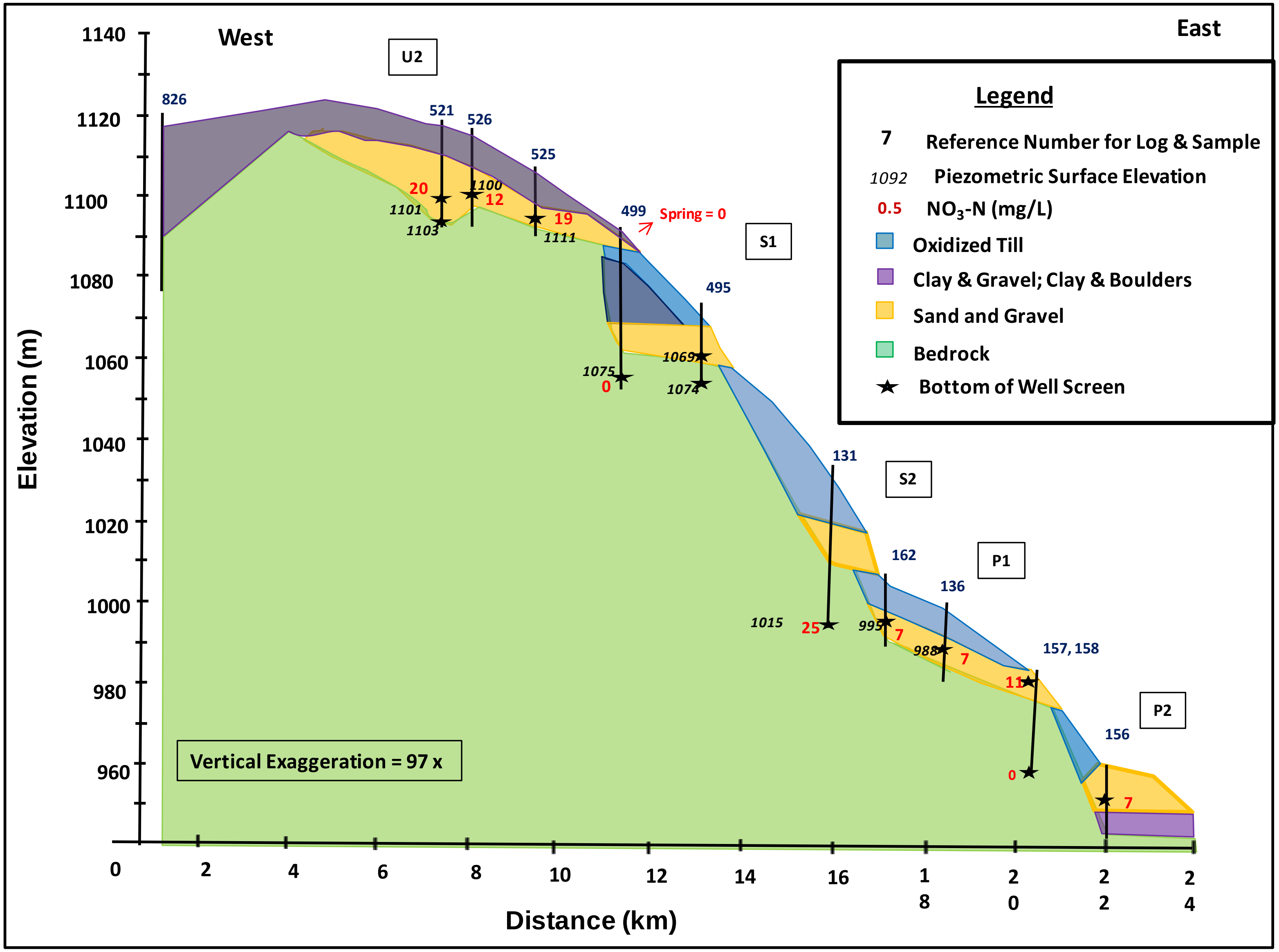

Fig. 15. Geologic cross-section along transect DD'; west to east (yellow line in Fig. 11).

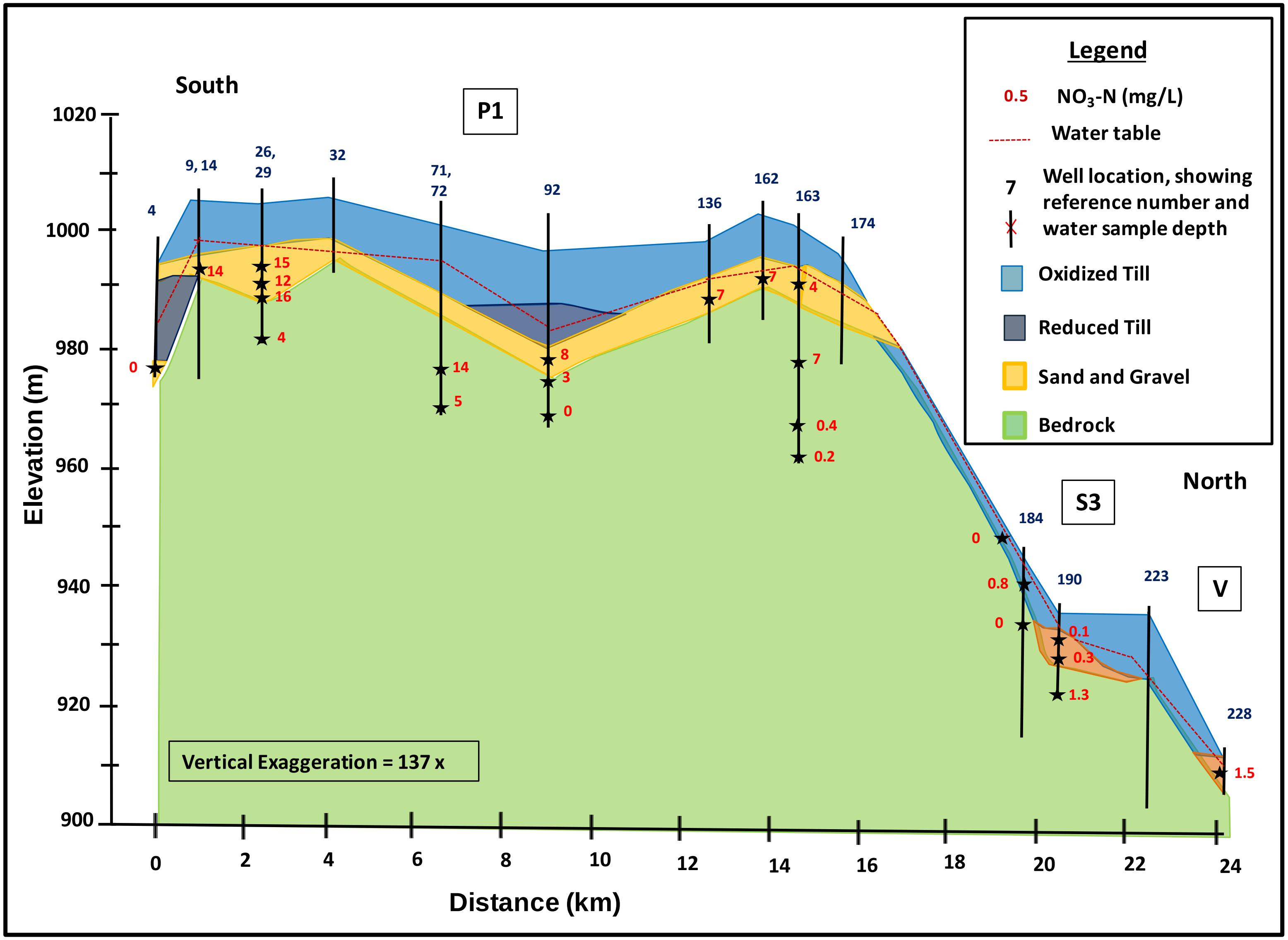

Fig. 16. Geologic cross-section along transect EE'; Rg. 25, south to north (orange line in Fig. 11).

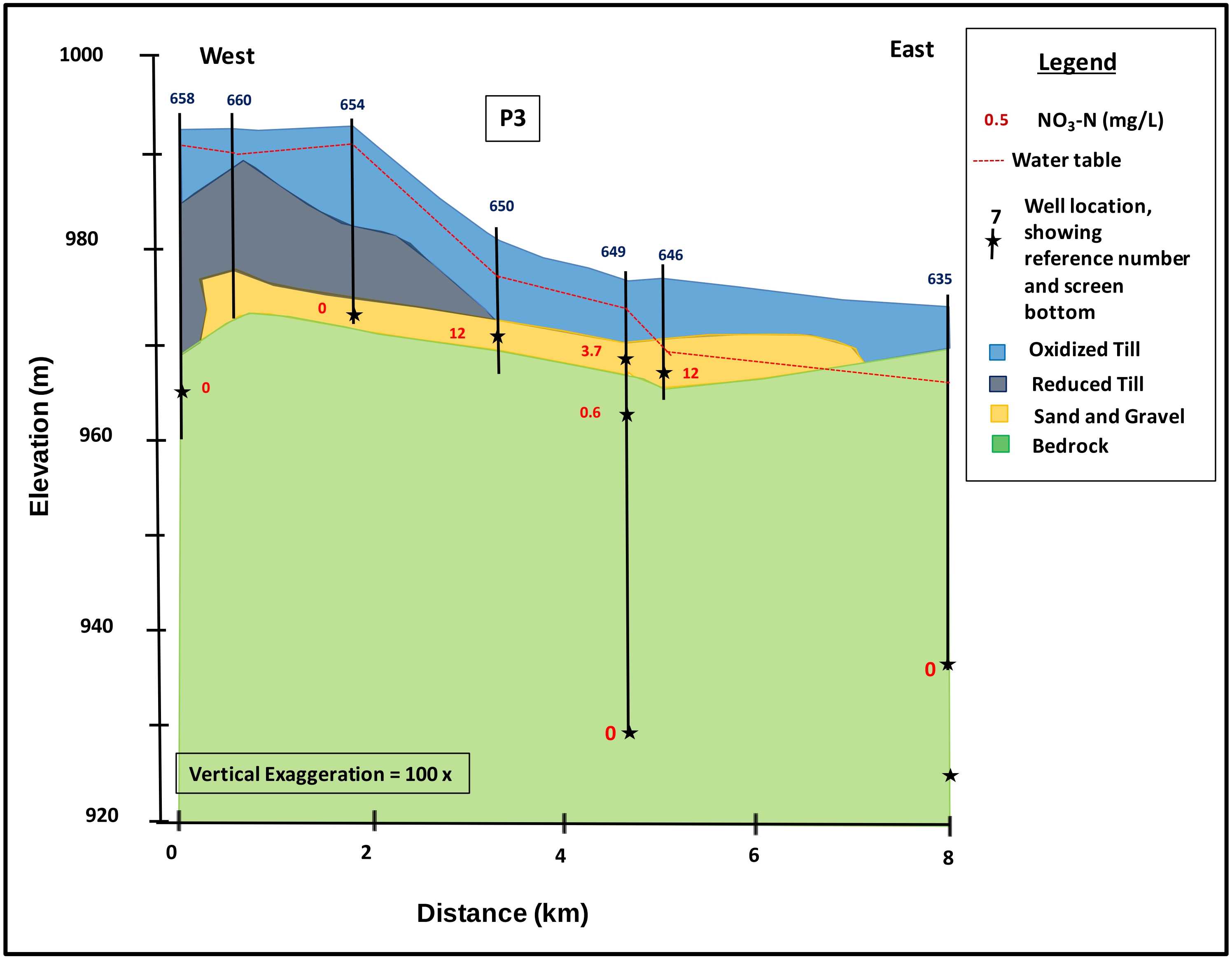

Fig. 17. Geologic cross-section along Transect Line FF';Tp. 8 Rg. 26, west to east (pink line in Fig. 11).

Preglacial sand and gravel deposits are highly variable in texture, as observed in gravel extraction pits (Plate 4), along scarp edges, and during drilling. Gravel sizes commonly ranged from pea-sized to cobbles and boulders. Matrix textures ranged from clay to sand. Some of the layers would be best described as diamicton (an unsorted mixture with a wide range of textures, including clay, gravel, cobbles and boulders). Main channel deposits are generally quite well sorted, consisting of mainly sand and gravel or cobbles, but the lithology generally grades to clay with gravel on channel edges and bottoms.

Physiographic Areas

Locations with water samples in the four major physiographic regions (uplands, scarps, plains and valleys) were subdivided into 10 physiographic areas to assist with description, characterization and investigation of the highly complex and variable geology and topography in the study area. Gravel layers are illustrated in gray in Fig. 11, and physiographic areas are labeled. Most of the areas are defined based on significant gravel layers, and their boundaries coincide with the gravel layers. These areas are simply shown in gray shading as gravel layers in Fig. 11. Physiographic areas with boundaries slightly larger than the major gravel layers they include are shown in colours on Fig. 11.

- Upland gravels on the Ardenville and McBride Benches (U1 and U2, respectively) represent the oldest gravel deposits in the study area, and they are relatively thick and substantial. U1 coincides with major gravel deposits. The McBride Bench (U2) coincides with a major gravel deposit, but it also includes an area to the south where wells are installed in bedrock, so U2 is shown in brown (Fig. 11).
- The upper scarp areas are termed Scarp 1 (S1) to the east of the uplands, and Scarp 3 (S3) to the north of Upland 2 (Fig. 11). Only small gravel areas are preserved in the upper scarp areas because these high-elevation areas were eroded by subsequent rivers and glacial events. S1 includes small isolated gravels, but mainly denotes the large area of thin till over bedrock in the eastern part of Tp. 7 Rg. 26, and the northern edge of Tp. 6 Rg. 26 (Fig. 11). Areas S1 and S3 are shaded in yellow and blue, respectively, to indicate they include areas where wells are installed in bedrock (Fig. 11).
- Relatively large and continuous gravel areas that trend from south to north are preserved at lower elevations along the eastern scarp (Scarp 2, S2), and the eastern plains areas (Plains 1 and Plains 2, P1 and P2) (Fig. 11). Transverse views of these gravels where they emerge at surface are shown in Figs. 14 and 15, and Fig. 16 shows a north-south cross-section through the P1 gravel.
- The Plains 3 (P3) gravel occurs at the north end of the study area (Figs. 12, 16 and 17). The P3 area includes only a few wells installed in bedrock. (Wells in the study area are usually installed in saturated gravel where it is present).
- Deep gravels covered with thick till occur adjacent to the river valleys (Figs. 13, 14 and 16). These are labeled “V” in Fig. 11.
- Few geologic logs were available for the area south of the Ardenville Bench, in Tp. 6 Rg. 26. This area is called Scarp 4 (S4) (Fig. 12).

The 10 areas are listed in Table 3, ordered in groups that include the upland, east of the upland, north of the upland and south of the upland. Areas within each group are listed from highest elevation to lowest. All areas are shown in plan view in Fig. 11, where the McBride Channel (M) is included with the McBride Bench (U2).

Table 4. Elevation of gravel bottom for 11 physiographic areas.

Physio-graphic Region	Area Name	Ground Elevation (m)	Elevation of Gravel Bottom (m)	Location and Geology
Arden-ville Bench. Figs. 12 to 14	Upland 1 (U1)	1170 to 1125	1140 to 1120	At the highest elevations along the southern part of the Ardenville Bench. Western: till over bedrock. Central: thick till overlying deep gravel, and thin till overlying a shallower gravel layer. Eastern: Shallow gravel layer pinches out at surface along the edge of the scarp, at S1 in the north and east and at S4 in the south.
McBride Bench Figs. 12 and 15)	McBride Channel (M)	1125 to 1110	No Gravel	In the central portion of Tp. 7 Rg. 26 glacial meltwater moving from west to east scoured away almost all surficial sediments, leaving an area where bedrock is very close to surface. Marked by relatively large wetlands that include an unnamed wetland adjacent to the Piikani First Nation, McBride Lake, and a moderately-sized wetland northeast of Ardenville.
	McBride Bench (U2)	1110 to 1090	1100 to 1080	An upland terrace north of the Ardenville Bench, at the north end of Tp. 7 Rg. 26. Gravel layer increases in thickness from about 4 m at the south to up to 15 m in the north-central area. Gravel is overlain by about 4 to 7 m of till or diamicton, and pinches out at the north at S3, and at the northeast at S1.
East of Upland (Figs. 13 to 16).	Scarp 1 (S1)	1120 to 1060	1130 to 1065	Eastern half of Tp. 7 Rg. 26 and northern edge of Tp. 6 Rg. 26. Moderate slopes immediately east and south of the uplands. Mostly thin till over bedrock, but discontinuous gravel layers at the south (bottom elevations 1130 to 1065) and north (bottom elevation 1065).
	Scarp 2 (S2)	1040 to 1020	1036 to 1006	A long and narrow south-to-north trending gravel terrace overlying bedrock along the eastern scarp on the west side of Tp. 7-25. At the south gravel is 10 to 14 m thick and overlain by only thin intermittent till. Elsewhere the gravel is generally only about 1 m thick and covered with up to 20 m of till.
	Plains 1 (P1)	1000 to 980	995 to 975	A long and narrow south-to-north trending preglacial gravel terrace that occurs between S2 and P2. The P1 gravel is about 1.5 to 3 km wide, and extends from the Waterton River in the south to near the middle of Tp. 8, Rg. The gravel is generally about 5 m thick and overlain by approximately 9 to 18 m of glacial till, which is mostly oxidized except below about 14 m.
	Plains 2 (P2)	950 to 980	940 to 960	A long and narrow south-north trending preglacial gravel layer, about 2 km wide, immediately east of P1 in Tp. 7 Rg. 25. About 14 to 18 m of till over preglacial gravel layer of 2 to 5 m thick. Redox boundary at about 14 m.
	Belly and Waterton River Valleys (V)	994 (Waterton River) to 954 (Belly River)	977 on Waterton to 945 on Belly River	Thick surficial deposits, 20 to 35 m thick, composed of a complex inter-layering of till and gravel. Water-bearing sand and gravel layers are common within the till (inter-till gravels) and between till and bedrock (preglacial gravels). Geology is highly variable, ranging from 34 m till, to 4 m

Physio-graphic Region	Area Name	Ground Elevation (m)	Elevation of Gravel Bottom (m)	Location and Geology
				till over 33 m gravel.
North of Upland (Figs. 12, 16 and 17)	Scarp 3 (S3)	1105 to 995	3 small gravel layers at 1005, 980 and 930 m	The steeply sloping scarp on the north side of the upland. Dominates the southern two-thirds of Tp. 8 Rg. 26, and the eastern portion of Tp. 8 Rg. 25. Shallow bedrock overlain by discontinuous thin till. Includes three small discontinuous gravel terraces near the base of the slope.
	Plains 3 (P3)	984 to 960	979 to 960	Gravel is up to 12 m thick, and occurs at surface or below up to 15 m of till.
South of Upland (Fig. 12)	Scarp 4 (S4)	1160 to 1050	No known major gravel layers	S4 encompasses most of Tp. 6 Rg. 26 because data is very limited in this area. Available data suggests the area is mostly till over bedrock, and that till thickens from about 3 m on the upper scarp to 26 m at the south end of the study area.

Hydrogeological Consultants Limited (HCL 2012) termed the preglacial gravels the “Lower sand and gravel”, and they subdivided them into three units with the following ranges of top elevations above sea level.

- Unit 3: terrace deposits – 968 to 1162 m. The majority of sand and gravel units described in the current investigation and listed in Table 3 correspond to the terrace deposits.
- Unit 2: Lethbridge Channel - 918 to 981 m. Unit 2 corresponds to the valley gravels on the Belly and Waterton rivers, as defined in Table 3. Valley gravels are equivalent to the river-connected alluvial aquifers described by Manwell and Ryan (2006).
- Unit 1: Orton Aquifer – 844 to 940 m. Unit 1 is associated with the Oldman River valley, and does not occur in the current study area.

Glacial Deposits

Glacial deposits, termed “upper surficial deposits” by HCL (2012), cover most of the study area. The most common glacial deposit is clay-rich till with small scattered rock fragments. However, diamicton occurs at numerous locations, particularly on the scarps. Diamicton is a non-genetic term, defined as a deposit of uncertain origin, composed of an unsorted mixture with a wide range of textures, including clay, gravel, cobbles and boulders. The till also contained minor sand layers.

Till thickness is illustrated in Fig. 18, based on GIC drill logs and drilling conducted in 2013. Till is 20 to 40 m thick along the high elevation area on the western side of the study area, but thickness decreases significantly on the western side of Range 26, and for much of the study area till is less than about 8 m thick. Till reaches 12 to 20 m in thickness at some terrace locations where slopes level off, and is more than 20 m thick at many locations along river valleys (Fig. 18).

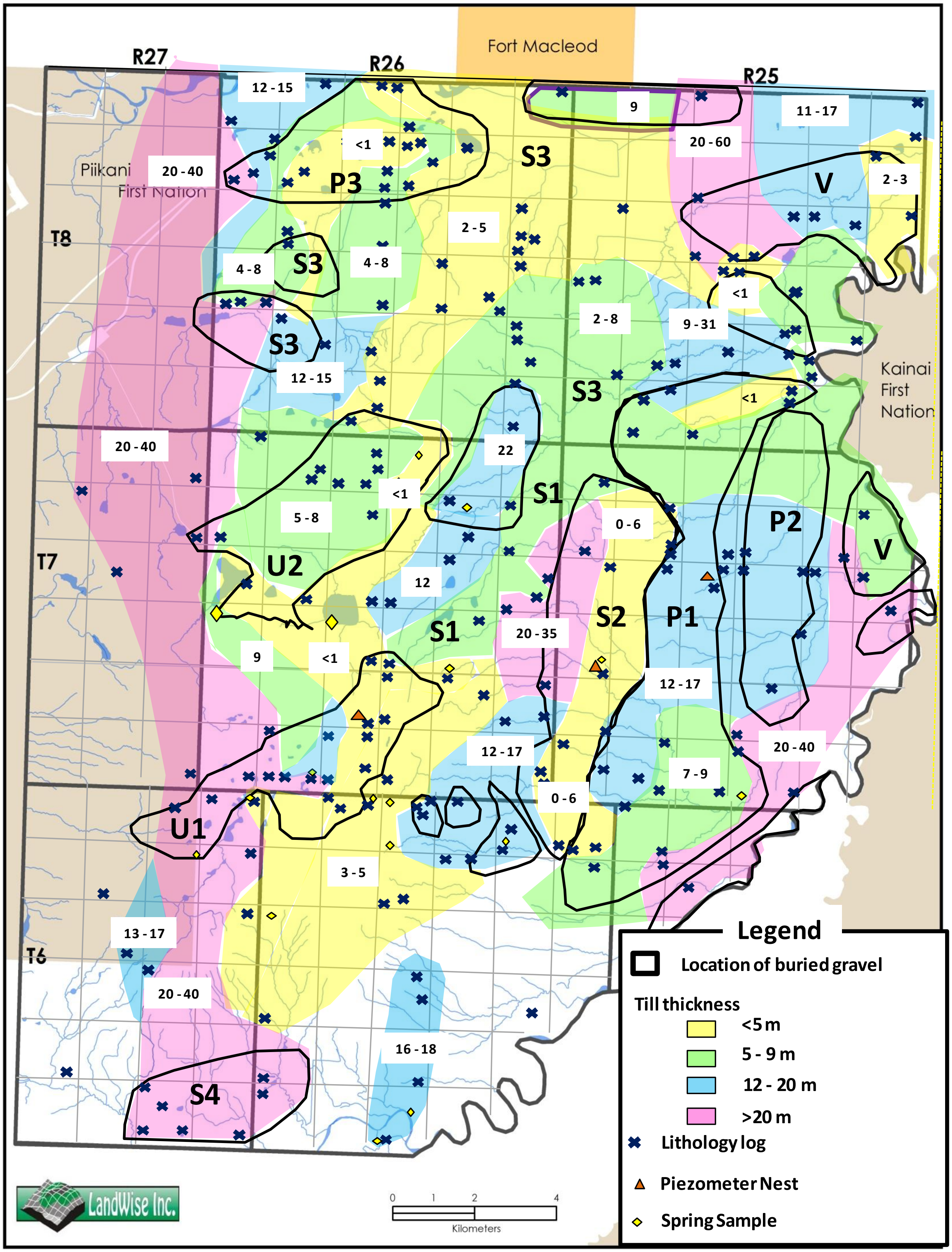

Fig. 18. Till thickness in the study area.

Groundwater Discharge and Drainage Channels

Preglacial gravels are generally buried by till or diamicton on the upslope side, and emerge at surface as elevation drops and till thins to the east, north and south. A location where gravels pinch out along the edge of the Ardenville Bench is shown in Plate 6. Locations where gravels intersect ground surface are shown in cross-sectional form for the Ardenville and lower scarp (S2) gravels in Fig. 14, and for the McBride, S1 and P1 gravels in Fig. 15. The plan-view map of till thickness (Fig. 18) illustrates that the Ardenville, McBride, and Scarp 2 gravels all come close to surface on their downslope sides.

Springs emerge where preglacial gravels on the upland intersect the eroded side-slopes of the Ardenville and McBride benches on the east, north and south. These flowing springs have eroded ravines that traverse the slopes of the Bench and carry seepage water and surface water to the Waterton and Belly rivers in the east and south, and to the Oldman River and wetlands in the McBride Lake area in the north. Drainage channels also originate where bedrock comes close to surface along the south and north scarps (Fig. 18). Numerous wetlands in the study area are spring-fed (Plate 7). Drainage channels can be seen on orthophotography (Fig. 6), and their locations are outlined on Fig. 3. The drainage channels have eroded till, and are usually incised into bedrock. Drainage channels therefore cause bedrock depth and till thickness to be highly variable. Plate 8 shows an ephemeral drainage channel at a location where bedrock occurs at surface.

Wells and Aquifers

Water wells installed at locations with saturated preglacial gravel layers are most commonly installed in the gravel, but approximately half the wells in the study area are installed in bedrock, and well depths cover a fairly wide range (Table 5). Approximately 20% of well records for bedrock in the GIC database were abandoned due to insufficient water production. The actual percentage of abandoned wells may be higher than this, since drillers are expected to be less likely to register dry wells in the GIC database.

Table 5. Installation depths for 258 wells in the study area.

Well Depth Range (m)	Percentage of Wells
<10	13%
11 – 19	25%
20 – 29	19%
30 - 39	15%
>40	26%

Drillers' logs (Appendix 5) indicate bedrock lithology is dominated by shale, suggesting groundwater flows predominantly through fractures. Transmissivity data are contained in Appendix 8. Transmissivity of bedrock wells plotted in two separate groups (Fig. 19).

- Wells shallower than 30 m were mostly located in the northern part of the study area, including the McBride Channel and Bench (U2), the north scarp (S3) and the northern plains area (P3). Transmissivity for these relatively shallow wells ranged from approximately 10 to 100 m^2/day.

- Bedrock wells in the remainder of the study area were deeper than 30 m, with transmissivity values of 0.1 to 10 m^2/day.

In addition to wells along the north scarp, one of the two wells along the upper east-facing scarp (S1) also exhibited a high transmissivity (Fig. 19). The higher transmissivity of shallow wells along the upper scarps suggests they are more highly fractured than deeper bedrock covered with thicker till. This is consistent with the exposed nature of bedrock along the upper scarps.

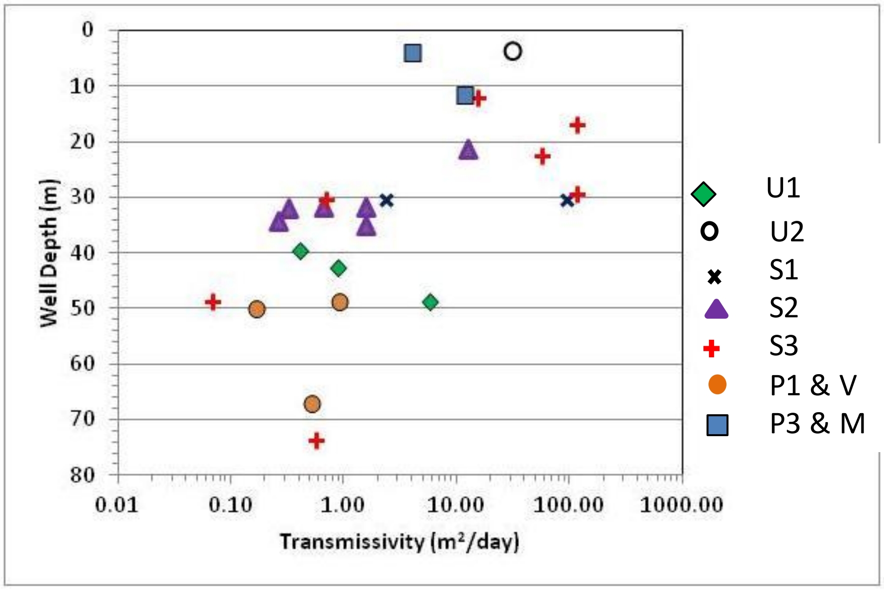

Fig. 19. Transmissivity of wells in bedrock, by area.

For pump tests conducted in February of 2013, many wells screened in gravel were not pumped long enough or fast enough to obtain drawdown, so they were not included in the results shown in Fig. 20. Transmissivity for gravel ranged from 10 to more than 1000 m^2/day. The trend of increasing transmissivity with increased pumping rate (Fig. 20) suggests these tests may also have been affected by low pumping rates. Drilling in gravel at all three piezometer nests indicated high yields from preglacial gravels, particularly from Nest 1 on the Ardenville Bench (Plate 9).

The approximate groundwater velocity through the preglacial gravel can be calculated based on transmissivity (T) values shown in Fig. 20, and formulas 1 and 2 below. An example is shown for the Ardenville gravel between wells 411 and 439 (Fig. 14).

Formula 1: $K = T/b$, where

K = hydraulic conductivity (m/yr)

T = transmissivity. 100 m^2/day for the Ardenville Bench, based on Fig. 20.

b = aquifer thickness. About 7 m between wells 411 and 439.

Formula 2: $v = (Ki)/n$, where

v = groundwater velocity

K = hydraulic conductivity from Formula 1.
i = hydraulic gradient, = 0.014 based on topographic slope between Wells 411 and 439.
n = porosity. Use 0.35

- The results suggest a groundwater flow velocity of about 200 m/yr for the gravels in this area.
- Using the same formulas for a bedrock T value of 1 m^2/day on the Ardenville Bench (Fig. 19) indicates a flow velocity of 2 m/yr.
- Flow velocities through very shallow weathered till are typically on the order of 10 cm/yr. Transport rates measured in long-term tracer tests tend to indicate higher chemical transport rates than values determined from relatively small-scale hydraulic conductivity testing (McKay et al. 1998), so actual transport rates may be higher than those indicated.

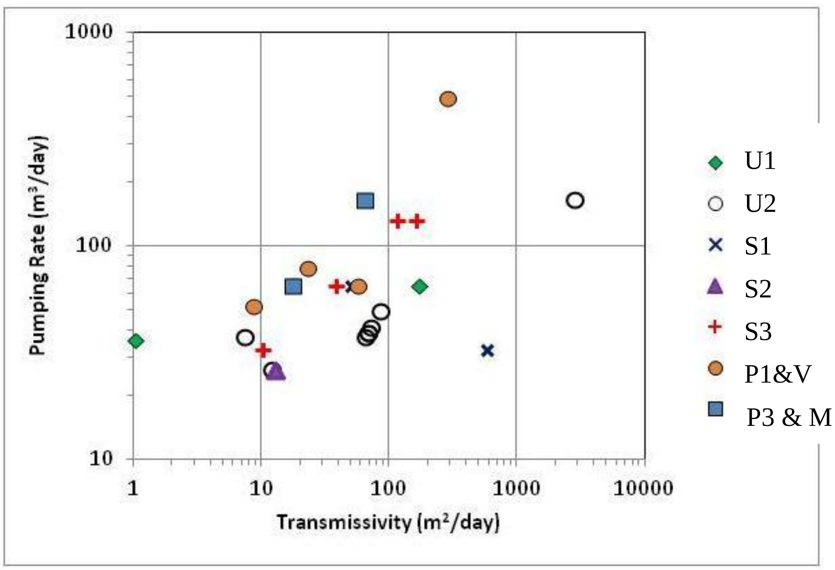

Fig. 20. Transmissivity of wells in gravel, by area.

