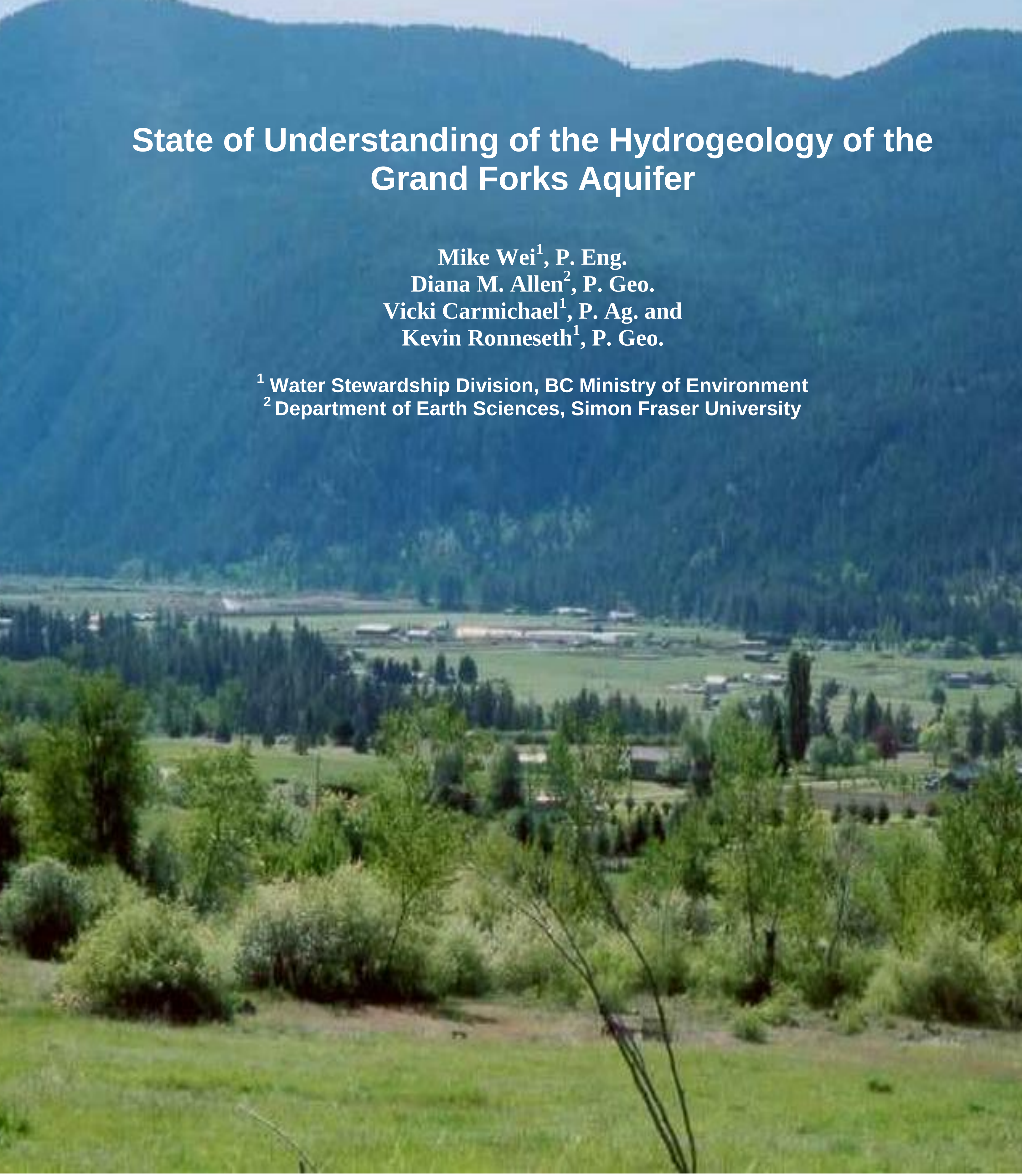

State of Understanding of the Hydrogeology of the Grand Forks Aquifer

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Executive Summary

The unconfined sand and gravel aquifer at Grand Forks, located in the southern interior of British Columbia is one of the most important aquifers in British Columbia; the aquifer has been classified by the Ministry of Environment as an "IA", heavily developed, highly vulnerable to contamination, aquifer. Studies have been conducted on the aquifer to address specific groundwater issues since the 1960's and initially focussed on developing community well water supplies. In the late 1980-1990's, additional studies were done to assess the extent of nitrate contamination. Since the late 1990's, the Ministry of Environment and Simon Fraser University have jointly focussed efforts in characterizing the aquifer to support the local community in groundwater protection.

This report summarizes the state of understanding of the groundwater characteristics of the Grand Forks Aquifer - its architecture, geology, the aquifer's thickness, potential yield, water chemistry, intrinsic vulnerability, and capture zone areas for community wells. The report also presents characteristics of the aquifer that are more dynamic, based on Simon Fraser University's finite-difference numerical model - the direction of groundwater flow, under non-pumping conditions as well as under pumping condition, the time of travel of water (for any non-reactive contaminants dissolved in the water) to reach pumping community wells, and the hydraulic relationship between the aquifer and Kettle River. The information has potential application to assist the local community in addressing potential risks to their groundwater, and also to enable them to consider groundwater sustainability and protection in land use decision-making and planning for growth.

This report provides a number of recommendations that would strengthen the current management and protection of this provincially important aquifer:

- The affects of proposed pumping of any new large capacity water supply well (e.g., >3,000 m^3/d or 500 gpm) on the water balance of the aquifer, flow in the Kettle River, and the capture zone areas should be assessd.
- Water supply systems should:
  - Monitor and assess the performance of their wells and well water quality on an on-going basis;
  - Actively promote conservative use of water and optimal application of fertilizers;
  - Renew their efforts to develop, implement and report on well protection plans for their community wells; and
  - Promote voluntary compliance of closure of abandoned wells and for the City of Grand Forks and Grand Forks Improvement District to consider adopting well closure bylaws for their service areas.
- The Regional District of Kootenay-Boundary and City of Grand Forks should explore how information on the Grand Forks Aquifer can be used to assist in making decisions related to land use and planning for growth to promote the sustainability and protection of the local groundwater.
- The Ministry of Environment should review its Observation Well and Ambient Groundwater Quality Monitoring networks in Grand Forks for adequacy of coverage, operation, and reporting.

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1 Introduction

Groundwater is an important source of water supply for the community of Grand Forks, a community located in south-central British Columbia (BC) 124 km west of the town of Osoyoos, along the Canada-USA border (see Figure 1). The Grand Forks area is very arid and groundwater from the underlying aquifer provides water for both domestic, municipal and irrigation uses. The aquifer straddles the Canada-USA border; approximately 95% of the aquifer occurs on the Canadian side, and the remainder on the US side.

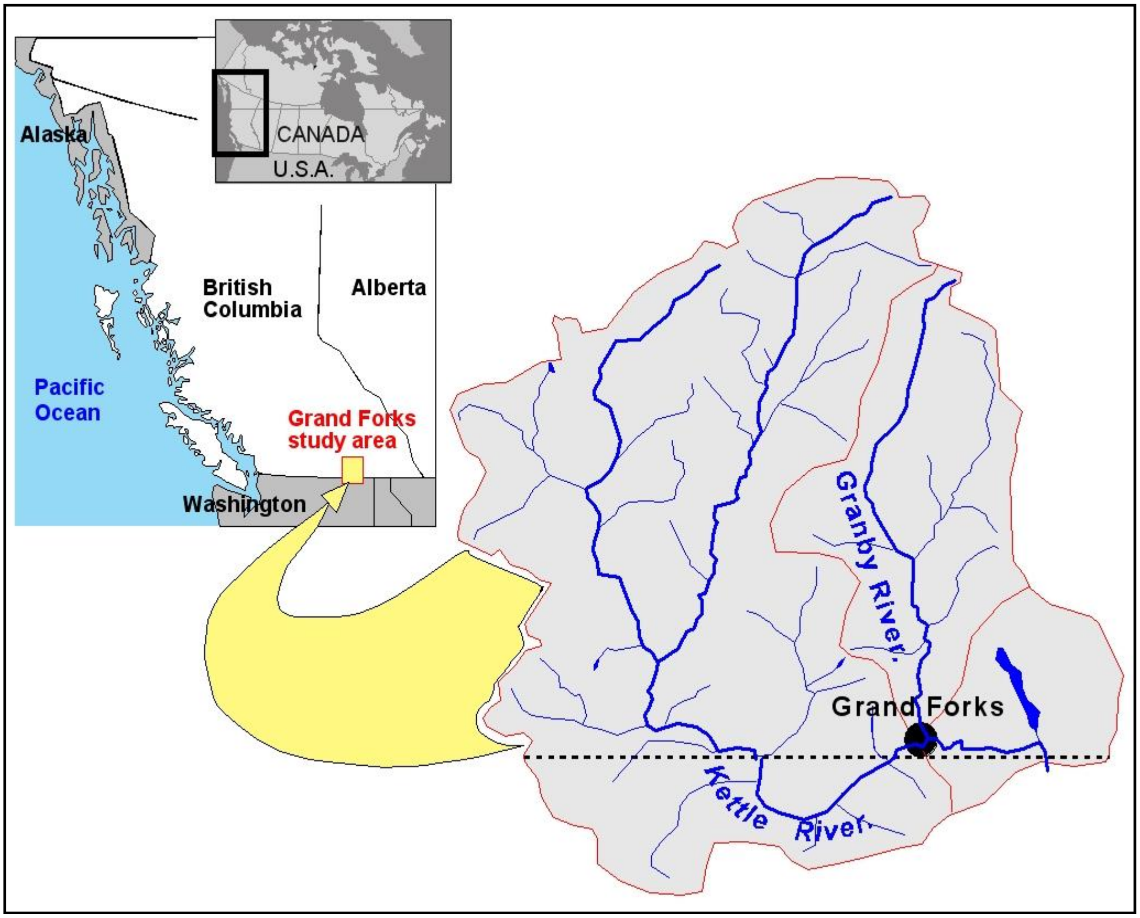

Figure 1 Location of the Grand Forks study area, and Kettle River and Granby River drainage areas.

The impetus for characterizing and assessing the aquifer at Grand Forks originated in the 1990's after the then Ministry of Environment[1] published a report of their well water quality survey in Grand Forks (Wei, 1992). The report identified the occurrence of nitrate-nitrogen in well water and the generally high vulnerability of the underlying aquifer from human activities as issues of

[1] The Ministry of Environment operated as the Ministry of Water, Land and Air Protection between 2000 and 2005 and as the Ministry of Environment, Lands and Parks from 1992 to 2000. For simplicity, the Ministry will be referred to in the report as the "Ministry of Environment" (its current name) or "Ministry".

concern. The Ministry has been monitoring ambient groundwater quality in the aquifer ever since.

As the aquifer at Grand Forks is the source of water for both private domestic and community wells, there was high interest from local community representatives, including the local health unit, to protect the aquifer. In 1997, the local water supply systems, Regional District of Kootenay-Boundary, local health unit, and interested residents formed the *Grand Forks Aquifer Protection Society*. The main objective of the Society was to develop and implement a groundwater protection plan to better safeguard the water quality of the underlying aquifer now and for future generations.

The importance of the aquifer at Grand Forks as a source of water supply, the high level of local community interest in developing a protection plan, and the Ministry's on-going interest in ambient groundwater quality monitoring in Grand Forks were major reasons for mapping and characterizing the aquifer to support these initiatives.

1.1 Previous Studies

There have been numerous groundwater studies carried out in the Grand Forks area over the past 40 years by the provincial government and also by various groundwater consultants for local water supply systems. Reports for some of these studies are available on line from the Ministry's Ecological Catalogue site (ECOCAT: http://www.env.gov.bc.ca/ecocat/). The major available groundwater reports in Grand Forks area are summarized in this section.

Many of the early groundwater reports describe the development of community well water supplies in Grand Forks. Livingston (1967) provided observations on quantity and sand pumping problems for three of the City of Grand Forks' original wells. All three wells were dug wells. Two of these wells are no longer in use and the third (City of Grand Forks no. 2 well) was deepened by drilling. Dakin and Brown (1969) reported on the construction and testing of the City of Grand Forks well no. 3. In the early 1980's, reports by Zubel (1982a) and Wei (1983a and 1983b) describe their assessments on gasoline contamination of the City's well no. 1 (the well has since been put out of service, soon after contamination was detected). Dakin (1988) reported on the design, construction and testing of the City's well no. 5, which was designed to partially replace well no. 1. Well no. 5 is located close to the previously constructed well City well no.4.

Livingston (1963) and Erdman and Brown (1968) reported on the test drilling, construction and pump testing of the production wells for Sion Improvement District (SID), one of the oldest water systems in Grand Forks. In the 1990's, Topp (1992, 1993, 1994, 1997) reported on the re-development and testing of some of these wells (Sion's domestic well no. 2, irrigation well nos. 1, 2 and 3) in an attempt to bring these wells back to their original performance. Brown and Sargent (2007) reported on the drilling and testing of Sion's latest production well (No. 6). Crider and Lidster (1974) summarized the Department of Highways' resistivity survey to identify potential test drilling areas in the Grand Forks Irrigation District (GFID) area. The GFID historically relied on the Kettle River for their irrigation supply. Test drilling, construction and pumping tests of the GFID production wells only occurred in the late 1980's (Burnett and Guiton, 1989). In reviewing the test-drilling results, Wei (1987) developed a hydrogeologic cross-section along Carson Road to show the occurrence of the aquifer in the GFID area. It was during the initial test drilling that elevated nitrate-nitrogen concentrations were also detected in some of the test wells.

Since the early 1990's the focus of groundwater studies in Grand Forks has shifted to include groundwater quality and groundwater protection. Elevated nitrate levels in the GFID test wells prompted the Ministry to assess occurrence of nitrate in the aquifer. Sather (1989) recommended that the Ministry conduct a well water quality survey and establish an Ambient Groundwater Quality Monitoring Network in Grand Forks, based on evidence of elevated nitrates from historical Water Quality Check Program data. Chwojka (1991) reported on the construction of Ministry nested piezometers at three sites in the GFID. Wei (1992) and Wei et al. (1993) reported on a field water quality survey of 100 private wells and initial results of sampling of 15 private wells and 12 nested monitoring wells in Grand Forks in 1989. The sampling results indicate three main areas of nitrate contamination: south of the airport, in the Nursery area, and east of North Fork Road. Nitrate-nitrogen concentrations exceeded the drinking water guideline in these local areas. The results also showed that elevated nitrate is associated with elevated specific conductance, total dissolved solids (TDS), calcium (Ca), magnesium (Mg), chloride (Cl), and sulphate (SO_4). The report by Wei (1992) presented the first series of water chemistry maps (nitrate-nitrogen (NO_3-N), Cl, specific conductance, hardness, and total alkalinity) of the Grand Forks aquifer. Wei (2001) summarized the results of nitrogen and oxygen isotopes sampling from some of the Ministry's Ambient Groundwater Quality Monitoring Network wells in 1991 and 1993 and inferred that the nitrate in the well water is generally from inorganic sources. Maxwell et al. (2002) reported on a Ministry survey of nitrate-nitrogen in well water from 88 wells in 1999. That report includes a hydrogeologic section along Carson Road, showing the distribution of nitrate-nitrogen in groundwater at depth.

In 1993, a door-to-door land use survey was completed by Sheppard (1995). The survey mapped land use as well as the locations of the septic systems and wells on properties in the entire valley. In 1999, Wei (1999) delineated preliminary capture zones for community wells in Grand Forks. Capture zones provide areas for local water supply systems to develop and apply measures to protect the quality of the water that supplies their wells. Allen (2000) developed a finite-difference numerical flow model to delineate capture zone areas for the major community wells to further refine the well protection areas. Due to uncertainties with recharge values at the time of that study, the capture zones were subsequently modified by Allen (2001).

Atkinson and Sacre (2003) of Golder Associates completed a contaminant inventory of the aquifer. The report presented the various land uses in Grand Forks, compiled relevant information and locations from the Ministry of Environment's Contaminated Sites Registry, as well as waste and spills databases to subjectively assess the risks in the well capture zone areas. This work helps the *Grand Forks Aquifer Protection Society* to address Step 3 of the Well Protection Toolkit (Province of BC, 2005).

In the past 30 years, several studies have been completed to assess the overall characteristics of the aquifer, most done to address specific groundwater-related issues. One of the earliest studies on the characteristics of the aquifer at Grand Forks was completed by Campbell (1971). Campbell identified the presence of an upper and lower aquifer zone and portrayed the structure of the aquifer through four cross-sections. Campbell also described the general direction of groundwater flow in the valley and estimated groundwater velocities in the upper unconfined aquifer zone. Moncur (1973) developed preliminary depth to water and water table map of the Grand Forks aquifer (in the GFID area), based on a well survey by R. Wittchen (1973) in August, 1973. In 1977, Choy (1977) assessed the cause of reported decline in the aquifer's water table and developed the first comprehensive hydraulic head map of the aquifer. Choy (1977) recommended that a survey of wells be done to update the inventory of wells and to establish observation wells to monitor the fluctuation of the aquifer's water table. In 1982, Zubel investigated the concern over basement flooding in the Pahoda Slough area. Zubel's (1982b) report examined groundwater levels in Observation Well No. 217 and gauge level in the Granby River with precipitation and cumulative precipitation data, and concluded that the high water level is most likely due to record high precipitation in two consecutive years in 1980 and 1981. Other contributing factors include shut-down of the City's nearby (No. 1) well (as a result of gasoline contamination), inadequate drainage in the floodplain area, and reduced pumping from the City's other wells resulting in a recovery of the water table. Dakin (1993) conducted a hydrogeological assessment of the aquifer and included information on preliminary water budgets. Allen (2001) assessed the potential impact of future climate change on the aquifer's groundwater level, flow direction and water budget. This work was published as one of the first scientific papers on impacts of future climate change on groundwater (Allen et al., 2004a). Subsequently, a detailed climate change impacts assessment was carried out to explore changes in recharge (Scibek and Allen, 2004b; Scibek and Allen, 2006) and interaction with the Kettle River (Scibek and Allen, 2003; Scibek et al., 2007). The composite study on climate change impacts submitted to the Climate Change Action Fund (Allen et al., 2004b; Scibek and Allen, 2004a) was published in a scientific journal by Scibek et al. (2008). Many of the characteristics of the aquifer presented in this report draw on the valuable information contained in these past reports and scientific papers.

1.2 Purpose

The purpose of this report is to summarize the characteristics of the Grand Forks Aquifer to promote greater understanding about the local groundwater resource and to support future local community well and aquifer protection initiatives and decision making. The information and map coverages generated from this study can be used to support well protection plans and source to tap assessments required under the *Drinking Water Protection Act*, and land use plans. The information can also be used by other agencies to allow them to make decisions about water allocation, and permitting effluent disposal, commercial, industrial and residential activities, for example, by taking into consideration the underlying groundwater resource and any potential impact these decisions and activities may have on it. Converting basic groundwater data into information that decision-makers can use allows for better management and protection of this hidden but valuable resource.

1.3 Scope of the Report

This report summarizes the aquifer characterization and assessment work done by the Ministry, in partnership with the Department of Earth Sciences, Simon Fraser University (SFU), and in cooperation with the local health unit of the Interior Health Authority and the *Grand Forks Aquifer Protection Society* between 1995 and 2005. This report also incorporates information on the characteristics of the aquifer from previous studies.

Aquifer characterization and assessment entail analyzing and interpreting data to develop an understanding of the aquifer's hydrogeologic and water quality characteristics to allow impacts of water use and/or human activities to be assessed or simulated. The understanding of the aquifer is portrayed in hydrogeologic maps and in the development of a regional numerical groundwater model. The numerical groundwater model allows the dynamic (hydraulic) behaviour of the aquifer to be simulated.

In finalizing the report, information on major water supply wells drilled after 2005 have been gathered and noted in the report; however, this most recent information could not be incorporated into the aquifer maps or the numerical model. Although the maps and model reflect our knowledge at the time of the study (up to ~2005), the maps and model can be updated in the future to incorporate new data. Finally, although the report discusses the regional groundwater quality characteristics of the aquifer, a detailed analysis of the results of ambient groundwater quality monitoring over the period of between 1990 to present is beyond the scope of this report and has not been done here.