Overview of Groundwater Age

Tritium data were not collected for the current investigation, but $\delta^{18}O$ and $\delta^{2}H$ were measured in groundwater from 19 water wells, 14 springs and three piezometer nests (Appendix 4).

Profiles of $\delta^{18}O$ and $\delta^{2}H$ with depth in groundwater provide information on relative groundwater age. Results reviewed in Appendix 1 indicate that $\delta^{18}O$ depth profiles through glacial till in Alberta and Saskatchewan exhibit shifts to more negative values with depth, reflecting the increasing influence of glacial-aged recharge at depth. Results reviewed in Appendix 1 indicate that groundwater with $\delta^{18}O$ values of -21‰ or lower can generally be considered to be predominantly glacial in age. Tritium in glacial till most commonly occurs in the uppermost 5 m, in groundwater with $\delta^{18}O$ values less negative than -18‰. Therefore, $\delta^{18}O$ values can be used to indicate approximate groundwater age as follows.

- groundwater with $\delta^{18}O$ values less negative than -18‰ was recharged predominantly in modern times,
- $\delta^{18}O$ values of -21‰ or lower indicate predominantly glacial-aged groundwater, and
- $\delta^{18}O$ values ranging from -18 to -21‰ represent a mixture of modern and glacial-aged recharge.

Plots of ^{18}O vs. ^{2}H compared to the local meteoric water line for Calgary (Fig. 21) indicate the following.

- Most spring samples have $\delta^{18}O$ values less negative than -17 ‰ and they plot below the meteoric water line for Calgary. These samples represent recently recharged groundwater that has been affected by evaporation.
- Several bedrock samples are characterized by $\delta^{18}O \leq -21$‰ and they plot on the local meteoric water line. Data reviewed in Appendix 1 indicate this is old groundwater that was recharged predominantly under glacial conditions.
- Some bedrock samples and all samples from gravel plot slightly below the meteoric water line and they are characterized by $\delta^{18}O$ values ranging from -18 to -21‰. This suggests they are composed of a mixture of relatively old groundwater and relatively young (recently recharged) groundwater.

One sample from gravel exhibited a heavy and evaporated isotopic signature similar to spring water (Fig. 21a). This sample was collected from a well installed in a spring-fed dugout, and the isotopic results suggest a significant influence from surface water in the dugout.

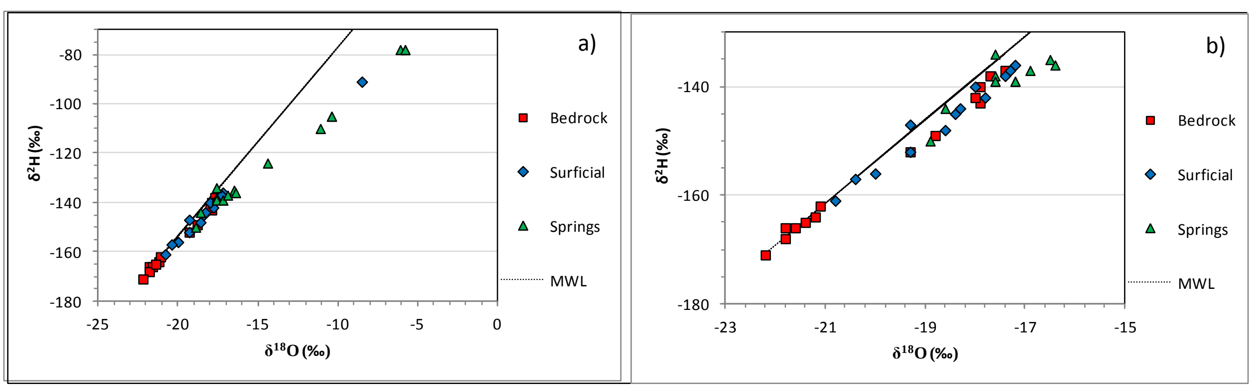

Fig. 21. ^{18}O and ^{2}H compared to the local Calgary meteoric water line. a) All samples. b) Excluding spring samples with ^{18}O values less negative than -15‰.

A plot using all ^{18}O data from the current study area suggests ^{18}O does not change significantly with depth in gravel or bedrock groundwater to 40 m depth (Fig. 22). However, isotopic shifts are apparent in plots of ^{18}O from four individual physiographic regions, where LVP data are included for comparison (Fig. 23). The samples were collected from different water wells in each physiographic area, so they are not true depth profiles from a single location.

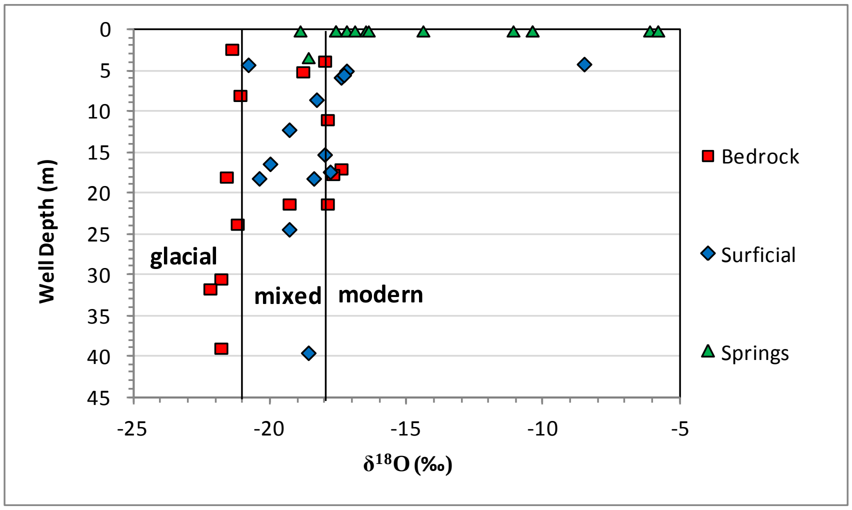

Fig. 22. 18O with well depth, all samples.

The depth profiles for physiographic areas P1 and S2 are both consistent with the isotopic shift to more negative values at depth, and ^{18}O values in bedrock are consistent with groundwater that recharged predominantly under glacial conditions.

- For physiographic area P1, $\delta^{18}O$ in groundwater in gravel ranges from -18.4 to -20.4‰, while samples in bedrock range from -21.2 to -21.8 ‰ (Fig. 23a).
- For physiographic area S2, $\delta^{18}O$ in groundwater in gravel ranges from -17.4 to -17.6 ‰, with a major shift to -21.2 to -21.8 ‰ for bedrock samples at 9 to 32 m (Fig. 23a).

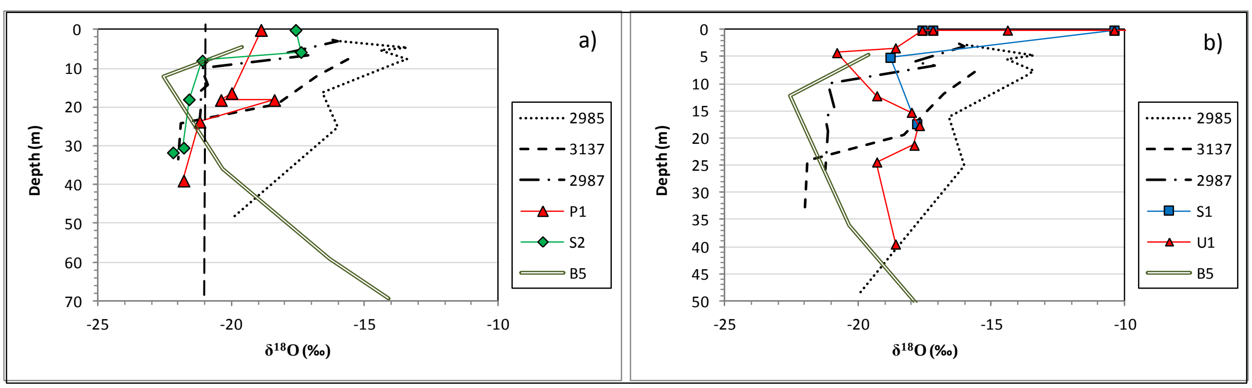

Fig. 23. Profiles of 18O with depth, compared to data from LVP study areas. a) Physiographic areas P1 and S2. b) Physiographic areas S1 and U1.

The profiles at physiographic areas U1 and S1 show a characteristic negative shift in the shallowest zone, followed by a shift to more positive values at deeper depths.

- Based on the few values for area S1, ^{18}O ranges from -17.2 to -18.8 ‰ in gravel and bedrock samples, and there is no shift to more negative values with depth (Fig. 23b).
- $\delta^{18}O$ values at area U1 range from -17.6 to -20.8‰, and there appears to be a shift to more negative ^{18}O values with depth in the top 5 m, followed by a general shift to more positive values at 5 to 40 m (Fig. 23b).

^{18}O data for the current study area are compared to ^{18}O data from the Blackspring Ridge (BR) area and the Lethbridge-Vauxhall-Picture Butte (LVP) areas in Fig. 24. Data from both study areas are reviewed in Appendix 1. The plots in Fig. 24 illustrate the following.

- ^{18}O data from the LVP areas is mainly from till to a maximum depth of about 40 m. ^{18}O becomes more negative with depth (Fig. 24b), consistent with the increasing influence of glacial-aged recharge, as discussed in Appendix 1.
- ^{18}O data from the BR area exhibits a slight negative shift in the uppermost 20 m, and a pronounced positive isotopic shift in bedrock below 40 m (Fig. 24a).
- ^{18}O data from the current study area are consistent with both the shallow LVP data and the deeper BR data (Fig. 24c).

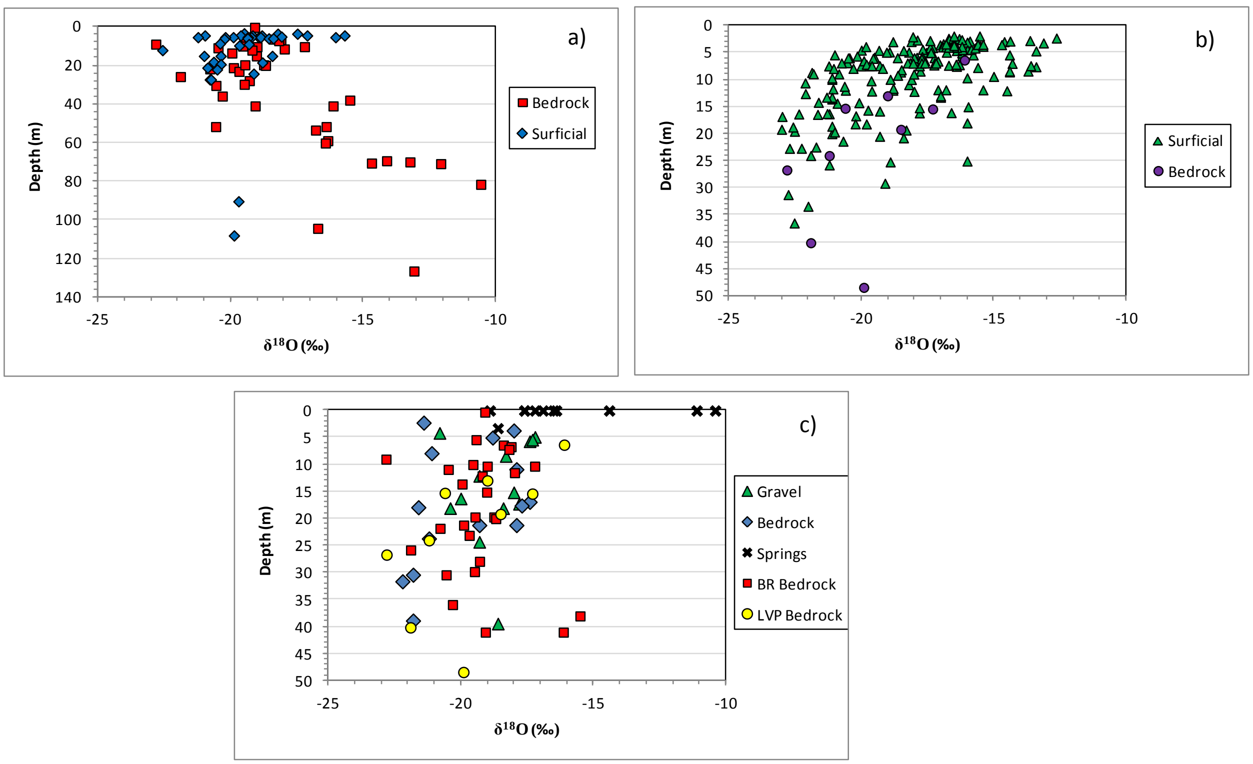

Fig. 24. ^{18}O with well depth. a) Blackspring Ridge (BR) (from Stein 1987). b) Lethbridge, Vauxhall and Picture Butte – Iron Springs (LVP) (from Rodvang et al. 1998). c) Current study area compared to bedrock from study areas BR and LVP.

Stein (1987) interpreted the positive shift in bedrock groundwater in the BR study area to indicate that bedrock groundwater recharged during the altithermal (a warmer and drier climate period that occurred about 4,000 to 6,000 years ago). This interpretation conflicts with the well-tested conclusion that groundwater with $\delta^{18}O$ values < -21 ‰ represents predominantly glacial-aged recharge (Appendix 1). As discussed in Appendix 1, it is more likely that the BR groundwater below 40 m represents a mixture of remnant seawater and meteoric water, thus making it much older than glacial-aged groundwater.

In summary, isotopic data for the study area indicate many bedrock groundwater samples are composed of water that recharged during glacial times, with $\delta^{18}O$ values < -21 ‰. Most groundwater samples are a mix of old groundwater and recent recharge, with $\delta^{18}O$ values ranging from -18 to -21 ‰. Most spring samples and some samples from shallow gravel have $\delta^{18}O$ values less negative than -18‰, representing predominantly modern recharge water.

Overview of Nitrate Distribution

Data for the current study area are limited to water wells and seven piezometers. More detailed data from the near-by study areas of Rodvang et al. (1998; 2002) are reviewed in Appendix 1 to illustrate typical profiles of agricultural and geologic nitrate in glacial till. Data for the current study area are much more difficult to interpret because the data set was much less detailed, data collection was not focused in areas where detailed land use information was available, and geology and physiography was more varied and complex.

$\delta^{18}O$ values are compared to NO_3-N concentrations for each physiographic area in Fig. 25. Nitrate occurs in bedrock and gravel groundwater with $\delta^{18}O$ values in the range of -16 to -21.2‰, indicating nitrate occurs in water that is recently recharged, in groundwater that is a mixture of old and recently recharged water, and in glacial-aged water. Most spring and gravel samples with $\delta^{18}O$ values less negative than -16 ‰ did not contain detectable nitrate (Fig. 25). The youngest groundwater occurred at areas U2, P3 and S1 (Fig. 25), but isotopes were not measured in river valley areas.

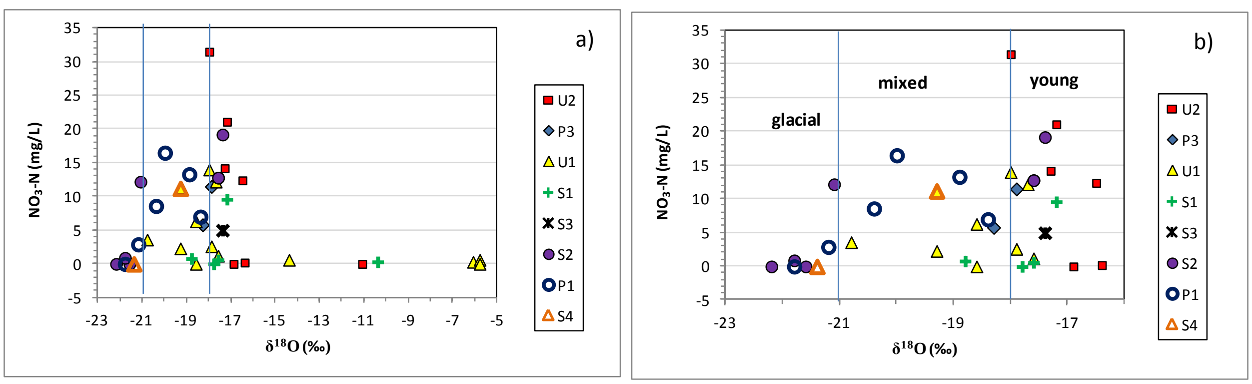

Fig. 25. $\delta^{18}O$ values compared to nitrate concentrations in each physiographic region. a) All data. b) excluding highly evaporated spring samples.

Nitrate was detected in the majority of groundwater samples from gravel and bedrock above 25 m in the study area. Nitrate was not detected at locations underlain by thick till, including the western side of the study area and adjacent to river valleys (Fig. 18). Nitrate distribution patterns exhibit unique characteristics in each physiographic region, as shown in Fig. 26. Nitrate distribution and other characteristics for each study area will be reviewed in detail in the next section, with the goal of determining nitrate source.

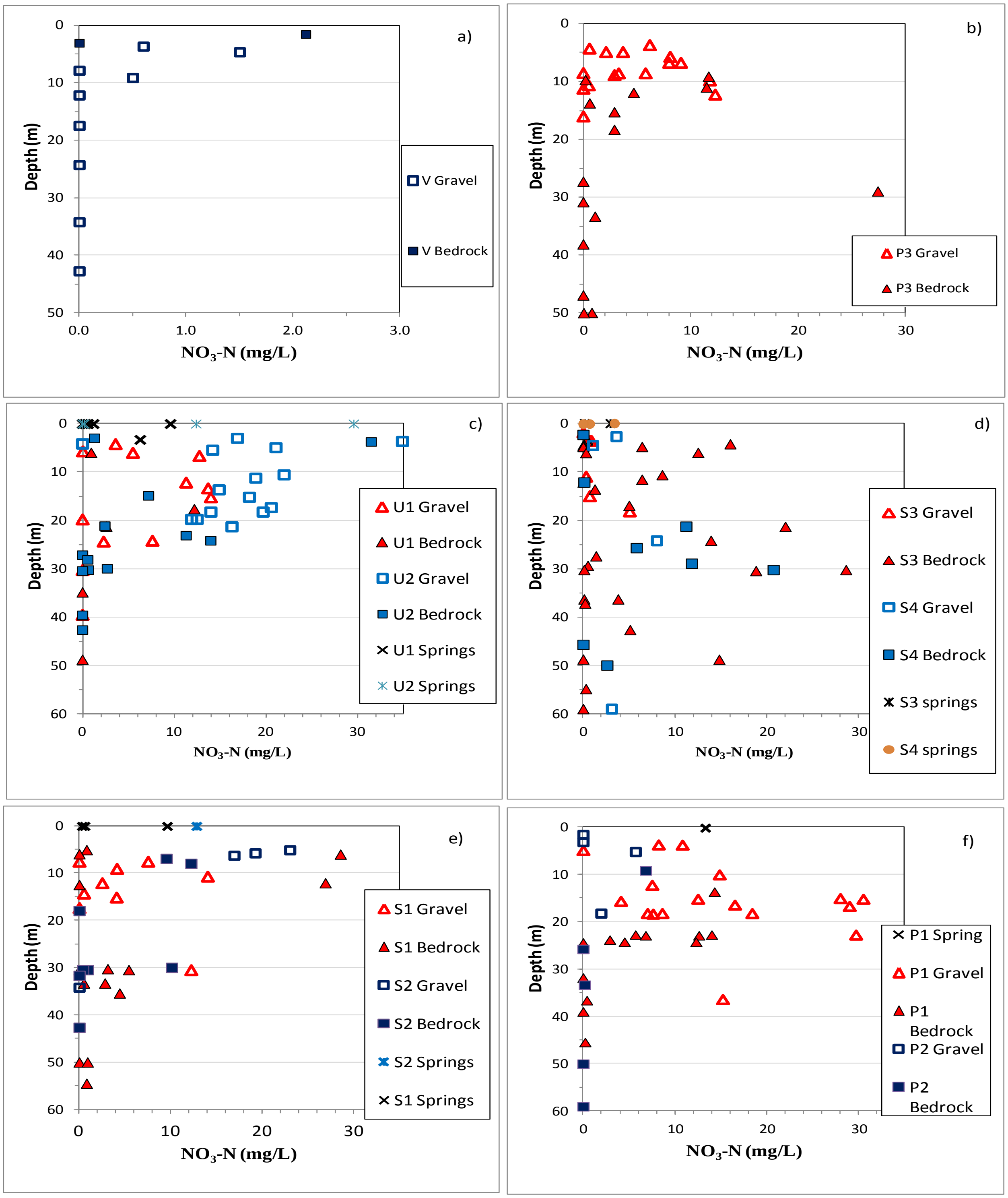

Fig. 26. NO_3-N with sample depth for each physiographic region. a) Near river valleys; b) North plain; c) Upland benches; d) South and north scarps; e) east scarps; f) eastern plains.

Nitrate Distribution by Physiographic Area

Each physiographic area (Table 4, Fig. 11) encompasses unique land use and hydrogeologic conditions that have a significant bearing on nitrate source and fate. In this section nitrate distribution and associated characteristics are assessed for five main regions:

1) River Valleys (V).
2) The north scarp (S3) and north plain (P3).
3) Southwest: the Ardenville Bench (U1) and south scarp (S4),
4) Central and East: The eastern slopes (S1 and S2) and eastern plains (P1, P2), and
5) The McBride Bench (U2).

The physiographic regions are usually referred to by their codes in this report.

Belly and Waterton River Valleys

Geology and Land Use

Geology adjacent to the Belly and Waterton river valleys generally consists of thick overburden (commonly 20 to 35 m thick) characterized by a complex inter-layering of till and gravel. Significant water-bearing sand and gravel layers are common within the till (inter-till gravels) and between till and bedrock (preglacial gravels). Geology is highly variable. For example, well logs related to groundwater samples in the area ranged from 34 m of till at one location, to 4 m till over 33 m gravel at another location.

Locations near the Belly and Waterton rivers have some of the most intensive agriculture in the study area. The majority of CFOs occur within 3 to 5 km of the Belly River valley in Range 25, and irrigated land in the study area is located entirely adjacent to the rivers (Fig. 7).

Nitrate Distribution, Source, and Denitrification

Eleven of the 12 groundwater chemistry samples from wells adjacent to river valleys were located along the eastern side of the study area, adjacent to the Belly River and the north end of the Waterton River (Figs. 13, 14 and 16)[2]. Nitrate in these valley gravels ranged from 0.6 to 2.5 mg/L in the top 9 m, and was not detected in deeper wells. The detection of nitrate in shallow groundwater in an area with relatively intensive land use indicates this nitrate is probably derived from agricultural sources. Half the samples from this area were collected before 1984, and no data were available to monitor trends with time.

Nitrate was not detected in bedrock (37 m depth), preglacial gravel (17 to 42 m) or inter-glacial gravel below a depth of 9 m (Fig. 26a). Valley gravels are buried below at least 12 m of till, and colour changes from brown to gray, indicating the visual redox boundary, were noted in gravel and till at several logs, most commonly at depths of about 6.7 to 11 m. Therefore, the lack of nitrate in deep valley gravels is consistent with the hypothesis that reducing conditions occur below thick till. Elevated concentrations of fluoride and dissolved iron were present in some

[2] The remaining sample was located near the Oldman River at the north end of the study area. Gravels in the P3 area are also associated with the Oldman River, but they are discussed in the next section.

samples without nitrate. The presence of elevated dissolved iron indicates groundwater at those locations was more reducing than required for denitrification (Simpkins and Parkin 1993).

North Scarp (S3) and North Plain (P3)

Geology and Land Use

Scarp 3 (S3) describes the sloping north face of the upland, which dominates the northern two-thirds of Tp. 8 Rg. 26, and the eastern portion of Tp. 8 Rg. 25 (Fig. 11). The north plain (P3) includes the northern one-third of Tp. 8 Rg. 26 (Fig. 11). Data were mostly not available for the north plain area in Tp. 8 Rg. 25.

Geology at S3 is predominantly fractured bedrock covered by thin or intermittent till (Fig. 12), so it is vulnerable to contamination from surface sources. Groundwater at the P3 area also has a high vulnerability to contamination, being characterized by intermittent till, mostly less than 5 m thick, overlying a significant thickness of gravel over bedrock (Figs. 12 and 17). Thick till, including unoxidized till, occurs on the western side of the S3 and P3 areas. Till is less than 5 m thick at most locations over P3 gravel (Figs. 17 and 18).

Land use at S3 and P3 is predominantly native range and tame pasture, but some areas of non-irrigated cropland occur. Two confined feeding operations are located in the upslope portion of S3, and two are located in P3 (Table 3; Fig. 7). Tp. 8 Rg. 25 has the highest density of confined feeding operations in the study area (Table 2) but groundwater data are very limited in that area (Fig. 3).

Groundwater Age and Nitrate Distribution

Groundwater age at S3 and P3 ranged from -17.4 to -18.3‰ in the three measured samples (Fig. 25), indicating groundwater that is predominantly modern. The only measured $\delta^{18}O$ value at S3 was -17.4 ‰ at 17 m depth in bedrock. The presence of relatively young groundwater at 17 m is consistent with the expectation that bedrock at S3 is fractured to significant depths.

- Nitrate was detected in most P3 gravel samples shallower than 10 m, and it was detected in bedrock at depths of 10 to 20 m. Nitrate concentrations decreased with depth in gravel and bedrock. Almost 30 mg/L NO_3-N were detected in one bedrock sample at 30 m in 1983 (Fig. 26b).
- NO_3-N was detected in one of the two springs in S3, at a concentration of 3 mg/L (Fig. 26d). Nitrate was not detected in the few gravel wells that were sampled, with the exception of one sample of deep gravel at 18 m, where almost 4 mg/L NO_3-N was measured in 1983. Nitrate was detected throughout S3 bedrock to depths of about 25 m. Concentrations decreased as depth increased from about 5 to 20 m, but nitrate was detected in several samples at depths of 30 to 50 m (Fig. 26d).

Time Trends and Nitrate Source at S3

Nitrate and major ion concentrations in a bedrock well at 21 m near the top elevation at S3 were stable or decreased slightly over the past 11 years (Fig. 27a). Nitrate increased by a factor of almost 3 in Well 626 (Fig. 27b) which is a fast-flowing shallow artesian bedrock well (4.8 m deep) at the bottom of the S3 slope. This well is in a local discharge area.

Changing nitrate concentrations with time, and the relatively young groundwater age at depth in S3 bedrock, suggest nitrate in the top 20 m at S3 may be derived from anthropogenic sources. Higher nitrate concentrations were detected in some samples at depths of 20 to 50 m (Fig. 26d). The depth of the nitrate detections below 20 m suggest a geologic source, but analysis of $\delta^{18}O$ and enriched tritium would provide more information on nitrate source at S3.

Time Trends and Nitrate Source at P3

Nitrate and major ions increased from 1980 to 2013 in all P3 wells with available time-trend data. This included wells at 6, 8 and 12 m (Figs. 28a , 28b and 29). Well 643 (Fig. 28a) was located on the same quarter section as a confined feeding operation, and the other wells (Figs. 28 and 29) were located on cultivated land that may have received manure.

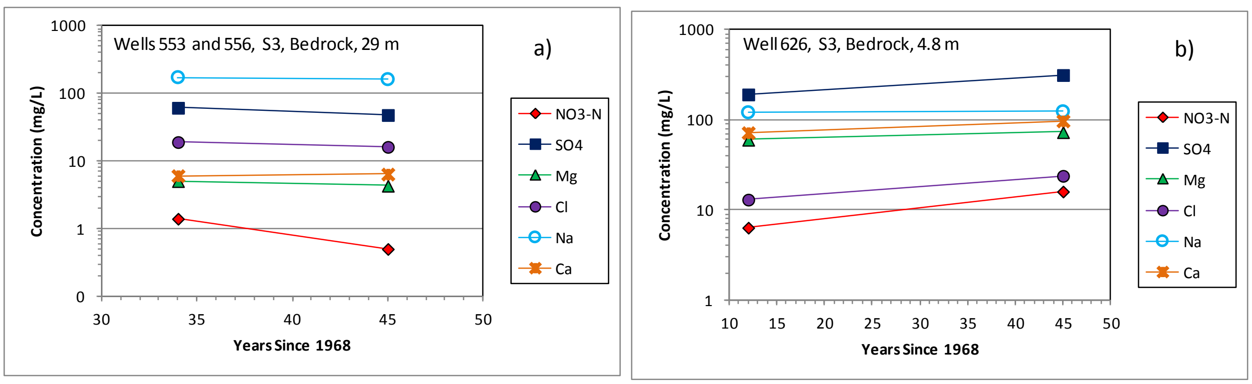

Fig. 27. Trends in major ion and nitrate concentrations with time at S3. a) Deep bedrock; b) shallow bedrock.

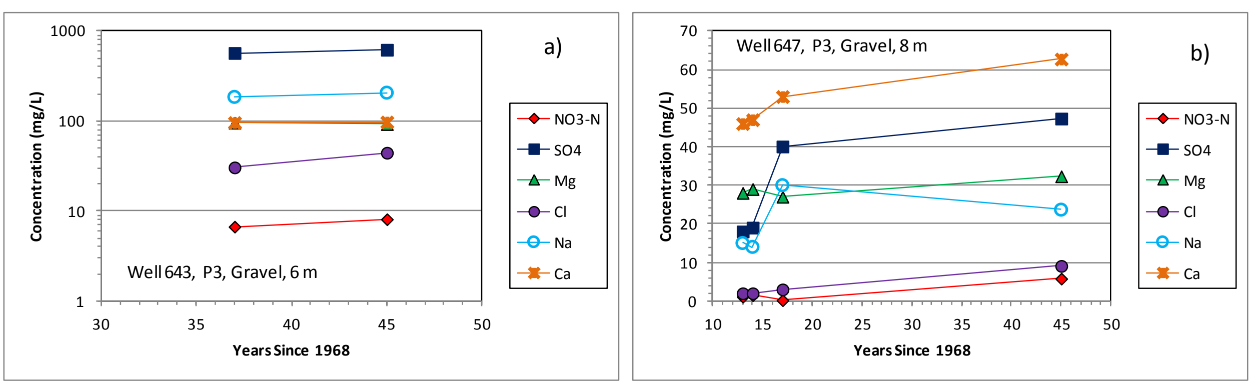

Fig. 28. Trends with time for nitrate and major ion concentrations at P3.

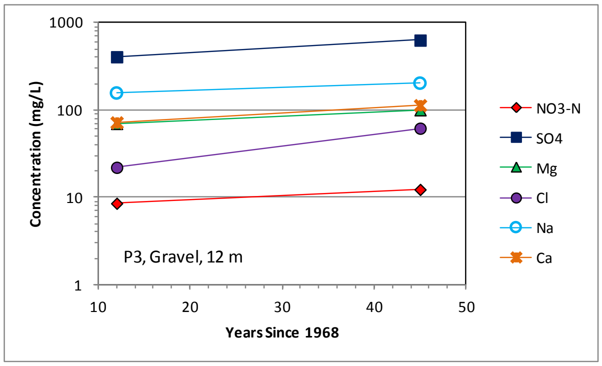

Fig. 29. Trends with time for nitrate and major ion concentrations at P3.

Nitrate in P3 gravel to a depth of 15 m is probably derived from an anthropogenic source, based on the increase in nitrate and major ion concentrations with time at 6, 8 and 12 m depth in an area where groundwater is highly vulnerable and some intensive agriculture occurs. Nitrate in P3 bedrock at depths of 10 to 20 m may also be derived predominantly from an agricultural source, based on the recent groundwater age in bedrock at 11 m. The single sample with nitrate at 30 m may be derived from a geologic source, based on depth.

South Scarp (S4)

Geology and Land Use

Only limited chemistry and lithology data were available for Tp. 6, Rg. 26, so all wells were grouped as Scarp 4 (S4) in this report. Bedrock elevation decreases along the south-facing scarp (Fig. 12). Limited available data suggests geology is dominated by till over bedrock, and seven of the eight wells were installed in bedrock. Land use on the south scarp is predominantly native range in the upslope areas and non-irrigated cropland at lower slope positions (Fig. 7).

Groundwater Age and Nitrate Distribution

Groundwater that enters bedrock at higher elevations on U1 flows downslope and discharges under artesian pressure along the S4 slopes. Both S4 wells measured for isotopes were located in areas where extensive discharge was observed to occur from bedrock along the south scarp. ^{18}O in S4 bedrock ranged from -19.3 to -21.4‰, indicating groundwater that recharged mainly during glacial times.

NO_3-N at S4 was not detected in wells at depths of 5 to 12 m, but was detected in all wells at depths of 20 to 30 m, at concentrations of about 5 to 20 mg/L. Low nitrate concentrations were also apparently detected at depths of 50 to 60 m (Fig. 26d).

Time Trends and Nitrate Source

Nitrate and major ion concentrations in a deep flowing artesian bedrock well at S4 were constant for three samples collected over the past 45 years (Fig. 30a). Concentrations were also stable in a bedrock spring at the south end of S4, near the Waterton River (Fig. 30b).

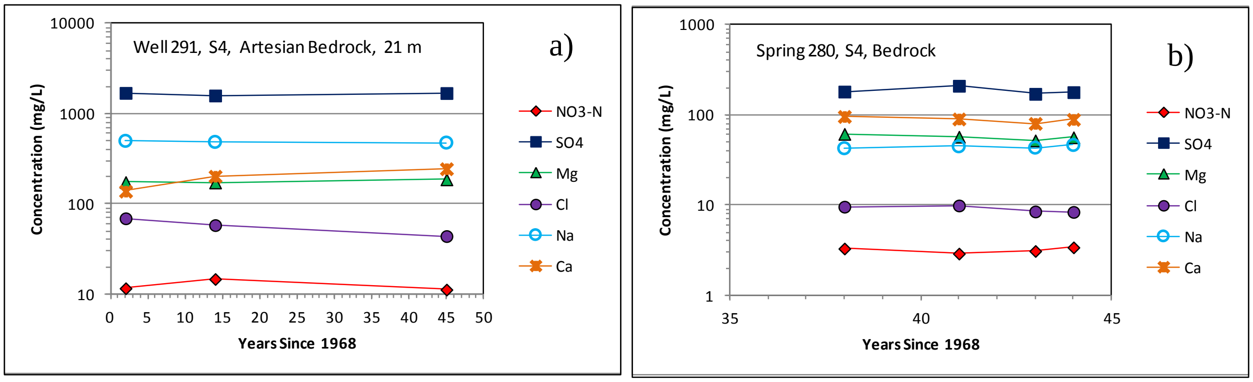

Fig. 30. Chemistry trends with time in bedrock at S4. a) 21 m, b) spring.

The detection of nitrate throughout S4 bedrock at depths of 20 to 30 m, in groundwater with an $\delta^{18}O$ value of -19.3‰, with no detections in shallow bedrock (Fig. 26d) and stable concentrations over the past 45 years, implies a geologic nitrate source.

Ardenville Bench (U1)

Geology and Land Use

A major gravel channel is deeply incised into bedrock on the Ardenville Bench (U1). The deep western part of the channel is characterized by up to 24 m of gravel overlain by about 20 to 34 m of glacial till (Figs. 13 and 14). The shallower eastern part of the channel occurs at a higher bedrock elevation, with only about 9 m of till overlying 10 m of gravel (Fig. 14). Preglacial gravels from the shallower channel discharge where they outcrop along the northeastern edge of the Bench, at the location where ground elevation drops into the S1 area (Fig. 14).

Agricultural land use at U1 is predominantly native range and tame pasture (Fig. 7). The area contains former hog and cattle facilities, and at least three bedding and feeding areas and two swine operations (Table 3).

Groundwater Age and Nitrate Distribution

Nine springs were sampled at U1, with repeat samples at four of them.

- Five of the nine springs contained $\delta^{18}O$ values of -5.8 to -14.4‰ (Fig. 31a), indicating recent recharge or predominantly surface water. These springs contained <0.6 mg/L NO_3-N.
- Four of the nine springs contained $\delta^{18}O$ values of -17.6 to -18.6‰, and 1.2 to 6.3 mg/L NO_3-N (Fig. 31b).

These results indicate that mixed-age spring water contained more nitrate than surface water and recently recharged spring water.

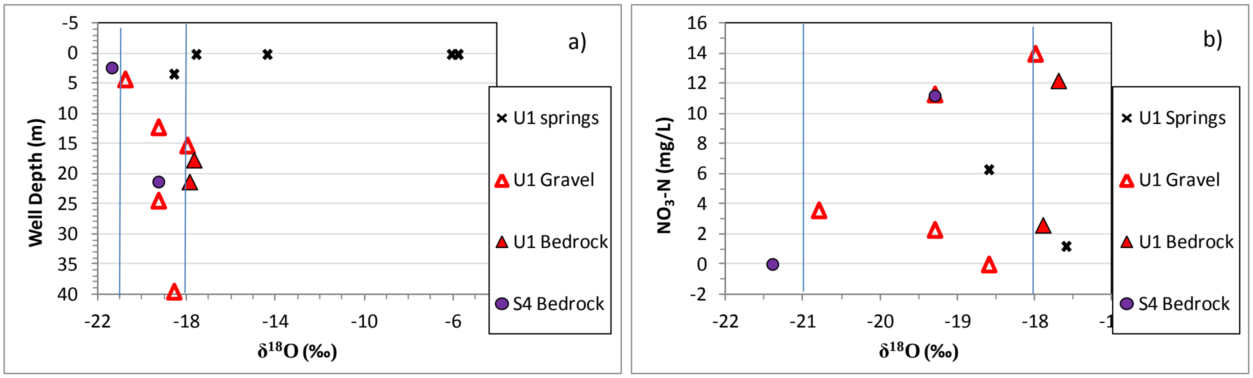

Fig. 31. δ18O in water at U1 and S4. a) with well depth. b) with NO3-N concentration.

Based on all sampled bedrock and groundwater wells and piezometers at U1, nitrate increased to a depth of about 15 to 18 m, was still detectable at 25 m, and was not detected below 28 m (Fig. 26c). NO_3-N concentrations at depths of 5 to 25 m mostly ranged from about 5 to 12 mg/L (Fig. 26c). $\delta^{18}O$ in groundwater with detectable nitrate ranged from -17.7 to -20.8 ‰ (Fig. 31b), indicating groundwater of a relatively old but mixed age. The most negative (oldest) $\delta^{18}O$ values occurred above 5 m at both the U1 and S4 areas (Fig. 31a), suggesting groundwater discharge at those locations.

Concentrations of NO_3-N in mg/L are shown as red numbers in geologic cross-sections (Figs. 12 to 14).

- Nitrate was not detected in the deep gravel channel at the west, where wells are deeper than 30 m (Figs. 13 and 14). These deep gravels are buried by thick till, including a significant thickness of reduced till below 18 m, as indicated by a gray colour reported by drillers (Fig. 14). The absence of detectable nitrate in these deep wells is consistent with reducing conditions where nitrate is not stable.
- The highest NO_3-N concentration (35 mg/L) was detected at the upslope edge of the shallow gravel channel, at location 416 (Fig. 14).
- Nitrate was detected in all wells in the shallower gravel channel and underlying shallow bedrock, where till is oxidized and less than 20 m thick (Figs. 14).
- Groundwater in the shallow U1 gravel channel discharges along the eastern and southern scarps, and nitrate concentrations were much lower in springs than in the gravel channel (Fig. 14). Spring S2 at the north end of the U1 gravel (location 450 in Appendix 4) was monitored six times from May to September of 2013. NO_3-N concentrations increased from 1.2 mg/L in May (as shown in Fig. 31b) to 3.4 mg/L in September. $\delta^{18}O$ ranged from -17.2 to -17.6‰ during the monitoring period.

A plan-view map of nitrate distribution at U1 is shown in Fig. 32. Numbers beside each symbol show NO_3-N concentrations in a bedrock well (green symbol and green numbers), a gravel well (red symbols and red numbers) or a spring (yellow symbol and black numbers). Well depths are divided into categories as shown on the legend for Fig. 32. Results on the map show that:

- Nitrate was not detected below thick till;
- Nitrate concentrations generally increased to the north (downslope in the shallow gravel channel shown in Fig. 14).
- Nitrate was not usually detected in bedrock wells shallower than 6 m or deeper than 27 m, although exceptions occurred (Figs. 26c and 32).

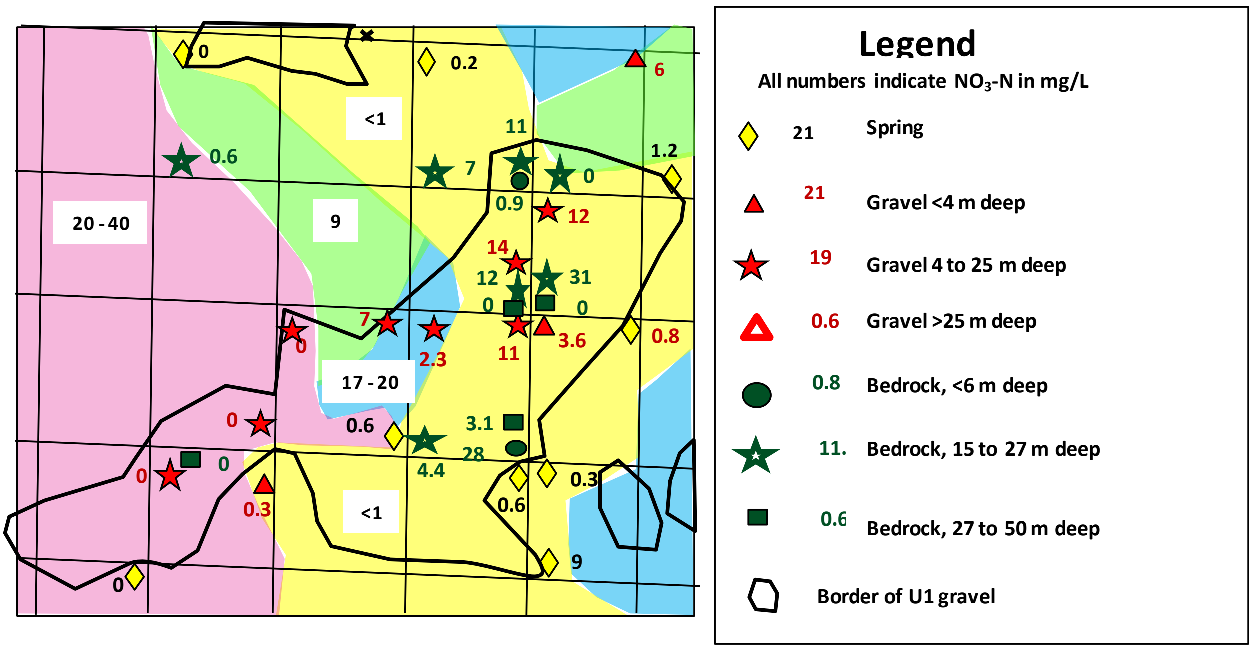

Fig. 32. Plan view map of nitrate distribution at U1 (the Ardenville Bench).

Time Trends and Potential Agricultural Sources

Five U1 well samples were located at depths shallower than 7 m.

- Three wells were sampled before 1987, with a maximum of 5.5 mg/L NO_3-N detected in 1986.
- Two samples were collected from shallow gravel wells in 2013.
    - No obvious sources of nitrate were observed in the vicinity of a well with 3.6 mg/L NO_3-N, with the exception of a winter feeding and bedding area located about 1.6 km upslope. This well contained an ^{18}O value of -20.8 ‰, suggesting the nitrate was not anthropogenic.
    - Well 435 was located in the vicinity of a temporary manure storage area. NO_3-N was measured at 11.5 mg/L in 1970 and 12.8 mg/L in 2013, while Cl apparently increased from 8 to 14 mg/L (Fig. 33a). A sample collected in 1986, apparently at the same location contained only 5.5 mg/L NO_3-N (Fig. 33a). ^{18}O was not measured on this well, and the source of nitrate requires more investigation.

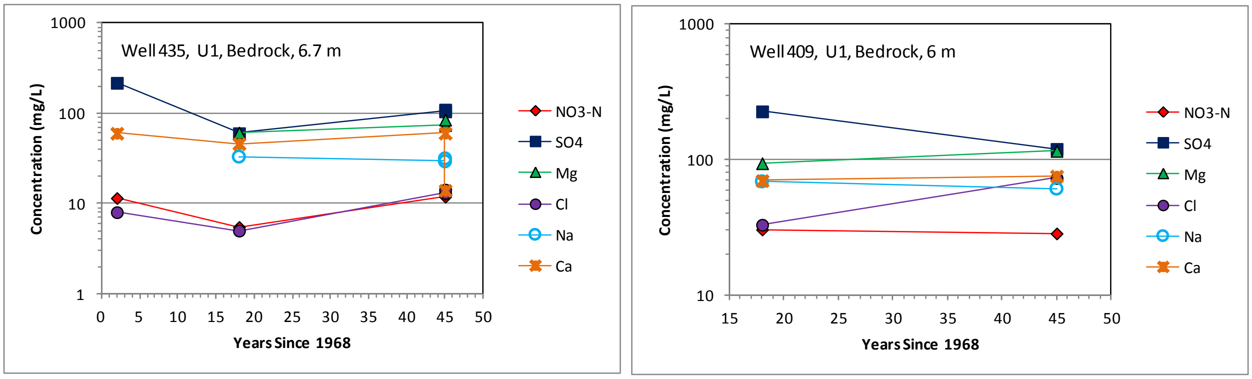

Fig. 33. Time trends at U1. a) Gravel at 6.7 m; b) Bedrock at 6 m.

The concentration of NO_3-N was remarkably stable in a 6-m bedrock well at U1, changing from 30.5 mg/L in 1986 to 28.5 mg/L in 2013. During the same time period, results suggested Cl increased and SO_4 decreased (Fig. 33b). This well was located adjacent to a bedding and feeding area. Cl and SO_4 often increase in groundwater impacted by manure (Rodvang et al. 2004). Chloride is often the best indicator of point-source manure impacts, because manure-derived nitrogen can be removed via plant uptake, denitrification, or ammonium adsorption (e.g., McCallum et al. 2008). If the increased Cl is related to contamination from animal manure, it suggests denitrification or plant uptake have kept nitrate concentrations constant at about 30 mg/L. The source of nitrate in Well 409 is uncertain.

Piezometer Nest 1

Piezometer nest 1 was located in the shallow gravel channel on the Ardenville Bench. Gravel occurs within 1 m of ground surface, and NO_3-N concentrations decreased from 14 mg/L in gravel to 2.6 mg/L in bedrock at 21 m (Fig. 34). With less than 1 m of till cover, the shallow gravel channel at nest 1 is highly vulnerable to surface sources of contamination, and the decrease in nitrate with depth suggests it may be derived from an anthropogenic source of nitrate. However, piezometer nest 1 is located on healthy native range near the highest point in the landscape for an extensive area (Fig. 4). Congregation of cattle in recharging depressions (Plate 10) may result in some nitrate leaching from manure (Plate 11), and other anthropogenic nitrate sources may also occur.

The decrease in nitrate with depth at nest 1 is not accompanied by a decrease in groundwater age, suggesting denitrification may be responsible for the decrease. This hypothesis is consistent with the slight increase in $\delta^{15}N$ with depth (Fig. 34). Groundwater in all three piezometers is of mixed age, suggesting old groundwater is mixed with more recent rain and snowmelt water.

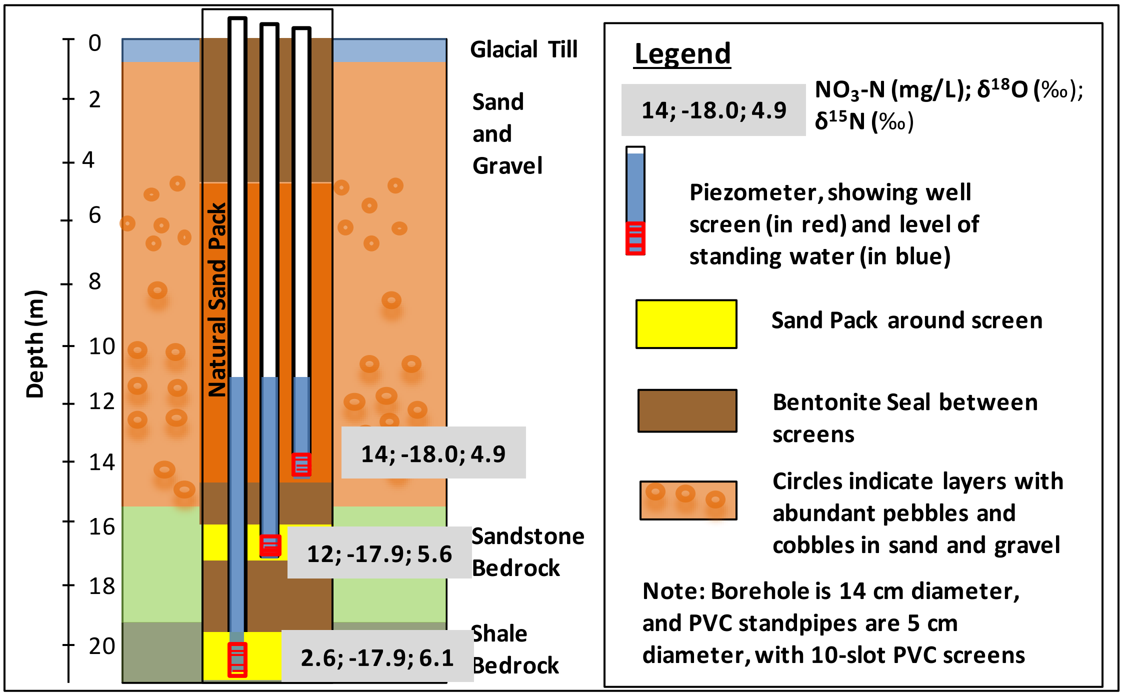

Fig. 34. Stratigraphic column for piezometer nest 1 on the Ardenville Bench.

Nitrate Source

Nitrate source at U1 is unclear based on current data. Nitrate at all depths occurs in groundwater that is a mixture of old and modern recharge. Repeat samples suggest nitrate stability with time, but the data are limited and somewhat uncertain. Agriculture is generally of low intensity at U1, but some manure sources occur. In moving from west to east, nitrate was first detected at the approximate location where till thins and gravels approach ground surface. The thinning till indicates increased vulnerability to anthropogenic nitrate sources, but it also indicates potential downward leaching from oxidized till (Fig. 32).

Some evidence supports a geologic source for at least part of the nitrate at U1. Geology data shown in Fig. 14 suggests the shallow gravel channel receives groundwater input from both bedrock and till in the area immediately upslope of nest 1 in the shallow channel, and either source could transport nitrate into the Ardenville gravel. The low ^{18}O values measured in the shallow gravel channel (Fig. 31a) are consistent with groundwater discharge, as are the limited data on hydraulic head. Leaching from till is consistent with the detection of 35 mg/L NO3-N at location 416, where the shallow gravel channel is overlain by oxidized till (Fig. 14). In summary, more investigation is required to determine nitrate source at U1.

The Upper East Scarp (S1)

Geology and Land Use

The upper portion of the east-facing scarp immediately east of the Ardenville and McBride benchs is termed the S1 physiographic area. It occurs at ground surface elevations of approximately 1170 to 1060 m, and includes the northern part of Tp. 6 Rg. 26, immediately south of the Ardenville Bench (Fig. 11). Geology is highly variable within S1 due to the moderate slopes, eroded drainage channels incised into bedrock, and the pinching out of gravel channels as elevation drops along the scarps. Gravels at S1 are thin, absent or intermittent. They usually occur close to surface or covered with thin till. Geology commonly includes very thin till over bedrock, up to 15 m of till over thin gravel over bedrock, and variable thicknesses of diamicton (an unsorted mixture of clay, gravel and boulders) over bedrock.

Land use is predominantly native range and tame pasture at area S1 (Fig. 7).

Groundwater Age, Nitrate Distribution and Nitrate Source

$\delta^{18}O$ data at S1 included two springs (-17.2 and -17.6 ‰) and two wells (-18.8 ‰ in bedrock at 5 m, and -17.8 in gravel at 17 m (Appendix 4). All samples therefore reflect recently recharged groundwater, although the age in the shallow bedrock suggests it may be affected by groundwater discharge.

Two sampled springs at U1 flowed through native range or tame pasture, and contained a maximum NO_3-N concentration of 0.6 mg/L. The third spring (Spring 382) flowed down from corrals. NO_3-N concentrations in spring 382 fluctuated from 9 mg/L in May, to 4 to 10 mg/L in June and July, to 15 mg/L in September. $\delta^{18}O$ ranged from -17.2 to -15.5‰ during the monitoring period. Nitrate in spring 382 was interpreted to be agricultural in origin, based on fluctuating nitrate concentrations and $\delta^{18}O$ values, young age, and association with a manure source.

Nitrate at S1 was detected in many, but not all, wells in bedrock and gravel between the depths of 5 and 25 m. Wells with detectable nitrate generally occurred near potential manure sources. For wells shallower than 12 m:

- Nitrate was not detected in three wells located on native range.
- A well containing 28 mg/L NO_3-N was located downslope of a winter feeding and manure storage area.
- Nitrate was detected in two wells on cultivated land.

The apparent association of nitrate with cultivated land or potential manure sources may be circumstantial.

Limited time trends at S1 indicated fluctuating nitrate concentrations with time, suggesting anthropogenic nitrate sources.

- Nitrate and major ion concentrations increased from 1976 to 2013 in a 10-m gravel well located downslope of corrals (Fig. 35a).
- Nitrate and major ion concentrations decreased from 1983 to 2011 in gravel at 12 to 14 m (Fig. 35b) in a well located in native range where no obvious sources of anthropogenic nitrate were noted (Fig. 7; Appendix 4).

Both time trends relied on only two data points, but the results suggest groundwater above 12 to 14 m depth is susceptible to anthropogenic inputs, consistent with data from groundwater age and nitrate distribution.

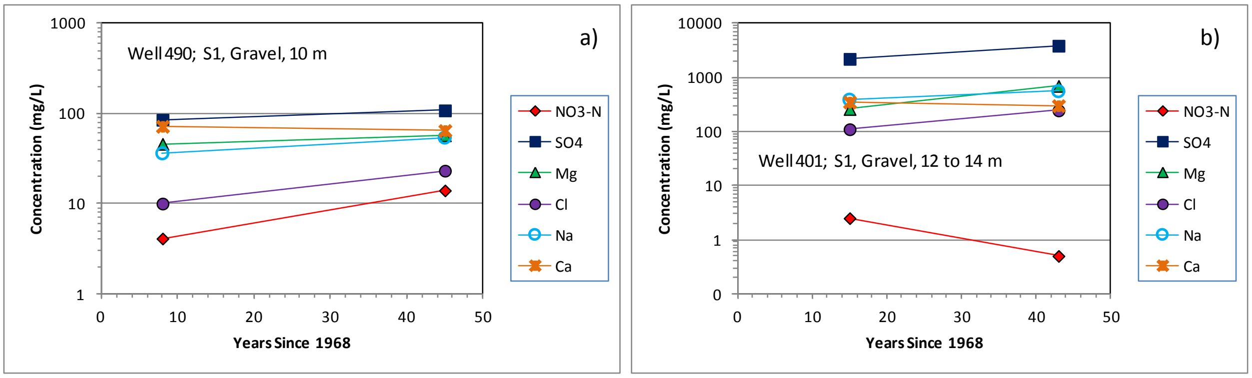

Fig. 35. Chemistry trends with time at the S1 area. a) Gravel and 10 m. b) Gravel at 12 to 14 m.

The association of animal agriculture with the detection of nitrate in springs and wells to 15 m depth, combined with relatively young groundwater ages and increasing nitrate concentrations with time at a location near corrals, suggest agriculture is the predominant nitrate source in gravel and shallow bedrock at area S1. Nitrate at 30 m depth in bedrock at S1 may be derived from geologic sources.

The Lower East Scarp (S2) and East Plains (P1 and P2)

Geology

- The lower eastern scarp unit (S2) occurs at a minor break in slope between the Uplands and Unit P1 (Fig. 11). The S2 unit includes a gravel layer with bottom elevations ranging from 1036 to 1006 m, occurring in a relatively narrow north-south strip along the eastern scarp on the western side of Tp. 7 Rg. 25 (Fig. 11). The gravel layer occurs directly above bedrock, and is covered with a variable thickness of till. The thickest gravel, of 10 to 14 m, occurs at the south end, where gravels occur within 3 m of ground surface and are not overlain by till. Elsewhere the gravel in S2 is generally only about 1 m thick and covered with 5 to 20 m of till. Similar to the other gravel channels, the sand and gravel grades to clay and gravel near the boundaries.

- The Plains 1 (P1) area is characterized by a long and narrow south to north trending preglacial gravel layer that occurs between S2 and P2. The P1 gravel is about 1.5 to 3 km wide, and extends from the Waterton River in the south to near the middle of Tp. 8, Rg. 25 (Fig. 11). The gravel is generally about 5 m thick and overlain by approximately 9 to 18 m of glacial till, which is mostly oxidized except below about 14 m (Fig. 18).

- The Plains 2 (P2) area is a similarly long and narrow south-north trending preglacial gravel layer that occurs immediately east of P1. The P2 gravel is about 2 km wide but the area is limited to Tp. 7 Rg. 25 (Fig. 11). Four geologic logs were available for the P2 area, all indicating about 14 to 18 m of till over a preglacial gravel layer of 2 to 5 m in thickness. The redox boundary was noted at 14 m at one location, as indicated by a change in till colour from brown to gray.

Land Use

Land use is predominantly non-irrigated cropping at the S2, P1 and P2 areas (Fig. 7). A relatively high density of confined feeding operations occurs in Tp. 7 Rg. 25 (Table 3), but the CFOs are all downslope of the P2 area, adjacent to the Belly River, and data were mostly not available for this area.

Groundwater Age

$\delta^{18}O$ values in water tended to decrease with increasing well depth, indicating groundwater generally becomes older with depth. All bedrock groundwater samples at S2 and P1 contained $\delta^{18}O$ values less than -21‰ (Fig. 36a) indicating this bedrock groundwater recharged predominantly under glacial conditions. Groundwater in gravel at P1 was of mixed age, while groundwater samples collected from gravel and springs at S2 were less negative than -18 ‰, suggesting groundwater that recharged predominantly in recent times (Fig. 36a). $\delta^{18}O$ values measured for S1 samples are included in Fig. 36a to show that groundwater becomes older as elevation decreases from S1to S2 to P1.

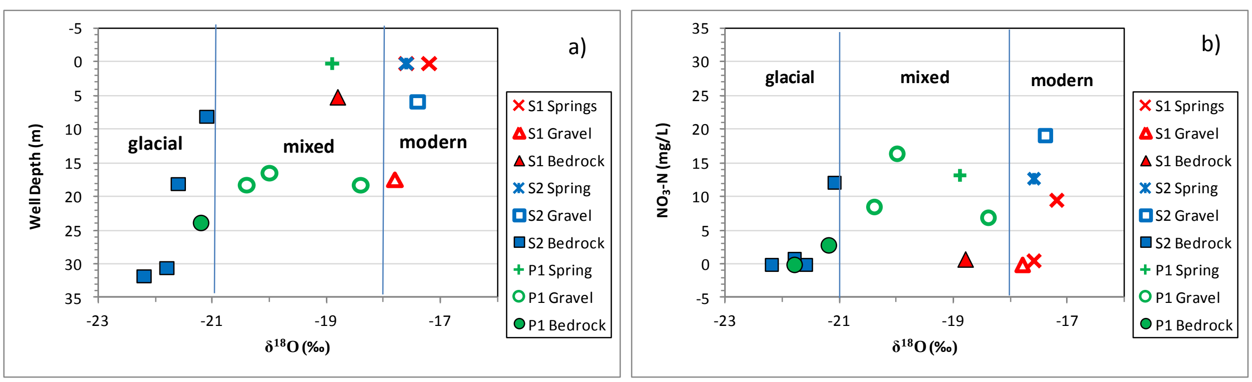

Fig. 36. $\Delta^{18}O$ in water at areas S1, S2, P1 and P2, compared to: a) well depth, and b) NO_3-N concentration.

Nitrate Distribution

Nitrate was present in most samples from bedrock and gravel at depths of about 5 to 25 m at the S2, P1 and P2 areas (Figs. 26e and 26f; Figs. 13 to 16). Samples with elevated nitrate contained $\delta^{18}O$ values ranging from -17.2 to -21.1‰ (Fig. 36b), indicating nitrate was present in groundwater including recently recharged, mixed age (-18 to -21 ‰) and glacial age (≤-21‰).

A plot of nitrate concentrations compared to screen elevation indicates that nitrate concentrations in gravel tended to increase at progressively lower elevations (Fig. 37). With the exception of two samples from S1 bedrock, NO_3-N concentrations were less than 10 mg/L at elevations higher than about 1060 m, while concentrations were commonly up to 30 mg/L at lower elevations (Fig. 37).

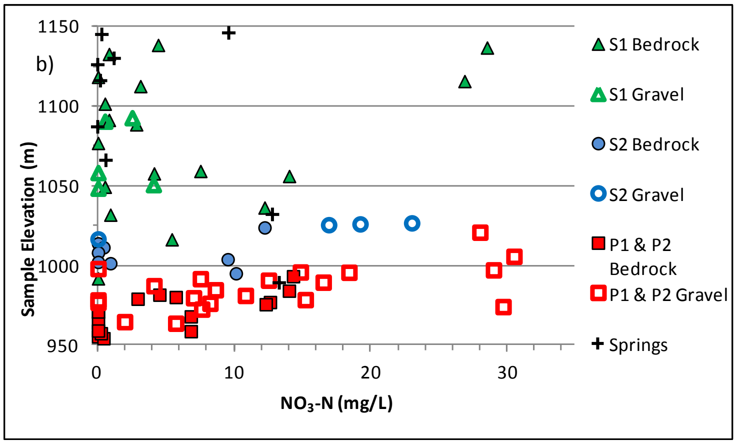

Fig. 37. NO_3-N concentrations with elevation at S1, S2, P1 and P2.

At least two water wells on the east plains were installed in thin sand layers within till. Well 36 contained 30 mg/L NO_3-N at 15 m depth, and well 99 contained 6 mg/L NO_3-N at 5 m depth[3] (Appendix 4). The detection of nitrate at depths of 5 to 15 m in glacial till is consistent with the findings of the results of Hendry et al. (1984) and Rodvang et al. (1998; 2002) for other locations in southern Alberta.

Time Trends

Nitrate and major ion concentrations were stable from 1975 to 2006 at Well 71 in P1 bedrock at 22 m (Fig. 38a). Concentrations of NO_3-N, Cl and SO4 decreased slightly from 1986 to 2013 in shallow water-well 77 in gravel near nest 2 (Fig. 38b).

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[3] The detection of nitrate in bedrock below almost 24 m of till, as shown for Well 490 in Fig. 14, is unusual, and suggests till may be thinner than recorded in the log at this location. Three geologic logs are available in the vicinity of Well 490, indicating till thicknesses ranging from 8 to 24 m.