2 Physical Setting

2.1 Topography, Demographics and Geography

The community of Grand Forks includes the City of Grand Forks and adjacent areas falling under Electoral Area D of the Regional District of Kootenay-Boundary. The Grand Forks area is located on a broad, relatively flat alluvial terrace at the confluence of the sediment filled Kettle and Granby River valleys (refer to Figure 2). The elevation of the valley bottom ranges from approximately 550 metres above sea level (m a.s.l.) in the west, where the Kettle River flows north into BC to 520 m a.s.l. in the east, downstream of the confluence of the Kettle and Granby Rivers. The width of the Kettle River valley in Grand Forks ranges from 4 km just west of the Granby River confluence in the vicinity of the city itself to about 1.5 km on the east and west sides of the City. Bedrock hills rise on all sides from the valley bottom up to elevations of approximately 1600 m a.s.l..

The City of Grand Forks was incorporated in 1897. Based on the 2006 census, the City of Grand Forks has a population of just over four thousand (population: 4,036). An estimated seven thousand residents live in the city and surrounding areas (Grand Forks Chamber of Commerce, pers. comm., 2004). Many residents can trace their origins to the Doukhobor religious sect that emigrated originally from Russia at the end of the 19th century seeking religious and social freedom in Canada. In the early part of the 20th Century, Grand Forks became the mining and smeltering center of BC, home to the largest non-ferrous copper smelter in the British Empire (2nd largest in the world). The agriculture industry had also contributed substantially to the economy as Grand Forks produced approximately one third of the apple crops in BC and was recognized for the nineteen different varieties of potatoes grown throughout the valley. Canadian Pacific Railway established a divisional and terminal point in Grand Forks, having five railways and two transcontinental lines. Today, forestry is the largest industry sector. Highway 3 is the major highway that links Grand Forks to other major communities in the Okanagan Valley to the west and Kootenay region to the east.

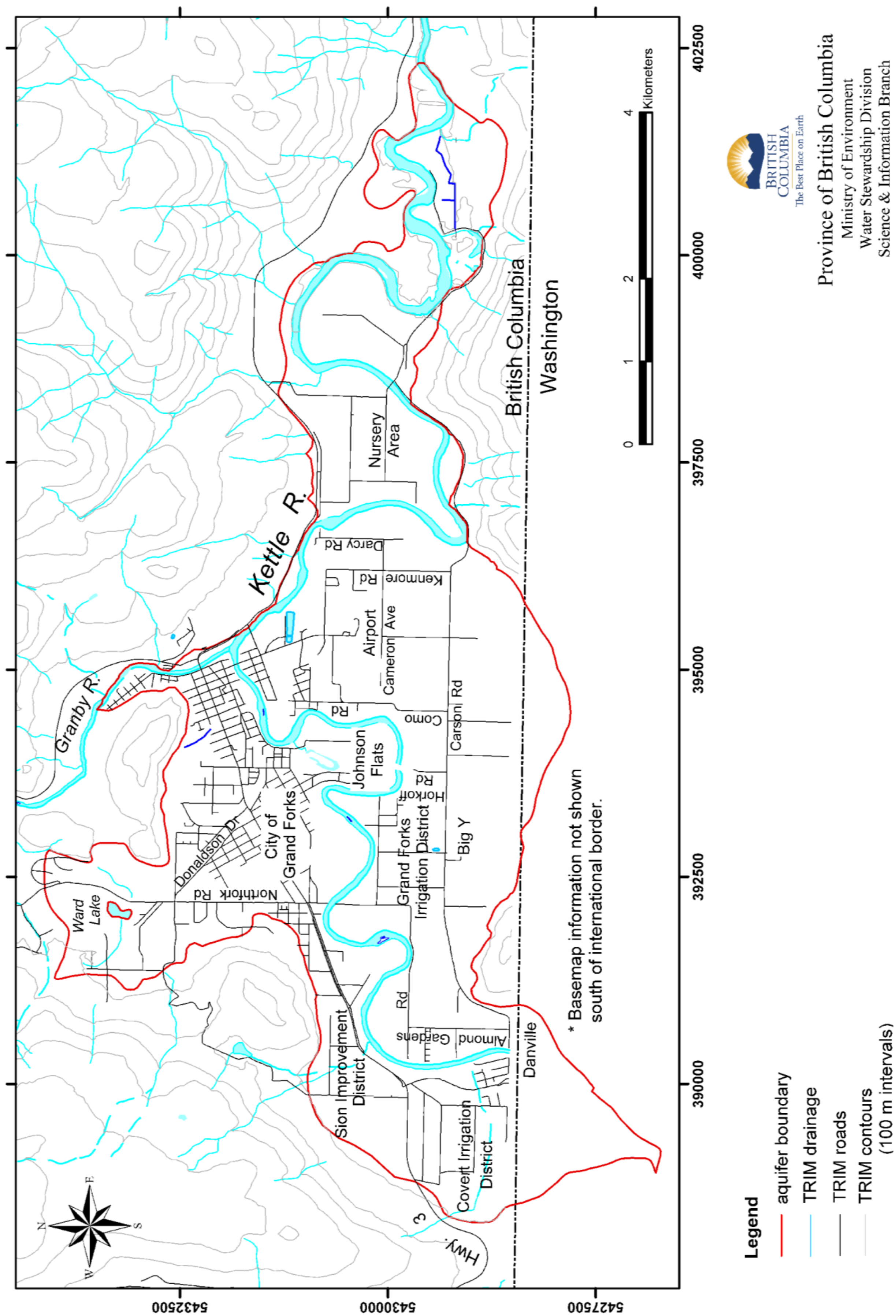

Figure 2 Map of the Grand Forks area.

2.2 Climate

Temperature and precipitation data are available from Environment Canada's climate station #1133270 in Grand Forks. Data are available from 1941 to present. Climate data are reported in the Canadian Climate Normals (1971-2000) (Environment Canada, 2002). The average daily maximum temperature for the year is 13.8ºC, the annual average daily minimum temperature for the year is 1.5ºC, and the annual average daily mean temperature is 7.7ºC. The highest daily mean temperatures occur in July and August, and the lowest daily mean temperatures occur in December and January.

Figure 3 shows the Canadian Climate Normals for average monthly precipitation for station #1133270. Approximately 391 mm of precipitation falls as rain and 119 mm falls as snow, with a total annual average precipitation of 510 mm. November to January and May and June are months of greatest precipitation. Most of the precipitation in December and January occurs as snow. Precipitation in May and June is rainfall. March, September, and October are typically the driest months of the year.

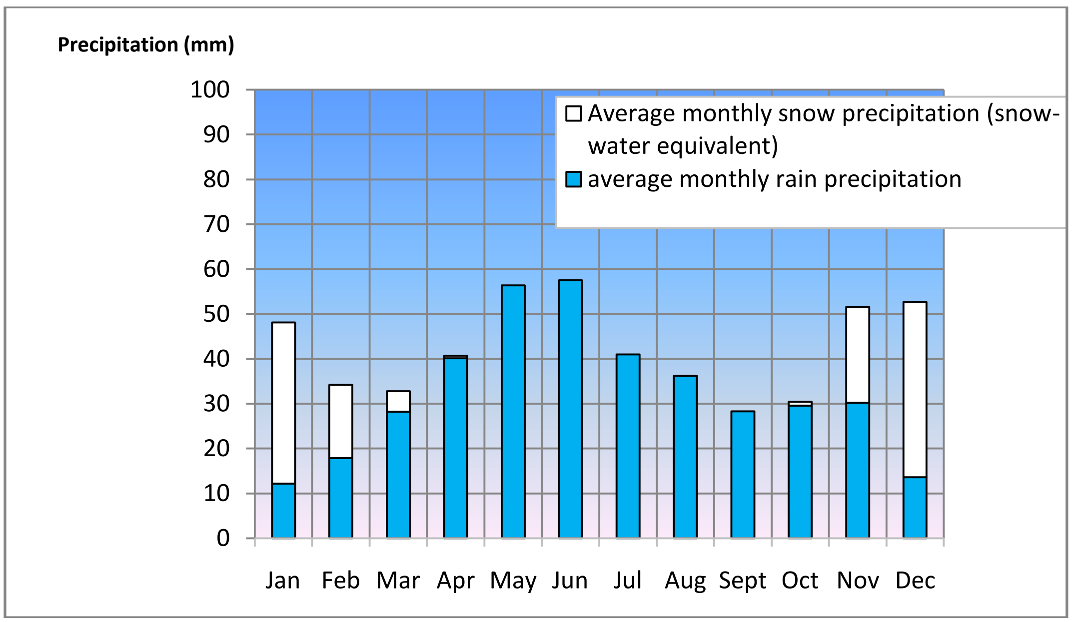

Figure 3 Average monthly precipitation in mm (as snow and rain) for Grand Forks climate station #1133270: 1971-2000.

2.3 Surface Water and Drainages

There are two major river systems in the Grand Forks area – the Kettle and Granby Rivers. The Granby River flows southward into the easterly flowing Kettle River at a confluence within the City boundaries (see Figure 2). The Granby River has a drainage area of 2,050 km^2, a mean discharge of 30.5 m^3/s, and an average basin runoff of about 469 mm. The maximum and minimum recorded discharge is 385 and 0.474 m^3/s, respectively.

The Kettle River flows southward towards Rock Creek from the Monashee Mountains and then south-eastward to Midway, where it crosses into the US. The river then flows north-eastwards back into Canada at Danville and then eastward past the City of Grand Forks. The flow again enters the US about 15 km east of Grand Forks at Laurier. The drainage area of the Kettle River upstream from Laurier is 9,800 km^2. The mean annual flow at Laurier is about 82 m^3/s and the average annual runoff is about 493 mm (Piteau Associates Engineering Ltd., 1995). The lowest recorded average daily flow was 0.23 m^3/s in January 1931. Scibek and Allen (2003) generated runoff from the periods of record for all gauging stations along the Kettle and Granby Rivers (Figure 4). Both rivers have historically flooded in the Grand Forks area. Annual peak flow generally occurs in May but peak flows have also occurred in both April and June.

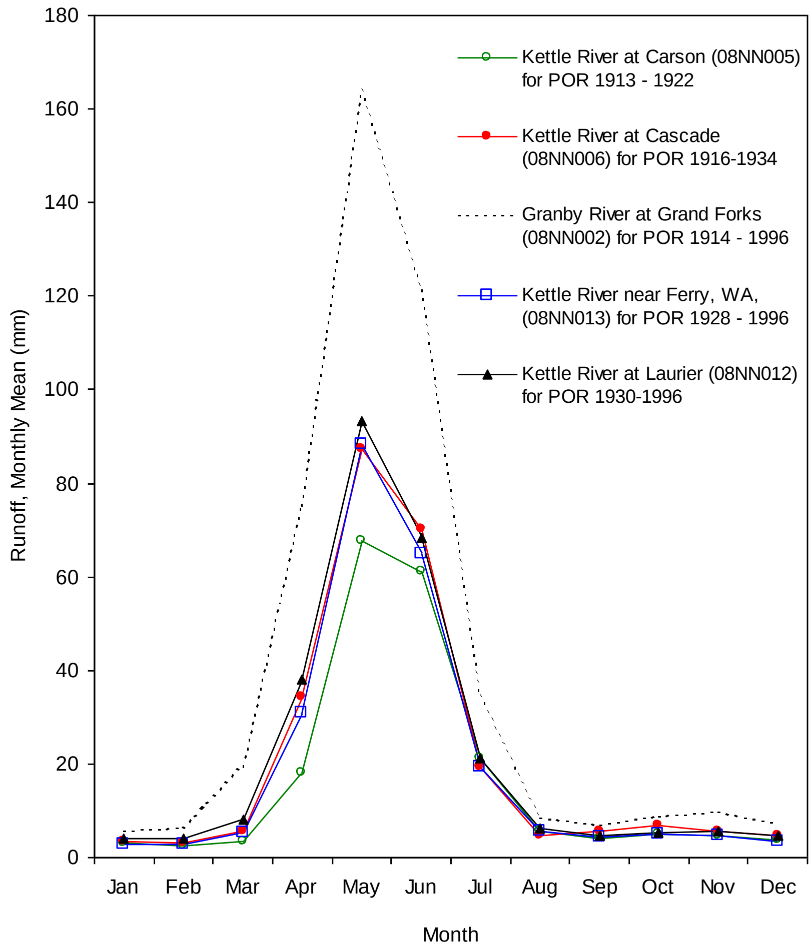

Figure 4 Monthly mean runoff calculated from monthly average discharges (for available period of record, POR) for selected hydrometric stations on Kettle and Granby Rivers (normalized by contributing watershed areas).

The small tributaries to the valley contribute only 0.64 to 0.91 m^3/s mean annual discharge to the larger Kettle River, within the extent of the Grand Forks aquifer (Scibek and Allen, 2003). On an annual basis, this flow represents about 2% of the Kettle River flow, or 1% of the combined Kettle and Granby River flow downstream of Grand Forks. During the summer months, many of the smaller creeks become ephemeral, discharging water only after large rain events, and only a few maintain base flow in dry periods.

2.4 Surficial and Bedrock Geology

The Kettle River Valley and adjacent portions of the Granby River Valley are underlain by alluvial and glacial drift consisting mainly of sand, gravel, silt and clay. Dakin (1993) provided a probable geologic history of the valley:

> "Glacial ice, moving primarily from the northwest, scoured out the bedrock into "u" shaped profiles in both of the Kettle and Granby River valleys. Possibly, some of the subsequent retreat and re-advance of this ice has left layers of till and outwash sediments. Most of the sediments deposited earlier than about 8,000 years ago have either been eroded away or buried at depths in excess of 100 m below the present valley bottom.
>
> When the ice last advanced it stalled and subsequently down wasted at both the site and upstream areas, resulting in the deposition of a thick sequence of outwash sediments. A review of water well logs in the area shows that the sediments tend to be progressively finer with increasing depth, and with increasing distance towards the east. This observation leads to the conclusion that soon after the ice retreated, the Kettle River valley was filled with a shallow lake. Subsequent deposition of glacial outwash sediments will have been primarily in the form of sands and gravel in deltas and associated flat lying fans.
>
> Over the last few hundred years there has been some reworking of the upper portion of these glacial outwash sediments, resulting in formation of a flat lying Granby River fan. Subsequent down cutting of a portion of this fan has left an elevated terrace deposit, upon which much of the City of Grand Forks is presently situated."

Bedrock is exposed on the hills located around the margins of the Kettle and Granby River valleys. In the Grand Forks area, the valley walls consist of highly metamorphosed "Grand Forks Group" gneisses and schists (Preto, 1970; Little, 1957). The inter-granular and fracture porosity and permeability of the bedrock is expected to be extremely low, relative to the surficial sands and gravels, but may provide some infiltration by mountain block recharge. The bedrock bounds the lateral extent of the sand and gravel aquifer at Grand Forks and also underlies the valley bottom at depth. Dakin (1993) estimated that the depth to bedrock is at least 150 metres deep and possibly up to 250 meters deep at some locations in the central portion of the valley whereas, along the perimeter of the valley depths range from 0 to 35 metres. Scibek and Allen (2004b; Map 9) modeled the bedrock surface using a parabolic or "u-shaped" paradigm based on 67 valley profiles constructed using the exposed bedrock and available well data. The modeled bedrock surface was up to 300 m deep in the center of the valley, thinning to 0 to 50 m deep around the edges.

2.5 Land Use

In summer 1993, a door-to-door land use survey was conducted in Grand Forks (Sheppard, 1995). Land use was mapped and classified using the BC Land Use Classification System (Sawicki and Runka, 1986). The study area covered approximately 4,400 hectares, and the breakdown showing the general land use categories is shown in Figure 5.

At the time of the survey, approximately 26% of the land area in Grand Forks was used for agricultural purposes, and 15% was former agricultural land not being used (unused land). Figure 6 shows the breakdown of the different types of agricultural land use in Grand Forks. Over 40% of the agricultural land was either in fallow or was not being used. The most widespread agricultural activity was forage crops (e.g., alfalfa, hay), followed by grazing, then ornamental shrubs and trees (e.g., nurseries), and vegetables (e.g., potatoes, peppers). Fertilizers were reportedly used on less than 25% of the areas mapped and the amount of fertilizers applied varied with each type of crop grown and site specific soil conditions.

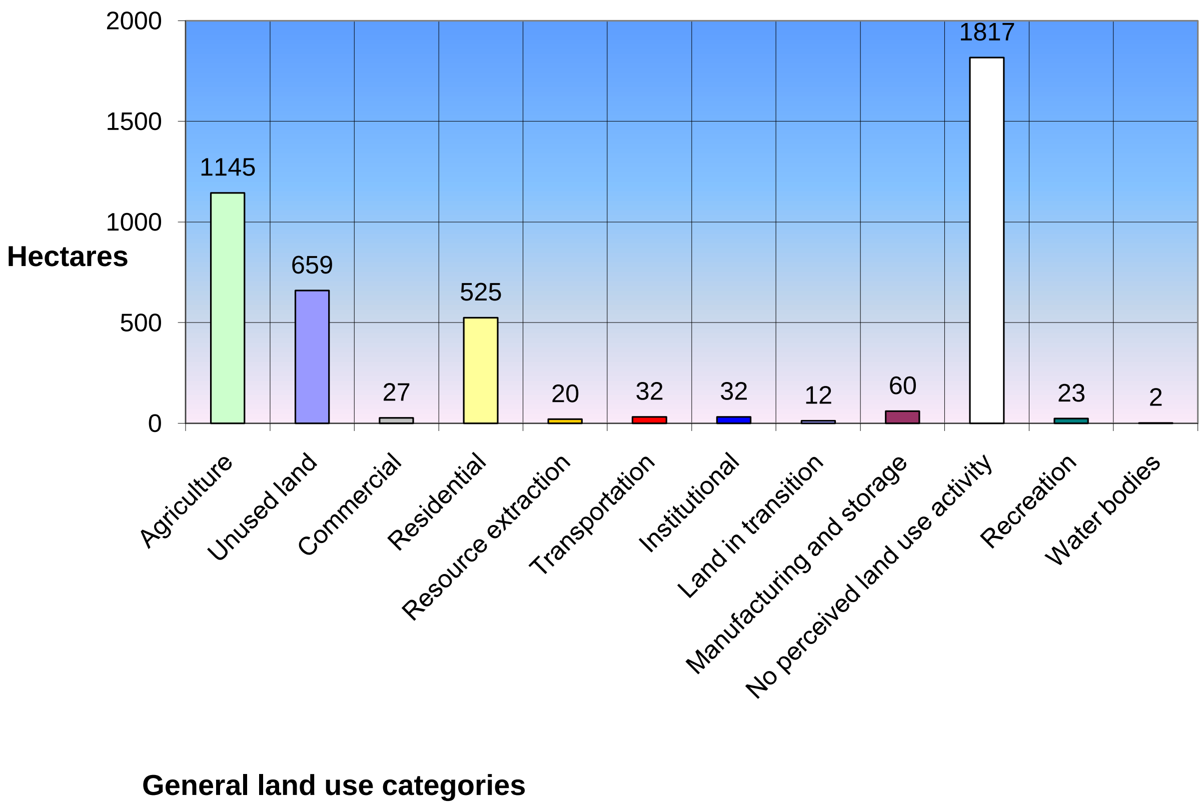

Figure 5 Breakdown of general land uses in Grand Forks (from Sheppard, 1995).