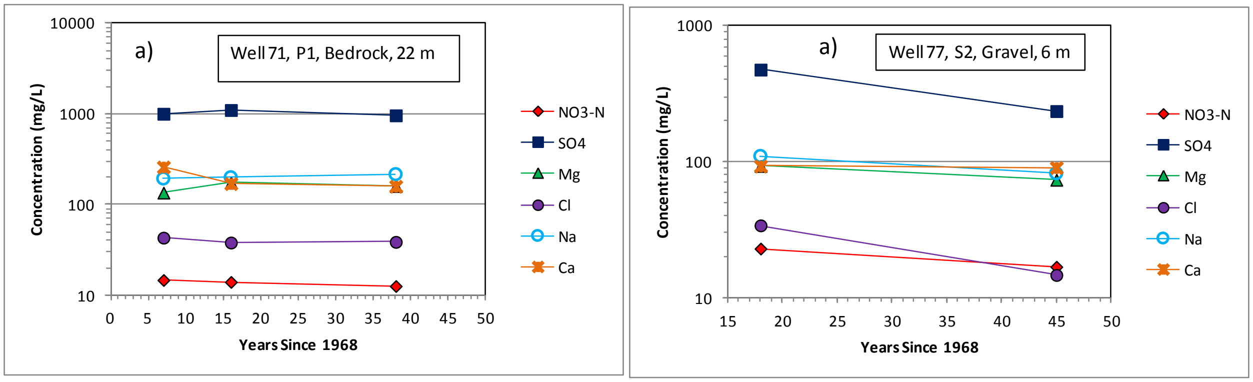


Fig. 38. Concentrations of NO_3-N and major ions with time. a) Gravel at 6 m; b) Bedrock at 22 m.

The data set of groundwater samples from gravel collected from 1965 to 1986 contained several nitrate concentrations that were higher than in the data set collected from 2002 to 2013 (Fig. 39). NO_3-N concentrations in gravel samples at depths of 9 to 24 m ranged from 12 to 76 mg/L in the 1965 - 1986 data set, and from 4 to 16 mg/L in the 2002 - 2013 data set. No differences were noted for bedrock between the two time periods (Fig. 39a). The differences in nitrate concentration between the two data sets for gravel was not related to well depth (Fig. 39b). The earlier data set also contained some samples that were somewhat higher in Cl (Fig. 39c) and SO_4 (Fig. 39d).

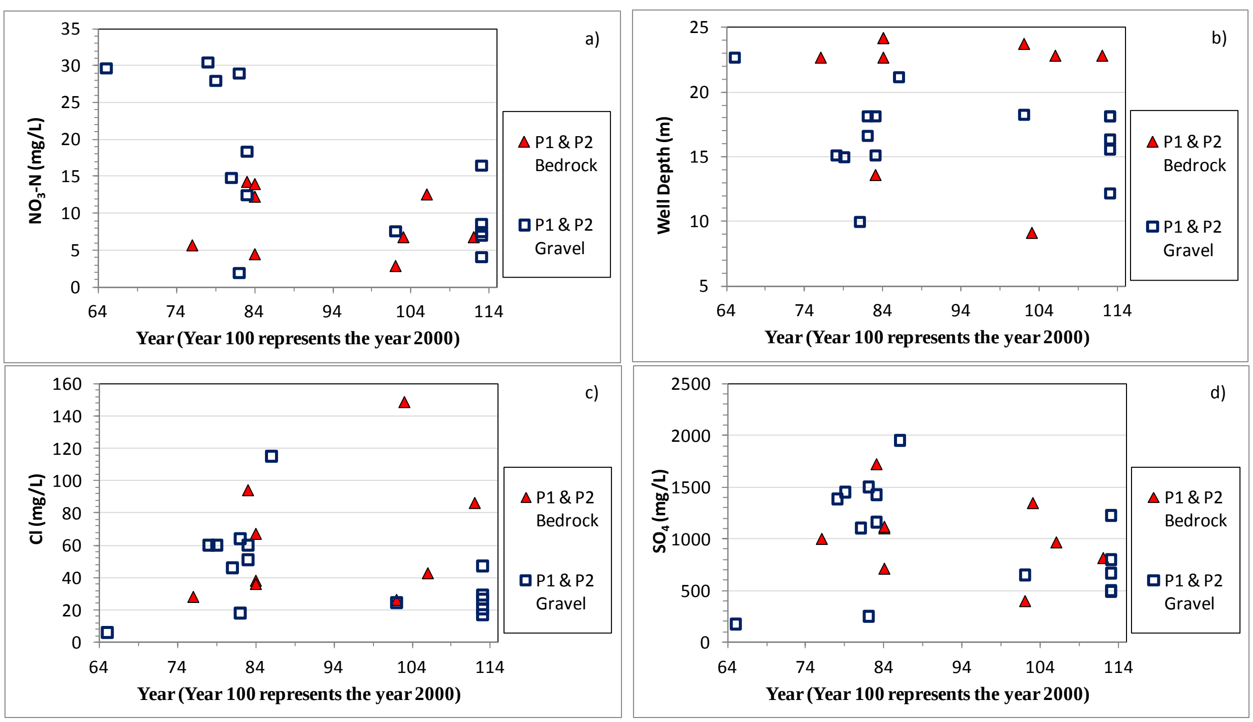


Fig. 39. Nitrate concentrations with time at P1 and P2, for all wells sampled from 1965 to 2013, at depths of 9 to 24 m. Sample year compared to: a) NO_3-N b) well depth; c) Cl; and d) SO_4.

The differences between the two data sets may reflect location, because samples with NO_3-N concentrations higher than 20 mg/L were all collected from the southern part of P1, which was not re-sampled in the later data set. Eight of nine samples in the 1965-1986 data set were located south of section 6-7-25, and four of six samples in the 2002-2013 data set were located north of section 28-7-25. However, nitrate concentrations were not correlated to till thickness within P1 (Fig. 18). The differences between the two data sets may also relate to differences in laboratories or sampling methodologies.

Nitrate Source in Shallow Groundwater and Springs at S2, P1 and P2

For wells in the top 6 m of the S2-P1-P2 area,

- Obvious anthropogenic nitrate sources were not observed at locations 25 and 115, and the three wells did not contain detectable NO_3-N.
- Three wells (111, 157 and 160) were located in the same quarter section as confined feeding operations, and they contained NO_3-N concentrations of 6 to 11 mg/L.

The association of nitrate with confined feeding operations suggests this nitrate may be anthropogenic, particularly since isotopic data indicate groundwater above 6 m in this area is of modern or mixed age (Fig. 36a). Changing nitrate concentrations with time in shallow gravel (Fig. 38b) are consistent with groundwater in shallow gravels that is vulnerable to contamination.

Two springs were sampled in the S2-P1-P2 area: Spring 77 in area S2, and Spring 22 in area P1 (Table 6). Both springs originated where gravels pinched out along the edge of the Ardenville Bench, and both springs contained about 13 mg/L NO_3-N. Concentrations of dissolved inorganic species at both springs were higher (particularly for sulphate) than at their point of origin on the edge of the Ardenville Bench, and very similar to concentrations in shallow gravel wells at the spring sampling location (Table 6). The two springs exhibited other differences.

- Spring 22 originated along a channel that flowed underground through non-irrigated cropland (Fig. 7). The spring flowed at a significant rate through the spring and early summer of 2013. From the point of origin at Spring 382 at the south edge of the Ardenville Bench (Fig. 12), the spring water received input from older groundwater with higher SO_4 concentrations. Spring 22 contained inorganic ion concentrations similar to the shallow gravel well at the sampling location, but nitrate concentrations much more similar to the spring origin at location 382 (Table 6). The comparison in Table 6 implies that Spring 22 contained nitrate derived from groundwater at the edge of the Ardenville Bench, but inorganic constituents from older groundwater on the plains. Spring 22 was sampled twice in May before it went dry. Both samples contained 13 mg/L NO_3-N.

- Spring 77 flowed from its origin at the north end of the Ardenville Bench, downslope over till and shallow bedrock (Fig. 14) through land use dominated by native range and tame pasture (Fig. 7). It was fast-flowing in February of 2013, but nearly stagnant in July of 2013. $\delta^{18}O$ values indicated recently-recharged water, with values nearly identical at the point of origin and at the downslope spring and shallow gravel well (Table 6). The comparison in Table 6 implies that spring 77 picked up nitrate as it flowed downslope from the Ardenville Bench.

Table 6. Two springs in Area S2-P1, compared to spring origin and shallow wells at the sampling location.

Location	Location Number	Isotope Value (‰)		Concentration (mg/L)						
		$\delta^{18}O$ (H_2O)	$\delta^{15}N$ (NO_3)	NO_3-N	Cl	SO_4	Mg	HCO_3	Ca	Fe
Origin Spring	450	-17.6	10.6	1.2	5	21	64	540	73	0.32
Downslope Spring	77	-17.6	7.1	12.8	18	313	82	487	94	0.08
Piezometer, 5 m	77	-17.4	4.6	19.2	15	244	78	428	95	0.63
Origin Spring	382	-17.2 to -15.5	10.6	4 to 15.5	51	310	87	381	51	0.03
Downslope Spring	22	-18.9	9.1	13.3	64	1464	182	404	205	0.27
Well, 4.8 m	25	N.D.	N.D.	0	71	1404	158	456	184	0.10

*N.D. = not determined.

Piezometer nest 2 was installed adjacent to Spring 77. Significant agricultural nitrate sources were not observed immediately upslope or in the vicinity of nest 2, but it was located immediately downslope of a farmyard. The source of nitrate in shallow gravels at this location requires additional investigation. Nitrate in relatively modern groundwater suggests a recent source, but the drainage channel at nest 2 is incised into bedrock, so there are expected to be locations where bedrock discharges into S2 gravel. In summary, the origin of nitrate in Spring 77 and piezometer nest 2 at location 22 requires additional investigation.

Nitrate Source in Deeper Groundwater at S2, P1 and P2

Bedrock groundwater at S2 and P1 was predominantly of glacial age, and groundwater in deeper gravel at S2 was predominantly of mixed age (Fig. 36a). Nitrate was detected in 17 of 17 samples from gravel at depths of 5 to 36 m, in nine of nine samples from bedrock less than 25 m deep, and in zero of ten bedrock samples at depths of 25 to 60 m (Fig. 26f). The deep samples without nitrate were characterized by calcium less than 25 mg/L, which was a typical characteristic for relatively deep groundwater in the study area.

The widespread occurrence of nitrate in glacial-aged groundwater suggests a geologic source. Piezometer nest 3 in area P1 was installed in bedrock below more than 17 m of heavy clay till that was partially unoxidized below 12 m (Fig. 40). The bedrock groundwater contained almost 3 mg/L NO_3-N, even though $\delta^{18}O$ was -21.2 ‰ (Fig. 40) indicating groundwater that was recharged predominantly under glacial conditions.

Observations of glacial till during drilling at piezometer nest 3 indicated a heavy clay-loam texture with low hydraulic conductivity (Plate 12). Gypsum was present between the depths of 4.6 and 10.7 m. Gypsum is associated with till that is enriched with shale. The till was dark gray below 11 m, but tiny fractures lined with iron-rich alteration products were evident throughout, indicating the till is partially oxidized throughout its depth. The oxidized heavy clay-loam till with abundant tiny fractures, rich in gypsum and iron alteration products, is very similar to till observed during drilling within 50 to 100 km from the study area, in the Picture Butte, Vauxhall and Lethbridge areas (Rodvang et al. 1998; 2002). This type of till is similar to the “Dalmeny Dry” location studied by Keller et al. (1991), where detailed investigations indicated a vertical flux of 0.3 cm per year. At that flux rate it would take more than 5,000 years for one pore volume of recharging groundwater to flush through 17 m of till to the underlying gravel. The presence of gypsum and iron-rich alteration products confirms that the till has not been extensively flushed with recharging groundwater (Keller et al. 1991).

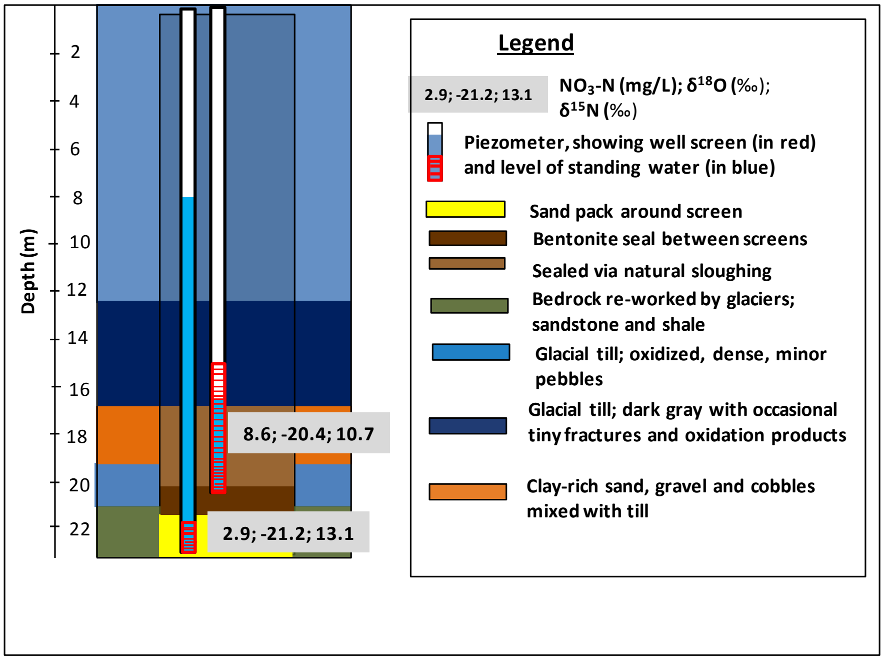


Fig. 40. Stratigraphic column at piezometer nest 3 in P1.

Till overlying the P1 gravel is 12 to 17 m thick, and the observations at nest 3 indicate it is oxidized throughout, but not extensively flushed. Therefore, chemical constituents produced in the till during oxidation processes are still diffusing into the underlying gravel and bedrock. Scracek (1993) documented diffusive input from glacial till into underlying preglacial gravel in the Lethbridge area. The area studied by Scracek was characterized by thick glacial till with a thick unoxidized zone, and very high concentrations of geologic nitrate in the oxidized till decreased to below detection at the redox boundary, so nitrate did not enter gravels from overlying till at that location (Scracek 1993).

Water-well 92 was installed at the same location as piezometer nest 3. The well was screened across the till/gravel/bedrock interface, but most groundwater entering the well is from gravel, based on the higher hydraulic conductivity of gravel compared to the overlying till and underlying bedrock. Compared to groundwater in the underlying shallow bedrock, groundwater in the P1 gravel contains a higher concentration of NO_3-N, a younger groundwater age, and a lower δ^{15}N value (Fig. 40). Static water levels (shown in light blue) indicate groundwater is discharging from bedrock to the overlying gravel (Fig. 40). Bedrock discharge to P1 gravel is consistent with the geologic cross-section through piezometer nest 3, where bedrock groundwater from higher elevations is in a position to discharge to gravel at nest 3 (Fig. 41).

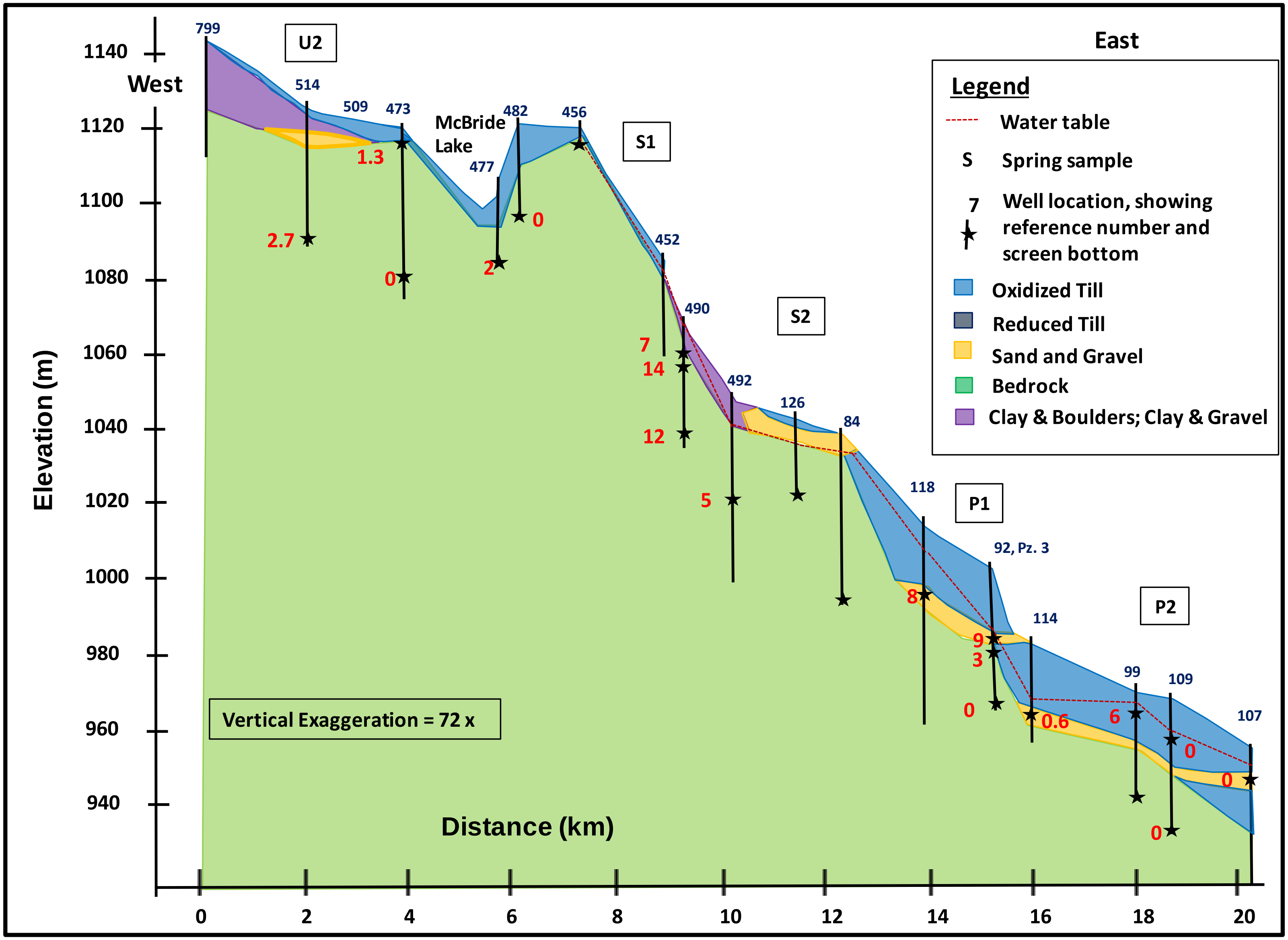


Fig. 41. Geologic cross-section along Transect line GG'. Green line in Fig. 11.

Groundwater in all three bedrock piezometers at nest 2 in area S2 was predominantly recharged under glacial conditions, with $\delta^{18}O$ values of -21.1 to -21.8 ‰, but NO_3-N was present in mudstone bedrock at 8.5 m depth (12 mg/L) and in deep bedrock at 30 m (0.9 mg/L) (Fig. 42). The presence of nitrate in very old groundwater suggests a geologic source of nitrate. The stability of nitrate and major ion concentrations with time in P1 bedrock at 22 m (Fig. 38a) is consistent with a geologic source. The recharge gradient at nest 2 indicates the gravel receives input from overlying till (Fig. 42). Geology illustrated in Fig. 14 indicates the gravels at nest 2 receive input from overlying till and from upslope bedrock.

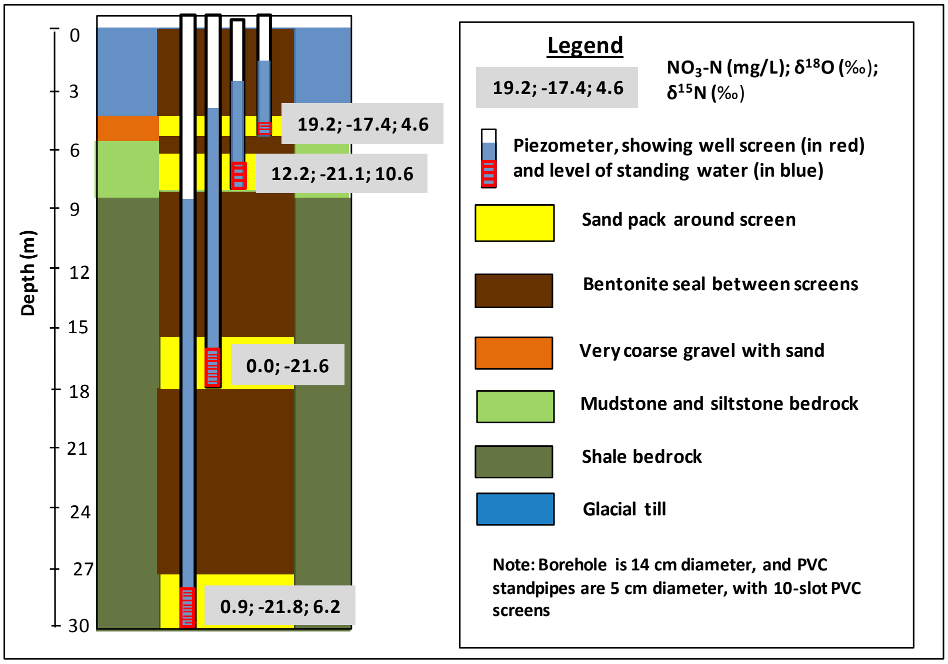


Fig. 42. Stratigraphic column at piezometer nest 2 in S2.

Most S2 bedrock wells are deeper than 30 m, and they did not contain detectable nitrate. Apparent inconsistencies were noted in nitrate detection at 30 m depth at nest 2 and water-well 77.

- 10 mg/L NO_3-N was detected in Well 77, screened at 29 to 32 m and located along the same drainage channel only a few hundred metres downslope of nest 2. The land owner indicated nitrate was elevated in this well ever since it was drilled in 1986. He also indicated that nitrate was elevated in springs upslope of nest 2 for at least the past 15 or 20 years.
- At nest 2, nitrate was not detected in shale bedrock at 18 m depth, but a low concentration (0.9 mg/L NO_3-N) was detected in the piezometer at 30 m depth (Fig. 42).

The deep nest-2 piezometer was sampled in 2013 at the same time as well 77. The installations were screened at approximately the same depth, only a short distance apart, and both were only a few metres from the same drainage channel, but well 77 contained almost ten times more NO_3-N than the 30-m piezometer. There are three main potential reasons for this discrepancy.

- It is possible the water well is receiving water from a shallower depth than the screen. However, the well record suggested the well was properly constructed, and it was well maintained and located in a hut with a good well cap. The well responded like typical bedrock wells in the study area during a one-hour pumping test in February of 2013.
- It is theoretically possible that well development via air blasting after drilling might oxidize nitrogen in sediments surrounding a well screen. In that case it is expected that nitrate concentrations would gradually decrease with time. The method of well development at Well 77 is unknown.
- Fractures tend to decrease with depth in both till and bedrock. Fractures in shallow deposits are usually well-connected, so groundwater tends to be well mixed. As fracture spacing increases, fractures are less likely to be connected, with the result that chemical constituents can leach to significantly deeper depths in a fracture than in the surrounding area between fractures. This mechanism may be responsible for the unusually deep nitrate detection in Well 77. This mechanism is also the best explanation for the detection of almost 1 mg/L NO_3-N in the 30-m piezometer at nest 2 (Fig. 42).

U2 (McBride Bench)

Geology

The Ardenville Bench slopes north to the next terrace at the McBride Bench (U2), which is about 20 to 40 m lower in elevation compared to the Ardenville Bench (Fig. 12). The recharge area for the McBride gravels includes shallow bedrock associated with the McBride Channel to the south, and thick till to the west (Figs. 15, 18 and 41). Sediments overlying the McBride gravel are recorded as till in some logs, and in other logs they are described as “clay and rocks” or “clay and gravel”, suggesting the covering material can be termed diamicton rather than till. The McBride gravels increase in thickness from about 4 m at the south to 5 to 15 m in the central and northern parts of the McBride Bench (Fig. 12).

Land Use

Land use is predominantly native range and tame pasture in the area upslope of the McBride Gravel, but non-irrigated cropland occurs over the gravel, and some of these cultivated lands receive periodic manure applications. The McBride gravel is expected to be relatively vulnerable to contamination because gravel is very shallow and covered by a relatively thin till or diamicton.

Groundwater Age

$\delta^{18}O$ values for bedrock and gravel at U2 are similar to those at S3, ranging from -17.2 to -18 ‰, and they are similar to the youngest values measured at U1 bedrock and gravel (Fig. 25). The less negative $\delta^{18}O$ values at U2 indicate groundwater that recharged predominantly in recent times. Most spring samples at U1 and U2 did not contain nitrate, and they contained $\delta^{18}O$ values indicative of recent recharge that has been partially evaporated (Fig. 25a). One gravel well was located in a dugout, and $\delta^{18}O$ in this sample was -8.5 ‰ (Fig. 21a), indicating it was heavily evaporated and affected by surface water in the dugout.

Nitrate Distribution

Nitrate was detected in all samples of U2 bedrock and gravel at depths of about 5 to 25 m, with concentrations ranging from 2.4 to 35 mg/L NO_3-N (Fig. 26c). Bedrock at depths of 27 to 42 m did not contain detectable nitrate (Figs. 26c), and Ca concentrations were <50 mg/L (Appendix 4), so this groundwater was characteristic of groundwater in relatively deep bedrock throughout the study area.

NO_3-N concentrations were generally higher in gravel than in bedrock, and mostly higher than concentrations at U1 (Fig. 26c). Nitrate concentrations at U2 were similar to those at S3, with the exception of higher nitrate in shallow wells at the downslope edge of the McBride gravel. Nitrate was detected at significantly deeper depths at S3 compared to U2 (Figs. 26c and 26d).

Groundwater nitrate distribution at U2 is shown in plan view in Fig. 43. Nitrate was detected in bedrock at depths of 15 to 24 m in the area of shallow bedrock immediately south (upslope) of the McBride gravel. Nitrate was not detected in most shallow gravel samples in the southern part of the gravel channel, but NO_3-N was detected at concentrations of 12 to 35 mg/L in all samples in the central and northern parts of the gravel (Fig. 43).

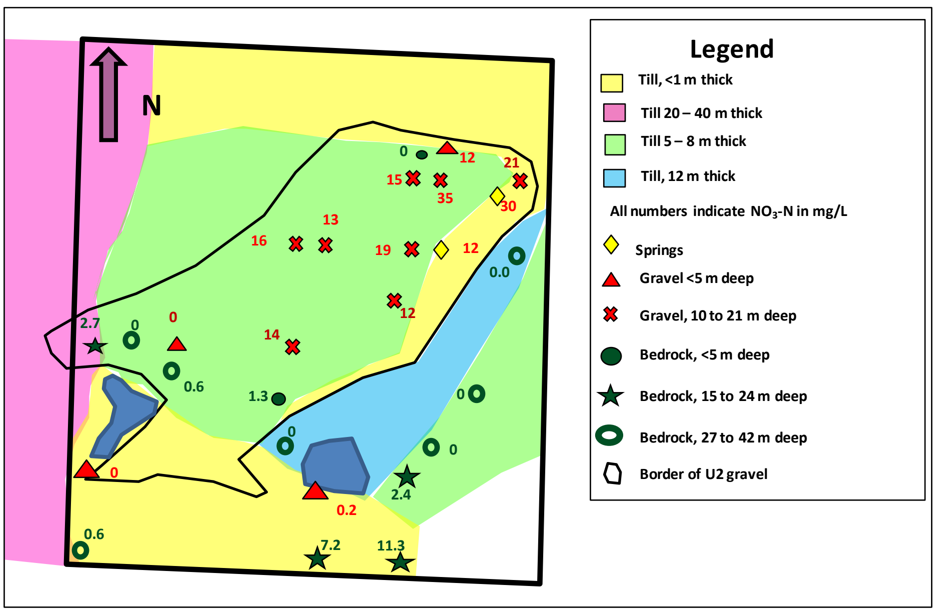


Fig. 43. Plan-view map showing NO_3-N distribution on the McBride Upland.

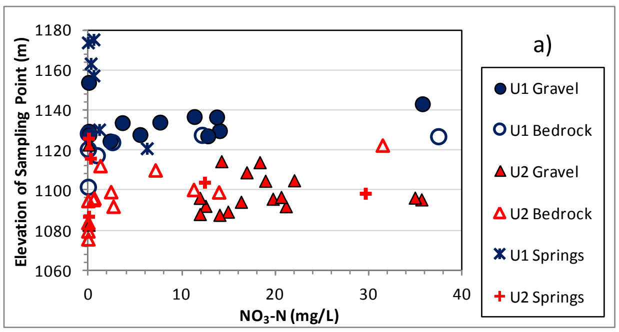
NO_3-N concentrations in bedrock and gravel wells less than 5 m deep at U2 were usually <1.3 mg/L. Two springs characterized by modern groundwater ($\delta^{18}O$ fluctuating from -16.9 to -14.7‰) that drained into McBride Lake and the McBride channel contained maximum NO_3-N concentrations of 0.2 mg/L throughout the summer of 2013. The springs were located in an area dominated by native range, and significant agricultural sources of nitrate were not observed.

Nitrate was detected in two samples shallower than 5 m:

- Springs and shallow gravel wells at the northeastern edge of the McBride gravel, where the gravel pinches out at the edge of the upland (Fig. 43), and
- A shallow bedrock well (Well 466) on the upland west of the McBride gravel, which contained 31 mg/L NO_3-N (Appendix 4).

Plots of NO_3-N with elevation indicate:

- NO_3-N concentrations are generally higher in gravel than in bedrock at U2.
- Gravel wells at U2 are shallower than bedrock wells (Fig. 26c) but at the same elevation (Fig. 44a), because ground surface and the bedrock surface slope toward the McBride gravel from the west (Figs. 15 and 41) and south (Fig. 12).
- NO_3-N concentrations in bedrock increase with decreasing elevation between U1 and U2 (Fig. 44a). This trend is similar to the increased NO_3-N with decreased elevation illustrated for geologic nitrate on the east plains (Fig. 37).



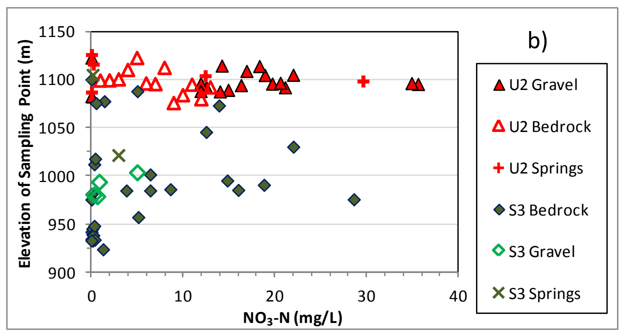


Fig. 44. NO_3-N distribution on the McBride Bench compared to sample elevation. a) With Area U1. b) With Area S3.

Time Trends and Nitrate Source

Chemistry trends with time are illustrated for five locations on the McBride Bench in Fig. 45. Data plotted in Figs. 45d and 45e may be for different wells, so they are called "locations" rather than "wells". The time trends indicate that nitrate and major ion concentrations have been relatively stable with time. NO_3-N concentrations in deep gravel did not change from 1983 to 2013 (Fig. 45c) and from 1975 to 2013 (Fig. 45d). Concentrations did not change with time in shallow wells, but data were only available for the past four to seven years (Figs. 45b and 45e).