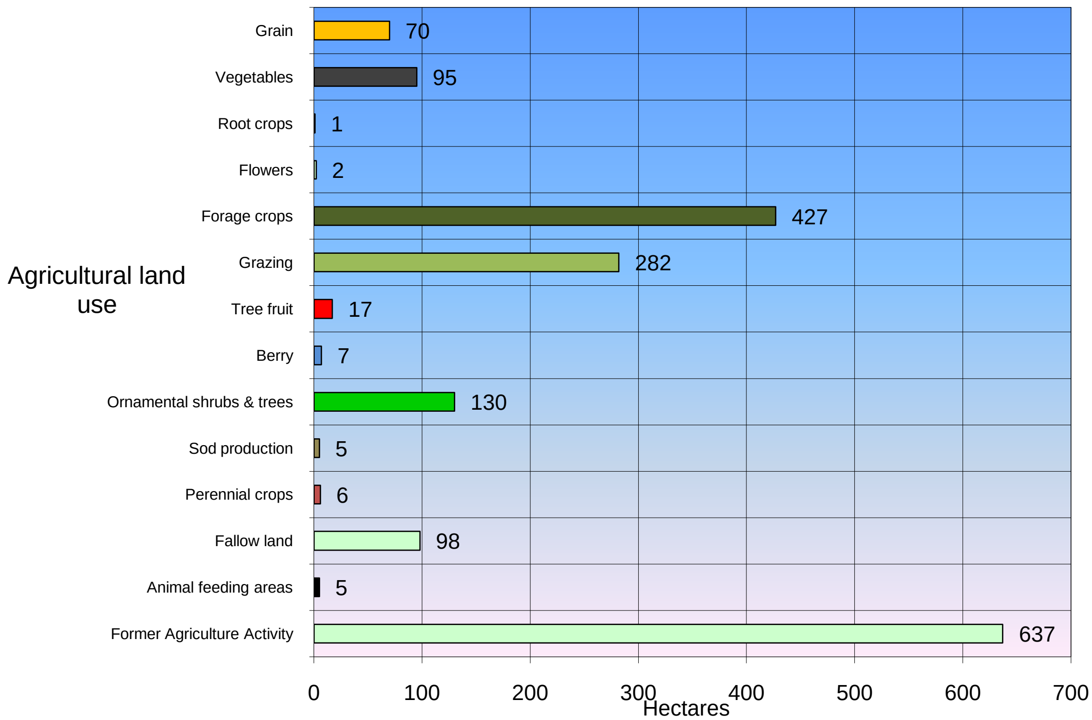

Figure 6 Breakdown of agricultural land uses in Grand Forks (from Sheppard, 1995).

3 Aquifer Characteristics

The following sections describe the hydrogeologic and general water quality characteristics of the aquifer at Grand Forks. The aquifer boundary was delineated through an examination of the lithologies of wells in the Grand Forks valley as well as interpreted from landforms evident from air photographs. The aquifer extent is shown in Figure 2.

3.1 Approach to Characterizing the Aquifer at Grand Forks

The following sources of available information and data were used to map and characterize the aquifer at Grand Forks:

- information on the wells (which provided the basic subsurface hydrogeologic information to obtain an understanding of the stratigraphy[2] of the area and architecture of the aquifer) was obtained from the provincial WELLS database;
- hydraulic parameters (i.e., the aquifer's transmissivity) and characteristics (e.g., how the aquifer responds to well pumping) were estimated from consultants' reports and through calibration of the numerical groundwater model;

[2] Lithology information from the well records was standardized using software developed by Simon Fraser University to correct any errors in syntax, grammar and spelling. The standardization process recognizes equivalent terms and classified materials into dominant types.

- river stage elevations and channel geometry determined from the survey data for the Kettle and Granby Rivers provided by the Ministry;
- all available data on the four Environment Canada hydrometric stations in the Grand Forks valley;
- Environment Canada meteorological records were used to verify weather series used for recharge modeling;
- estimates of return flow from an irrigation perspective obtained through consultation with experts in the field of irrigation;
- irrigation rates determined through consultations with the large scale groundwater users;
- soil and geologic maps for the Kettle River Valley (Sprout and Kelly, 1964);
- available water chemistry data from historical water quality surveys conducted by the Ministry (in 1989, 1993 and 2001) and well water chemistry data from the Interior Health Authority; and
- groundwater level information from the Ministry Observation Well No. 217.

Detailed methodologies used to develop the series of map coverages can be found in Appendix 1.

Information on regional geology, hydrostratigraphy and estimates of hydraulic parameters, climate data, surface drainage survey data, well locations and static head elevations were used to develop the conceptual model for the Grand Forks Aquifer. A transient finite-difference MODFLOW numerical model was then developed by SFU and calibrated using available composite hydraulic head data[3] and transient data obtained during pump tests at several community wells (Scibek and Allen, 2004b). Capture zones for the major production wells were estimated using the numerical model. Methodologies for the modelling work conducted on the Grand Forks Aquifer are found in Appendix 2.

3.2 Wells in Grand Forks

3.2.1 Distribution of Wells and Well Types

The distribution of wells in Grand Forks (by type of construction) is shown in Figure 7. Well types for wells in the Grand Forks area were categorized by their construction method: drilled wells, dug or other (driven) wells, and well types where the method of construction was not reported.

[3] "composite hydraulic head data" means hydraulic head data in the well records determined from different times and years.

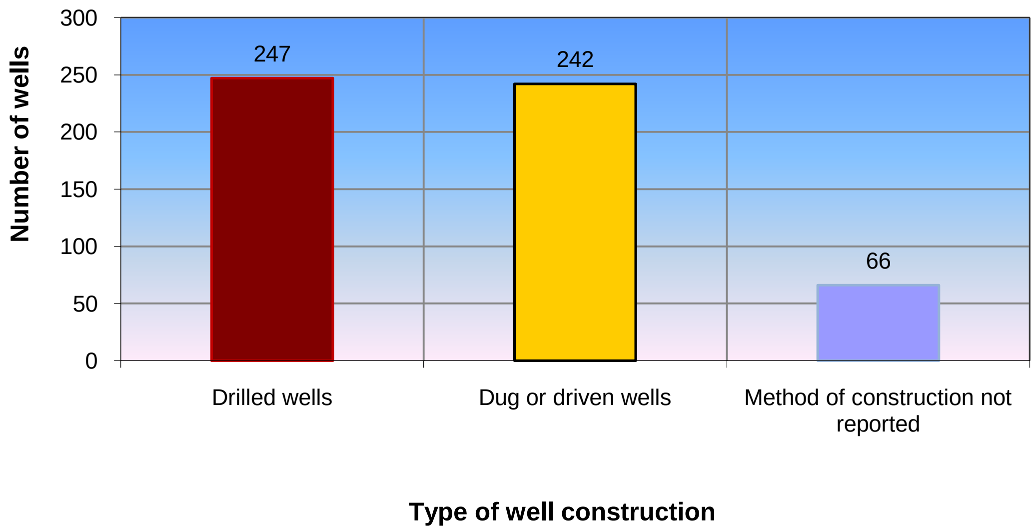

Figure 7 Distribution of wells in the Grand Forks area by type of construction.

There are almost an equal number of drilled and dug wells in the Grand Forks aquifer. Although there are close to 550 wells in the provincial water well database (WELLS), it is likely that more wells exist in the study area. Historically, well construction reports for drilled wells were submitted by water well drilling contractors on a voluntary basis. Dug wells were typically constructed by a backhoe excavator and well construction reports for these types of wells are generally not available. Dug wells in the Grand Forks area were primarily identified and entered into WELLS as a result of field surveys conducted by the Ministry. For example, the land use survey conducted by Sheppard (1995) identified many dug wells, and these were subsequently entered into WELLS. The wells where construction methods are unknown are also primarily captured into the WELLS database as a result of field surveys.

3.2.2 Well Depth

The range of well depths and the approximate number of wells in each depth range in the Grand Forks area are shown in Figure 8. The spatial distribution of wells by depth is shown in Figure 9.

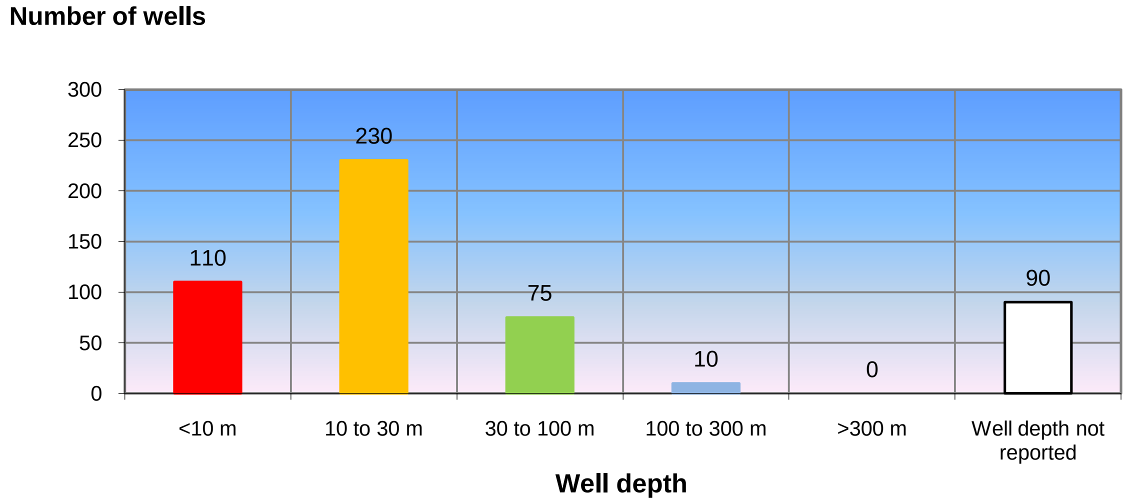

Figure 8 Distribution of wells in Grand Forks by reported well depth.

Reported well depths for wells drilled in the valley bottom range from a minimum of 2 m to a maximum of 156 m. The median and average reported well depths are 16 m and 23 m, respectively. Over 20% of the wells in Grand Forks are shallow (<10 m deep); two-thirds of the wells in Grand Forks are <30 m deep. The shallow wells (<10 m deep) are mostly dug wells and are found closer to the river, in the lower elevation lands in the Almond Gardens Road area, the Cameron and Darcy Road area, and the Nursery area, where the water table is shallow and where aquifer thickness may be limited. Shallower wells are also found in areas where the demand is only for domestic supply. Other areas where there are dug wells are Johnson Flats in the City of Grand Forks, where, even though municipal water services were introduced into the area in 1995 (S. Bird, City of Grand Forks, pers. comm., 2009), some residents may still be relying on their own dug wells for water supply, and the residential area at the Danville border crossing (Figure 2). The 10 to 30 metre deep wells are found throughout the aquifer except on the terraced bench area in the western end of the aquifer; there wells are known to be deeper.

In Grand Forks, over 15% of the wells are >30 m in depth, including all of the City of Grand Forks', Sion Improvement District's, Covert Irrigation District's wells and 6 of 8 Grand Forks Irrigation District's wells. These deeper wells are also the highest yielding (some with yields of >75 L/s or >1000 gpm) and supply groundwater to the majority of the residents in the valley. By comparing Figure 9 with the map of aquifer thickness (Figure 14), it is evident that the deepest wells are located in areas where the aquifer is thickest and where wells of maximum capacity can be constructed to supply irrigation and residential supply or at the higher elevation benches.

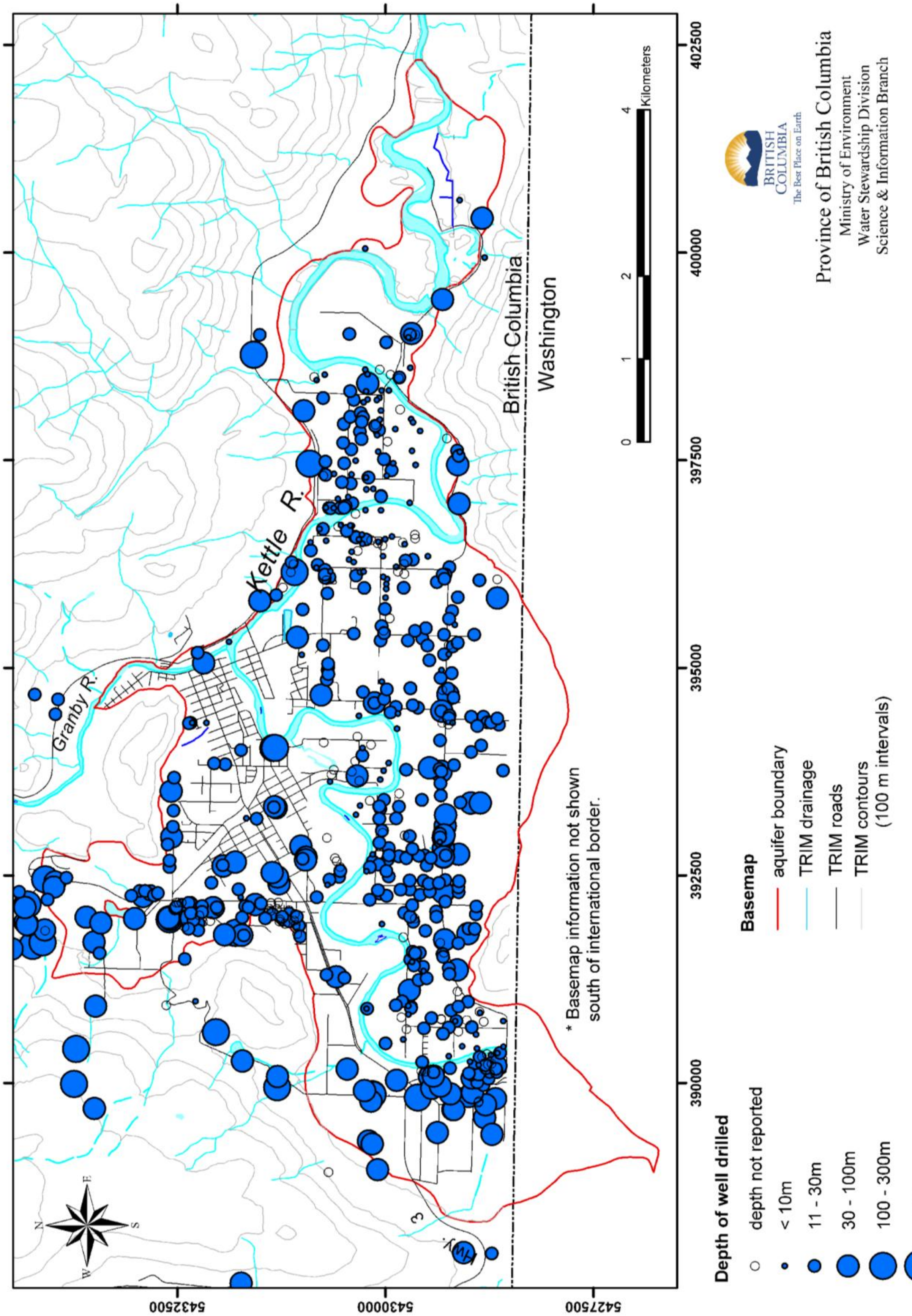

Figure 9 Map of well reported well depths in the Grand Forks area.

3.2.3 Well Use

Although intended well use is often reported in the original record, the status of the use of a well may change over time. Just because a well is in the WELLS database and plotted on a map does not mean that the well is necessarily in current use. It is believed that a significant number of wells for the study area in the WELLS database may no longer be in use because the evolution of groundwater supply development in Grand Forks over the past few decades has seen a general trend of replacement of private well water supplies by community wells.

In general, the areas covered by the major water district and the City of Grand Forks are now serviced by community wells. Residential areas that lie outside of these areas are mainly serviced by private domestic wells. The main exceptions are the mobile home parks which operate their own community wells.

In 2005, there were 23 wells in Grand Forks that supply water to residents:

- the City of Grand Forks currently operates 4 wells,
- Grand Forks Irrigation District operates irrigation 8 wells (including the well at Copper Ridge[4]),
- Sion Improvement District operates 3 irrigation wells[5],
- Covert Irrigation District operates 3 wells, and
- there are also a number of wells that supply mobile home parks.

The locations of water supply system wells having modelled capture zone areas are shown in Figure 33 in Section 3.8 of this report. Other wells, such as the well at the Boundary Hospital and the well at Hutton School, which are located within the City serviced area, may still be in use, but only for irrigation.

Historically, the irrigation supply for the GFID was the Kettle River, and residents in the District relied on their own private wells for drinking water. Many of the residents dug their own wells. Since the late 1980s, most of the drinking and irrigation water in the District area has been supplied by large capacity wells from the GFID. As a condition of hooking up to the District's wells, residents had to disconnect their private well. Consequently, a significant number of (drilled and dug) wells in the District are likely no longer in use and are in various states of abandonment. There are also wells within the GFID that are still in use because those residents had not hooked up to the District's wells.

Pockets of areas where active individual domestic wells can still be found include: along the North Fork Road area west of the City boundary, the Cameron/Kenmore/ Darcy Road area Almond Gardens Road area, the residential area at the Danville border crossing, and

[4] GFID also operates domestic wells during the non-irrigation season, such as well 87-6 (or locally named Nursery No. 3) in the Nursery Area.

[5] SID also has a domestic well at two of the well sites (at Reservoir Road and Canning Road and at Hardy Mountain Road and North Fork Road) for use during the non-irrigation season. In 2007, SID drilled a new irrigation well (Sion Production Well No. 6 near their community centre).

the southern end of the Nursery area, along South Nursery Road. The number of active individual domestic wells in the Grand Forks area is probably less than 20% of total wells for the area in the WELLS database. Consequently there may be several hundred wells in Grand Forks that are abandoned and may not have been properly closed. Abandoned wells in Grand Forks are therefore a local groundwater protection issue.

In a door-to-door survey in 1983, Wei (1983b) also found a number of wells along Highway 3 (Central Avenue) between 25th Street and 22nd Street that may no longer be in use. However, these wells were never entered into the WELLS database.

3.2.4 Potential Well Yield

Reported yield from the WELLS database for wells drilled in the valley bottom in Grand Forks ranges from a minimum of 2 gpm[6] (10 m^3/d) to a maximum of 2,400 gpm (13,000 m^3/d - refer to Figure 10). The median and average reported well yields are 40 gpm (220 m^3/d) and 310 gpm (1,700 m^3/d), respectively. Well yield is reported by the driller at the time of drilling and may reflect the maximum yield from the well, not the actual water use.

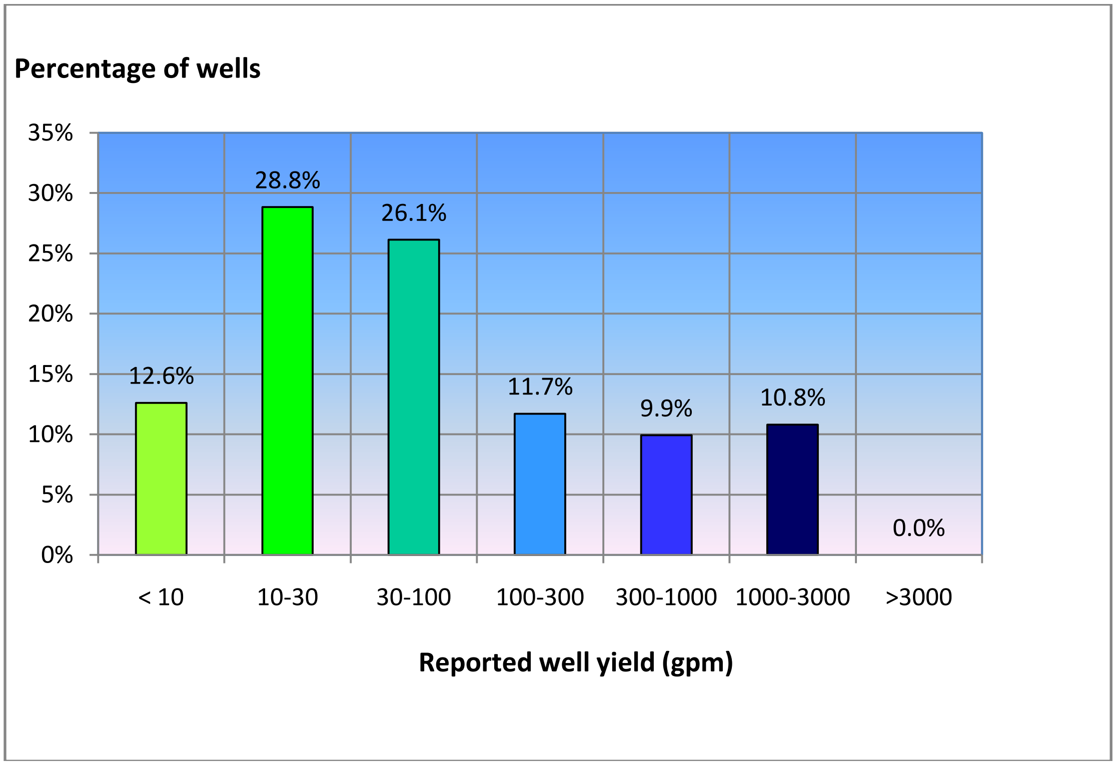

Figure 10 Histogram of reported well yield[6].