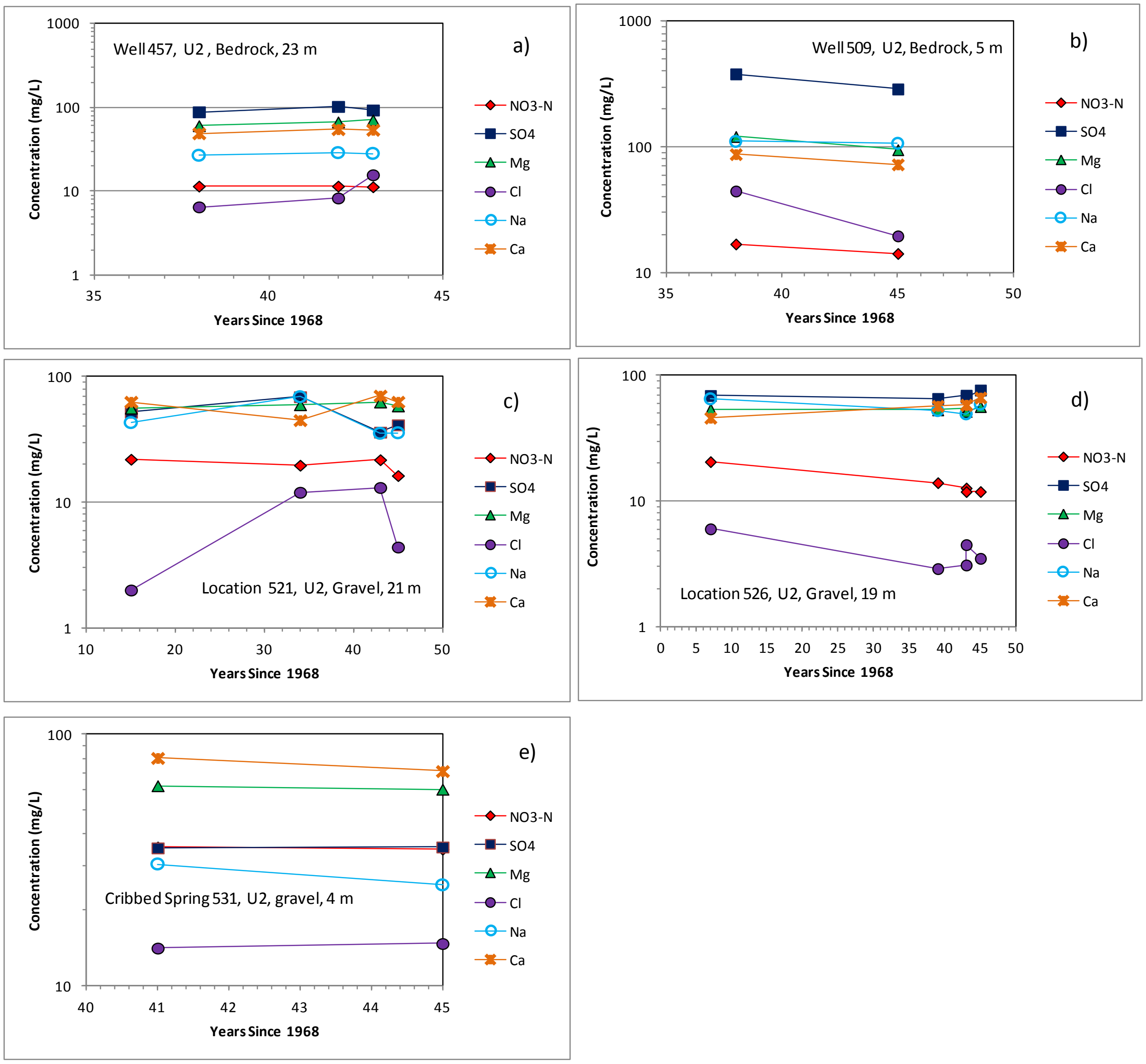


Fig. 45. NO_3-N and major ion concentrations with time at U2.

Geology data and ^{18}O values indicate the U2 (McBride) gravel aquifer contains modern recharge and is vulnerable to surface sources of contamination, but nitrate concentrations were stable with time in all five wells where long-term data were available, including deep gravel (1975 to 2013), and shallow gravel (2006 to 2013), suggesting at least a portion of nitrate on the McBride Upland may be natural. The U2 gravel may receive input from overlying diamicton and/or from upslope bedrock. Agricultural nitrate may also be present. Additional investigation, age dating, and continued monitoring with time is required to determine the predominant nitrate source to this aquifer.

Nitrate Source

Data presented above indicate both natural and geologic sources of nitrate are present in the study area. Several types of data are required to determine nitrate source in groundwater, ideally including detailed land use information, groundwater age, nitrate profiles with depth at increasing distances from potential nitrate sources, and detailed characterizations of groundwater flow and geology data. The current study was based mainly on $\delta^{18}O$ data, time trends, nitrate distribution at available water wells, and very general land use information. The following discussion reviews interpretations regarding the most probable nitrate sources by area, based on available data.

Locations Without Detectable Nitrate

Nitrate is not stable in unoxidized till (Appendix 1). In the current study area unoxidized till occurs only where till is more than about 20 thick, including, the high elevation area on the western side of the study area, and at many locations along river valleys (Fig. 18). Till reaches 12 to 20 m in thickness at some terrace locations (Figs. 13 to 15). Nitrate was not detected at locations with thick till because reducing conditions in unoxidized till prevent nitrate stability. These locations include the following.

- In the deep gravel channel at U1 (Figs. 12 to 14), and below thick till along the western side of the P3 channel (Fig. 17).
- Below thick till in the river valleys (Figs. 13, 14, and 16).
- Below other locations with thick till, including 444 (Appendices 4 and 5).

Nitrate was also not detected in many wells shallower than about 5 m. Geologic nitrate is generally present in very shallow groundwater only in discharge areas (Appendix 1). Therefore, nitrate is generally not expected in shallow groundwater except in discharge areas or near anthropogenic sources.

Agricultural Nitrate in Shallow Groundwater

Agricultural land use in the study area is not intensive at most locations. Land use in the majority of the study area is dominated by native range, tame pasture, or non-irrigated cropland. However, confined feeding operations and winter feeding and bedding areas are not uncommon. This investigation relied on the sampling of available water wells, and samples were not available for many locations with more intensive confined feeding operations. However, nitrate detections in shallow modern groundwater in gravel and bedrock were often associated with confined feeding operations or winter feeding and bedding areas. The results are consistent with previous detailed investigations of groundwater nitrate in southern Alberta, which indicate nitrate tends to impact groundwater when it is present in quantities higher than plants require.

Evidence of potential agricultural nitrate was detected in most physiographic areas except S4, as reviewed below. (The predominant nitrate source at U1 and U2 is uncertain).

- **River Valleys:** Nitrate was detected in the uppermost 9 m in areas near CFOs.
- **S3:** The relatively young groundwater age at depth in S3 bedrock, and changing nitrate concentrations with time, suggest nitrate in the top 20 m at S3 may be derived from anthropogenic sources.
- **P3:** Predominantly agricultural sources are indicated by trends of increasing nitrate with time, decreasing nitrate concentrations with depth below ground, the relatively young groundwater age, and the high vulnerability of groundwater in an area with some intensive land use.
- **S1.** Predominantly agricultural sources are indicated by the relatively young groundwater age, fluctuating nitrate concentrations with time, and the association of nitrate detections with potential manure sources.
- **S2, P1 and P2:** Shallow wells (to a depth of 6 m) contained modern or mixed age groundwater, time trends (available for one well) indicated fluctuating nitrate concentrations with time, and nitrate detections were associated with CFO locations.

Geologic Nitrate

Nitrate occurs in glacial-aged groundwater in bedrock at depths of about 5 to 30 m, at concentrations that have not changed over the past 30 to 40 years. The results suggest this groundwater was derived from a geologic source. Nitrate detections in bedrock were widespread and at a relatively uniform concentration range of 5 to 15 mg/L NO_3-N.

- **S4 and S3.** NO_3-N (5 to 15 mg/L) was commonly detected in S3 and S4 bedrock at depths of 20 to 30 m, with nitrate undetected (at S4) or detected at lower concentrations (at S3) in shallower samples. Nitrate occurred in old groundwater ($\delta^{18}O$ in bedrock ranged from -19.3 to -21.4 ‰) and concentrations were stable with time for wells with available monitoring data.
- **S1.** Low NO_3-N concentrations in S1 bedrock at 30 m, at a maximum concentration of 5.4 mg/L, may have a geologic source.
- **S2, P1 and P2.** Bedrock groundwater at S2 and P1 was predominantly of glacial age ($\delta^{18}O$ values less than -21‰). NO_3-N (5 to 15 mg/L) was detected in most samples from bedrock and gravel at depths of about 5 to 25 m. Time trend data was available for one well, indicating stable nitrate concentrations from 1975 to 2006.
- **U1 and U2.** Some evidence suggests a geologic source for at least some nitrate at U1 and U2, but agricultural sources may also be present.

The Source of Geologic Nitrate in Gravel

It is hypothesized that gravels in the S2, P1 and P2 areas receive geologic nitrate from overlying oxidized tills, as indicated by the following evidence.

- Continental till in this part of southern Alberta contains geologic nitrate, as discussed in Appendix 1 and confirmed by the presence of nitrate in two water wells installed in thin sand layers within till on the east plains (water wells 36 and 99).
- Buried gravels receive recharge through the overlying till, as indicated by geology data (Figs. 14, 15, 16 and 41) and piezometric data for piezometer nests 2 and 3 (Figs. 40 and 42).
- Sracek (1993) detected more than 400 mg/L NO_3-N in oxidized till in the Lethbridge area, and he concluded that the underlying preglacial gravels were subjected to high diffusion loading from the overlying till. In this case the gravels did not contain nitrate because they were separated from the oxidized till by thick unoxidized zones where nitrate is not stable (Appendix 1). The findings of Sracek (1993) support the conclusion that gravels receive input from overlying till.
- Nitrate concentrations in P1 gravel were higher at depths of 10 to 20 m than in the top 5 m (Fig. 26f).
- Nitrate concentrations in gravel increased with decreasing elevation (Fig. 37), a distribution pattern that is consistent with long-term transport to lower elevations via groundwater flow.
- Nitrate concentrations at P1 and S2 were higher in gravel than in the underlying bedrock (Figs. 26e and 26f), consistent with input from overlying oxidized tills.

Gravel layers at S2, P1 and P2 may also receive nitrate via discharge from oxidized bedrock along the slopes. Bedrock discharge is suggested by geologic cross-sections with limited piezometric data. For example, the piezometric pressure at Well 131 is higher than the piezometric pressure immediately downslope in gravel wells 162, 136, and 160 (Fig. 15), suggesting bedrock groundwater with elevated NO_3-N (25 mg/L) at Well 131[4] would tend to discharge into the P1 gravel. Bedrock discharge may be a plausible source for the NO_3-N concentrations of 7 to 11 mg/L in the P1 gravel at wells 162, 136 and 160 (Fig. 15).

Nitrate concentrations are significantly correlated with inorganic ion concentrations only in gravel at areas P1-P2, and to a lesser extent in bedrock at S4. This is shown for sulphate (SO_4) concentrations in Fig. 46, and for chloride (Cl) in Fig. 47. The south scarp (S4) and eastern plains (P1-P2) areas are the only areas overlain by a significant thickness of till, and the correlations indicate nitrate and inorganic ions may both be derived from weathering processes in till. The presence of a lesser correlation with inorganic ions in P1-P2 bedrock is consistent with less leaching from till into bedrock than into gravel.

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[4] The detection of nitrate at 36 m in Well 131 (Appendix 3), below 21 m of till, is unusual (Fig. 15). However, lithology is listed as "clay and rocks", suggesting the covering material is diamicton rather than till.

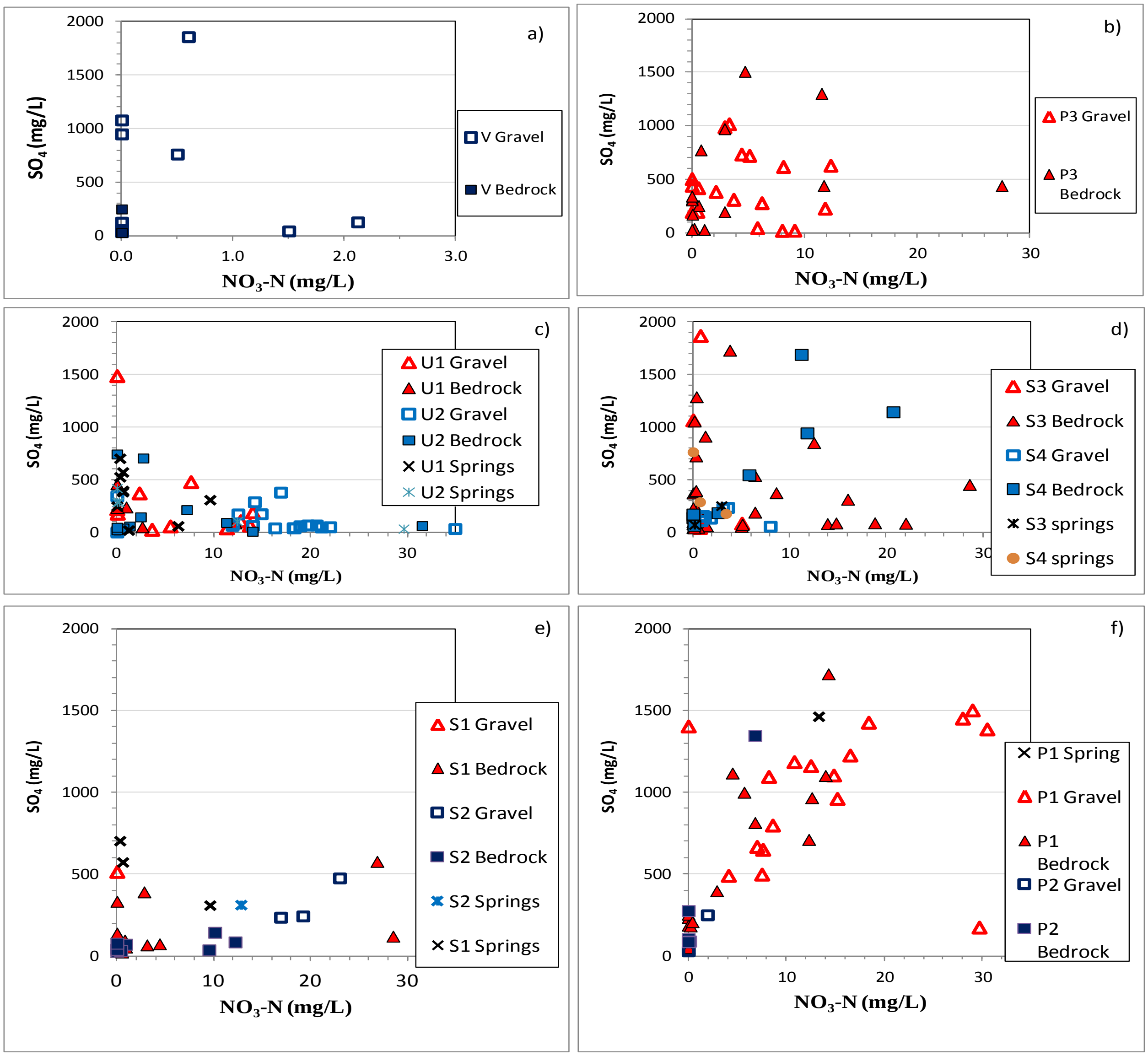

Fig. 46. Nitrate concentrations compared to sulphate concentrations at all sites.

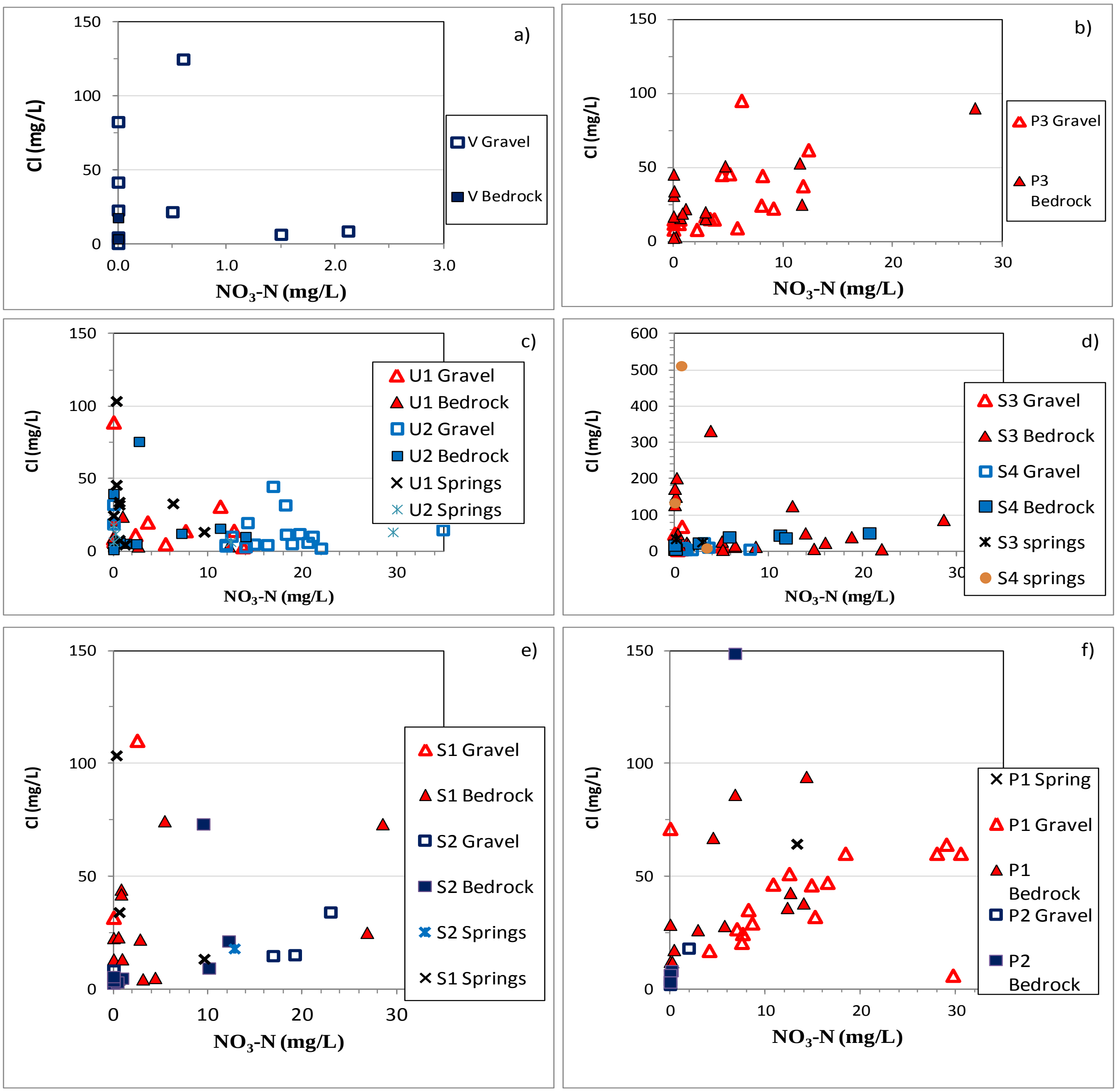

Fig. 47. NO_3-N concentrations compared to Cl concentrations at all sites.

The Source of Geologic Nitrate in Bedrock

Nitrate in relatively old groundwater in bedrock in the P1 and P2 areas may have been derived by downward leaching from overlying oxidized till. Nitrate was detected in shallow bedrock immediately below locations with high nitrate in till in the Vauxhall area (Rodvang et al. 1998; 2002).

Geologic nitrate is also present in bedrock in upper scarp locations (S1, S3 and S4) where till is currently thin or absent. Geologic nitrate was detected at deeper depths in scarp areas, where bedrock is expected to be fractured to deeper depths than in Plains areas. Potential sources for this geologic nitrate include: i) in situ oxidation of organic nitrogen contained in till and clay-rich bedrock; ii) downward leaching from oxidized till that was subsequently eroded from most upland and scarp locations, or iii) leaching from a large organic near-surface deposit such as a swamp or a bog that perhaps covered a significant area, or iv) a combination of two or more of the above sources.

Surficial geology indicates that the study area was influenced by both continental and mountain tills. The study area contains an erratics train (Plate 13), which in near-by locations of southern Alberta marks the contact between continental and Cordilleran glaciations. Till on the west side of the upland has a higher stone content than tills on the east side, and the lithology also points to till with a more significant Cordilleran influence. It is not known whether natural nitrate occurs in Cordilleran till. The study area shows evidence of bedrock erosion by numerous river levels, and subsequent erosion by more than one glacial event, as evidenced by the preservation of two gravel channels separated by 14 m of till on the Ardenville Bench (Fig. 14). A significant proportion of well logs indicate the presence of clay below gravels in the study area (Appendix 5). These clay layers may indicate earlier till events.

Nitrate Source at U1 and U2

Nitrate source in the Ardenville (U1) and McBride (U2) gravel aquifers is difficult to determine unequivocally based on existing data. Both aquifers are highly vulnerable to surface sources of contamination at locations where they are not covered with significant thickness of till (Figs. 32 and 43). Land use in both areas is dominated by native range and tame pasture, but confined feeding operations and bedding and feeding areas occur, and manure spreading may occur on cultivated land in U2. Nitrate was detected in gravel and bedrock at piezometer nest 1 on the Ardenville Bench, on native range in good condition near the apex of the recharge area, but anthropogenic sources may occur, such as concentration of manure from grazing cattle in recharging depressions in hummocky topography.

The U2 area was characterized by recently-recharged groundwater, while isotope samples at U1 indicated nitrate occurred in groundwater ranging in age from modern ($\delta^{18}O$ = -17.7 ‰) to almost glacial in age ($\delta^{18}O$ = -20.8‰) (Fig. 25b). Although groundwater ages were modern, nitrate and major ion concentrations were apparently stable with time over the long term at the seven locations where time trend data were available (Figs. 33 and 45).

The U1 and U2 gravel aquifers both occur on uplands and they are approximately the same size and shape (Fig. 11). Both gravels are buried by thick till on the west, and they both approach ground surface and pinch out where ground elevation decreases at the east (Figs. 14, 15 and 18). Both gravels receive recharge through overlying till and discharge from bedrock, based on geology and the sloping channel configurations (Figs. 14 and 15). The increase in $\delta^{18}O$ with depth below 5 m at U1 (Fig. 23b) is consistent with groundwater discharge into U1 gravels. Nitrate is present in bedrock at U1 (Fig. 26c), so discharge from bedrock may be a source of nitrate to U1 gravels. As mentioned above, the presence of nitrate in till on the western side of the study area has not been confirmed, so the potential contribution from till is unknown. Nitrate concentrations at U1 and U2 both apparently increase in a downslope direction, consistent with progressive input from a natural source.

Nitrate concentrations hypothesized to be of geologic origin at areas P1, P2, S2 and S4 were most commonly in the range of 2 to 15 mg/L NO_3-N, although gravels at P1-P2 contained up to 30 mg/L NO_3-N (Fig. 26f). Nitrate-N concentrations at U1 are a maximum of about 12 mg/L, but much higher concentrations (up to 35 mg/L NO_3-N) occurred at U2, possibly related to input from an agricultural source. However, progressive leaching from till might also account for the higher nitrate in the U2 gravels, because the U1 gravels are not covered with diamicton for most of their distance (Figs. 14, 15, 33 and 43).

More investigation is required to determine the source of nitrate in the Ardenville and McBride aquifers. The most cost-effective tools including monitoring of nitrate concentrations with time, and analysis of enriched tritium and tritium-helium age dates at key locations.

Agricultural vs. Geologic Nitrate in the Study Area

In order to estimate the importance of agricultural compared to geologic nitrate sources in the study area, an attempt was made to interpret the most probable nitrate source at each water well and spring. Agricultural nitrate was interpreted to occur in shallow groundwater with $\delta^{18}O$ values more positive than -18 ‰, and was associated with confined feeding operations. Geologic nitrate occurred in bedrock at depths below 10 to 20 m, and in deep gravels buried by till, in groundwater with $\delta^{18}O$ values less than -19 to -21 ‰.

Interpretations of nitrate source are summarized in Table 7, based on the following assumptions.

- The identified source represents the best interpretation based on available data. The most commonly used indicators were $\delta^{18}O$ values, nitrate depth profiles, time trends, and land use information. Age dating with enriched tritium and helium could be used to test and verify the results interpreted in Table 7.
- The purpose of Table 7 was to estimate the relative importance of each source for existing water wells. Therefore,
    - for locations that were sampled on more than one date, only the most recent date was included, and
    - piezometers were not included because they represent research instruments rather than water production wells.
- Undetectable nitrate was defined as $\leq$ 0.5 mg/L NO_3-N.

Explanations for the interpretations in Table 7 are provided in Table 8.

Table 7. Interpretation of nitrate source for each water well.

Physio-graphic Area	Agricultural Nitrate			Geologic Nitrate			Nitrate as N ≤ 0.5 mg/L)		Uncertain Source	
	Depth Range (m)	[z]n	**Range of NO_3-N (mg/L)**	**Depth Range (m)**	[z]n	**Range of NO_3-N (mg/L)**	**Depth Ranges (m)**	[z]n	**Depth Range (m)**	[z]n
V	1.8 – 4.6	3	0.6 to 2.1	Not present	0	Not present	7.8 to 42.7	9		
P3	3.6 – 18.3	21	0.6 to 12	27 - 50	3	0.8 – 27	8.5 – 16 27 - 50	4 5		
S3	0.1 – 18.2	11	0.7 - 16	21 - 49	9	3.8 – 29	0.6 – 15 30 - 60	10 8		
S1	0.1 - 15	9	0.6 - 27	30 - 54	6	0.8 – 12	0 – 17 30 - 50	6 4		
U2	Nitrate source requires additional investigation						0 – 4.2 27 - 43	5 4	0.1 - 43	26
U1	Nitrate source requires additional investigation						0 – 5.8 20 - 49	3 6	0.1 - 30	16
S2	N source at 5 to 7 m at location 77 is uncertain			32	1	10	30 - 60	7	0 - 7	4
P1	0.1 – 3.7	3	8 – 13	10 - 37	22	[Y]4 – 30	4.8 m 24 - 50	1 6		
P2	5	1	5.7	9	1	6.8	1.5 – 3 26 - 59	2 4	9	1
S4	No evidence for agricultural nitrate was obtained			0.1 - 59	15	0.8 - 21	0 – 12 46	3 1		
Totals		**48**			**57**			**87**		**47**

[z]n = number of samples per category

[Y]The concentration value of 76 mg/L NO_3-N measured in 1986 was excluded because it was the only value higher than 30 mg/L.

Table 8. Explanations for interpretations in Table 7.

Physio-graphic Area	Depth Range (m) and Assumptions Used to Interpret Source Agricultural Nitrate	Geologic Nitrate	Uncertain Source
V	1.8 – 4.6 m: Shallow gravel associated with agricultural sources	No N detected below 5 m, and most wells to a depth of 35 m are in gravel	
P3	3. 6 to 18 m: $\delta^{18}O$ = -17.9 to -18.3‰; shallow gravel associated with agricultural sources, and increasing N with time.	27 – 50 m: Mostly not detected from 20 to 30 m	
S3	0.1 to 18m: $\delta^{18}O$ = -17.4‰ at 17 m; N increased with time in 5-m well.	21 to 49 m: Higher concentrations below 20 m than above.	
S1	0.1 – 15 m: $\delta^{18}O$ = -17.8 to -18.8‰ to a depth of 17.4 m; N increased with time and was associated with agricultural sources.	30 – 54 m: Deep depth	
U2	Additional investigation is required to determine nitrate source.		$\delta^{18}O$ = -17.2 to -18.0‰ in bedrock and gravel, but concentrations apparently stable with time.
U1	Additional investigation is required to determine nitrate source.		6.1 – 30 m: $\delta^{18}O$ = -18 to -20.8‰.
S2	N source at 5 to 7 m at location 77 is uncertain	32 m: $\delta^{18}O$ = -21.1 to -22.2 ‰ in all bedrock samples.	0 – 7 m: May be anthropogenic based on $\delta^{18}O$ = -17.4, but source not identified.
P1	0 – 3.7 m: $\delta^{18}O$ = -18.9; N was associated with agricultural sources.	10 – 37 m; $\delta^{18}O$ = -20.0 to -21.8 ‰ below 16 m	
P2	5 m: shallow groundwater associated with agricultural sources	Assumed to be geologic nitrate at 9 m, but somewhat uncertain	
S4	No evidence for agricultural nitrate was obtained. N was stable with time in a shallow spring and a well at 21 m.	0.1 – 59 m: $\delta^{18}O$ = -19.3 to -21.4 ‰	

Nitrate interpreted to be derived predominantly from agricultural sources was detected in 48 of 239 water wells and sampled springs (Table 7). The wells were installed in both bedrock and gravel, and were located in most physiographic areas. Most of these wells were installed at depths less than 7 m, but agricultural nitrate was potentially present to depths of 15 to 18 m in upper scarp locations (S1 and S3) (Table 7). Most agricultural nitrate occurred in groundwater with $\delta^{18}O$ values more positive than -18‰. The wells often occurred in areas near confined feeding operations or feeding and bedding areas, and nitrate concentrations in some wells increased from the early 1980s to 2013. Almost 20% of nitrate detections interpreted to be agricultural exceeded the drinking-water guideline of 10 mg/L NO_3-N, with a maximum detected concentration of 27 mg/L.

Nitrate interpreted to be derived predominantly from geologic sources was detected in 57 of 239 water wells (Table 7). Geologic nitrate most commonly occurred in bedrock below 20 m depth, but was also interpreted to occur in gravels buried below till in the P1 area. Geologic nitrate occurred in groundwater with $\delta^{18}O$ values less than -19 to -21‰. Concentrations were often higher at depth than near ground surface, and concentrations did not change with time since the early 1980s. Approximately 45% of nitrate detections interpreted to be geological exceeded the drinking-water guideline of 10 mg/L NO_3-N, with a maximum detected concentration of 76 mg/L in 1986.

Existing data were not sufficient to interpret the most probable nitrate source for 47 wells, most of which were located in the upland areas (U2 and U1) (Table 7).

NO_3-N concentrations were $\leq$ 0.5 mg/L in 87 of 239 water wells where chemistry data were available. The majority of wells that did not contain nitrate were either deeper than 20 to 30 m depth (49 wells) or shallower than 6 m (22 wells) (Table 7).

Potential Indicators to Distinguish Agricultural Nitrate from Geologic Nitrate

Tritium

Enriched tritium is one of the most valuable indicators to distinguish agricultural from geologic nitrate, because its detection generally indicates groundwater that recharged since the 1960s.

Chloride and Other Major Ions

Groundwater chemistry in the study area is highly variable, and patterns are difficult to discern. This complex groundwater chemistry relates to the complex topography and glacial history, in addition to mixing by groundwater flow.

Chloride (Cl) is usually the best and most cost-effective indicator of leaching to groundwater near point sources of manure. Chloride concentrations are often more difficult to interpret as distance from the manure source increases, particularly in prairie groundwater, where Cl concentrations tend to be highly variable due to natural concentrations in marine Cretaceous bedrock, and mixing by groundwater flow and diffusion (Hendry et al. 2000; Nzojibwami 2001; Rodvang et al. 1998; 2002).

Chloride and other major ions were not good indicators of manure impacts in the current investigation because data were obtained from available water wells, which were not necessarily located in close proximity to potential manure sources. Nitrate is not correlated with major ions (represented by sulphate in Fig. 46) or chloride (Fig. 47) in most physiographic areas. The poor correlations among Cl, nitrate, and the dominant major ions suggest groundwater flow and mixing have reduced correlations among major ions. The high correlations at S1, P1 and P2 are consistent with a sluggish flow system dominated by long-term input from till.