[6] Well yields have historically been reported in well construction reports in USgpm, Igpm, or gpm (not specified US or Imperial). Since these reported well yields are rough estimates only, the values were all lumped together and reported well yield statistics have been reported in "gpm". Well yield is the only parameter that is reported in English units in the report because it is still more readily identifiable than yield in "L/s" or "m^3/d").

A map of potential yield to wells is shown in Figure 11. The map was generated based on an analytical equation (see Appendix 1). Potential yield in Figure 11 may differ from the yield reported by the driller at any given location because although realistic hydraulic parameters and aquifer thickness were used to derive potential yield, other site specific factors related to the construction of a well were not considered. Factors such as well depth, well diameter, length and type of screen, method of well development are all factors that determine the ultimate yield of a well. Furthermore, a well typically ages over time and becomes less efficient (e.g., due to incrustation of the screen), resulting in lowering of the well yield. The equation also does not consider the effect of interference of neighbouring wells on a well's yield because this phenomenon is site specific. The map of potential well yield represents what is the likely maximum yield that can be developed for a single well at a given location. Despite the assumptions used in the equation, the map is still useful to illustrate the relative potential yield to wells over the entire aquifer area.

The potential yield to wells map has been represented as zones. Since reported well yield appears to be log-normally distributed, the zones of potential well yield are represented in half orders of magnitude intervals (e.g., 10 to 30 gpm (55 m^3/d to 165 m^3/d), 30 to 100 gpm (165 m^3/d to 545 m^3/d), etc.). Figure 11 shows that a significant portion of the aquifer has the potential to yield >1000 gpm (5,500 m^3/d) to wells, and much of the aquifer has the potential to supply hundreds of gpm (hundreds to thousands of m^3/d) to wells. The areas of greatest potential yield lie in the western half of the aquifer, where the saturated thickness of the aquifer is greatest. A comparison of the potential well yield map and the map of aquifer thickness (Figure 14) shows that both maps are strongly correlated; areas where the aquifer is thickest correspond to areas of greatest potential well yield. This is expected because the aquifer is thought to be relatively homogeneous with respect to hydraulic conductivity and specific storage and, therefore, potential well yield depends on aquifer thickness. Potential yield of the aquifer decreases in the Nursery area as the thickness of the aquifer is limited there. However, the map suggests that wells of tens of gpm to hundreds of gpm (tens to hundreds of m^3/d) may still be constructed in that area. Generally, the aquifer is considered very productive; areas identified with potential yield < 10 gpm (<55 m^3/d) is limited to a few areas along the Kettle River, downstream from the confluence with the Granby River where aquifer thickness is very limited (a metre or so).

The estimate of potential yield to wells is supported by well yields reported in the WELLS database. Many of the largest capacity wells located away from the river are found in the western portion of the aquifer. Potential well yield decreases towards the east portion of the aquifer as the thickness of the saturated sand and gravel decreases there. However, Figure 11 suggests that wells of tens of gpm to hundreds of gpm may still be constructed in that area. The high reported well yields (several hundreds of gpm to over 1,000 gpm) for two Grand Forks Irrigation District wells in the east portion of the aquifer is because these wells are located adjacent to the Kettle River and induce infiltration of river water during pumping; potential yield in the east portion of the aquifer, for wells located further away from the river, is expected to be lower.

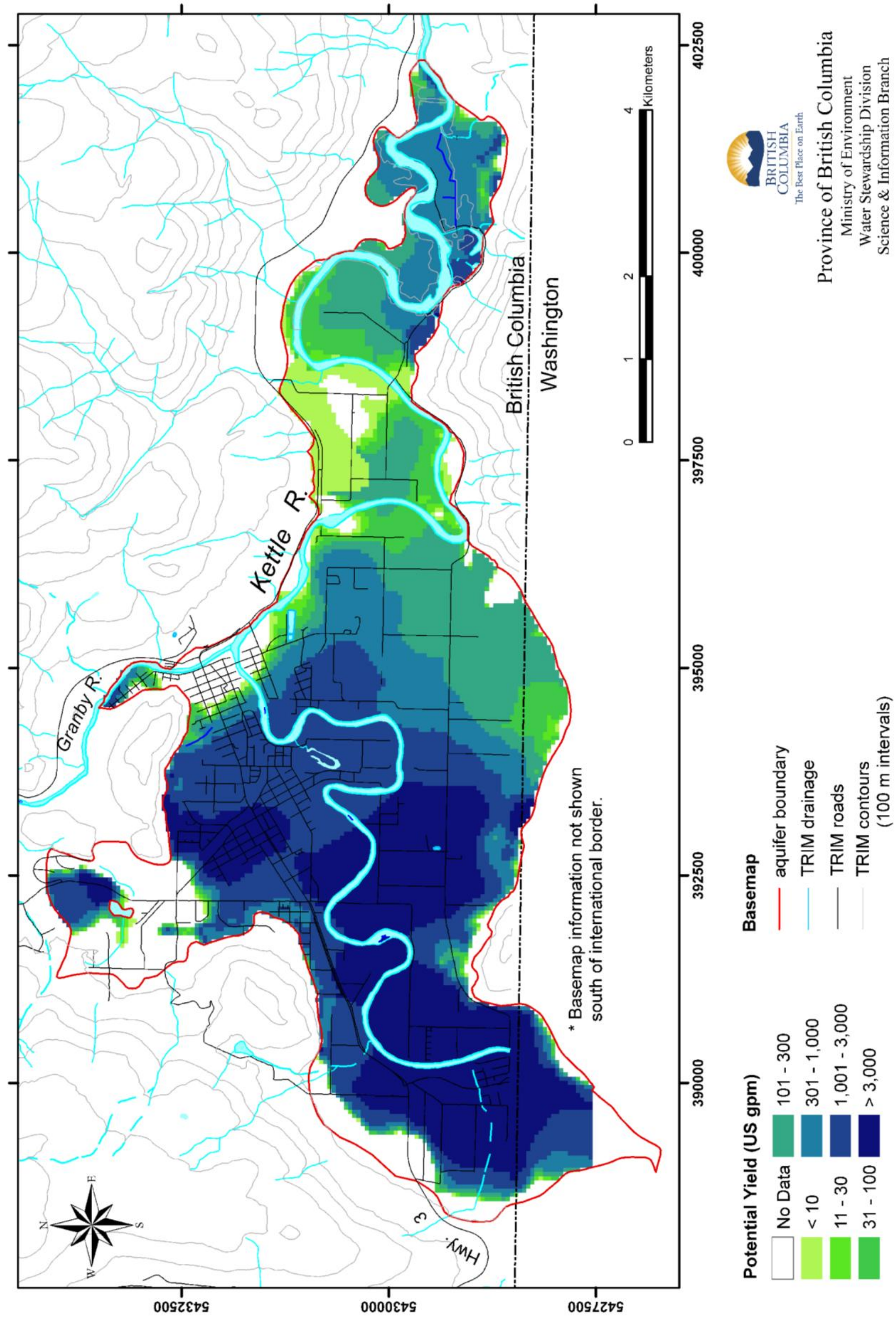

Figure 11 Map of possible well yields in the Grand Forks area.

3.3 *Hydrostratigraphy and Architecture*

Interpretation of the lithologic descriptions in the well records and landforms from air photographs allows the stratigraphy and recent geological history to be interpreted and the architecture of the Grand Forks aquifer to be defined. In the Grand Forks area, the stratigraphy of the major surficial and bedrock deposits is summarized in Table 1 below.

Figure 12 is a fence diagram – a series of joined hydrogeologic cross-sections running west-east and north-south, viewed at an oblique angle, looking northwest – showing the various surficial geology layers (refer to Table 1) and the underlying bedrock. Lithologic unit boundaries from the fence diagram were interpolated to construct a geological or aquifer architecture model (Figure 13) for input to the groundwater model (Scibek and Allen, 2004b).

A description of the various surficial lithologic units follows. The discussion focuses on each unit's occurrence in the study area, the depositional environment in which the unit was likely formed, and its hydrogeologic significance (with respect to the flow and storage of groundwater).

Table 1 Schematic column showing the general hydrostratigraphy in Grand Forks.

Lithology	**Layer in Scibek and Allen (2004b) numerical model**	**Description of lithologic unit**	**Hydrogeologic significance**
	Layer 1	Glaciofluvial gravel, minor fluvial gravel (along river channel), minor colluvium (locally along edge of valley bottom)	Vadose zone, unconfined aquifer (where saturated)
	Layer 2	Glaciofluvial sand	Principle upper unconfined aquifer zone
	Layer 3	Glaciolacustrine silty sand, silt, fine sand	Aquitard
	Not part of model	Glaciofluvial sand (near Donaldson Road and North Fork Road only)	Lower confined aquifer zone
	Layer 4	Glaciolacustrine clay	Aquitard
	Not part of model	Till (underlies valley slopes and uplands)	Aquitard
	No-flow model boundary	Bedrock – altered dioritic (igneous) rocks, metamorphic rocks (underlies the upland areas, valley slopes and valley bottom)	Aquitard-limited aquifer

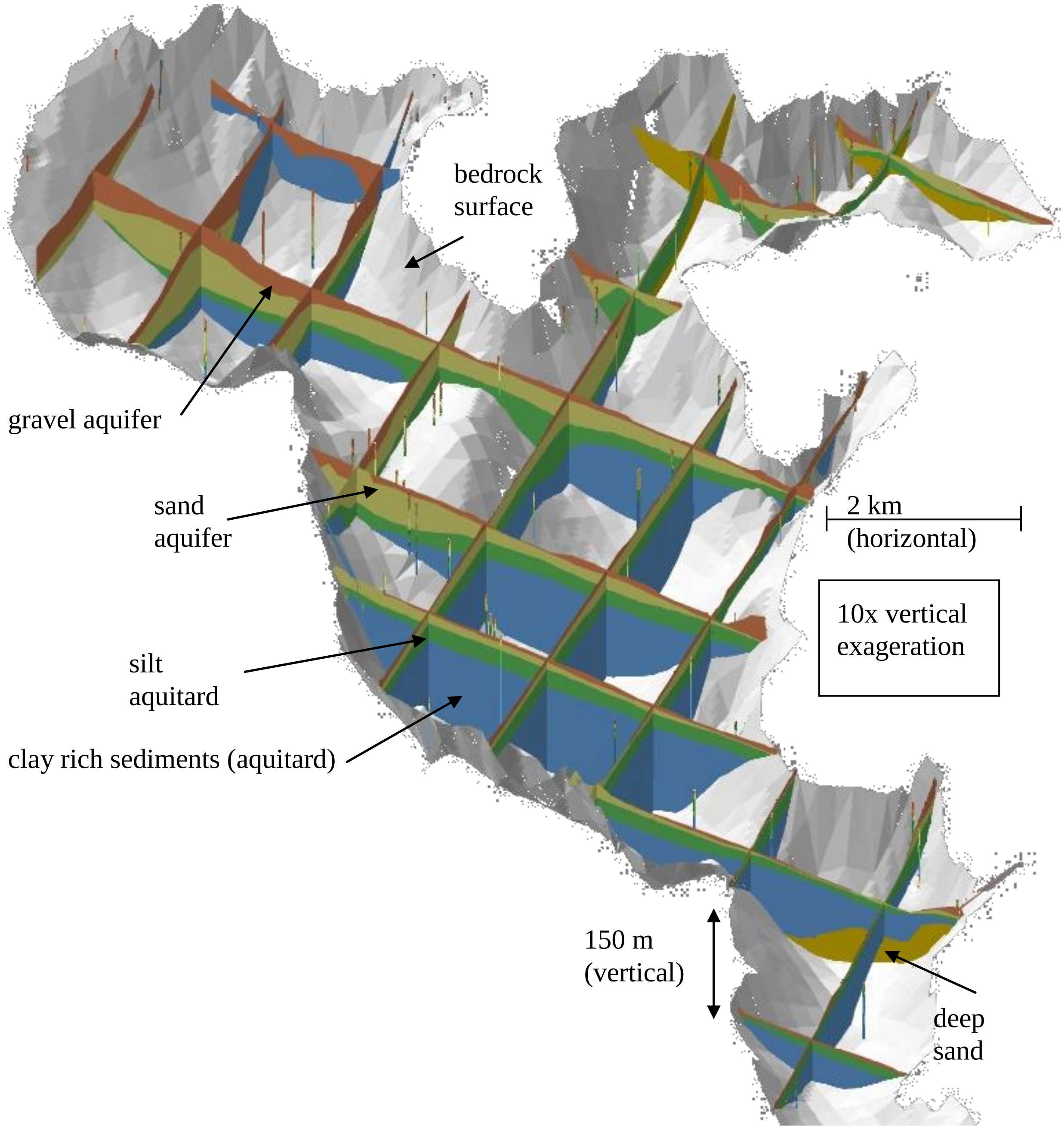

Figure 12 **Fence diagram showing the various geologic layers in the Grand Forks area. The uppermost gravel layer (Layer 1) is coloured orange, the sand layer (Layer 2) is yellow, the silt layer (Layer 3) is green, the clay layer (Layer 4) is blue and the underlying bedrock is grey.**

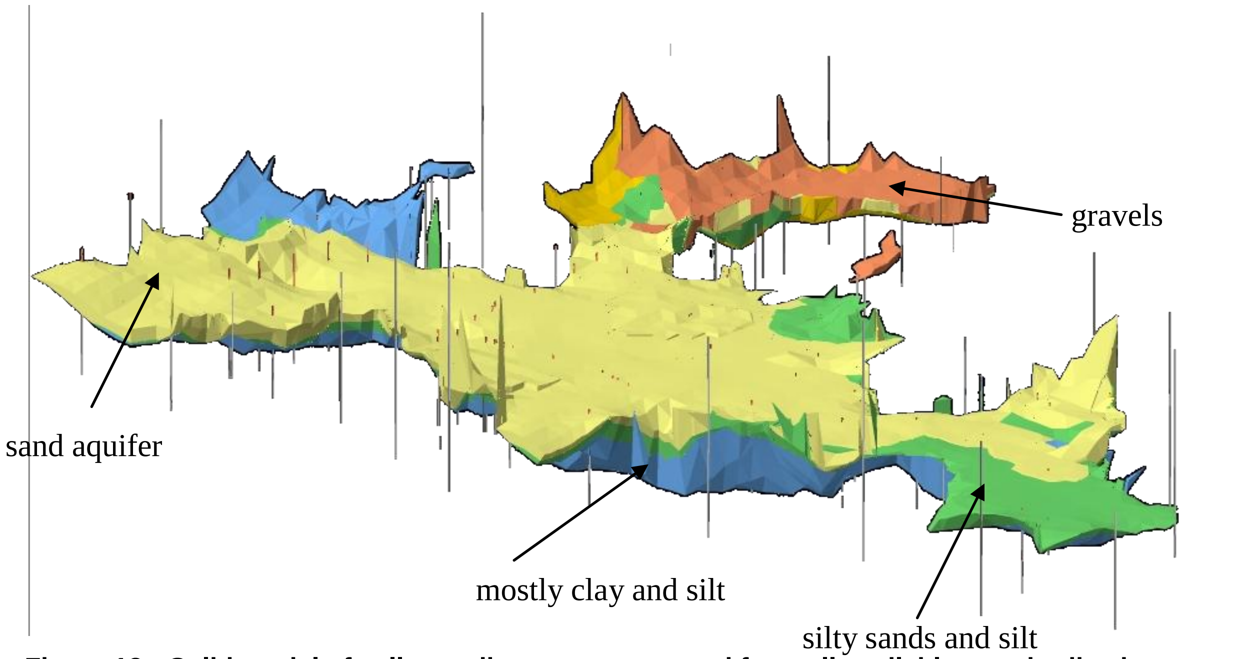

Figure 13 **Solid model of valley sediments constructed from all available standardized borehole lithologs (vertical lines represent control points from well logs and bedrock). Colours correspond to those in Table 1 and Figure 12.**

3.3.1 Description of Lithologic Units

Glaciofluvial/fluvial gravel and minor colluvium unit (Layer 1 in the numerical groundwater flow model) – an extensive layer of gravel directly underlies the valley (see Figures 12 and 13). This gravel unit is approximately 30 m thick and was deposited in a high energy depositional environment, characteristic of running water. Some gravel may have been deposited recently by the Kettle and Granby Rivers while some, particularly the gravel underlying terraces in the valley bottom but above the rivers, were likely deposited as outwash gravels at the end of the last period of glaciation as the ice melted away. Coarse colluvium also forms part of this unit and occurs locally along the edge of the valley bottom. This unit is permeable and in areas of the valley where it occurs below the water table, forms the upper part of the aquifer. The gravel layer above the water table is variably saturated and forms a permeable vadose zone above the aquifer. The occurrence of this permeable gravel layer above the aquifer renders the aquifer highly vulnerable to potential contamination from human activities at the land surface.

Glaciofluvial sand unit (Layer 2 in the numerical groundwater flow model) - lithologic descriptions in the well records reveal that an extensive layer of sand underlies (and therefore is just older than) the gravel unit in the valley bottom (refer to Figures 12, 13 and 14). The sand unit is aerially extensive in the valley bottom but variable in thickness. Thickness of the sand unit ranges up to over 100 m thick in the Covert Irrigation District area. The sand unit is thicker in the western half of the valley bottom where it is generally at least 40 m thick. In the eastern half of the valley, the sand unit is generally thinner, less than 20 m thick. The sand unit was likely formed by deposition of sandy sediments from the glacial river that occupied the valley bottom. The sand unit is also permeable and together with the overlying gravel, form the principle zone of the aquifer at Grand Forks.

Glaciolacustrine silt unit (Layer 3 in the numerical groundwater flow model) - lithologic descriptions in the well records for deeper wells in the valley bottom reveal the presence of a silty sand layer underlying the sand unit. There is limited information about this silty sand unit due to lack of data because drilling is usually terminated when the percentage of silt in the drill cuttings increases. The top of the silt unit occurs near the land surface towards the east (areas where the upper aquifer is thin or absent) and gradually deepens westward (see Figures 12 and 13). The boundary between the overlying sand unit and the silt unit appears to be gradational – Choy (1977) describes this silt layer to comprise fine sand near the top, grading vertically downward to silty sand and finally to silt with increasing depth. This gradation reflects that early deposition occurred in a stillwater environment, such as a glacial lake with later deposition occurring in a progressively higher energy environment, such as slow moving water. Because of its lower permeability, the silt unit is considered an aquitard directly underlying the upper principle zone of the Grand Forks aquifer. The thickness of the unit varies, based on well lithology information, but has an average thickness of approximately 40m.

Deep glaciofluvial sand unit (isolated deposits in numerical flow model) – in the area of Donaldson Road and North Fork Road, a deeper sand unit occurs underneath the silt unit. The deep sand unit is composed of outwash sediments ranging from fine-grained to medium-grained sand to pebbles but little is known about the thickness and lateral extent of this unit (see Figures 12 and 13). A well (well tag number 75353) drilled in the Johnson Flats area within the central portion of the valley suggest that the unit is absent from this part of the valley. This deep sand unit is saturated and forms the lower zone of the aquifer at Grand Forks. This sand unit was likely formed by deposition of running water. Its occurrence just south of the narrow northern extension of the aquifer by Ward Lake suggests either that the Granby River in glacial times may have flowed through the present day area occupied by Ward Lake and the deep sand unit may represent a prehistoric delta formed where prehistoric Granby River emptied into the main Kettle River Valley or the deep sand unit represents alluvial fans from the flanks of the nearby valley sides.

Glaciolacustrine clay unit (Layer 4 in the numerical groundwater flow model) - there is little information about the deepest sediments in the Grand Forks valley, but the predominance of clay in borehole lithologs at depth led to representation of this layer as "clay", or "clay-dominant" sediments. Some sand lenses are still present but groundwater flow is probably much slower than in all above layers. The clay was likely formed by deposition of very fine textured sediments in still water, such as a glacial lake, and is assumed to be present at depth (see Figures 12 and 13). This unit is an aquitard. The thickness of the unit extends from the base of the silt to the bedrock surface in the model.

Till unit (this unit was not represented in the numerical groundwater flow model and does not appear in Figures 12 or 13) – till is believed to be the oldest major surficial deposit in the study area. The presence of till in the well records is not well documented but till does occur above the valley bottom in the valley slopes. This unit was likely formed by glacial ice as the ice churned up rock and sediment debris during the last period of glaciation. The permeability of the till unit is likely low and this unit, together with bedrock laterally bound the aquifer at Grand Forks.

3.4 Groundwater Flow and Aquifer Hydraulic Properties

3.4.1 Groundwater Flow and Direction

Regional groundwater flow in the aquifer is predominantly from west to east, in the same direction as Kettle River flow. Figure 15 depicts the contours of modelled hydraulic head[7] in the aquifer from Scibek and Allen's (2004b) model, under non-pumping, steady-state conditions. Steady-state conditions generally simulate the summer low flow period, when most of the river flow is baseflow generated by discharging groundwater somewhere in the watershed. Thus, a steady-state model is generally representative of August or September conditions.

The range in hydraulic head values in the aquifer is 530 m a.s.l. in the western end of the aquifer to 490 m a.s.l. in the eastern end of the aquifer, and suggests the groundwater flow is regionally from west to east. Overall, the hydraulic head values from the numerical model matched hydraulic head values determined from actual reported well water levels from the well construction reports. The normalized root mean square (NRMS) error – the best estimate of the numerical model error – was < 2.4m or 8.9%, which is considered excellent (Scibek and Allen, 2004b). The correlation coefficient was 0.919. The numerical model appears to give a realistic representation of the hydraulic heads and, therefore, groundwater flow directions in most areas of the aquifer.

The way the hydraulic head contours cross the Kettle River west of Johnson Flats - hydraulic head contours on both sides of the river point downstream as the contours reach the Kettle River - implies that during the late summer (baseflow period), the Kettle River is generally a losing stream in the western half of the aquifer area; the Kettle River looses water to (and is a source of recharge to) the underlying aquifer. At and east of Johnson Flats, the hydraulic head contours on either side of the Kettle River point upstream as the contours reach the river, implying that the Kettle River downstream of Johnson Flats is generally a gaining stream. East of Johnson Flats to the Nursery area, groundwater discharges out of the aquifer, into the Kettle River, sustaining the river with baseflow. At the Nursery area where the Kettle River meanders across the entire north-south width of the aquifer, flow between the aquifer and the river may be more complex. The regional steady-state hydraulic head contours at the Nursery area suggest groundwater may recharge the river along the west bank while the river looses water to the aquifer along the east bank, as illustrated in the schematic cross-section in Figure 16.

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[7] Hydraulic head is essentially the groundwater level elevation, and is a measure of the energy of groundwater.

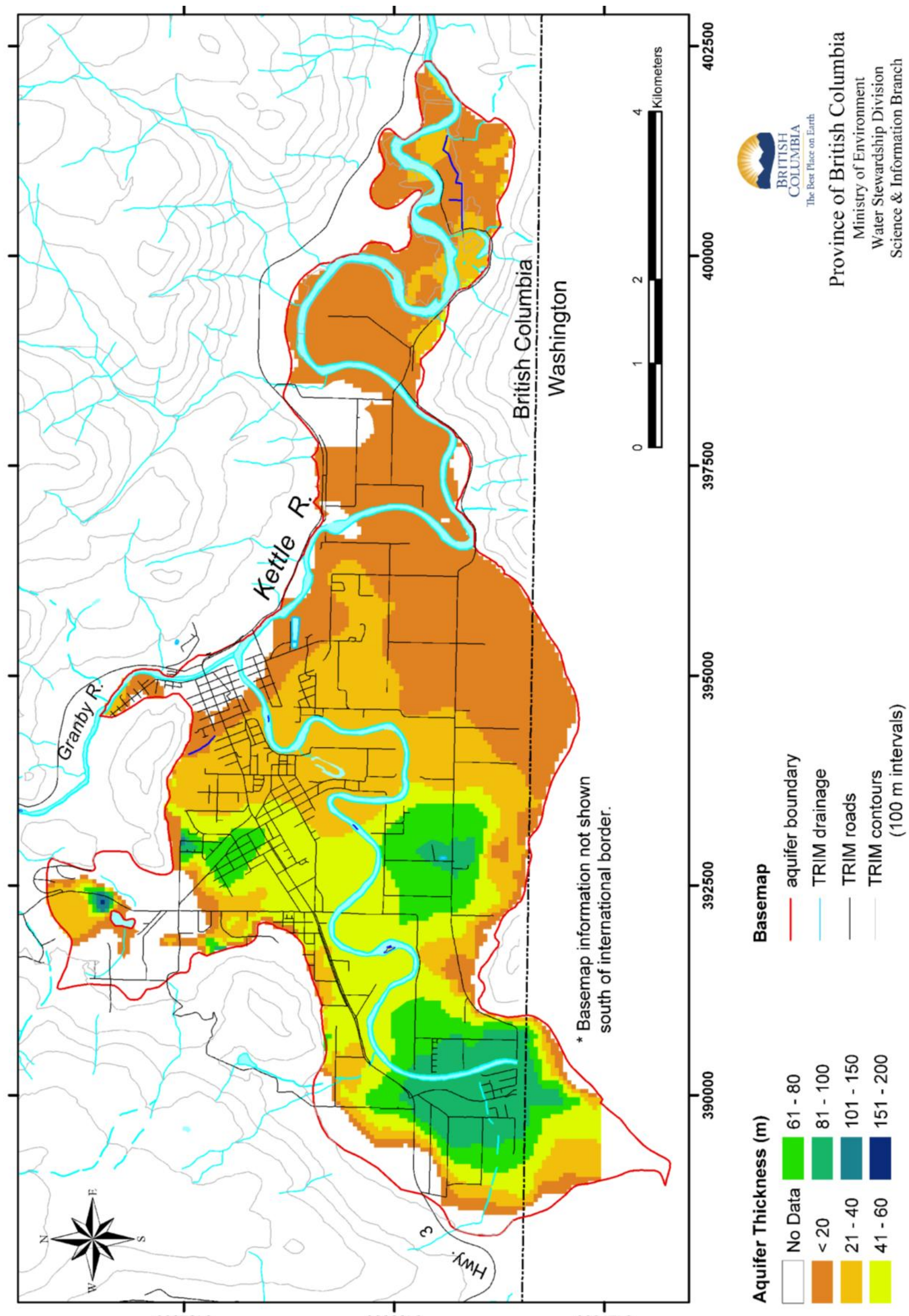


Figure 14 Map of the thickness of the Grand Forks Aquifer.

The transient groundwater levels observed over the course of a year are more complex. Scibek and Allen (2003, 2004b) showed that the aquifer is in close hydraulic connection with the Kettle River. In the spring, during the freshet, high river levels recharge the aquifer along its length causing groundwater levels to rise. The response of the aquifer becomes progressively less at greater distances from the river as discussed in Section 3.5.2. Following the freshet, there is a reversal of groundwater flow direction, generally toward the river along most of its length.

Figure 17 depicts the hydraulic head contours in the aquifer from the numerical model if all the community wells were pumping (see pumping rates in Table A2-2). A comparison of Figures 15 (non-pumping) and 17 (pumping) shows that, under pumping conditions, hydraulic heads are lowered and groundwater flow directions altered in the vicinity of the pumping community wells. The areas where effects of pumping is most pronounced are in the Big Y area, where a number of high capacity Grand Forks Irrigation District wells are located, in the City of Grand Forks, and the extreme west part of the aquifer where the Sion Improvement District and Covert Irrigation District wells are located. The numerical model shows that in the Big Y area, the hydraulic head would drop 6 m, and in the City of Grand Forks, the hydraulic head would drop up to 11 m (most notably around wells no. 4 and 5). The hydraulic head map (Figure 17) also suggests that pumping has induced infiltration from the Kettle River to the aquifer. This is especially obvious in the Big Y and City of Grand Forks area where the hydraulic head contours are sub-parallel to the Kettle River and the contours on either side of the river are even more pronouncedly pointed downstream compared to under non-pumping conditions.

The groundwater flow numerical model assumed that pumping from other wells (i.e., private domestic wells and private irrigation wells) is negligible. This assumption may not be valid in some local areas of the aquifer where heavy seasonal pumping of private wells for irrigation supply does occur (e.g., Boundary Hospital well, wells used to water school fields, wells where farmers have chosen not to hook up to a community water supply). Therefore, Figure 17 is one representation of a specific pumping scenario (pumping of community wells only) and should be interpreted in a qualitative sense to understand the effects pumping have on the aquifer. In this example, pumping rates in Table A2-2 were used and pumping of the Copper Ridge well and recently drilled Sion Production Well No. 6 were not considered in the model. The model does, however, allow other pumping wells to be “turned on” to simulate other pumping scenarios.

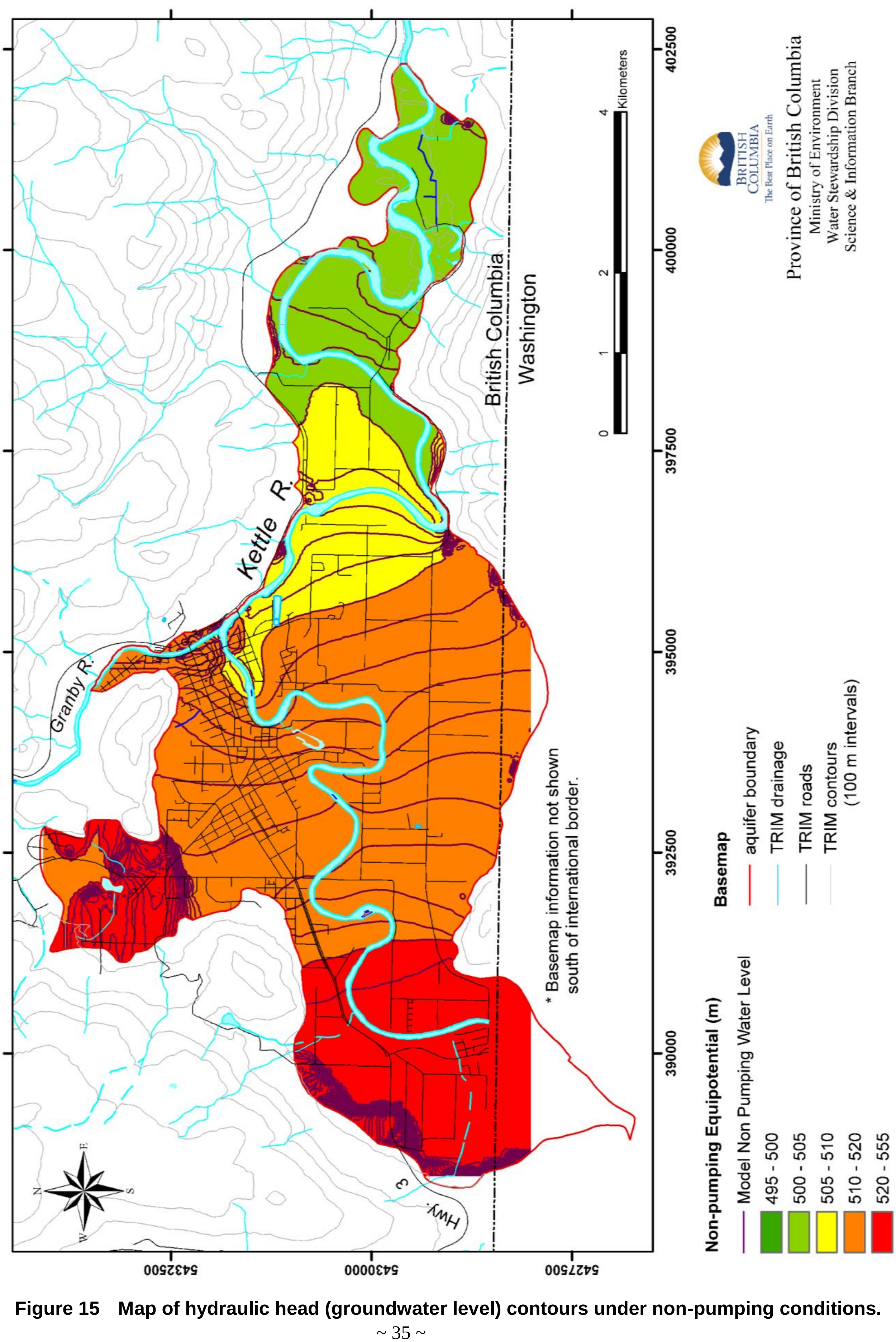


Figure 15 Map of hydraulic head (groundwater level) contours under non-pumping conditions.

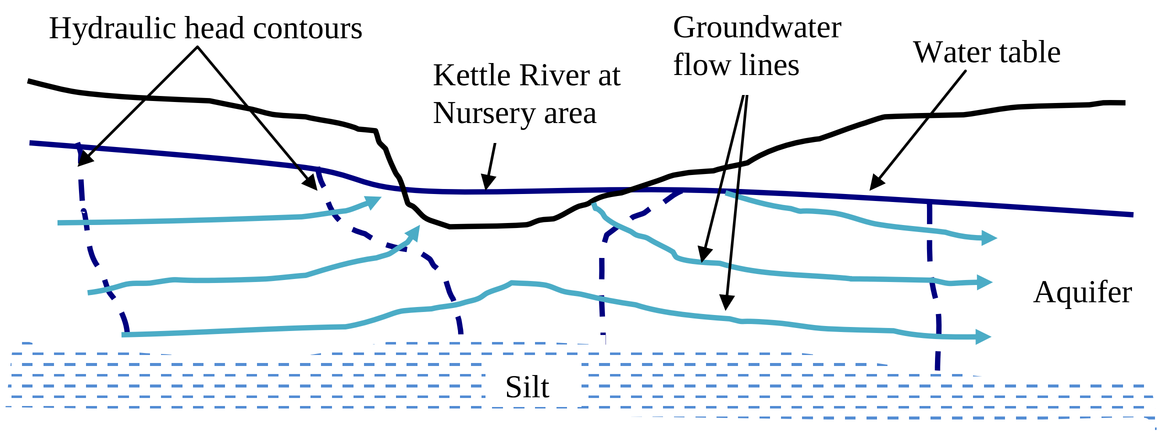


Figure 16 Schematic cross-section (looking north) at the Nursery area, showing the Kettle River gaining water from the aquifer along the west bank and losing water to the aquifer along the east bank.

3.4.2 Aquifer Hydraulic Properties

Direct measurements of the aquifer's hydraulic properties– hydraulic conductivity and specific storage - were beyond the scope of this study. The aquifer's hydraulic properties are, nevertheless, critical in allowing, for example, rate of groundwater flow and velocity of groundwater to be determined. Hydraulic properties of the aquifer and of the other surficial layers in the Grand Forks valley are also required for the numerical groundwater flow model. Hydraulic properties for the model layers were estimated by Scibek and Allen (2004b), based on Dakin (1993) for the aquifer (layer 2) and values expected for the type of surficial materials comprising the other layers (see Appendix B). The hydraulic properties were also verified through the calibration process for the numerical model. For the hydraulic heads to be reproduced accurately under steady state and transient conditions, reasonable estimates of the hydraulic conductivity and specific storage are needed for the range of aquifer recharge values expected.

Historical pumping test data for some of the community wells allow for estimation of transmissivity (and sometimes storativity, if data from an observation well[8] are available) of the aquifer in the vicinity of the community well. Wei (1999) reviewed the available reports for the 23 community wells to obtain aquifer transmissivity and storativity values for calculating well capture zones. Table 2 summarizes the available well specific capacity[9], transmissivity and storativity values for the aquifer. The geometric mean for

[8] "observation well" is used here in a generic sense, in reference to a neighbouring or nearby well where water level measurements are taken during a pumping test. "Observation well" does not, in this context, refer to the provincial Observation Well No. 217.
[9] Specific capacity is a measure of the well's performance and is defined by the pumping rate divided by the drawdown at a specific time.

specific capacity and transmissivity are 1,100 m^3/d/m and 3,700 m^2/d, respectively and are within the range expected for productive sand and gravel aquifers along medium sized streams (Wei et al., in press).

Table 2 Summary of reported specific capacity, transmissivity, storativity and specific yield values for the aquifer from available pumping tests of community wells.

Well	Well Tag Number in WELLS database	Reported specific capacity (m^3/day/m)	Reported transmissivity (m^2/d)	Reported storativity (-)	Reported specific yield (-)	Comments
City of Grand Forks Hutton Well #2	19226	1,538	-	-	-	From well log
City of Grand Forks Well #3	22427	916	1901	-	-	From Dakin and Brown, 1969
City of Grand Forks Well #4	37325	-	1584	-	-	Average from Dakin, 1988
City of Grand Forks Well #5	62941	332	3,598	2.68 (10^{-4})		Average from Dakin, 1988; Dakin, 2000 pers. comm.
GFID Big Y#1	58671	2,039	6,100		0.08	From Burnett and Guiton, 1989
GFID Big Y#2	58638	1,123	6,700		0.04	From Burnett and Guiton, 1989
GFID Big Y#3	58733	938	3,500		0.10	From Burnett and Guiton, 1989
GFID 87-2	56888	747	9,000		0.12	From Burnett and Guiton, 1989
GFID 87-5	75317	779	6,000		0.12	From Burnett and Guiton, 1989
GFID Big Y#4	58745	5,642	11,000		0.19	From Burnett and Guiton, 1989
GFID Nursery #1	58625	627	2,500		-	From Burnett and Guiton, 1989
GFID Nursery #2	58601	1,123	8,400		-	From Burnett and Guiton, 1989
GFID 87-6 (Nursery #3)	75309	981	3,500		0.2	From Burnett and Guiton, 1989
SID irrigation #1	20502	1,287	-		-	From Topp, 1993
SID irrigation #2	21189	968	-		-	From Topp, 1994
SID irrigation #3	20497	1,590	-		-	From Topp, 1997
SID irrigation #6	-	527	350	0.002	-	From Brown and Sargent, 2007
CID #1	21752	1,227	-		-	From well log
CID #3	57771	1,097	-		-	From Golder Associates, 1987
Geometric mean		**1,100**	**3,700**			

GFID=Grand Forks Irrigation District; SID=Sion Improvement District; CID=Covert Irrigation District.