Nitrate Isotopes

Nitrate isotope values are summarized in Table 9.

Table 9. Summary of nitrate distribution and isotope content.

Physiographic Area		Maximum NO_3-N concentration (mg/L)			Range of $\delta^{18}O$ Values (‰) Range of $\delta^{15}N$ Values (‰)		
		[z]Br	[z]Gr	[z]Spr	Br	Gr	Spr
U1	Ardenville Bench	12	12	1.2	-17.7 to -17.9 5.6 to 6.1	-18 to -20.8 4.9 to 16.9	-5.8 to -17.6 10.6
S4	South Scarp	15	15		-19.3 to -21.4 11		
S1	Upper East Scarp	[Y]14	5	9.6	-18.8	-17.8	-10.4 to -17.6 10.0
S3	North Scarp (Well 554)	22	5		-17.4 (Well 554 at 17 m depth) [X]28.6 (Well 554 at 17 m depth)		
S2	Lower East Scarp	10	20	12.8	-21.1 to -21.8 6.2 to 10.6	-17.4 4.6	-17.6 7.1
P1-P2	Eastern Plains	12	30	13.3	-21.2 to -21.8 13.1	-18.4 to -20.4 8.2 to 10.7	-18.9 9.1
U2	[W]McBride Bench	12	20	12.4	-18 11.5	-17.2 to -17.3 7.1 to 7.3	-11.1 to -16.9 6.4
P3	Northern Plains	10	10		-17.9 9	-18.3 7.2	

[z]Br indicates wells in bedrock, Gr indicates gravel, and spr indicates springs.
[Y]With the exception of one higher concentration in shallow bedrock.
[x]Located immediately downslope of an animal feeding operation
[W]Values for a well located in a dugout were extremely evaporated, so they were not included in Table 9.

Typical ranges for $\delta^{15}N$ values for three major sources of nitrate are summarized in Appendix 1. Nitrate isotope data for the study area generally plot in the range of a mix of mineralized soil organic matter and manure (Fig. 48). Groundwater samples in the study area generally follow a trend of increasing $\delta^{15}N$ (NO_3) with increasing $\delta^{18}O$ (NO_3) (Fig. 48). The trends were most evident at the U1, S2 and P1 physiographic areas because most samples were collected from those areas (Fig. 48).

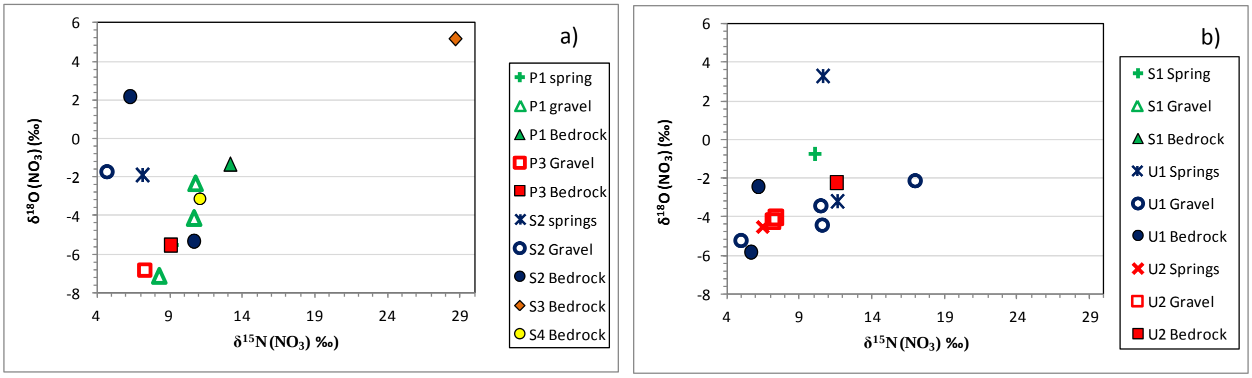

Fig. 48. Nitrate isotope data for the study area.

Well 554, located in the S3 area, in shallow bedrock in a drainage channel immediately downslope of a seasonal bedding operation, contained much higher nitrate isotope values than any other location (Fig. 48a). However, the observed values for $\delta^{15}N$ (28.6) was not elevated compared to $\delta^{15}N$ values in natural nitrate in glacial till at other locations in southern Alberta, where $\delta^{15}N$ commonly ranged from 11 to 41‰ (Rodvang et al. 2002). Therefore, absolute $\delta^{15}N$ values are not promising indicators to distinguish agricultural and geologic nitrate.

Nitrate isotopes (^{15}N and ^{18}O in nitrate) tended to increase with decreasing $\delta^{18}O$ in water (Fig. 49), suggesting higher isotopic values in older groundwater.

Nitrate isotope values at most areas in the current investigation followed a trend of increasing $\delta^{15}N$ and $\delta^{18}O$ in nitrate with decreasing nitrate (Fig. 50). This trend is consistent with that observed for geologic nitrate at other locations in southern Alberta (Rodvang et al. 1998). In contrast, samples at areas P3 and U2 showed a slight tendency for $\delta^{15}N$ and $\delta^{18}O$ to increase with increasing nitrate concentration (Fig. 50). Nitrate derived from manure tends to have higher nitrate isotope values (Appendix 1), so the results may suggest a larger component of manure-derived nitrate at the P3 and U2 areas. In summary, a trend of increasing $\delta^{15}N$ with increasing nitrate may be a potential indicator of manure-related impacts.

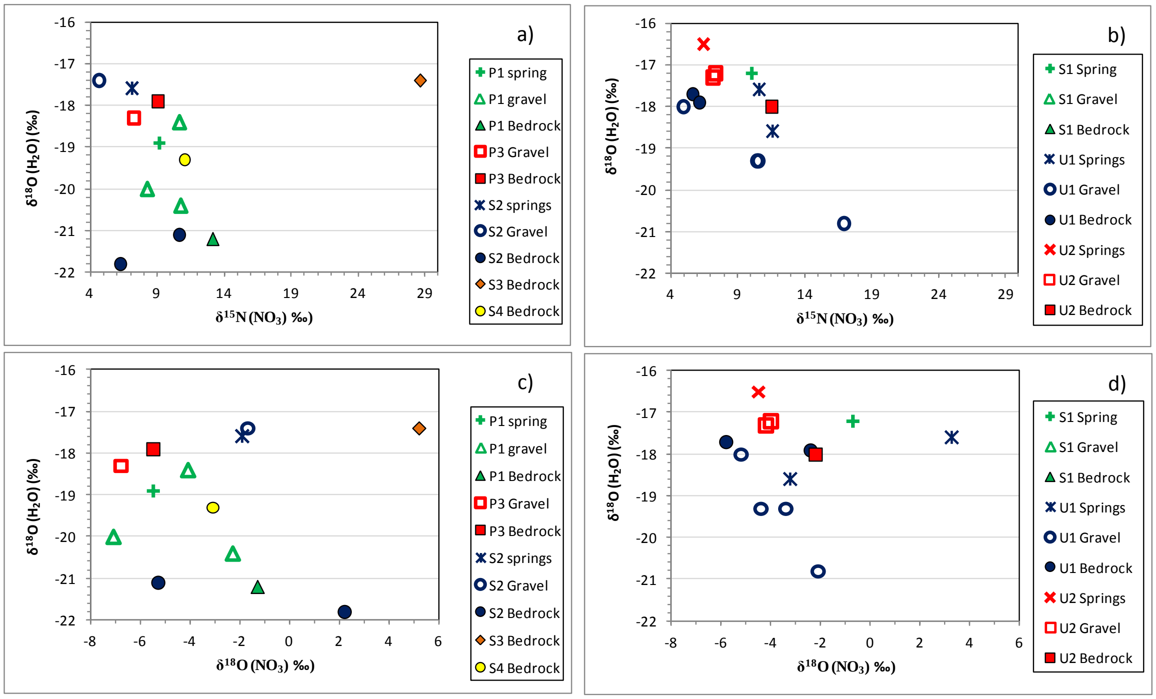

Fig. 49. Nitrate isotope data compared to NO_3-N concentrations. a and b) δ15N compared to NO_3-N. c and d) $\delta^{18}O$ (NO_3) compared to NO_3-N.

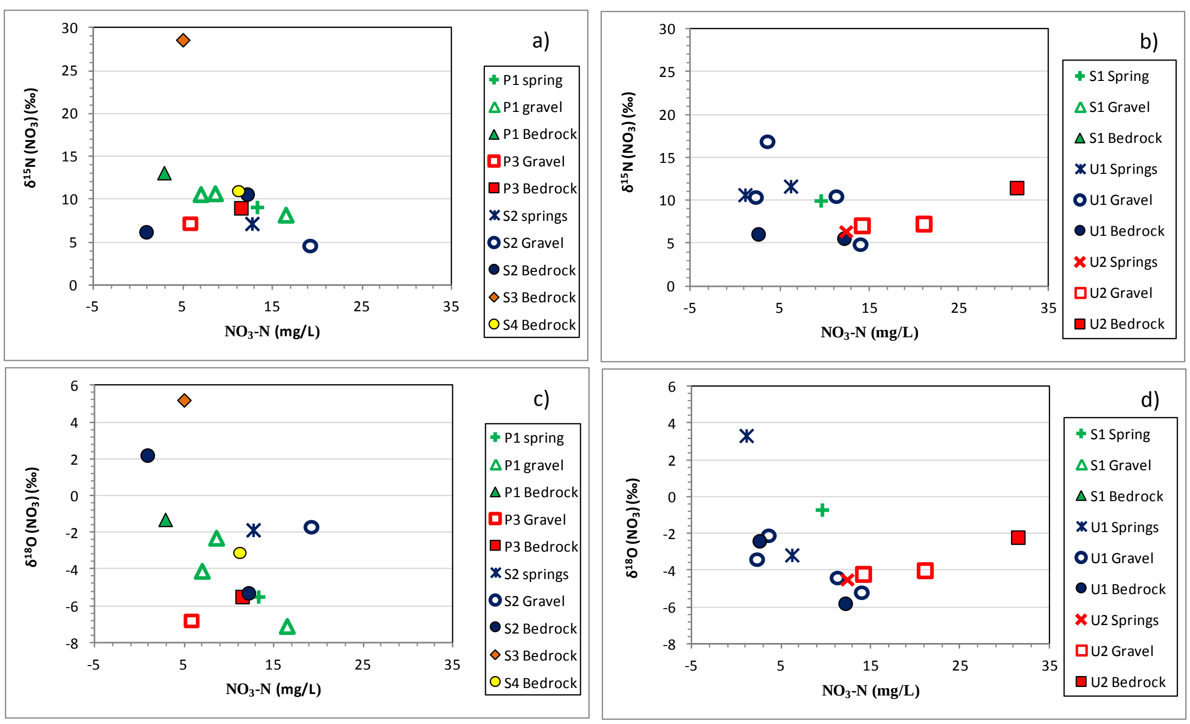

Fig. 50. δ18O (H_2O) compared to nitrate isotopes. a and b) δ18O (H_2O) compared to δ15N. c and d) δ18O (H_2O) compared to $\delta^{18}O$ (NO_3).

CONCLUSIONS

A major bedrock upland occurs on the west side of the study area, composed of the Ardenville Bench at the south end of Tp. 7, and the lower-elevation McBride Bench at the north end of Tp. 7. Bedrock is predominantly shale with some sandstone partings. Glacial till is 20 to 40 m thick on the western edge of the bedrock upland, and decreases in thickness to less than 5 to 8 m for the majority of the bedrock upland. Till is thin or intermittent on scarps that slope away from the bedrock upland to the south, east and north. Till thickness increases to about 12 to 18 m in the plains areas, and to thicknesses of 20 to 40 m in the river valleys.

The study area contains at least six preglacial gravel aquifers between till and bedrock, and smaller areas of productive preglacial gravel are preserved at numerous locations. Gravels are usually covered with till on their upslope sides, and pinch out along sloping lands on their downslope sides. Surface drainage channels originate where gravel layers intersect ground surface at the edges of the uplands and along the scarps. They also originate where bedrock comes close to surface along the south and north scarps. Drainage channels have eroded till and are incised into bedrock along the scarps, and they transport groundwater and surface drainage from upland areas to the rivers.

Land use is dominated by native range, hay land, or improved pasture on upland and scarp areas, and by non-irrigated annual cropping at lower elevations. The study area contains several confined feeding operations, with the highest density adjacent to the Belly River. Several confined feeding and bedding sites occur on the uplands.

Nitrate interpreted to be derived predominantly from agricultural sources was detected in 48 of 239 water wells and sampled springs. The wells were installed in both bedrock and gravel, and were located in almost all physiographic areas except S4. Most of these wells were installed at depths less than 7 m, but agricultural nitrate was potentially present to depths of 15 to 18 m in upper scarp locations (S1 and S3). Most agricultural nitrate occurred in groundwater with $\delta^{18}O$ values more positive than -18‰, and nitrate concentrations in some wells increased from the early 1980s to 2013. The goal of this study was not to identify specific agricultural sources, but wells with agricultural nitrate most commonly occurred near confined feeding operations or winter feeding areas. Manure spreading is a potential non-point source of agricultural nitrate. Almost 20% of nitrate detections interpreted to be agricultural exceeded the drinking-water guideline of 10 mg/L NO_3-N.

Nitrate interpreted to be derived predominantly from geologic sources was detected in 57 of 239 water wells. Nitrate interpreted to be from a geologic source most commonly occurred in weathered bedrock below 20 m depth. Geologic nitrate also occurred in gravels buried below oxidized till in the P1 area, probably due to leaching from overlying oxidized till, with the potential for additional input via discharge from oxidized upslope bedrock. Geologic nitrate occurred in groundwater with $\delta^{18}O$ values less than -19 to -21‰. Concentrations were often higher at depth than near ground surface, and concentrations did not change with time since the early 1980s. Approximately 45% of nitrate detections interpreted to be geological exceeded the drinking-water guideline of 10 mg/L NO_3-N, with maximum concentrations most commonly in the range of 15 to 30 mg/L.

Previous investigations in the Picture Butte – Lethbridge – Vauxhall areas indicate geologic nitrate most commonly occurs below the zone of most active recharge (e.g., below 5 m depth) in oxidized clay-rich glacial deposits. The current investigation has extended the range of geologic nitrate to the study area south of Fort Macleod, and has documented its occurrence in gravel and bedrock aquifers. Geologic nitrate has not been reported or documented at other Alberta locations, although the aerial extent of geologic nitrate in the province requires investigation.

NO_3-N concentrations were ≤ 0.5 mg/L in 87 of 239 water wells where chemistry data were available. The majority of wells that did not contain nitrate were either shallower than 6 m (22 wells) or deeper than 20 to 30 m (49 wells). Geologic nitrate is generally not present in groundwater shallower than 6 m, except in groundwater discharge areas. Nitrate is not stable in reduced till, which occurs at depth where till is relatively thick (e.g., thicker than 15 to 20 m). Nitrate was not commonly detected at locations underlain by thick till, including the western side of the study area and adjacent to river valleys. Geologic nitrate does not occur in gravels overlain by thick till (including the western side of the study area and the river valleys) because the gravels are separated from oxidized till by low-conductivity unoxidized till that does not contain nitrate.

The source of geologic nitrate in glacial till and bedrock in the Fort Macleod to Vauxhall areas requires additional investigation. Potential sources include: i) leaching from a large organic near-surface deposit such as a swamp or a bog that perhaps covered a significant area; or ii) in situ oxidation of organic nitrogen contained in till and clay-rich bedrock. Geologic nitrate in bedrock in the current study area may have been transported down from an organic surface deposit, or it may have been leached from oxidized till that was subsequently eroded from most upland and scarp locations.

The study area has a complicated geology and topography with a complicated groundwater flow system and the presence of both geologic and agricultural nitrate. Water wells with elevated nitrate were evaluated on a case-by-case basis to establish whether they are impacted by geologic or agricultural nitrate. Existing data were not sufficient to determine nitrate source for 47 of the 239 water wells, most of which were located in the upland Ardenville and McBride aquifers (Fig. 1). The gravels may receive geologic nitrate from upslope bedrock and/or overlying till, or the predominant source may be agricultural. Values of $\delta^{18}O$ (H_2O) were useful to identify groundwater recharged under glacial conditions (where nitrate is exclusively geologic), but groundwater in the majority of wells contained $\delta^{18}O$ values indicative of a mixture of glacial and recent recharge, making source determination difficult.

RECOMMENDATIONS

Conduct Additional Research

- **Nitrate Source in the Study Area.** Conduct additional investigation of nitrate source in the study area, particularly for the upland aquifers (Ardenville and McBride), where the current investigation was inconclusive. Determine groundwater age dates for key water wells using enriched tritium and tritium-helium, to provide more information on nitrate source in the study area, and to test and verify the interpretations contained in this report. Age dates will be useful for most locations in the study area, particularly for the Ardenville and McBride aquifers, where existing data could not be used to determine nitrate source. A Master of Science thesis from the University of Calgary is currently being conducted to provide additional interpretations of data collected for the current investigation, including the interpretation of carbon and sulphur isotope data (^{13}C and ^{34}S), which were not discussed in the current report.

  Groundwater monitoring is also warranted near the Belly River in Range 25, Townships 7 and 8, where a relatively high density of CFOs occur, and groundwater quality data were not available for the current investigation.

- **Extent of Geologic Nitrate in Alberta.** Research is required to determine the aerial extent of geologic nitrate in Alberta. Previous studies, along with data collected and interpreted for the current investigation, show that geologic nitrate occurs in oxidized clay-rich glacial deposits over an area that encompasses Picture Butte, Lethbridge and Vauxhall. The current investigation south of Fort Macleod has documented geologic nitrate in gravels underlying oxidized till, and in oxidized bedrock. Geologic nitrate has not been reported or documented at other Alberta locations, although the aerial extent of geologic nitrate in the province requires investigation. The investigations should initially focus on locations with relatively thick oxidized till (i.e. at least 7 metres thick), because that is where geologic nitrate is most likely to occur, and where nitrate source will be most easily determined via sampling of small nests of piezometers at key locations. Potential occurrence in gravels and bedrock at other locations could be more easily investigated once the aerial extent of geologic nitrate in till has been documented.

- **Source of Geologic Nitrate.** Additional research is required to determine the source of geologic nitrate in Alberta, and the conditions under which it occurs. The occurrence of geologic nitrate in relatively thick oxidized till has been well documented, and gravel aquifers in the P1 and P2 areas of the current study area contain geologic nitrate transported from overlying oxidized till. Geologic nitrate was also commonly detected in shallow shale bedrock in the current study area. Geologic nitrate in oxidized till may be produced via oxidation of organic nitrogen contained in the till, or it may have leached from a near-surface organic source such as a swamp or bog. Similarly, geologic nitrate in bedrock in the current study area may be the result of oxidation of organic nitrogen in the clay-rich bedrock, or it may have been leached from oxidized till or a near-surface organic source that was subsequently eroded from most upland and scarp locations. An improved understanding of the source and extent of geologic nitrate would allow improved predictions about where it is likely to occur.

- **Tools to Identify Nitrate Source.** Research toward an increased understanding of the source and aerial extent of geologic nitrate, as discussed in the previous two bullets, will probably provide the most valuable information regarding the identification of geologic nitrate. Cost-effective geochemical or isotopic indicators may also potentially be developed to distinguish agricultural from geologic nitrate. Enriched tritium or trium-helium age-dating is currently the tool with the most potential to distinguish the two nitrate sources.

Protect Groundwater Quality

Nitrate interpreted to be derived predominantly from agricultural sources was detected in shallow groundwater in bedrock and gravel throughout the study area, even though groundwater quality data were not available for areas with the highest density of CFOs near the Belly River. Almost 20% of nitrate detections interpreted to be agricultural exceeded the drinking-water guideline of 10 mg/L NO_3-N. Contamination of groundwater in upslope positions could significantly impact downslope locations within relatively short time frames, because groundwater in gravel aquifers in upslope locations discharges along upper slopes and is carried via drainage channels to the rivers.

Landowners should be provided with information about local groundwater conditions and nitrate sources, and management practices that protect local groundwater should be encouraged. Information and assistance regarding protection around well heads will also be important, although direct well-head contamination was not found to be a major issue during the current investigation. Protective agricultural practices at vulnerable locations will be the best option to maintain or improve groundwater quality. Management practices will be particularly important at locations with relatively high groundwater vulnerability, including upland areas (U1 and U2) and scarp areas (S1, S2, and S3) where till is relatively thin over gravels or bedrock. Vulnerability decreases as till thickness increases, but glacial till must be at least 5 m thick before it provides even minimal protection for underlying aquifers. Groundwater at locations where till is more than 15 to 20 m thick have relatively low groundwater vulnerability.

Shallow groundwater is a valuable resource that requires protection. The current investigation highlights the importance of shallow groundwater as a water supply and as a potential source of contamination to surface water. Regulatory programs should be reviewed to ensure they include adequate protection for shallow groundwater even where it is not currently used as a water supply.

Geologic nitrate has not been reported or documented at other Alberta locations, although the aerial extent of geologic nitrate in the province requires investigation. Investigation of potential geologic sources of nitrate may be warranted at locations where obvious agricultural sources are not present, and where other factors suggest a geologic source, such as occurrence in relatively deep groundwater or association with oxidized clay-rich glacial deposits. Under such conditions, geologic nitrate would be particularly suspected in the documented area where geologic nitrate is known to occur (the area from south of Fort Macleod to northeast of Vauxhall). Potential agricultural nitrate sources should initially be investigated because they may be more common and they are more easily identified than geologic sources. In addition, a confirmed agricultural source may help to identify possible management changes that may lead to improved groundwater quality. Annual collection of samples from key water wells could provide direct information on how changes in agricultural practices are affecting water quality. Drinking-water treatment will be required at locations where nitrate exceeds drinking water guidelines.

Collect and Manage Groundwater Data

The Groundwater Information Centre (GIC) Database, which is maintained by Alberta Environment and Sustainable Resource Development, collects and maintains water-well installation details and lithology logs for water wells drilled in Alberta. Groundwater quality data were originally kept with the GIC database, but since 1986 Alberta Health has analyzed drinking water quality for well owners and maintained the database of groundwater quality.

One of the most valuable tools for identification of potential anthropogenic impacts on groundwater is the repeated collection of groundwater samples over the long term at wells with known lithology and well installation details. Groundwater quality cannot be understood in isolation from controlling factors such as well depth, lithology, and installation details. Therefore, groundwater quality data should be maintained within the same database as the well installation and lithology data. The analytical service provided by Alberta Health is highly valuable, and it would be much more valuable if all groundwater chemistry results were forwarded to ESRD for inclusion in the GIC database.

The agency responsible for maintaining the GIC database, along with the proposed addition of post-1986 groundwater quality data, should be staffed with sufficient manpower to allow staff to determine or confirm well depth when samples are submitted for analysis, and as far as possible to match chemistry samples with existing well logs with documented lithology and installation details. The database of groundwater information, including lithology and groundwater quality, should be easily accessible to the public, using a system similar to the one maintained for the current GIC database of lithology and well installation details. A detailed GIC database that includes long-term groundwater quality data will be instrumental for researchers, in addition to planners and regulators charged with maintaining or improving groundwater quantity and quality in the province.

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APPENDIX 1: BACKGROUND INFORMATION

Typical Groundwater Settings in Southern Alberta

The most common hydrostratigraphic sequence in the agricultural region of Alberta is soft sedimentary bedrock overlain by glacial till, with sand and gravel aquifers overlying, within or underlying glacial deposits at some locations.

Glacial Till

Most till in Alberta was deposited by the Laurentide (Continental) ice sheet, which advanced from the arctic and Hudson Bay region. Till in parts of western Alberta near the Rocky Mountains was deposited by the Cordilleran ice sheet, which came from the Rocky Mountains (Grasby et al. 2010).

The top few metres of glacial till in southern Alberta are usually highly weathered and fractured, and oxidized to a brown colour. Weathering is the result of oxidation of minerals and organic carbon, and subsequent accumulation or migration of weathering products. Hendry et al. (1986) concluded that oxidation occurred when the water table dropped considerably during the Altithermal, a dry period that occurred 8,000 to 5,000 years ago (MacDonald 1989). The weathered zone is generally referred to as “oxidized” because it is a brown color (i.e, Hue of 5 or 10 YR and Values > 5 on the Munsell Chart) due to Fe-sesquioxide formation (Rodvang and Simpkins 2001).

Brown fractured weathered till is underlain by gray unweathered till, and fractures, where they exist, are rare and less connected. The boundary between the weathered and unweathered zones coincides with a change in groundwater from oxidized to reduced conditions, and is sometimes called the redoxcline (Postma et al. 1991).

The weathered zone is generally about 6 to 15 m deep in Alberta (Grasby et al. 2010). Weathered zones tend to be thicker in topographic highs and thinner in low areas. Thick tills, which occur in the Lethbridge area and in eastern Alberta, tend to contain substantial unweathered zones (Rodvang et al. 1998; 2002; Scracek 1993. Till in central Alberta is generally thin, with the result that the till tends to be oxidized throughout its depth (Grasby et al. 2010).

Thin tills that are oxidized and fractured throughout have much higher conductivities compared to thick tills that tend to be oxidized and fractured only in the shallow zones. Keller et al. (1988) conducted rigorous studies of groundwater flux in two Saskatchewan tills.

- The Dalmeny till was 18 m thick and fractured throughout, with a vertical flux ranging from 0.3 to 3.5 cm/yr.
- The Warman till was 60 m thick, and only the uppermost 8 m was fractured and oxidized. Groundwater flux through the Warman till was only 0.03 cm/yr (Keller et al. 1988).

The highest rate of groundwater flow through oxidized till occurs in the shallowest zone very close to the water table. Rigorous studies by McKay et al. (1998), including a long-term tracer test using chloride, indicated a lateral transport rate of about 40 to 100 cm per year through very shallow till.

Sand and Gravel Aquifers

Sand and gravel deposits that occur within or overlying till are generally quite small aquifers. Recent sand and gravel deposits tend to occur as river-connected alluvial aquifers along rivers with significant flow. River-connected alluvial aquifers are up to 15 or 20 m thick and typically directly overlie bedrock. They constitute some of the few highly productive unconfined aquifers in southern Alberta, and they are typically in complete hydraulic connection with surface water (Manwell and Ryan, 2006).

Alberta is underlain by a vast network of buried river valleys that were formed by rivers flowing from the Rocky Mountains before the last glaciation, mainly during the Tertiary Period. These valleys are often called pre-glacial or Saskatchewan Sands and Gravels (Scracek 1993). They form channels in the bedrock, and they are usually at least partially infilled with sand and gravel deposits and overlain by till. Buried river valley sands and gravels are very productive aquifers at many locations, provided the deposits are sufficiently thick (greater than about 2 m) and not highly cemented. Preglacial sands and gravels are usually the most productive aquifers in the plains region of Alberta.

Bedrock Aquifers

Bedrock is usually considered to be solid rock, but bedrock in the Alberta plains is typically unconsolidated, and is termed softrock. It is defined as all sedimentary material that is Tertiary-aged or older (Robertson and Hendry 1982). The rate of flow through most bedrock in southern Alberta is controlled by the extent of fracturing. The upper surface of bedrock is often a productive groundwater zone because fractures tend to be denser near the bedrock surface. Stein (1987) reported fractured shale to depths of more than 30 m in the Blackspring Ridge area, which is a bedrock ridge located approximately 50 km northeast of the current study area. The fractures were attributed to glacial overriding.

Groundwater Chemistry in Alberta Till and Bedrock

Groundwater in weathered glacial till on the prairies often contains very high concentrations of sulphate (SO_4^{2-}), sodium (Na^+), and magnesium (Mg^{2+}), due to the oxidation of pyrite during weathering in the Altithermal period (Hendry et al. 1986; Van Stempvoort 1990; Rodvang et al. 1998; Rodvang et al. 2004). Pyrite oxidation caused the dissolution of calcite and dolomite and the precipitation of gypsum. Sodium, which dominated clay exchange sites before weathering, was desorbed by preferential sorption of Ca^{2+} and Mg^{2+}. Equilibrium with calcite and dolomite tends to maintain the pH at 6 to 8, and to limit the solubility of Fe^{3+}. Precipitation of calcite ($CaCO_3$) and gypsum ($CaSO_4$) tends to increase the Mg^{2+} to Ca^{2+} ratio above 1. The concentrations of Na^+, SO_4^{2-} and Mg^{2+} tend to be linearly related, consistent with their common origin during weathering. Weathering processes in fine-textured lacustrine sediments are probably similar to those in till, because the clays are also carbonate-rich, with high cation exchange capacities, and may contain pyrite (Van Stempvoort 1990).

Groundwater chemistry in bedrock is largely controlled by recharge through overlying glacial till (Grasby et al. 2008). Thin tills are usually completely oxidized, and sulphate is leached into the underlying bedrock. Bedrock groundwater along the western edge of the province recharged through Cordilleran till, and SO_4^{2-} concentrations are much lower than for the rest of the province, where groundwater recharges through Laurentide till (Grasby et al. 2008).

Weathering reactions similar to those in weathered till can produce sodium-sulphate rich groundwater in shale. Coarse-textured bedrock formations that are highly flushed with recharge tend to have low salt concentrations. Salt concentrations in bedrock tend to increase from west to east, reflecting the decrease in precipitation. TDS in the Paskapoo, Porcupine Hills and Willow Creek Formations are characterized by low TDS, often less than 1000 mg/L (Pupp et al. 1989).

Isotopes for Groundwater Investigations

Isotopes are forms of an element with the same number of protons but different numbers of neutrons. Water is typically composed of ^{1}H and ^{16}O. The water isotopes deuterium (^{2}H), oxygen 18 (^{18}O) and tritium (^{3}H) are commonly used as indicators of approximate groundwater age.

Tritium

Tritium (^{3}H) is a natural radioactive isotope of hydrogen with a half life of 12.43 years, meaning that half the isotopes present decay every 12.43 years. One tritium unit (TU) in water corresponds to one ^{3}H atom in 10^{18} hydrogen atoms. Small amounts of tritium are constantly produced in the upper atmosphere, but much higher levels entered the atmosphere from nuclear bombs starting in the 1950s. This is why tritium is a commonly-used tracer to indicate groundwater that recharged predominantly after 1950.

Tritium content in shallow groundwater has steadily decreased since the 1950s due to decay and dilution. The accuracy of direct tritium measurements is currently low due to the low concentrations of tritium in groundwater. Enrichment of samples is usually required to accurately determine tritium levels, and the measurements are called “enriched tritium”.

Oxygen-18 and Deuterium

Stable isotopes are typically measured in delta (δ or Δ) notation. The following example is shown for ^{18}O, where R is the ratio of $^{18}O/^{16}O$, and units are in parts per thousand (per mil, or ‰).

$\Delta = (R_{sample} - R_{standard})/R_{standard} * 1000$.

The standard used for 18O and deuterium (2H) measurements is SMOW, or standard mean ocean water. For example, $\delta^{18}O = -10‰$ means that the sample is depleted in ^{18}O relative to SMOW by 1%.

Craig (1961) found that ^{18}O and ^{2}H in precipitation are linearly related, and he defined the global meteoric water line as $\delta^{2}H = 8 * \delta^{18}O + 10$ ‰. $\delta^{18}O$ and $\delta^{2}H$ collected at individual sites also follow a strong linear relationship that usually deviates slightly from the global MWL, and is called the local MWL.

Two factors that affect ^{18}O and ^{2}H content of groundwater are important for the current investigation.

- For groundwater that has been subjected to partial evaporation, the linear relationship between $\delta^{18}O$ and $\delta^{2}H$ has a lower slope on a plot of $\delta^{2}H$ on the y axis and $\delta^{18}O$ on the x axis (Payne 1988). Therefore, very shallow groundwater and spring water (groundwater that discharges at surface) often exhibit lower slopes on the local MWL, indicating partial evaporation.
- Precipitation that occurs in cold climates tends to be more depleted in heavy isotopes, so Canadian groundwater that recharged during glacial times has more negative $\delta^{18}O$ and $\delta^{2}H$ values than groundwater that recharged in modern times.