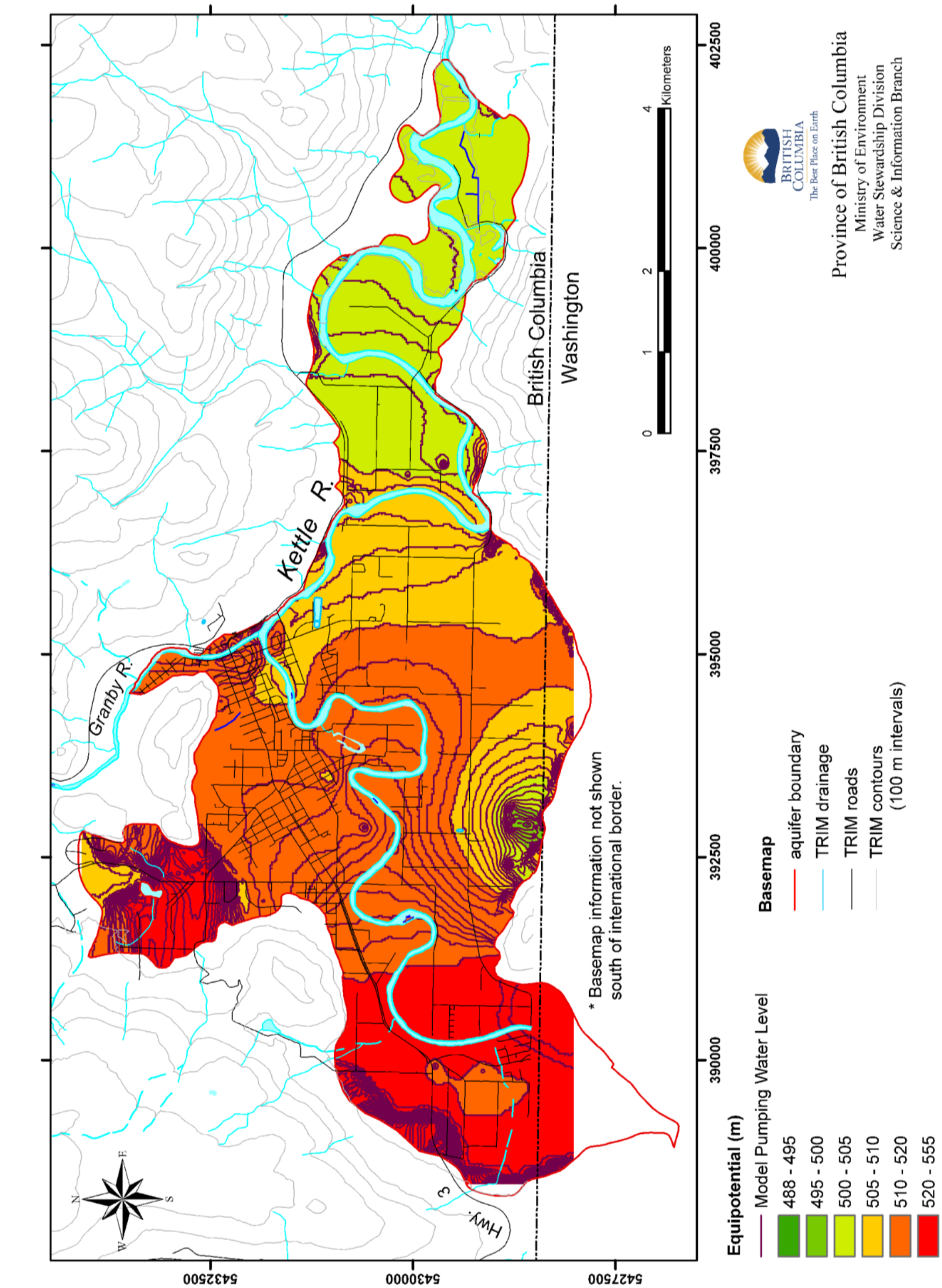


Figure 17 **Map of hydraulic head (groundwater level) contours under pumping conditions.**

3.5 Aquifer Water Balance and Groundwater/Surface Water Interactions

3.5.1 Water Balance

The steady-state numerical MODFLOW model allowed the water balance in the aquifer and transfer of water between the Kettle River and the aquifer to be quantitatively assessed. The model was divided up into four discrete zones (see Figure 18) to facilitate the interpretation of water flow into and out of each different parts of the aquifer. The zones extended vertically downward through all 4 model layers, although most of the flow occurs in the top two layers of the model.

Zone 1 occupies the western part of the aquifer where two of the Sion Improvement District irrigation wells and Covert Irrigation District wells are located. Zone 2 covers the central area of the aquifer and includes the Big Y area, the City of Grand Forks, and the airport area. Zone 3 covers the northern part of the aquifer, including the northern part of Sion Improvement District. Finally, Zone 4 covers the Nursery area and east. In the model, groundwater flow in and out of each zone was partitioned into:

- water that originates from the rivers or exits the aquifer to the rivers (i.e., from constant head nodes in the model),
- water that is lost via evapotranspiration (ET) – set to zero in the model because ET was taken into account with net recharge,
- water that enters the aquifer as recharge (net recharge), and
- water entering/exiting the zones from other neighbouring zones.

Water balances were estimated for both non-pumping and pumping conditions (with all of the community wells were pumping).

For non-pumping conditions, the total amount of groundwater inflow ranged from just over 3,800 m^3/d into Zones 3 (the smallest zone) to just under 38,000 m^3/d into Zone 2, the largest zone (see Figure 19a). Recharge from precipitation accounted for 8-29% of the total inflow to the zones. Water from the Kettle (and Granby) River (constant head nodes in the model) accounted for 34-87% of the inflow and groundwater inflow from neighbouring zones accounted for 3-37% of the total inflow into the zones (see Figure 20 (Inflow)).

The steady-state numerical groundwater model requires that outflow should equal inflow, and Figure 19a shows that groundwater inflow to and outflow from each zone are essentially balanced (no change in storage). Groundwater outflow from the zones is primarily to the Kettle River (constant head nodes) and loss to other neighbouring zones (Figure 20 (Outflow)). Even under non-pumping conditions, the water balance indicates that there is a significant exchange of water between the Kettle River and the aquifer. Discounting the inflow of groundwater from neighbouring zones (that water already exists in the aquifer), the amount of inflow from recharge and from the river for the entire aquifer (all 4 zones combined) totals roughly 80,265 m^3/d and equals the total amount of groundwater outflow from the aquifer – this rate equates to 14,720 USgpm.

Under pumping conditions, there is a significant re-distribution of water within each zone. The total amount of groundwater inflow ranged from just over 6,000 m^3/d into Zone 3 to over 64,000 m^3/d into Zone 2 (see Figure 19b). The total rate of inflow for Zones 1 and 2 is almost twice as large as it was under non-pumping conditions (Figure 19b). There is relatively little change in inflow and outflow for Zones 3 and 4 because well pumping is not significant in these zones. For inflow, recharge accounts for a smaller percentage of the total inflow (5-18%) but the percentage of inflow from the river (constant head nodes) has increased to 23-93% (see Figure 21 (Inflow)).

Figure 22 shows the net change in inflow and outflow in each zone as a result of pumping of the community wells. Significant net increases in inflow are observed in Zones 1 and 2 where there is a 100% increase of inflow from the Kettle River and some minor increases/decreases in inflow from neighbouring zones (Figure 22 (Inflow)). The most significant increase in outflow in all four zones is discharge to the pumping community wells (Figure 22 (Outflow)). There is a 2-41% decrease in outflow to the river. These results illustrate that the increased amount of water inflow under pumping conditions is generally derived from the river (constant head nodes). The other consequence of well pumping is a resultant decrease in outflow back to the river (constant head nodes) and to neighbouring zones, especially in Zones 1 and 2 where large reductions in outflow were noted.

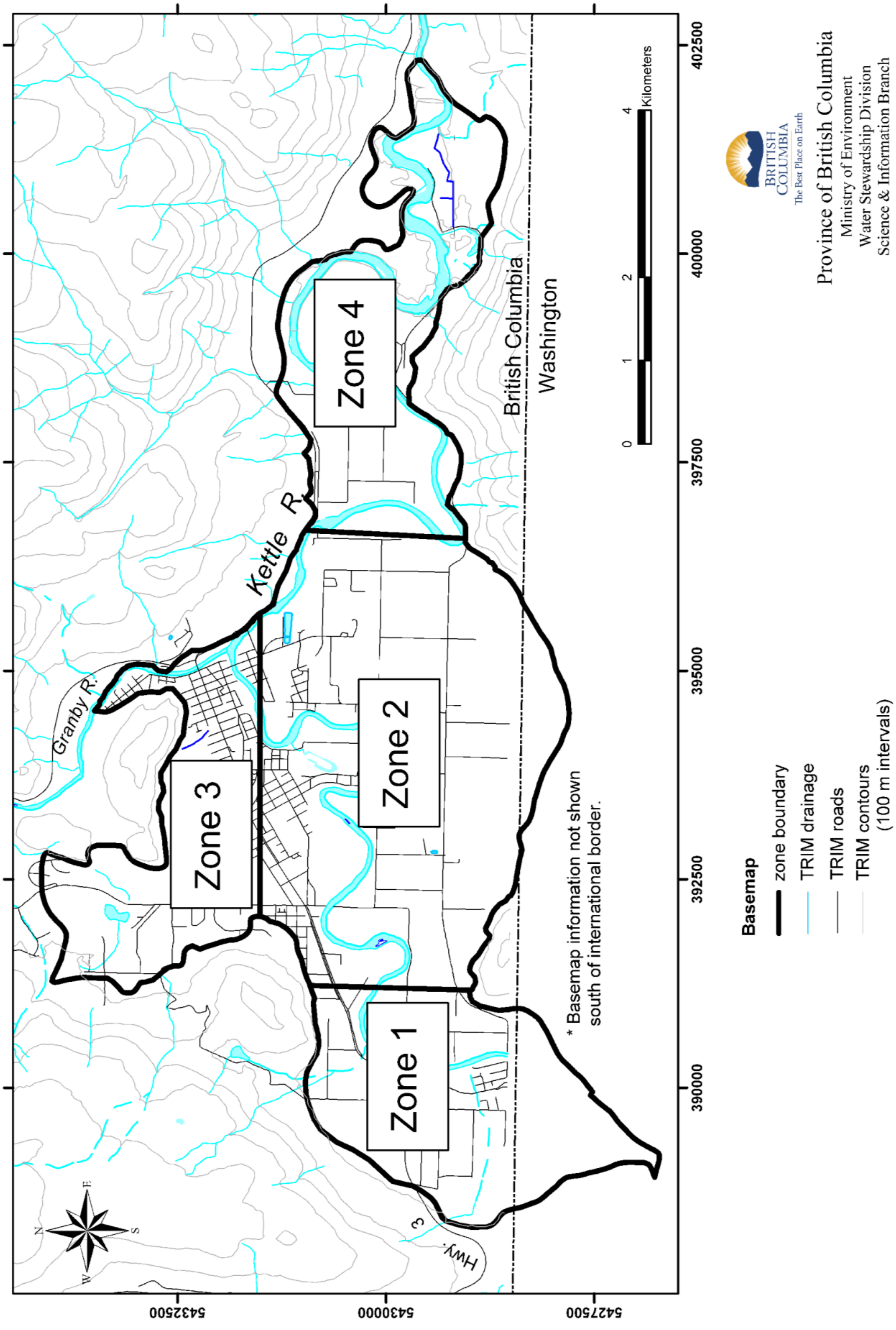


Figure18 **Map of the water budget zones for the numerical model.**

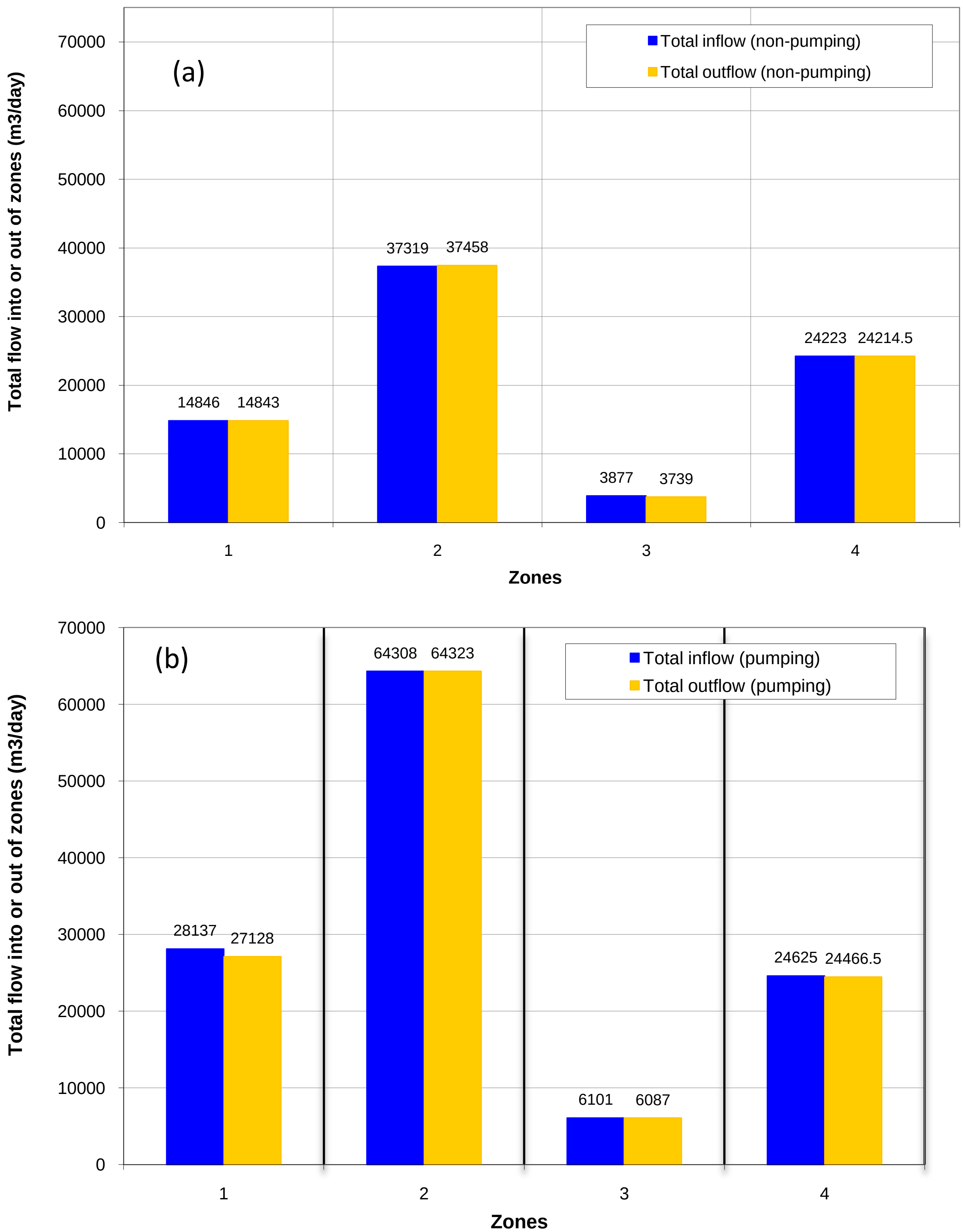


Figure 19 **Total water inflow and outflow for each zone under steady-state conditions (a) non-pumping and (b) pumping.**

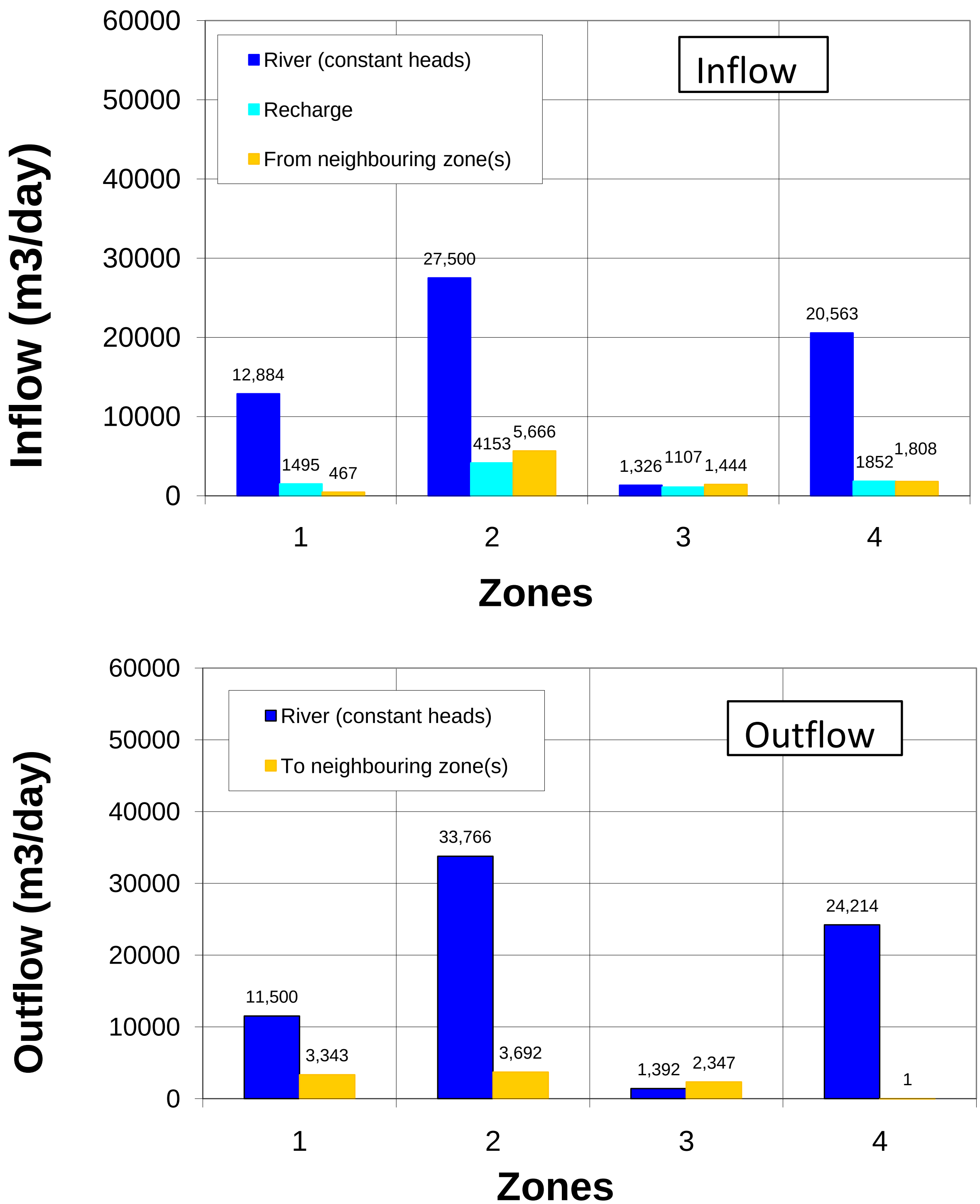
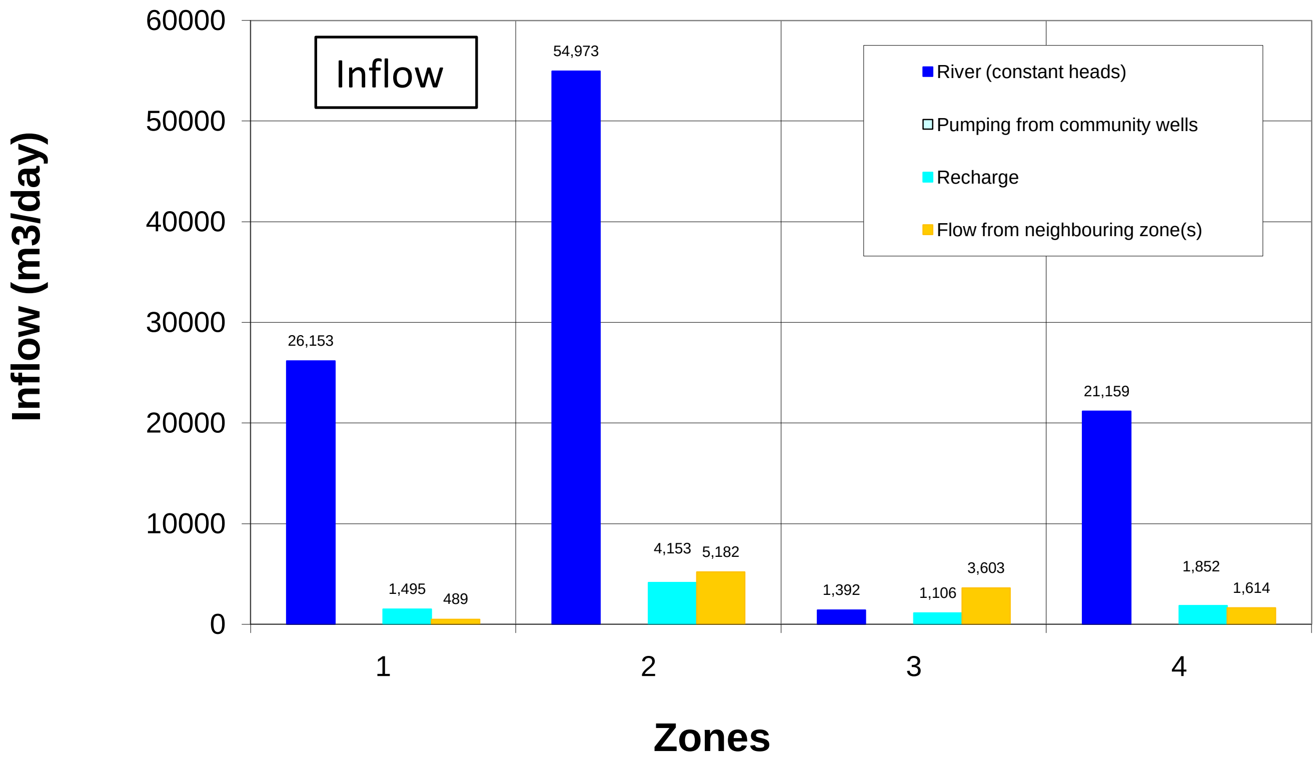