^{18}O and ^{2}H Data from Similar Study Areas

Profiles of ^{18}O and ^{2}H in thick glacial till typically show a shift with depth, from modern groundwater near ground surface, to more negative isotopic values at depth. The more negative values at depth represent groundwater that has been influenced by recharge under colder glacial conditions, about 10,000 years ago.

Remenda et al. (1996) used $\delta^{18}O$ profiles at the Warman site in Saskatchewan to indicate that groundwater flux was negligible in the thick unfractured till, and transport was controlled by diffusion. $\delta^{18}O$ at the Warman site ranged from -17.2 to -19 ‰ in the upper 10 m, and decreased gradually to -21‰ by 20 m depth. $\delta^{18}O$ was a minimum of -21.5‰ at this site (Remenda et al. 1996). The conclusion that isotopic profiles at Warman reflect diffusion of modern groundwater into glacial-aged groundwater were supported by numerous other researchers (Shaw and Hendry 1998; Hendry and Wassenaar 1999; Keller et al. 1988; Keller et al. 1989). The results indicate that groundwater with $\delta^{18}O$ values less than -21‰ were recharged predominantly under glacial conditions.

Stein (1987) and Rodvang et al. (1998; 2002) conducted detailed investigations within 100 km of the current study area. Both studies were multi-year investigations with extensive drilling, piezometer installation and data analysis. Data from these rigorous and detailed investigations can be used to assist with interpretations in the current study area.

- Rodvang et al. (1998; 2002) investigated agricultural and geologic nitrate in study areas in the Lethbridge, Vauxhall and Iron Springs to Picture Butte areas of southern Alberta (abbreviated as the LVP areas in this report). Most locations were characterized by about 10 to more than17 m of till over bedrock, although some study areas were characterized by shallow sand over fine-textured lacustrine over till. Only a very few piezometers were installed in bedrock.

- Stein (1987) investigated the origin of salinity on Blackspring Ridge, which is a bedrock ridge located in Tp. 12, Rg. 22 W4, about 50 km northeast of the current study area. Blackspring Ridge rises about 50 m above the surrounding plain, and is characterized by extensive salinity related to upwelling groundwater from bedrock. Bedrock of the Horseshoe Canyon formation is overlain by stratified till, lacustrine and aeolean sediment with thicknesses ranging from about 2 m on top of the ridge to 110 m in buried valleys (Stein 1987). Numerous piezometers were installed in surficial sediments and bedrock.

Rodvang et al. (1998) reported profiles of δ^{18}O with depth at numerous piezometer nests in relatively thick glacial till (more than 10 m thick) in the LVP areas (all areas are within 100 km of the current study area). Examples for four locations are illustrated in Fig. A1.1.a. All profiles showed the decrease in δ^{18}O values with depth, suggesting a shift to older groundwater with a glacial influence at depth. Profiles varied with location; locations in recharge areas (3137 and 2985) started to shift to more negative values below about 10 m depth, while the shift is observed starting at about 5 m at locations in discharge areas (2987 and BP1) (Fig. A1.1.a).

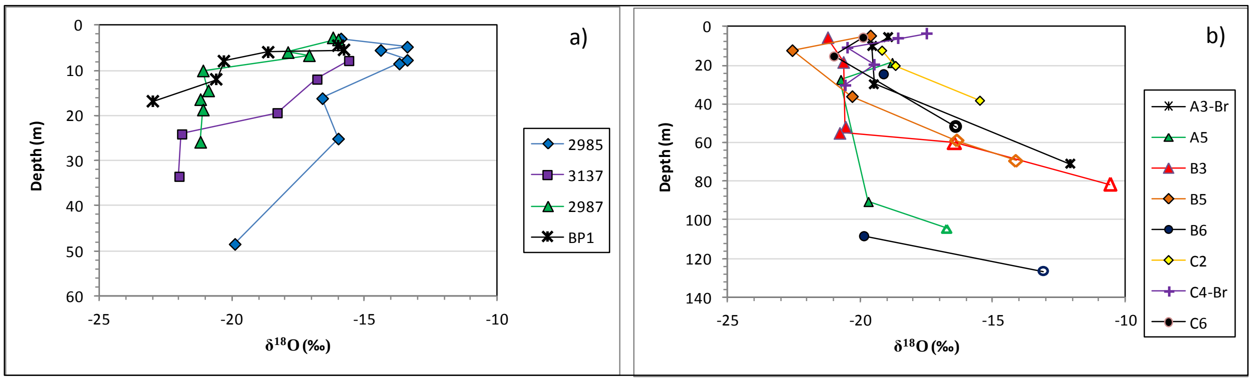

Fig. A1.1. Profiles of ^{18}O with depth. a) Lethbridge, Picture Butte and Vauxhall areas (from Rodvang et al. 1998). b) Blackspring Ridge area (from Stein 1987).

Stein (1987) reported numerous ^{18}O profiles in surficial sediments and bedrock in the Blackspring Ridge area. The dominant trend at Blackspring Ridge is one of nearly constant values throughout surficial sediments, and a significant shift to more positive ^{18}O values in bedrock below about 40 m (shown with open symbols in Fig. A1.1.b). Stein (1987) interpreted this positive shift in bedrock groundwater to indicate that it recharged during the altithermal (a warmer and drier climate period that occurred about 4,000 to 6,000 years ago).

It is more likely that this groundwater represents a mixture of remnant evaporated seawater and meteoric water. Hitchon and Friedman (1969) used enriched ^{18}O and ^{2}H values to conclude that groundwater in the western Canada sedimentary basin was derived by mixing of diagenetically altered remnant seawater with infiltrating meteoric water. The remnant marine water was enriched in ^{18}O through extensive exchange with the rock matrix, but variations in H isotopes were interpreted as reflecting the degree of mixing with meteoric water. Steuber and Walter (1990) used similar methods to conclude that groundwater in the Illinois basin was derived from the mixing of meteoric water with remnant seawater.

In summary, interpretations of the profiles in Fig. A1.1.b suggest shallow surficial groundwater on Blackspring Ridge is a mixture of meteoric water and glacially-recharged water, and deeper bedrock groundwater is a mixture of meteoric water and remnant seawater. In other words, isotopic data suggest the groundwater on Blackspring Ridge is much older than suggested by the original interpretations of Stein (1987), and much older than glacial age.

Tritium Data from Similar Study Areas

Stein (1987) measured tritium on piezometer samples, but the results were inconclusive because enriched tritium is usually required for accuracy. Consistent results were obtained from core samples, which indicated un-enriched tritium was detected to depths of about 3 to 5 m in all cores (Stein 1987). Actual tritium penetration through fractures may occur to deeper depths, because core samples generally indicate tritium levels in the matrix between fractures (Ruland et al. 1991).

Rodvang et al. (1998) measured enriched tritium at numerous locations in the Lethbridge, Picture Butte and Vauxhall areas.

- For locations SP and BB, which were in till of approximately 15 m in thickness, tritium was not detected below 5 m at most locations (Fig. A1.2.a), and tritium was detected only in groundwater with $\delta^{18}O$ values less negative than -18‰ (Fig. A1.2.b).
- Tritium was detected to deeper depths at locations characterized by sand overlying till or fine-textured lacustrine sediments at locations VP and LB. Tritium at one LB location was detected at 14 m depth (Fig. A1.2.a), in fine-textured lacustrine sediments below 7 m of sand. Tritium in three samples was detected in groundwater with $\delta^{18}O$ values ranging from -19 to -21‰ (Fig. A1.2.b). The three samples with tritium in glacially influenced groundwater may represent contaminated water, due to the difficulty of installing piezometers below caving sand (Rodvang et al. 1998), but they may also be true indications of tritium.

In summary, tritium in glacial till most commonly occurs in the uppermost 5 m, in groundwater with $\delta^{18}O$ values less negative than -18‰.

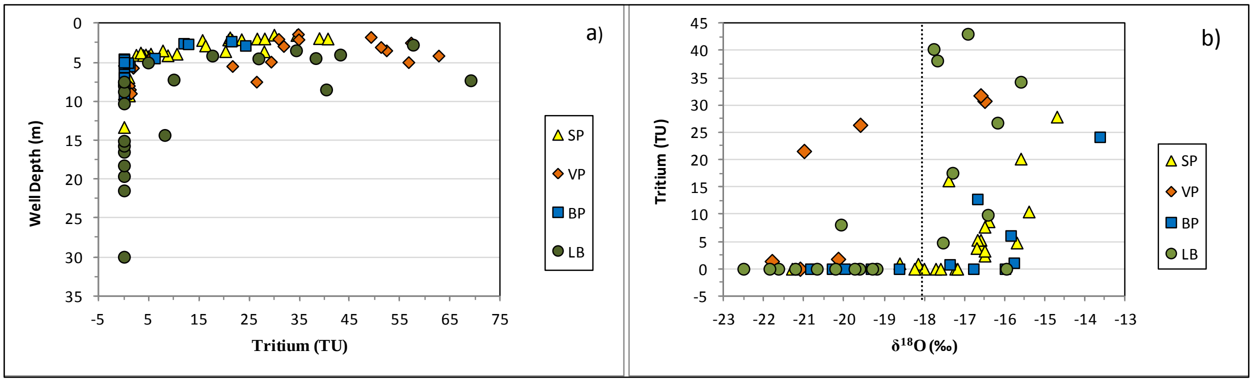

Fig. A1.2. Tritium profiles (from Rodvang et al. 1998). a) Tritium with depth. b) Tritium with ¹⁸O.

Nitrogen Isotopes

The stable isotopes of nitrate (nitrogen 15= ^{15}N and oxygen 18 = ^{18}O) in nitrate (which is most commonly composed of $^{14}N^{16}O_3$) are used as tools to provide information regarding nitrate source and the occurrence of denitrification in groundwater. Typical ranges for $\delta^{15}N$ values for three major sources of nitrate are summarized in Table 1, based on a review by Heaton (1986).

Table A1.1. Typical range of nitrate isotope values for three nitrate sources.

Nitrate Isotope	Range in Inorganic Fertilizer (‰)	Range in Mineralized Soil Organic Matter (‰)	Range in Manure (‰)
$\delta^{15}N$	-7 to 3	1 to 7	8.5 to 19.5
$\delta^{18}O$	-3.5 to 4	-7 to -2	-7 to -2

Predictable isotopic fractionation occurs during the bacterial conversion of nitrogen to nitrate. During microbial denitrification, the heavy isotopes ^{15}N and ^{18}O become enriched in the residual nitrate, but the degree of enrichment depends on environmental conditions and is difficult to predict (Heaton 1986). The enrichment of ^{18}O is often a better indicator of denitrification than the enrichment in ^{15}N (Heaton 1986). Several groundwater studies have found that ^{15}N is twice as enriched as ^{18}O during denitrification (Heaton 1986; Aravena and Robertson 1998).

Nitrate isotopes are most useful in simple well-defined groundwater systems where specific nitrate concentrations in recharge water are known (Heaton 1986). However, interpretations are complicated and usually semi-quantitative at best. Nitrate isotopes have rarely been used to convincingly demonstrate widespread nitrate contamination from inorganic fertilizer. This is because even in heavily fertilized areas the dominant nitrate source is still soil organic nitrogen. Inorganic N fertilizer reacts with the soil plant system, and in many cases loses its isotopic identity by exchange with the large amount of soil organic nitrogen (Heaton 1986).

Nitrate in Groundwater

Agricultural Nitrate

Nitrate is a common groundwater contaminant in agricultural areas. The guideline for NO_3^--N in the Canadian Drinking Water Quality Objectives is set at 10 mg/L because the consumption of nitrate is linked to numerous health concerns (Ward 2005). A 1997 survey of approximately 900 rural farm water wells in Alberta indicated more than 32% of tested wells exceeded at least one health related parameter, and almost 6% exceeded the Canadian drinking water guideline for nitrate (Fitzgerald et al. 1997). Agricultural sources of nitrate include manure and commercial fertilizer nitrogen. Numerous investigations have concluded that shallow aquifers in intensive agricultural areas are highly vulnerable to nitrate contamination (e.g., Harter et al. 2002; Rodvang et al. 2004). Rodvang et al. (2004) found elevated nitrate in a shallow alluvial aquifer in an area with intensive CFOs located about 80 km northeast of Fort MacLeod.

Geologic Nitrate

Organic-rich sedimentary rocks (usually shale) often contain a high concentration of organic nitrogen, which is mineralized to ammonium during diagenesis (Holloway and Dahlgren 1999). When the ammonium is nitrified, it produces geologic nitrate.

Geologic nitrate is common in weathered till and fine-textured lacustrine sediments in southern Alberta. Geologic nitrate in till was first documented by Hendry et al. (1984), in the Vauxhall area of Alberta, and later confirmed by Rodvang et al. (1998; 2002) in the Lethbridge, Vauxhall and Picture Butte areas of southern Alberta (Rodvang and Simpkins 2001). Grisak (1975) sampled more than 200 water-table wells installed to 12-m depth over an area of 78,000 ha around Lethbridge. He found most wells contained high levels of nitrate, at an average concentration of 181 mg/L NO_3-N. Geologic nitrate in the above studies occurs in relatively stagnant groundwater in oxidized glacial deposits overlying bedrock of the Oldman and Bearpaw formations. More than 100 mg/L NO_3-N was also detected in shallow bedrock of the Horseshoe Canyon Formation in southern Alberta, associated with elevated nitrate in the overlying weathered till (Rodvang et al. 1998). All study areas mentioned in this paragraph were located within 50 to 100 km of the current study area.

Geologic nitrate in till in the Lethbridge,Vauxhall and Picture Butte areas usually occurs below the shallow zone of significant groundwater flow, and above the redoxcline, because nitrate is not stable below the redoxcline. The intermediate zone with geologic nitrate most commonly occurs at depths of about 5 to 12 m, in relatively stagnant groundwater in oxidized till. Geologic nitrate is concentrated near ground surface in local discharge areas, and leached to deeper depths in local recharge areas (Rodvang et al.1998). Groundwater with geologic nitrate was characterized by $\delta^{18}O$ values commonly ranging from about -17.5 to -19.5‰, but values as low as -21.1‰ were also often found with geologic nitrate in recharge areas, and values as high as -16.6 ‰ occurred with geologic nitrate in groundwater discharge areas (Rodvang et al. 2002).

The occurrence of geologic nitrate associated with organic-rich shale has been documented at several locations in the United States, including North Dakota and eastern Montana (Power et al. 1974), Nebraska and South Dakota (Boyce et al. 1976), Colorado (Reeder and Berg 1977), and California (Strathouse et al. 1980; Holloway and Dahlgren 1999), as reviewed by Rodvang and Simpkins (2001). To the authors' knowledge, geologic nitrate has not been documented in other areas of Alberta or Canada, including Saskatchewan, where the organic-rich Bearpaw shale also occurs. Researchers did not find geologic nitrate in groundwater in till in the Saskatoon area (Fortin et al. 1991). The extent of the occurrence of geologic nitrate in Alberta is unknown. The source of the nitrate may be related to organic nitrogen that was entrained in the till as glaciers moved over the shale-rich bedrock. It is also possible that some of the area was covered with a large organic-rich wetland (marsh), and nitrate was leached downward from a surface source.

Redox Controls

Nitrate is highly soluble in groundwater and it does not interact with clay particles, so it tends to move at the speed of groundwater flow. Once nitrate enters groundwater it remains there unless it is denitrified. Denitrification occurs when bacteria obtain energy by catalyzing a redox reaction in which an electron donor is oxidized while nitrate is reduced to nitrogen (N_2) or nitrous oxide (N_2O) gas. Denitrification occurs in oxygen-poor groundwater, and it requires the presence of electron donors (Korom 1992). The most common electron donors are organic carbon and pyrite (FeS_2).

Denitrification Using Organic Carbon in Manure

Manure contains a rich supply of organic carbon that could be used as an electron donor for denitrification if it were labile (i.e. bacteria can use it to catalyze denitrification). Aravena and Robertson (1998) concluded that dissolved organic carbon (DOC) concentrations present in groundwater with nitrate are usually too low to provide substantial denitrification, and the DOC is likely to consist of the most recalcitrant fraction that is less available for denitrification. Several other studies suggest the majority of DOC leached to groundwater from manure has a low lability for denitrification. These studies have been conducted in sand in Alberta (McCallum et al. 2008), in till in Iowa (Helmke et al. 2005), and in sand and gravel in British Columbia (Wassenaar 1995). Robertson and Schiff (2008) found evidence for very limited denitrification of poultry manure in sand in Ontario.

Denitrification with Pyrite in Deep Glacial Sediments

A literature review by Rodvang and Ryan (2011) concluded that nitrate is generally stable above the redoxcline and is completely and rapidly denitrified to harmless N_2 gas below the redoxcline in unoxidized till. This is because electron donors (organic carbon or pyrite) have been oxidized and removed from sediments above the redoxcline, but electron donors are available for denitrification below the redoxcline. Investigations in southern Alberta have shown that nitrate does not occur below the redoxcline in glacial sediments in southern Alberta, consistent with the finding that it is not stable in reduced sediments (Rodvang et al. 2002).

Most investigations conclude that pyrite is the most important electron donor in reduced glacial deposits. Solid organic carbon (SOC) tends to increase only slightly and gradually, if at all, below the redoxline, and bacteria cannot use coal fragments or dissolved organic carbon (DOC) as electron donors for denitrification (i.e. they are not labile) (Rodvang and Ryan 2011). Several studies indicate pyrite is a highly labile (easy for bacteria to use) electron donor for denitrification when it is present at concentrations similar to those measured in unoxidized till in southern Alberta. Denitrification with pyrite releases dissolved iron and SO_4, so those parameters may increase when denitrification with pyrite (autotrophic denitrification) occurs. However, a study in Iowa found that denitrification with pyrite did not result in increased SO_4^{2-} in groundwater because SO_4^{2-} leaches downward and re-precipitates as pyrite (Schilling and Tassier-Surine 1995).

In summary, denitrification with pyrite effectively removes nitrate from groundwater in unoxidized till, but unoxidized till occurs only in locations where till deposits are relatively thick (e.g., more than 10 to 20 m thick). Pyrite is a common mineral in shale, and is expected to be available for denitrification in unoxidized shale.

Denitrification with Recent Organic Carbon

Some investigations have concluded that recent forms of organic carbon are labile for denitrification (Simpkins and Parkin 1993; Aravena and Robertson 1998; Helmke et al. 2005). Recent organic carbon is generally present at higher concentrations in riparian areas, and this usually results in some increase in denitrification rates. Many studies find that substantial nitrate removal occurs as groundwater discharges to surface water, with potential removal processes including denitrification, plant uptake and dilution (Clausen et al. 2000; Devito et al. 2000). The amount of nitrate removal in riparian areas is highly influenced by groundwater flow paths and the organic carbon content in the riparian area. Detailed characterization of groundwater flow paths and isotopic profiles are essential to determine nitrate removal processes, since dilution from deeper groundwater often contributes to decreasing nutrient concentrations in riparian zones (Mengis et al. 1999; Clausen et al. 2000; Devito et al. 2000; Zilkey 2001).

In a review of nitrate removal in stream riparian zones, Hill (1996) concluded riparian zones effectively remove nitrate from aquifers that are underlain at shallow depths (usually less than 3 m) by impermeable layers. This type of hydrogeologic scenario maximizes the interaction of groundwater with riparian soils and vegetation, thus promoting root uptake and denitrification in organic-rich soils. Limited research suggests less effective nitrate depletion in riparian areas connected to thick aquifers, where interaction with organic soils is limited, and where groundwater flows in deeper and more vertical paths that bypass the riparian zone and discharge upwards into the stream channel (Hill 1996).

Low rates of denitrification are generally measured in unconfined sand aquifers, but increased denitrification often occurs with increased soil organic carbon in riparian areas where the fluvial sediments are of recent origin (Vidon and Hill 2004; Hill et al. 2004). Research along the Battersea drain near Picture Butte in southern Alberta suggests substantial nitrate removal as groundwater discharges to the drain from medium-textured sediments (Rodvang and Riemersma 2002).

Profiles of Agricultural and Geologic Nitrate in the Vicinity of the Study Area

Rodvang et al. (1998; 2002) documented the presence of both geologic and agricultural nitrate in glacial till in the Lethbridge,Vauxhall and Picture Butte (LVP) areas of southern Alberta. The identification of nitrate source was aided by very detailed land use information, along with data for ^{18}O, enriched tritium, and groundwater flow. Selected profiles are discussed below to illustrate typical distinguishing characteristics of the two nitrate sources in the LVP areas.

Geologic nitrate generally occurred at deeper depths than agricultural nitrate, and concentrations were stable with time from the early 1980s to the late 1990s, with only minor fluctuations. Geologic nitrate in till typically occurs at depths below the zone of most active groundwater flow, in the zone characterized by $\delta^{18}O$ values representing a mix of recent recharge and old groundwater (in the range of approximately -17 or -18 to -21 ‰) (Rodvang et al. 1998; 2002). In contrast, recent sources of agricultural nitrate are usually detected near ground surface, and they tend to extend to deeper depths in coarse-textured locations than in till.

Four typical depth profiles of geologic nitrate in till are illustrated in Fig. A1.3.

- The first two sites (LB5 and LF1) illustrate locations where nitrate was not detected in the near surface, but was detected at depths of 7 to 15 m, at depths where $\delta^{18}O$ was < -19 ‰, and tritium was not detected (Figs. A1.3a and A1.3b).
- Fig. A1.3c illustrates Location BP3, where agricultural nitrate occurs in the shallowest piezometer on fertilized cropland, associated with tritium and an evaporated $\delta^{18}O$ value. Agricultural NO_3-N decreased to below detection in the next two deepest piezometers, but geologic nitrate was detected at depths of 7 to 11 m, in groundwater with $\delta^{18}O$ values < -19 ‰.
- Fig. A1.3d illustrates a profile of geologic nitrate in a discharge area (BP4). In this case geologic nitrate occurs in shallow groundwater with tritium, and with $\delta^{18}O$ values of -17 ‰. Nitrate source at this location was identified as geologic based on several other detailed profiles at the same location with the same land use, along with detailed groundwater flow information (Rodvang et al. 1998). The profile shown in Fig. A1.3d illustrates that geologic nitrate can also occur near ground surface in groundwater discharge areas.

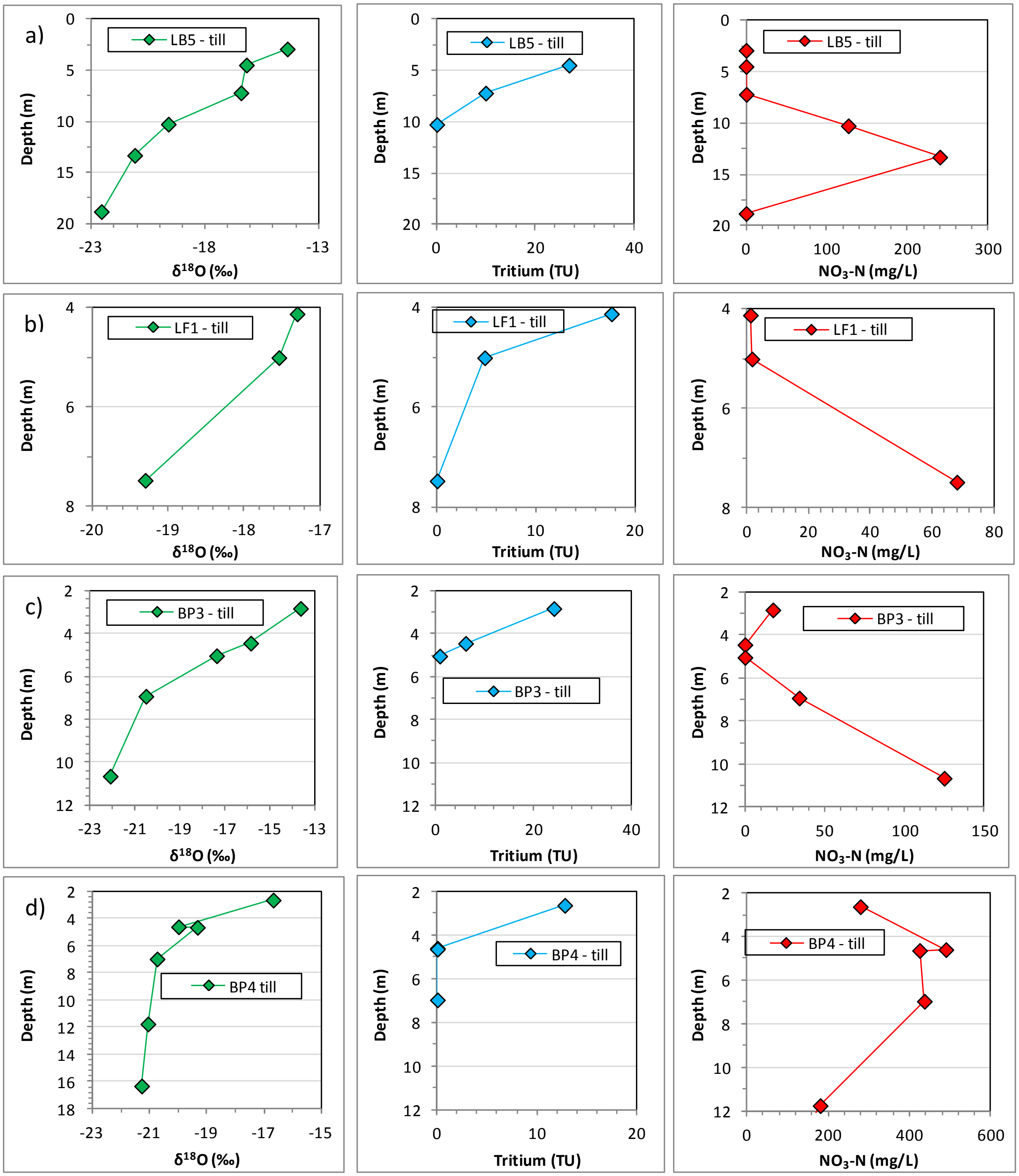

Fig. A1.3. Profiles of geologic nitrate in till groundwater. From Rodvang et al. (1998).

A typical profile of nitrate derived from manure or inorganic fertilizer is shown in Fig. A1.4. Agricultural nitrate typically decreases with depth, and occurs with enriched tritium and $\delta^{18}O$ values on the order of -18 ‰ or less negative. Agricultural nitrate in the study areas by Rodvang et al. (1998; 2002) was generally limited to the uppermost approximately 8 m, but most locations were in till. Deeper leaching depths for agricultural nitrate are expected to occur through coarser textured surficial sediments and fractured bedrock.

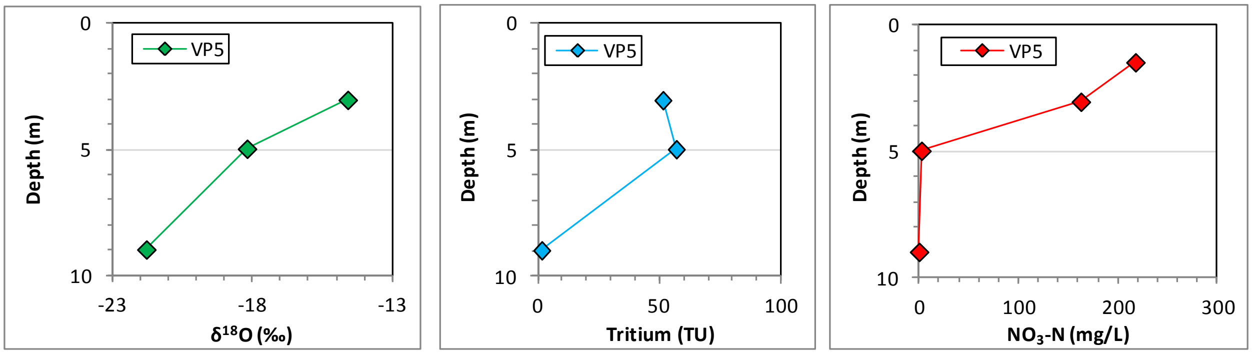

Fig. A1.4. Profile of agricultural nitrate in groundwater. From Rodvang et al. (1998).

Stein (1987) measured nitrate concentrations in groundwater in the Blackspring Ridge area, which is more a geologically similar to upland areas in the current study area. Nitrate was detected in shallow groundwater above 5 to 10 m depth at several locations (Fig. A1.5a), but the source cannot be determined with existing data. Nitrate data for Blackspring Ridge are compared to data from the LVP areas in Fig. A1.5, and profiles from several locations are shown in Fig. A1.6. $\delta^{18}O$ values in groundwater with nitrate ranged from -18 to -22 ‰, and most values were < -19 ‰ (Fig. A1.6). Stein (1987) presents rigorous flow nets illustrating upward groundwater flow from bedrock in this study area. This suggests nitrate is concentrated in the shallow zone via groundwater flow, but the source remains in question.

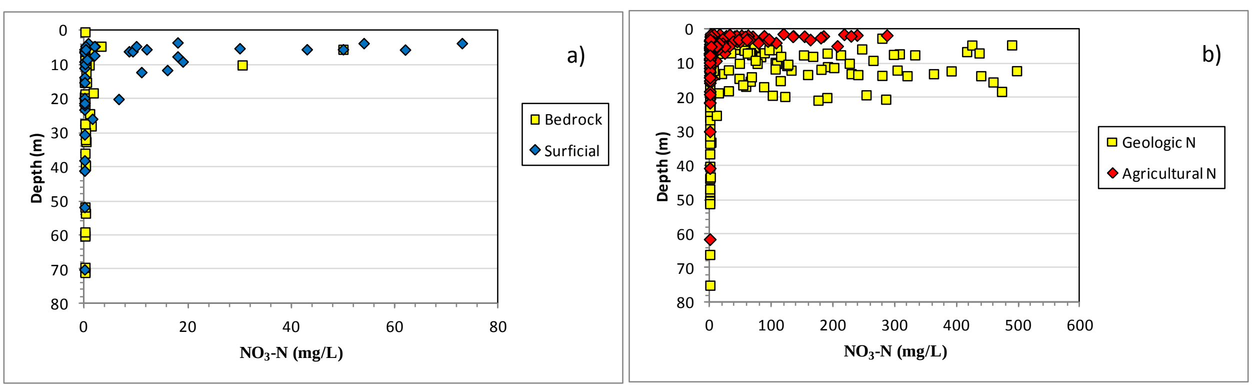

Fig. A1.5. NO3-N concentrations with depth. a) All data collected by Stein (1987) for the Blackspring Ridge area. b) All data collected by Rodvang et al. (1998) for the Lethbridge, Vauxhall and Picture Butte areas.