Figure 20 **Groundwater inflow to and outflow from each zone partitioned among the river (constant heads), recharge and groundwater flow from or to neighbouring zones - non-pumping conditions.**



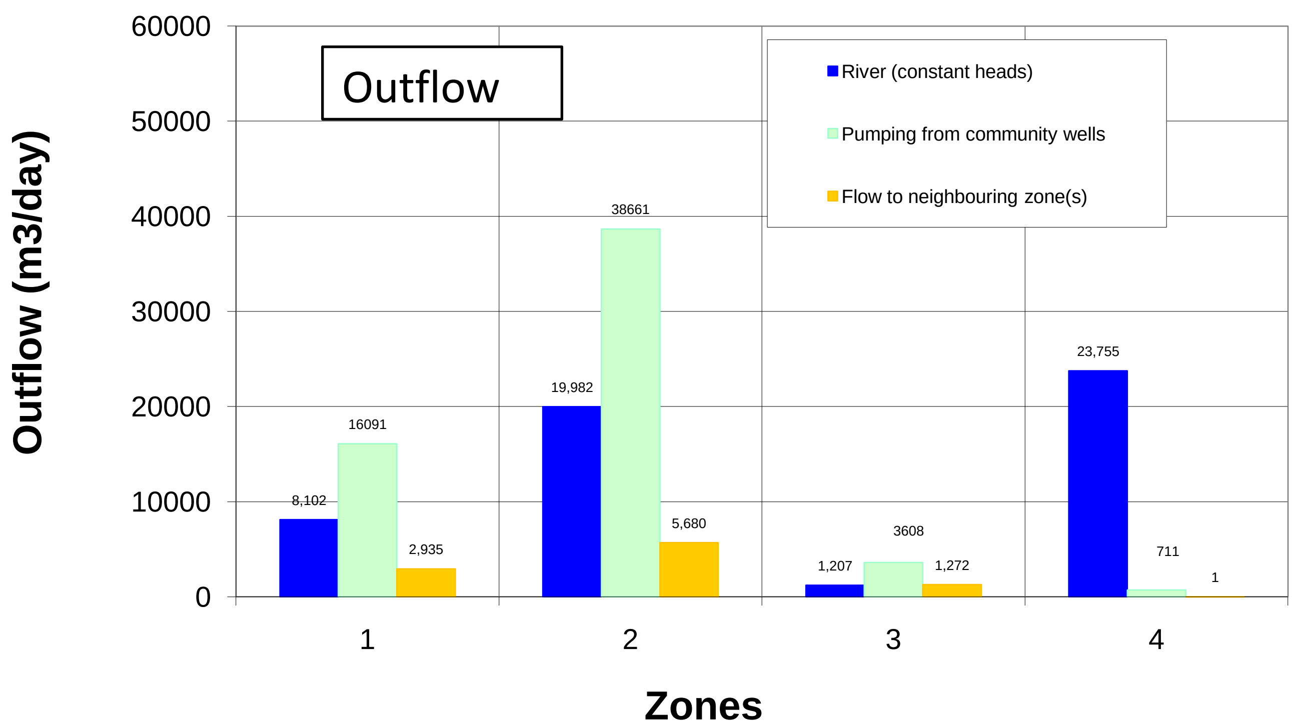


Figure 21 **Groundwater inflow to and outflow from each zone partitioned among the river (constant heads), evapotranspiration, recharge and groundwater flow from or to neighbouring zones - pumping conditions.**

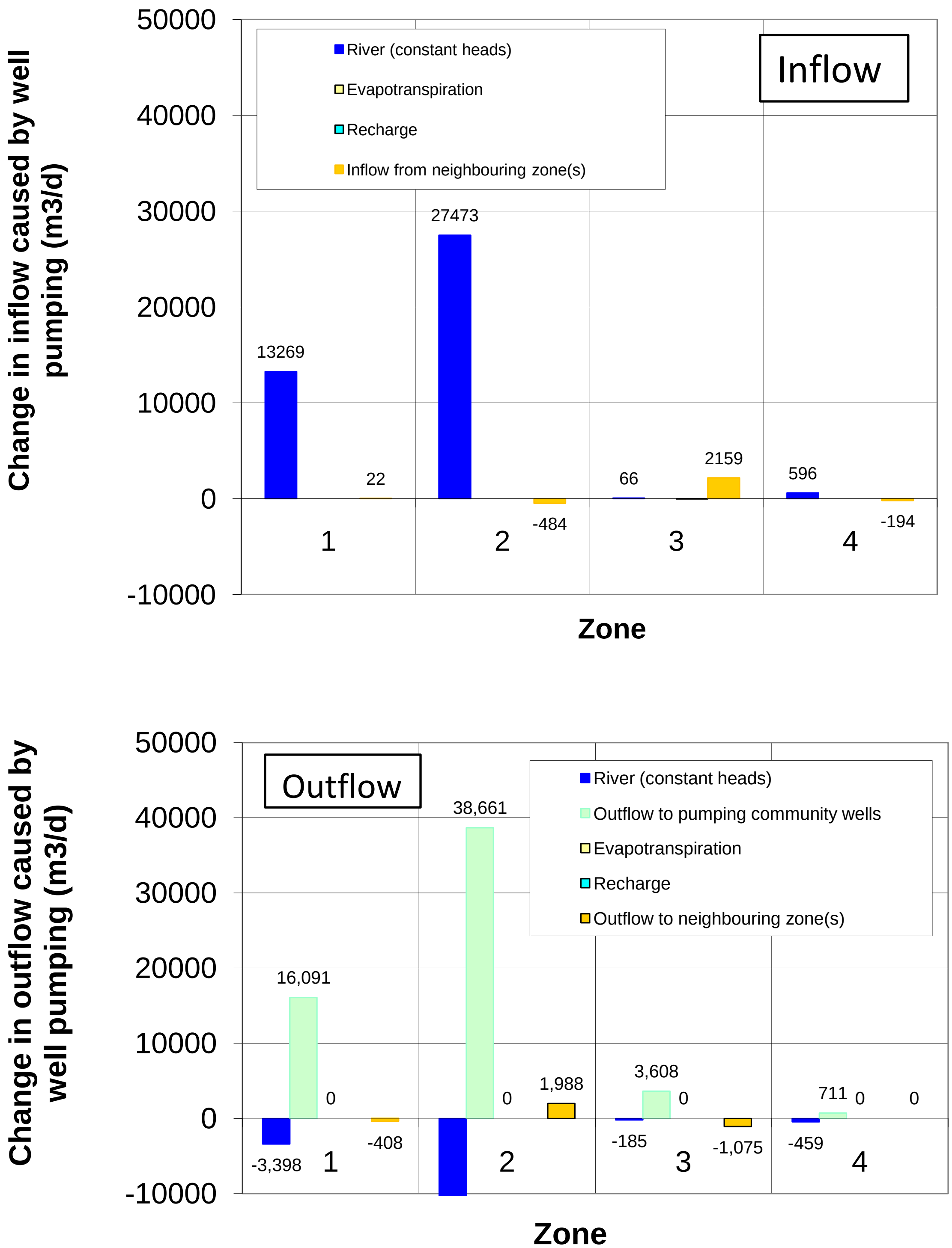


Figure 22 **Changes in inflow to and outflow from each zone as a result of pumping of community wells.**

3.5.2 Groundwater/Surface Water Interactions

There is evidence from the surficial geology, surface and groundwater water level elevations, pumping tests, the numerical groundwater model, and groundwater chemistry (discussed later in Section 3.6) that the Kettle River and Granby River and the underlying aquifer at Grand Forks are hydraulically connected. There is no extensive till or low permeability silt or clay material overlying the highly permeable sand and gravel in the river beds. The shallow, more permeable portion of the upper unit (i.e., the gravel layer) appears to be closely linked with the Granby and Kettle Rivers as evidenced by the corresponding rising and falling of water levels in shallow wells situated close to the rivers (Dakin, 1993; Scibek and Allen, 2004b). All wells completed in this shallow aquifer layer exhibit a static level approximately at river elevation, indicating that the groundwater regime is likely strongly linked to the surface water regime. Dakin (1988)'s pumping test of City of Grand Forks Well no. 5 shows that pumping water levels approach stabilization after a few hundred minutes of pumping (Figure 23), suggesting that the cone of drawdown had extended laterally and reached a source of recharge, which is likely the Kettle River.

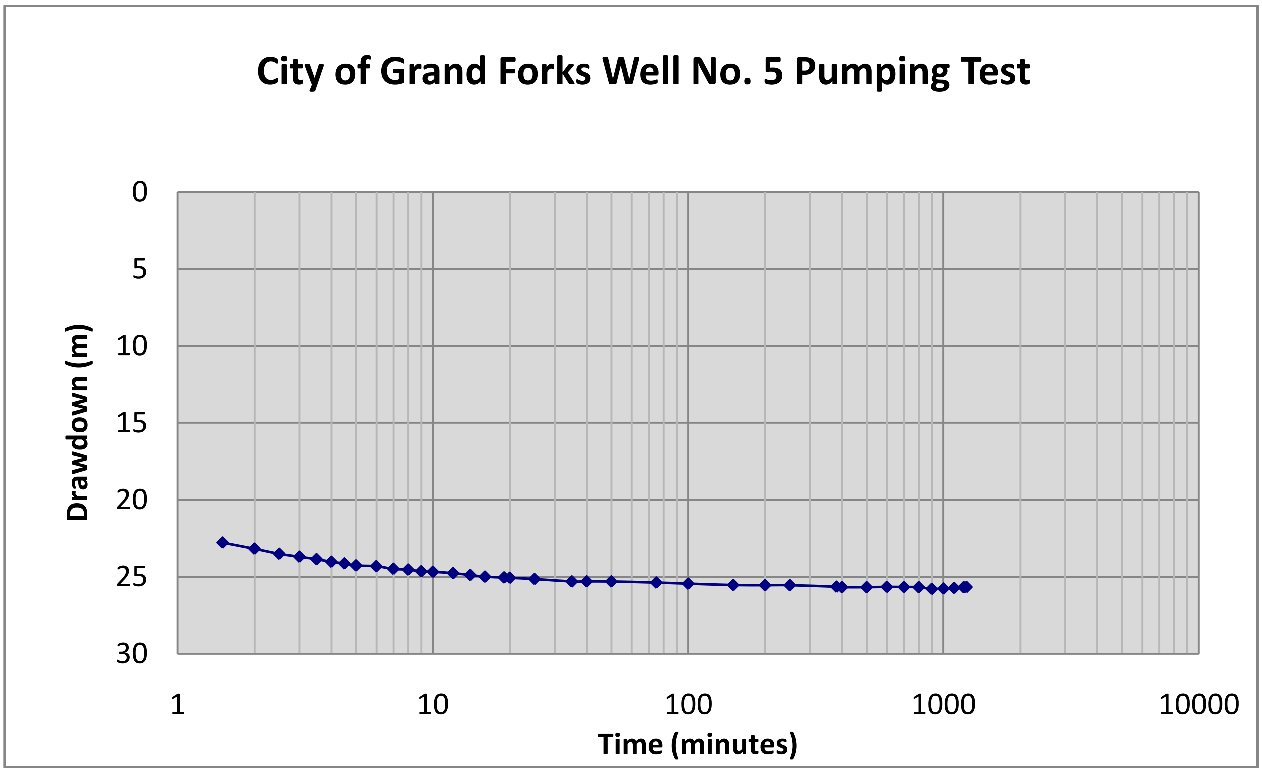


Figure 23 **Semi-log plot of drawdown in City of Grand Forks Well No. 5's pumping test.**

The groundwater hydrograph for Provincial Observation Well No. 217 displays a regular seasonal pattern, similar to the stage hydrograph of the Kettle River (Figure 24). The maximum groundwater level corresponds to maximum river stage during the spring freshet, with a time lag in the groundwater level of a few weeks. The lowest groundwater and river water levels occur during the winter months. The amplitude of seasonal groundwater fluctuations in Observation Well No. 217 shows a dampening effect (fluctuation does not seem to be as great as the Kettle River and the period of groundwater level peaks seem to be longer), which would be expected to increase with distance away from the river.

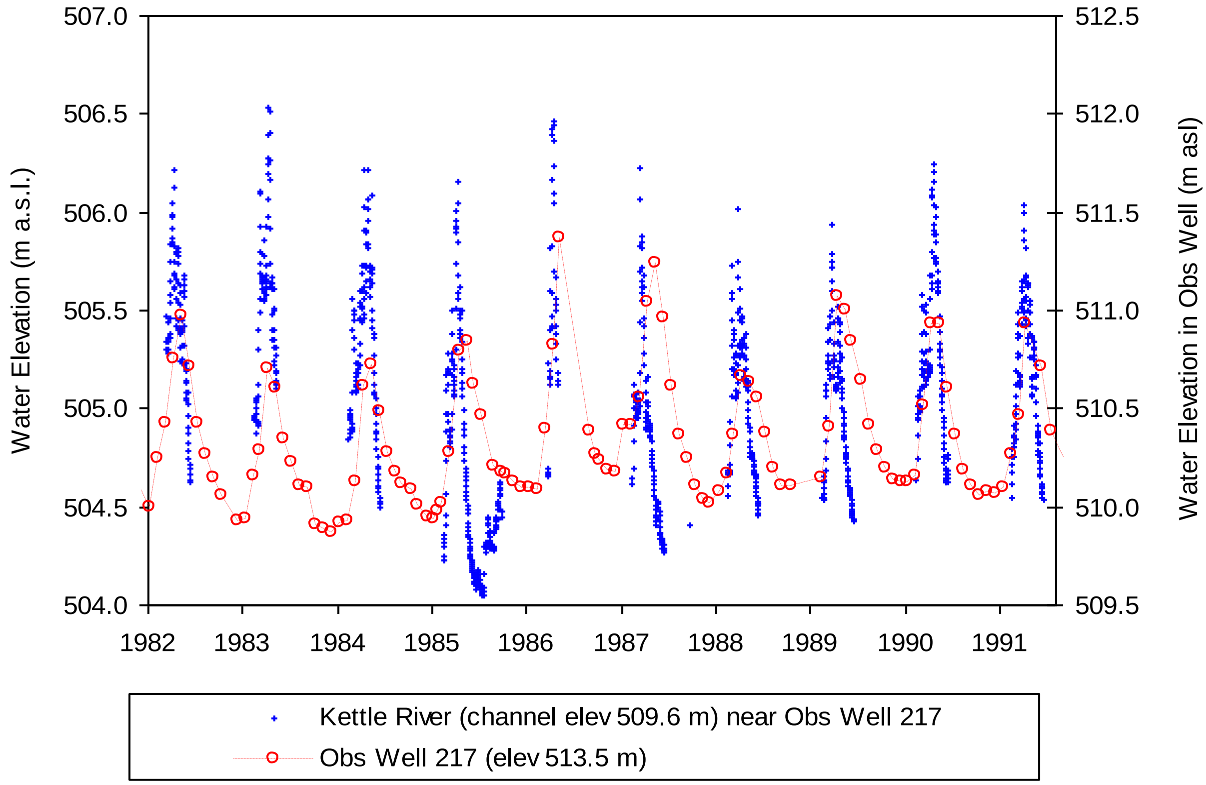


Figure 24 **Water elevations at Observation Well 217 and on the Kettle River (08NN024), for the selected period of record from 1982 to 1991.**

3.6 Groundwater Quality[10]

3.6.1 Ambient Groundwater Quality

Maps of general chemistry of the groundwater in the aquifer – total dissolved solids (TDS), specific conductance, hardness, total alkalinity, chloride, and nitrate-nitrogen – are presented in Figures 25 through 30, respectively. Methodology for their development is presented in Appendix 1. The water chemistry parameters are discussed below.

[10] Section 3.6 discusses the general groundwater quality characteristics of the aquifer and potential sources of nitrate only. Section 3.6 does not discuss the quality of the water supplied by the water supply systems in the Grand Forks area; for that information, the reader should enquire specifically with the water supply system or the Drinking Water Officer responsible for the Grand Forks area. Any reference to water supply system names in this section is done to refer to the area covered by the specific water supply system and not to the quality of the water supplied by the water supply system.

TDS: TDS is a measure of the amount of minerals dissolved in the groundwater. The TDS of groundwater in the aquifer ranges from a low of <50 mg/L to >700 mg/L with an average of 350 mg/L. Groundwater with TDS of <200 mg/L is generally found along the Kettle River (refer to Figure 25) and may indicate mixing of groundwater with less mineralized surface water. TDS of 300 – 400 mg/L is found in groundwater in the Covert Irrigation District, Sion Improvement District, in the Grand Forks Irrigation District, south of Carson and Cameron Roads and in the Nursery area. Groundwater with TDS of >500 mg/L is found near the junction of east Carson Road – Kenmore Road and locally in the Nursery area and reflects local groundwater quality impacted by agricultural activities (i.e., leaching of calcium, magnesium, nitrate, chloride to the groundwater from chemical fertilizers and lime applied to the soil, thereby increasing the total mineralization dissolved in the groundwater in those local areas). The Canadian Drinking Water Quality Guideline limit, based on aesthetic objective, for TDS is ≤500 mg/L.

Specific conductance: Specific conductance is a measure of how well the groundwater conducts electricity; this property is directly related to the amount of total dissolved solids in the groundwater. The greater the amount of dissolved minerals, the greater the specific conductance of the water generally. Specific conductance in groundwater in the aquifer ranges from a low of <100 μS/cm to 1,000 μS/cm with an average of 480 μS/cm. Groundwater with specific conductance of <250 μS/cm is generally found along the Kettle River (refer to Figure 26). Farther away from the Kettle River, the specific conductance varies from 250 to over 500 μS/cm. Groundwater with specific conductance of >750 μS/cm is found near the junction of east Carson Road – Kenmore Road and reflects local groundwater quality impacted by agricultural activities (i.e., leaching of calcium, magnesium, nitrate, chloride to the groundwater from chemical fertilizers and lime applied to the soil, thereby increasing the electrical conductance of the groundwater locally in that area).

Hardness: Hardness is a measure of the amount of calcium, magnesium, and iron in groundwater; the greater the amount of calcium, magnesium or iron, the harder the water. Hard water affects soap consumption and scaling of fixtures. Hardness in groundwater in the aquifer ranges from a low of about 50 mg/L (considered soft water) to over 500 mg/L (considered very hard water) with an average of about 300 mg/L (very hard). Groundwater with hardness of <200 mg/L is generally found along the Kettle River (refer to Figure 27). Groundwater with hardness of between 200 mg/L and 400 mg/L occurs in the Covert Irrigation District, Sion Improvement District, along North Fork Road, along Carson Road, and in the Nursery area. Groundwater with hardness of >400 mg/L is found near the junction of east Carson Road – Kenmore Road and reflects local groundwater quality impacted by agricultural activities (i.e., leaching of calcium and magnesium to the groundwater from chemical fertilizers and lime applied to the soil, thereby increasing hardness locally in that area). A comparison of Figures 25, 26, and 27 shows a strong correlation between TDS, specific conductance and hardness in the groundwater in Grand Forks.

Total Alkalinity: Total alkalinity reflects the buffering capacity of the water to acids. Total alkalinity in groundwater in the aquifer ranges from a low of <50 mg/L to 300 mg/L, with an average of 185 mg/L. Groundwater with total alkalinity of <200 mg/L is generally found along the Kettle River (refer to Figure 28). Total alkalinity of >200 mg/L is found in groundwater in the Covert Irrigation District, Sion Improvement District, along North Forks Road area, south of Carson and Cameron Roads and in the Nursery area. Wei et al. (1993) showed that the ratio of Total alkalinity to TDS decreases in areas of high nitrate-nitrogen concentrations. The relative decrease in total alkalinity in elevated nitrate areas may reflect a relative decrease in bicarbonate ions due to acidification of the local groundwater from formation of nitrate from ammonia.