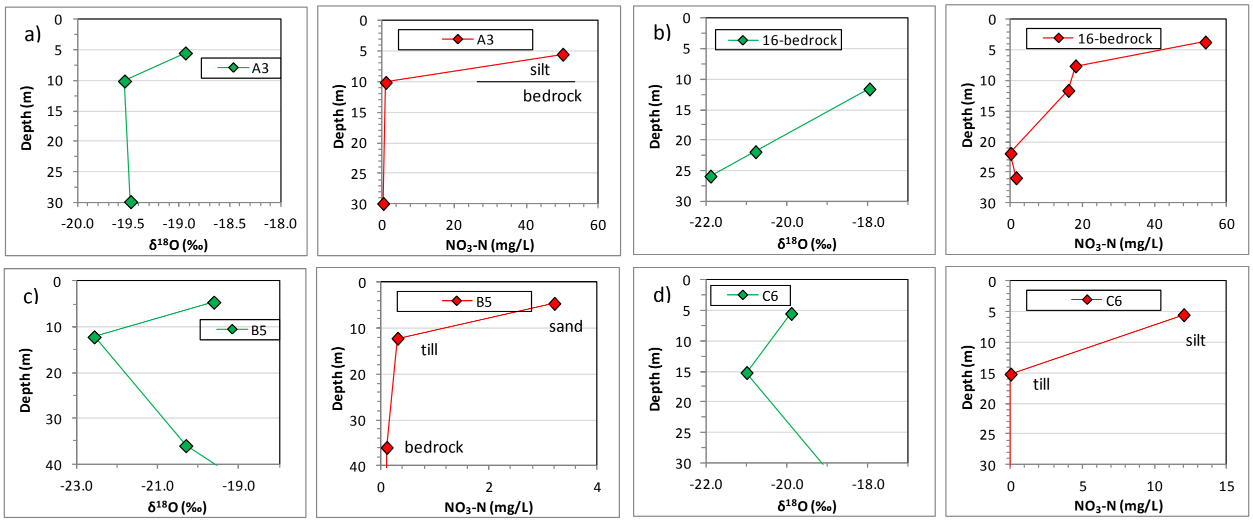

Fig. A1.6. Nitrate profiles in groundwater in the Blackspring Ridge area. From Stein et al. (1987).

APPENDIX 2. Location Numbers for Wells and Geologic Logs

Alberta's legal location numbering system is based on townships and ranges.

- Each township is 6 mi^2 and contains 36 sections, numbered as shown in the left diagram below.
- Each of the 36 sections are subdivided into 16 legal subdivisions (LSDs), as shown in the right diagram below. For example, the SW portion of a section includes LSDs 3, 4 5 and 6.
- Range numbers west of the 4th meridian increase from east to west starting at the Saskatchewan border. Township numbers increase from south to north starting at the Canada – U.S. border. The current study area encompasses most of Ranges 25 and 26, and most of townships 6, 7 and 8, as shown in Fig. 3 of this report.

31	32	33	34	35	36
30	29	28	27	26	25
19	20	21	22	23	24
18	17	16	15	14	13
7	8	9	10	11	12
6	5	4	3	2	1

13	14	15	16
12	11	10	9
5	6	7	8
4	3	2	1

For this report, water wells, piezometers and geologic logs are numbered starting with 1 in the bottom right corner of the study area. Numbers increase in the order shown for section numbers above, but each quarter section contains four numbers. All quarter sections are numbered as shown in Fig. A1-1 on the following page.

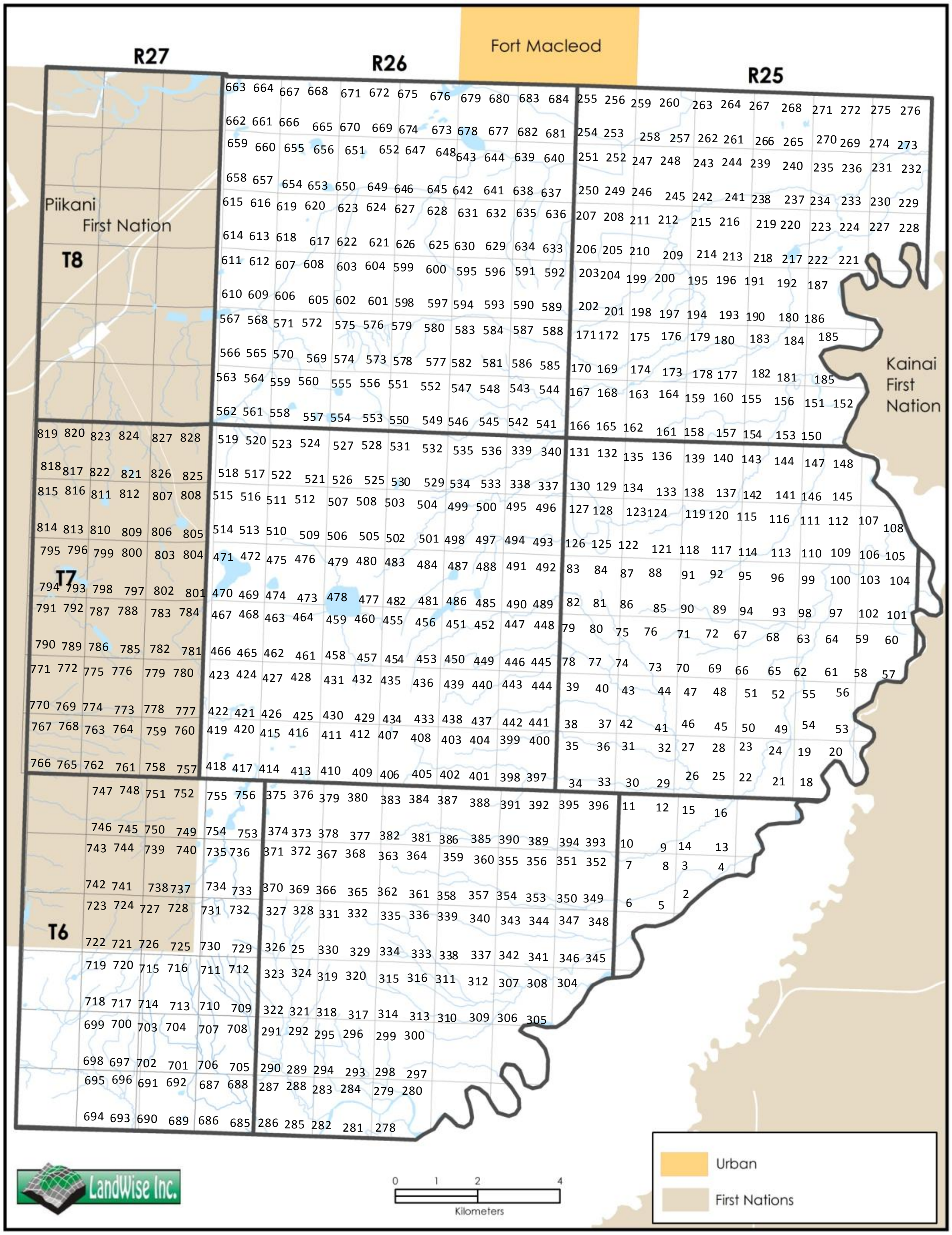

Fig. A2-1. Location numbers used in this report.

APPENDIX 3. Plates.

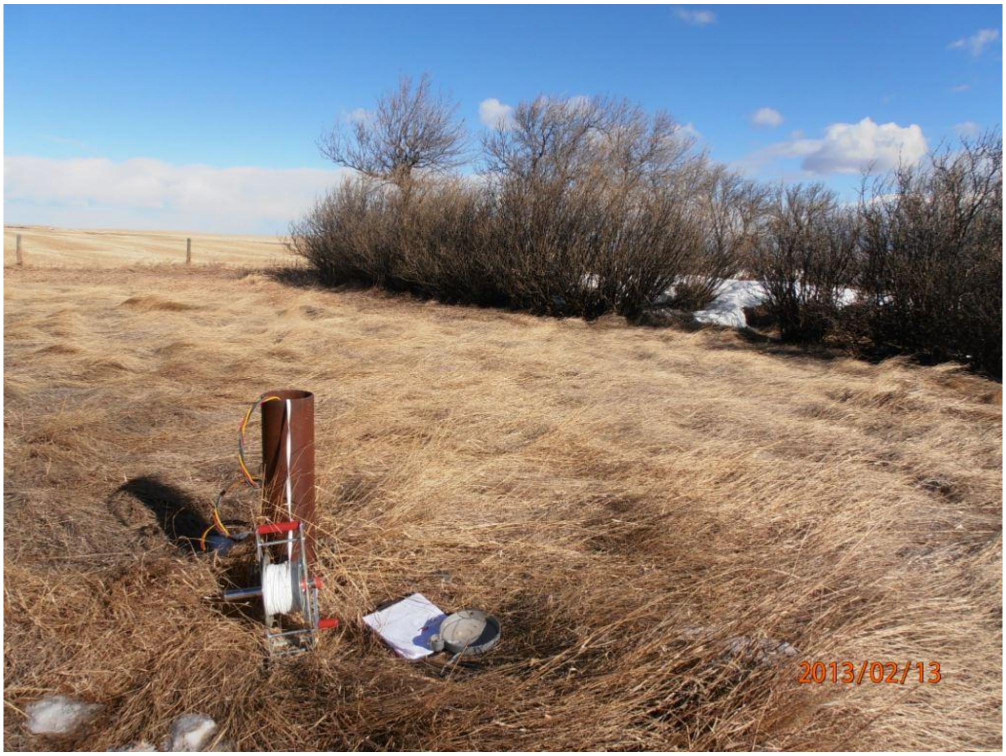

Plate 1. Measuring the static level in a well.

Plate 2. Shale bedrock exposed in a road cut in Tp. 8 Rg. 26.

Plate 3. Gravels overlying shale bedrock along the Belly River Valley in Tp. 8 Rg. 25.

Plate 4. Ardenville Gravels exposed in a gravel pit.

Plate 5. Cemented gravels on the Ardenville Bench.

Plate 6. Ardenville Gravels pinching out at ground surface.

Plate 7. Wetland fed by water from Ardenville Gravels.

Plate 8. Ephemeral drainage channel on shallow bedrock.

Plate 9. Water production from Ardenville Gravels at piezometer nest 1.

Plate 10. Recharging depression on the Ardenville Bench.

Plate 11. Recharging depression on the Ardenville Bench, showing manure from grazing cattle.

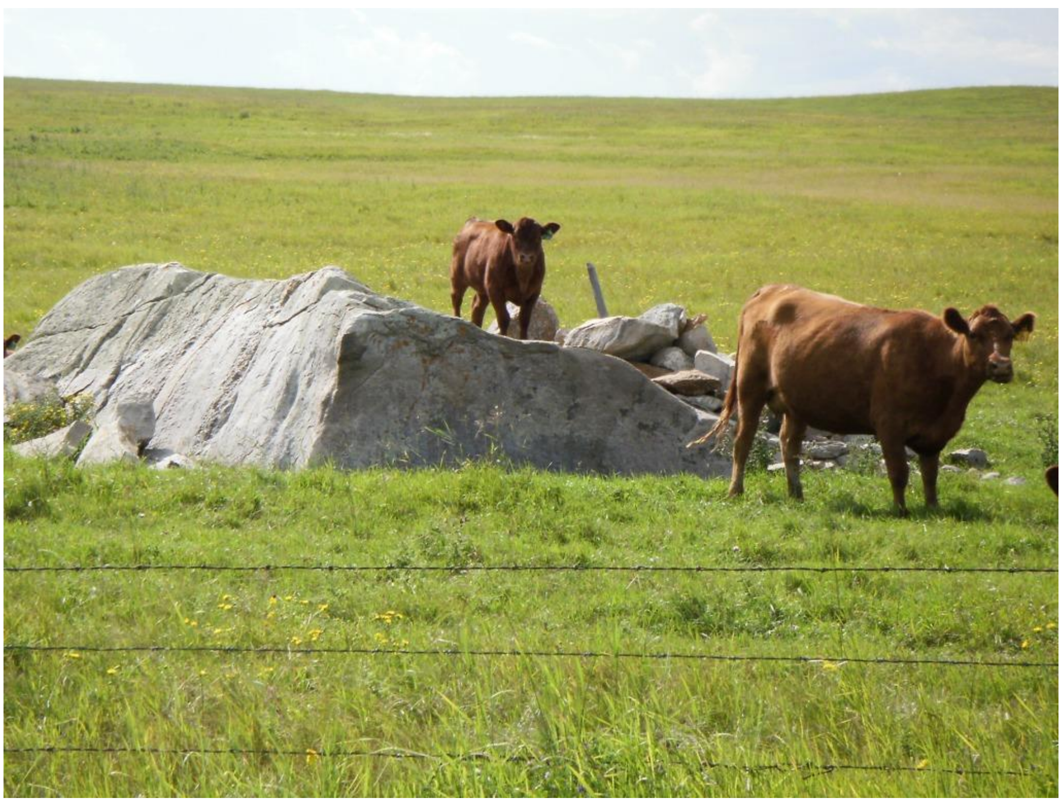

Plate 12. Glacial erratic on the McBride Channel south of the McBride Gravels.

Plate 13. Glacial till encountered during drilling at piezmeter nest 3.

APPENDIX 4. Groundwater Chemistry in Water Wells.

See Attached Excel File. chem litho app. 4&5.xlsx

APPENDIX 5. Geologic Logs.

See Attached Excel File. chem litho app. 4&5.xlsx

APPENDIX 6. Piezometer Installation Details.

Piezometer Nest 1: SE 9-7-26-W4. Elevation = 1145 ±3 m. Immediately west of caragana hedge on native range, at highest location visible.

Geologic Log

Depth (m)	Lithology Description	Moisture	Munsell Colour
0 – 0.76	Clay loam till, sub-rounded pebbles	Slightly moist	10YR5/2 (grayish brown)
0.76 – 1.5	Gravel and medium-grained sand		10YR6/2 (light brownish gray)
1.5 – 2.1	Sand		
2.1 – 2.3	Gravel and sand	Dry	10YR6/3 (pale brown)
2.3 – 4.6	Gravel with medium-grained sand. Sub-rounded pebbles of chert and quartzite		Brown
4.6 – 6.1	Gravel and cobbles with very little sand		Brown
6.1 – 6.9	Medium-grained sand with a large range of stone sizes		2.5Y4/4 (olive brown)
6.9 – 7.6	Medium-grained sand with angular quartzite pebbles		2.5Y5/4 (olive brown)
7.6 – 9.1	Clean medium-grained sand and gravel in approx. equal proportions		
9.1 – 9.9	Sand and gravel with some finer sand included. Flat rounded quartzite pebbles		2.5Y4/4 (olive brown)
9.9 – 10.7	Pebbles and cobbles in a matrix of coarse-grained sand. 1.5” diameter pebbles of green argillite.	Moist	
10.7 – 15.5	Gravel with some very coarse sand and 1.5” diameter pebbles common.	Water at 13 to 15.5 m	2.5Y4/4 (olive brown)
15.5 – 15.8	Sandstone bedrock. Soft, very-fine grained	Water	2.5Y5/4 (light olive brown)
15.8 – 18.2	Sandstone. Soft, fine to medium grained	Wet	2.5Y5/4 (light olive brown)
18.2 – 19.5	Sandstone. coarse grained		2.5Y4/4 (olive brown)
19.5 – 21.3	Shale, soft, with thin partings of hard sandstone		2.5Y4/2 (dark grayish brown)

Piezometer Nest 2: SE 18-7-25-W4. Elevation = m. Immediately upslope of drainage channel.

Geologic Log

Depth (m)	Lithology Description	Texture	Moisture	Munsell Colour
0 - 3	Till. occasional tiny sub-rounded shale particles of gravel-size	Silty clay loam	Wet	10YR2/1 (black) at 0.7 m; 10YR3/3 (dark brown) at 3 m
3.0 – 4.6	Till.	Clay loam to clay		10YR4/3 (dark brown) at 3.8 m; 10YR6/3 (pale brown) at 4.6 m
4.6 – 5.1	Gravel, very coarse, with a wide range of sand sizes from fine to very coarse. Pebbles 1.5” diameter.			10YR4/4 (dark yellowish brown)
5.1 – 5.6	Gravel, clay-rich, with rounded pebbles and shale fragments.			
5.6 – 6.1	Bedrock, mudstone to siltstone			10YR5/2 (grayish brown)
6.1 – 6.7	Bedrock, mudstone			10YR6/3 (pale brown)
6.7 – 6.8	Mudstone, reddish		Water	7.5YR6/4 (light brown)
6.8 – 8.4	Siltstone		Water	Gray
8.4 – 22.8	Shale. Water zone at 16.7 m			2.5Y5/0 (gray)
22.8 – 24.4	Shale.			7.5YR5/2 (brown)
24.4 – 29.7	Shale.			7.5YR5/2 (brown)

Piezometer Nest 3: NE 21-7-25-W4. Elevation = 1,000 ± 4.7 m. Plains. Date: August 1, 2013

Geologic Log

Depth (m)	Lithology Description	Munsell Colour
0 – 0.3	Sand, very fine	10YR5/3 (brown)
0.3 – 1.5	Till. Silty clay loam	10YR4/4 (dark yellowish brown)
1.5 – 4.6	Till. Abundant fragments of black organic matter and black shale. Fragments of orange oxidation product. Rounded chert pebbles.	10YR4/3 (brown)
4.6 – 7.6	Till. Silty clay loam (SiCL). Gypsum and salts along fractures. Black organic staining along fractures. Fragments of orange-yellow and reddish weathering products. Tiny angular to sub-rounded chert pebbles but very few stones.	10YR4/3 (brown)
7.6 – 9.1	Till, SiCL - SiC. Heavy till. Stones are more abundant and larger than above, angular to sub-rounded, including small fragments of highly weathered shale, rounded chert (gravel to pebble sized). Salts precipitated around stones. Organic matter and purplish staining along fractures. Gypsum, some in well-formed crystals. Weathered pinkish clasts, yellow streaks.	10YR5/3 (brown)
9.1 – 10.7	Till, Clay, minor silt. Even heavier than above. Same small fractures with red and yellow alteration products and gypsum. Few stones, angular and sub-rounded. Tiny fragments of red shale. Flecks of organic matter still present.	2.5Y4/2 (dark grayish brown)
10.7 – 12.2	Till, transition zone between oxidized and unoxidized. Mottles of brown and gray. Red and yellow alteration products around stones and along abundant tiny fractures. Minor gravel- and pebble-sized stones, angular and sub-rounded, including a sandstone pebble.	5Y2.5/2 (black)
12.2 - 13.7	Till. Abundant tiny fractures, and a few larger fractures. Fewer vertical fractures below 13 m. Iron-rich alteration products around stones and along fractures. Minor coal fragments.	5Y2.5/2 (black)
13.7 – 15.2	Till. Silty clay to clay. Few stones. Iron-rich alteration products coating fractures and tiny weathered rock fragments. Sub-rounded pebbles of chert, purple quartzite and argillite. Minor coal.	5Y2.5/2 (black)
15.2 – 16.8	Till. Dense silty clay. Larger pebbles. Subrounded and sub-angular pebbles of chert, purple quartzite, and limestone. Fewer flecks of weathered rock. Alteration products along fractures.	5Y2.5/2 (black)
16.8 – 18.2	Till. Heavy, with larger and more abundant pebbles and cobbles. River stones include weathered and unweathered purple sandstone, green chert. Some water.	2.5Y5/2 (grayish brown)
18.2 – 19.8	Sand and gravel, poorly sorted, clay rich, and mixed with till. including 4" diameter rounded sandstone cobbles. Wet.	Sand is 10YR5/3 (brown)
19.8 – 21.3	Till, gravelly, with abundant chert and sandstone cobbles. River stones include limestone and quartzite	2.5Y5/2 (grayish brown)
21.3 – 22.8	Bedrock, reworked by glaciations. Weathered reddish and yellow soft sandstone with shale partings.	10R5/3 (brown) and 10YR6/6 (brownish yellow)

Piezometer Installation Details.

Note: All screens are 2" diameter 4-row 10-slot PVC. All pipes are 2" PVC.

Location	Borehole Diameter (cm)	Piezometer Number	Depth Below Ground (m)			Formation
			Screen	Sand Pack	Bentonite Seal	
1 (SE 9-7-26-W4)	16.8	1-3	14.2 – 14.7	*14.2 – 4.9	4.9 - 0	Preglacial gravel
	16.8	1-2	16.0 – 16.5	16.7 – 15.5	15.5 – 15.8	Sandstone bedrock
	16.8	1-1	20.3 - 21.3	20.3 - 21.5	16.7 - 20.3	Shale bedrock
2 (SE 18-7-25-W4)	16.8	2-4	4.7 – 5.1	4.4 – 5.5	5.5 - 0	Preglacial gravel
	16.8	2-3	6.4 – 7.9	6.1 – 8.2	5.5 – 6.1	Mudstone Bedrock
	16.8	2-2	16 - 18	15.7 - 18	8.2 – 15.7	Shale bedrock
	**16.8	2-1	28 - 30	27.5 - 30	27.5 - 17.7	Shale bedrock
3 (NE 21-7-25-W4)	20.3	3-2	7.6 – 9.1	7.3 – 9.4	7.3 - 0	Oxidized till
	20.3	3-1	21.9 – 22.8	21.6 – 22.8	20.4 – 21.6	Weathered bedrock

*Natural sand pack formed by caving sand and gravel.
** Separate hole from piezometers 1-2, 1-3 and 1-4.

APPENDIX 7. Pesticide Analyses and Results

Pesticide trace analysis for 13 samples from the Fort McLeod area

Claudia Sheedy, Jesse Horn and Denise Nilsson
Agriculture and Agri-Food Canada, 5403 1st Avenue South, Lethbridge, AB T1J 4B1

A total of 13 groundwater samples were collected from selected wells included in the Nitrate study led by Rodvang, Good and Ryan. The samples were extracted and analyzed for a suite of 104 pesticides including both historic-use as well as current-use pesticides.

1.1 Water collection.

One L groundwater was collected for pesticide analysis from every site. All wells and piezometers were purged and allowed to replenish prior to water collection. A amber glass bottle (1 L volume) was filled with well water until no headspace was left to minimize vapour losses of pesticides. A separate bailer was used for each well to prevent cross-contamination between wells. Filled sample bottles were inserted in plastic sleeves ("bubble wrap") to prevent breakage during transportation and placed in coolers. All samples were kept on ice until arrival to our laboratory. The water samples were then transferred to a fridge and kept at 4°C until extraction and analysis. Samples were extracted within 48 hours post-arrival prior to their analysis by gas chromatography- mass spectrometry (GC-MS).

1.2 Pesticide analysis

Water samples were analyzed for an analytical suite of 104 pesticides (see Appendix 2). The analytical method was adapted from that of Bruns et al. (1991) and Hill et al. (2002). Briefly, water samples were filtered through glass wool, acidified with concentrated sulfuric acid to pH 2 and extracted by liquid-liquid partitioning with dichloromethane. Extracts were then dried with acidified Na_2SO_4, concentrated, methylated using diazomethane, transferred to hexane and adjusted to a final volume of 10 mL.

Esterified extracts were analyzed (2 µL injections) using a Hewlett Packard (HP) 6890 Series gas chromatograph with a HP 5973 mass selective detector (MSD) in selected ion monitoring mode. The column was PAS-1701 (30 m ×1.25 mm i.d., 0.25 µm film thickness, electron capture detector-tested 1701 siloxane). Temperature programming was: 120°C for 2 min, ramped at 20°C/min to 160°C, held for 10 min, ramped at 10°C/min to 170°C, held for 6 min, ramped at 30°C/min to 265°C and held for 10 min. Total analysis time was 34.2 min. The ratio of four fragments ions to each other was determined for each detection, compared with the ratio of those ions in a standard, and only those with Q values greater than 80% (Q = an instrument -calculated confidence level where ratios must be at least 80% of expected) were accepted as positive pesticide detections. The limit of detection was circa 0.025 μg for all pesticides (see Appendix 2). Detections below these limits were outside the range of the external standard curve and were assigned values of zero (none detected). Method blanks were run with each set of groundwater samples analyzed.

1.3 Results

Of the 104 different pesticides included in the current analytical suite (See Appendix 2), none were detected in any of the 13 groundwater samples analyzed. This could be due, among other reasons, to the fact that the sampling was only performed once and that the samples were collected from an area of low- intensity agriculture. The "age" of the water could also provide an explanation with regards to these results.

For comparison purposes, groundwater samples collected at the same date in areas of Alberta with high intensity agriculture have shown pesticide detections. Moreover, surface water samples collected from southern Alberta and the Oldman river west of Fort McLeod have also revealed the presence of agricultural pesticides in the area.

1.4 References

Bruns, G.W., Nelson, S., and Erickson, D.G. 1991. Determination of MCPA, bromoxynil, 2,4-D, trifluralin, triallate, picloram and diclofop-methyl in soil by GC-MS using selected ion monitoring. Journal of the Association of the Official Analytical Chemists 74: 550-553.

Hill, B.D., Harker, K.N., Hasselback, P., Inaba, D.J., Byers, S.D. and Moyer, J.R. 2002. Herbicides in Alberta rainfall as affected by location, use and seasons: 1999-2000. Water Quality Research Journal of Canada 37: 515-542.

Table 1. Name, location and lithology of sites sampled for pesticide residue analysis - Fort McLeod 2013.

Chem Sample ID	LSD	Sec	Tp	Rg	Well Depth (m)	Depth of Screened Interval (m)	Lithology (numbers indicate depth in m to bottom of preceeding lithology)	Sample Date	Pesticide*
W2	SE	18	7	25	6.3		CL till 4.6, grv 5.6, mudstone & sist 8.4, shale 29.7	F-13	N.D.
W45	NW	3	7	26	4.3		grv 6.1, sand&grv 7.3, clay&grv 9.8, soft shale 12.2	M-13	N.D
W39	NE	4	7	26	12.2	6.1 - 7.9	grv 6.1, sand&grv 7.3, clay&grv 9.8, soft shale 12.2	M-13	N.D
W43	SE	29	7	26	5.5			M-13	N.D
W55	SE	30	7	26	4.2			M-13	N.D
W18	SW	33	7	26	10.7		clay 7.3, sand 12.8, s&grv 17.4	F-13	N.D
W19	NW	34	7	26	3.7		gravel 4	F-13	N.D
WR28	SE	4	8	25	3.7		sand&grv 5.8, shale 36.6	J-13	N.D
W29	16	24	8	25	4.6	4.6 - 6.1	clay 2.1, grv. 6.1	M-13	N.D
W22	SW	22	8	26	4.3			M-13	N.D
W38	NW	26	8	26	5.7	4.3 - 6.4	clay 2.1, clay&grv 4.3, grv. 6.1, sh 6.4	M-13	N.D
W24	NW	27	8	26	8.5	6.7 - 8.2	sand &silt 2.4, s&grv 7.3, grv 8.2, till&clay 10.7, sh&sist 12.2	M-13	N.D
W26	SW	29	8	26	8.5	8.2 - 9.8	sand 4.9; sand&rocks 5.5; clay&rocks 7.6; cg grv 9.7; s&grv 10.3	M-13	N.D

*See Appendix 2 for 104 pesticides included in analytical suite. N.D. indicates pesticide was below detection limit.

Appendix 2: Pesticides included in analytical suite: name, type and limit of detection (LOD)

	Pesticide name	Type	LOD (µg/L)
1	2,4-D	Herbicide	0.0272
2	2,4-DB	Herbicide	0.0233
3	2,4-Dichlorophenol	Herbicide	0.0340
4	Alachlor	Herbicide	0.0253
5	Aldrin	Insecticide	0.0289
6	Allidochlor	Herbicide	0.0283
7	Atrazine	Herbicide	0.0240
8	Benalaxyl	Fungicide	0.0858
9	Benfluralin	Herbicide	0.0230
10	Bentazon	Herbicide	0.0234
11	Benzoylprop-Ethyl	Herbicide	0.0249
12	a-BHC	Insecticide	0.0261
13	b-BHC	Insecticide	0.0314
14	d-BHC (d-HCH)	Insecticide	0.0315
15	Bifenthrin	Insecticide	0.0255
16	Bromacil	Herbicide	0.0296
17	Bromophos-Ethyl	Insecticide	0.0259
18	Bromopropylate	Acaricide	0.0526
19	Bromoxynil	Herbicide	0.0239
20	Bupirimate	Fungicide	0.0249
21	Butachlor	Herbicide	0.0804
22	Butralin	Herbicide	0.0377
23	Butylate	Herbicide	0.0236
24	cis-Chlordane	Insecticide	0.0222
25	t-Chlordane	Insecticide	0.0255
26	Chlormephos	Insecticide	0.0335
27	Chloroneb	Fungicide	0.0487
28	Chlorpyrifos	Insecticide	0.0258
29	Chlorpyrifos-Methyl	Insecticide	0.0283
30	Chlorthal-Dimethyl	Insecticide	0.0203
31	Chlorthiamid	Herbicide	0.0254
32	Clomazone	Herbicide	0.0238
33	Clopyralid	Herbicide	0.0312
34	Cycloate	Herbicide	0.0252
35	o,p-DDD	Insecticide	0.1772
36	p,p-DDD	Insecticide	0.0232
37	o,p'-DDE	Insecticide	0.0271
38	p,p'-DDE	Insecticide	0.0263

39	o,p-DDT	Insecticide	0.0320
40	p,p-DDT	Insecticide	0.0304
41	Desmetryne	Herbicide	0.0249
42	Diazinon	Insecticide	0.0233
43	Dicamba	Herbicide	0.0638
44	Dichlobenil	Herbicide	0.0273
45	Dichlorprop	Herbicide	0.0242
46	Dichlorvos	Insecticide	1.0977
47	Diclofention	Nematicide	0.1455
48	Diclofop	Herbicide	0.0259
49	Dieldrin	Insecticide	0.0283
50	Dimethachlor	Herbicide	0.0340
51	Dimethoate	Insecticide	0.1345
52	Dioxathion	Insecticide	0.0445
53	Diphenamid	Herbicide	0.0257
54	α-Endosulfan	Insecticide	0.0358
55	Endrin	Insecticide	0.0234
56	Eptc	Herbicide	0.0285
57	Ethalfluralin	Herbicide	0.3118
58	Ethion	Insecticide	0.0291
59	Ethofumesate	Herbicide	0.0248
60	Etradiazole	Fungicide	0.0273
61	Etrimphos	Insecticide	0.0517
62	Fenchlorophos	Insecticide	0.0391
63	Fenoxaprop	Herbicide	0.0311
64	Fenthion	Insecticide	0.0259
65	Flamprop-Isopropyl	Herbicide	0.1189
66	Flamprop-Methyl	Herbicide	0.0522
67	Flumetralin	Growth Reg	0.0330
68	Fluroxypyr	Herbicide	0.0230
69	Fonofos	Insecticide	0.0241
70	Heptachlor	Insecticide	0.0294
71	Heptachlor Epoxide	Insecticide	0.0233
72	Imazethapyr	Herbicide	0.0257
73	Isofenphos	Insecticide	0.0328
74	Lindane	Insecticide	0.0236
75	MCPA	Herbicide	0.0248
76	Mecoprop	Herbicide	0.0322
77	Methoxychlor	Insecticide	0.0444
78	Metolachlor	Herbicide	0.0270
79	Mirex	Insecticide	0.0241
80	Nitrapyrin	Bactericide	0.0589
81	cis-Permethrin	Insecticide	0.0314

82	trans-Permethrin	Insecticide	0.0252
83	Phorate	Insecticide	0.0284
84	Picloram	Herbicide	0.0592
85	Pirimicarb	Insecticide	0.0375
86	Pirimiphos-Ethyl	Insecticide	0.0228
87	Pirimiphos-Methyl	Insecticide	0.0236
88	Procymidone	Fungicide	0.0233
89	Prometon	Herbicide	0.0268
90	Propham	Herbicide	0.0402
91	Propyzamide	Herbicide	0.0342
92	Quinclorac	Herbicide	0.0255
93	Quintozene	Fungicide	0.0375
94	Simazine	Herbicide	0.0238
95	Sulfotep	Insecticide	0.0814
96	Sulprophos	Insecticide	0.0425
97	Terbacil	Herbicide	0.0295
98	Terbufos	Insecticide	0.0225
99	Terbutryne	Herbicide	0.0248
100	Tetradifon	Acaricide	0.0713
101	Tetrasul	Acaricide	0.0269
102	Triallate	Herbicide	0.0306
103	Triclopyr	Herbicide	0.0242
104	Trifluralin	Herbicide	0.0275

APPENDIX 8. Hydraulic Conductivity Testing

See Attached Excel File Appendix 8 Pump test data.xls.

APPENDIX 9. Static Water Level Data

See Attached Excel File. chem litho app. 3&4.xlsx