Chloride: Chloride in groundwater in the aquifer ranges from a low of <5 mg/L to 50 mg/L. The median chloride concentration in Grand Forks is about 10 mg/L. Chloride concentration in most parts of the aquifer is <30 mg/L (see Figure 29). Elevated chloride concentrations of >30 mg/L near the junction of Carson Road – Kenmore Road reflect local groundwater quality impacted by agricultural activities (i.e., leaching of chloride to the groundwater from chemical fertilizers applied to the soil thereby increasing the chloride concentration locally in that area). The Canadian Drinking Water Quality Guideline limit, based on aesthetic objective, for chloride is ≤250 mg/L.

Nitrate-nitrogen: Nitrate is not known to occur naturally in significant amounts in groundwater in the province. The presence of nitrate in groundwater is, therefore, an interpreted to be from an anthropogenic source (e.g., fertilizers, septic systems, agricultural wastes). Nitrate-nitrogen in groundwater in the aquifer ranges from a low of <0.01 mg/L to >30 mg/L (Figure 30). The median nitrate-nitrogen concentration in Grand Forks is 3.4 mg/L. A plot of nitrate-nitrogen versus well depth shows that nitrate is generally highest in shallower wells, and nitrate concentration generally decreases with well depth (Figure 31). Wei et al. (1993) concluded that the natural background concentration of nitrate-nitrogen in the aquifer is likely <0.1 mg/L. Elevated nitrate-nitrogen concentrations >3 mg/L generally occur along the North Fork Road area, in the Grand Forks Irrigation District area, south of Carson Road and along Cameron Road, and in the Nursery area (refer to Figure 30). It is generally accepted that nitrate-nitrogen above 3 mg/L in groundwater reflects negative water quality impact from human activities. Areas where groundwater contains nitrate-nitrogen generally above 10 mg/L (above the Canadian Drinking Water Guideline, based on health objectives) are locally along Carson Road, east of the Big Y and south of Cameron Road and locally in the Nursery area.

The maps show that specific water chemistry parameters in groundwater do not occur independently of each other. For example, there is a high correlation between the distribution of chloride and nitrate-nitrogen in the groundwater at Grand Forks (Wei et al., 1993) because much of the chloride and nitrate are likely from the same anthropogenic source(s). In areas where nitrate-nitrogen is high, there also seems to be a relative decrease in total alkalinity. There are two implications here. Firstly, in assessing nitrate contamination in the aquifer, it is important to analyze for other inorganic chemicals. These data allow a more comprehensive interpretation of water quality impacts. Second, in developing a particular map theme, such as the chloride map, it is necessary to constantly refer to other related maps, such as nitrate-nitrogen and TDS to check that the contoured zones were consistent from one map theme to the other.

3.6.2 Source(s) of Elevated Nitrate

Elevated nitrate in the aquifer has been known since 1989 (Sather, 1989). The source of elevated nitrate in the aquifer is of interest because, if known, the occurrence of nitrate in the aquifer may then be more effectively addressed. Whether the nitrate is derived from agricultural activities or sewage disposal systems is, to-date, inconclusive. The following discussion is based on a land use survey by Sheppard (1995), and results of sampling of nitrogen and oxygen isotopes in 1991, 1993, and 2002 (Wei, 2001 and Allen and Bishop, 2004).

^{15}N isotope[11] analyses of well water samples collected from the network of piezometers and domestic wells for 1991, 1993 and 2002 generally indicate relatively low $\delta^{15}N$ values (median $\delta^{15}N = 3.2$ for samples from 1991, 4.0 from samples from 1993 and 4.8 for samples from 2002), suggesting the source of the nitrate is mostly from inorganic sources (e.g., fertilizers) and not from manure or septic effluent. The 1993 land use survey (Sheppard, 1995) and information from John Parsons of the then Ministry of Agriculture, Fisheries and Food also indicate that farmers in the valley use inorganic fertilizers and that the use of manure is not wide-spread. John Parsons (pers. comm., 2001) advised that 34-0-0 (ammonium-sulfate and urea), 21-0-0 (ammonium-sulfate) or 13-16-10 (ammonium-sulfate) fertilizers that are a mixture of ammonium-sulfate and urea or straight ammonium-sulfate are water soluble and used in the valley. Other farmers in the valley may also be using slow release fertilizers that are likely urea-based.

Some areas of higher density septic systems, such as the residential area near the Danville border crossing or at Almond Gardens, are not areas of elevated nitrate, while other areas where septic density is lower, such as the Big Y area have historically had elevated nitrate in groundwater. This suggests nitrate from septic systems is not the major source of nitrate contamination that has been observed.

[11] Nitrogen atoms generally have 14 neutrons. However, some (rare) nitrogen atoms have 15 neutrons. Nitrogen with 15 neutrons is an isotope of nitrogen. The relative abundance of nitrogen with 15 neutrons (^{15}N) compared to nitrogen atoms with 14 neutrons in the nitrate in groundwater has been used to infer the source of the nitrogen.

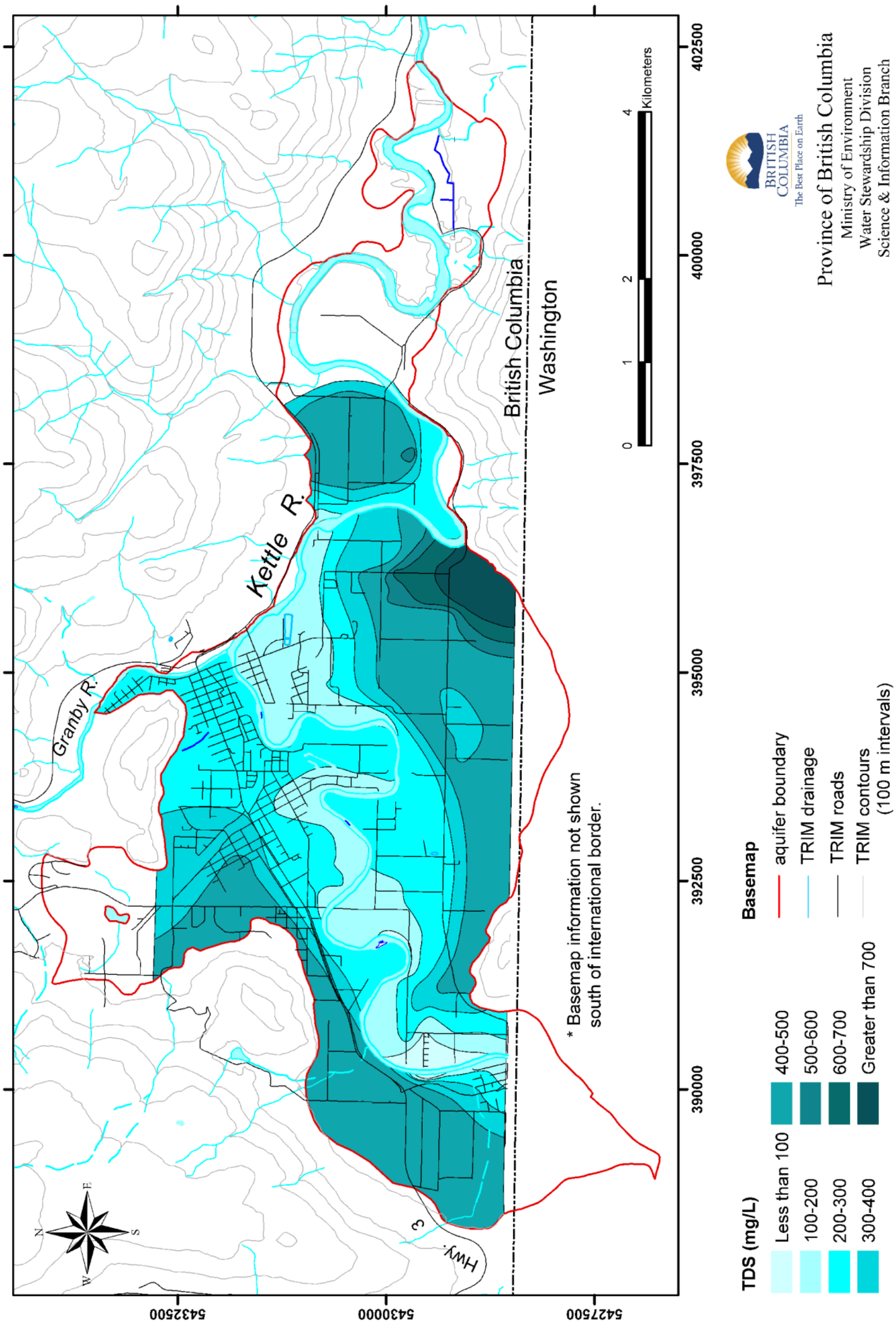


Figure 25 **Map of distribution of total dissolved solids in Grand Forks.**

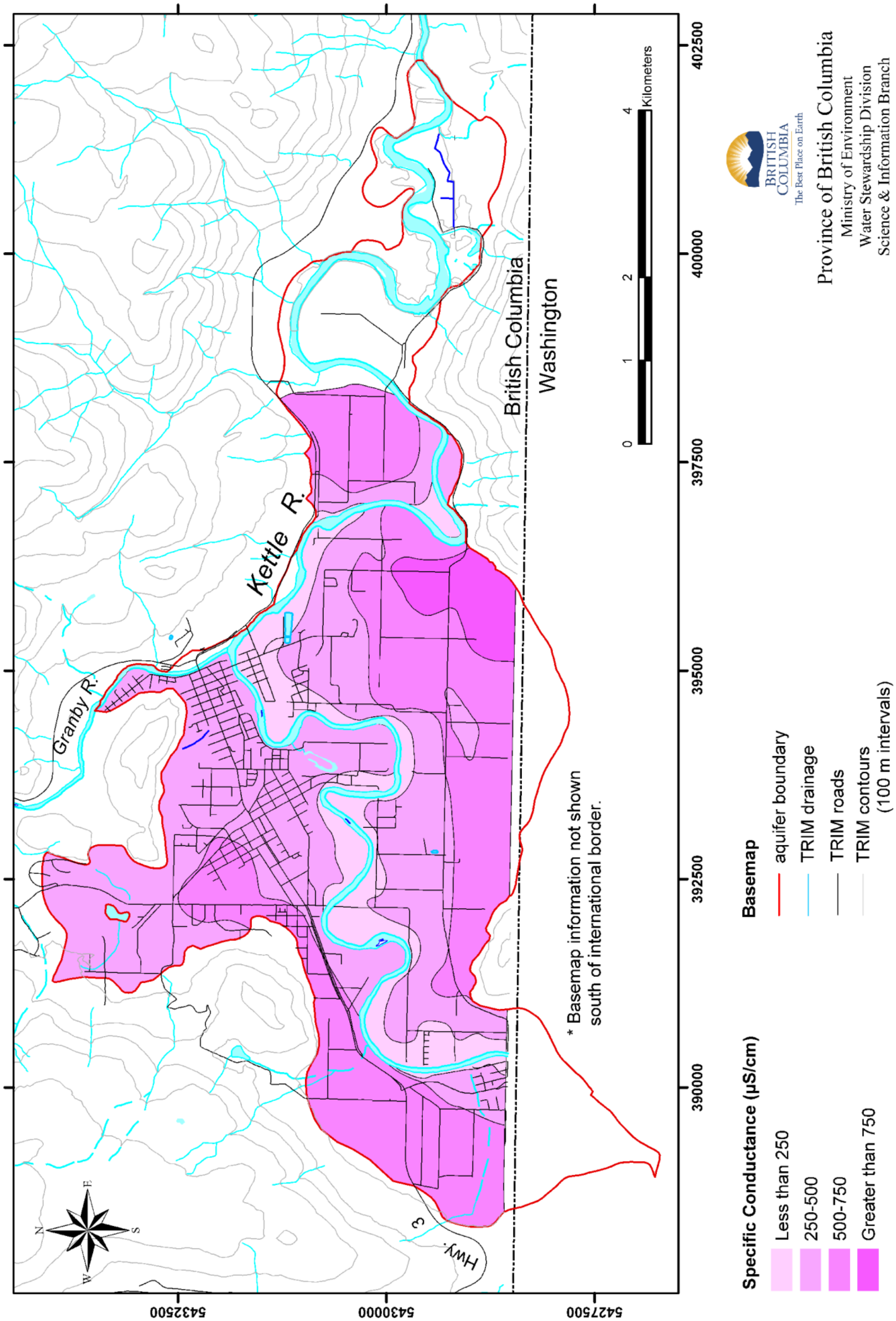


Figure 26 **Map of distribution of specific conductance in Grand Forks.**

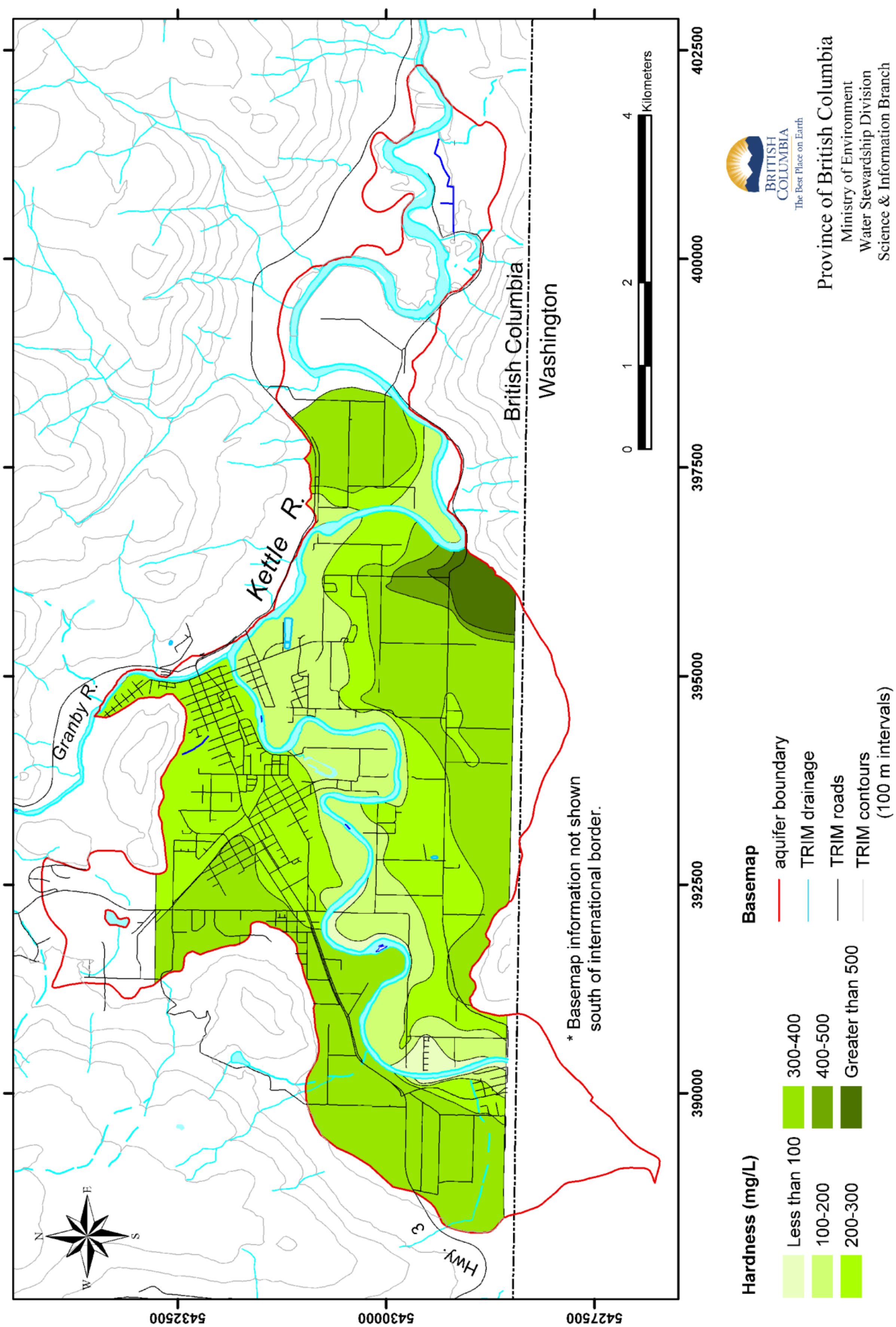


Figure 27 Map of distribution of hardness in Grand Forks.

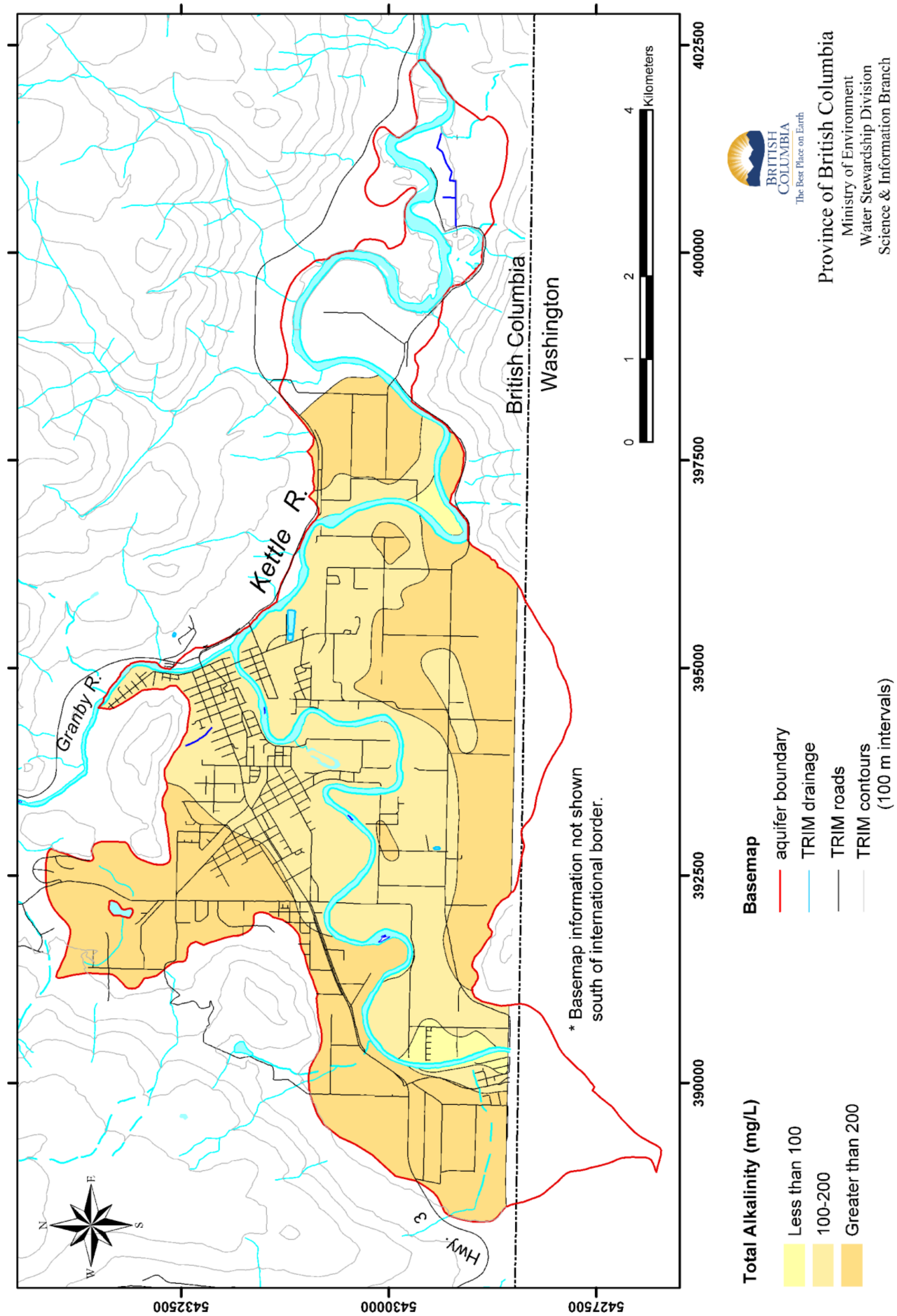


Figure 28 Map of distribution of total alkalinity in Grand Forks.

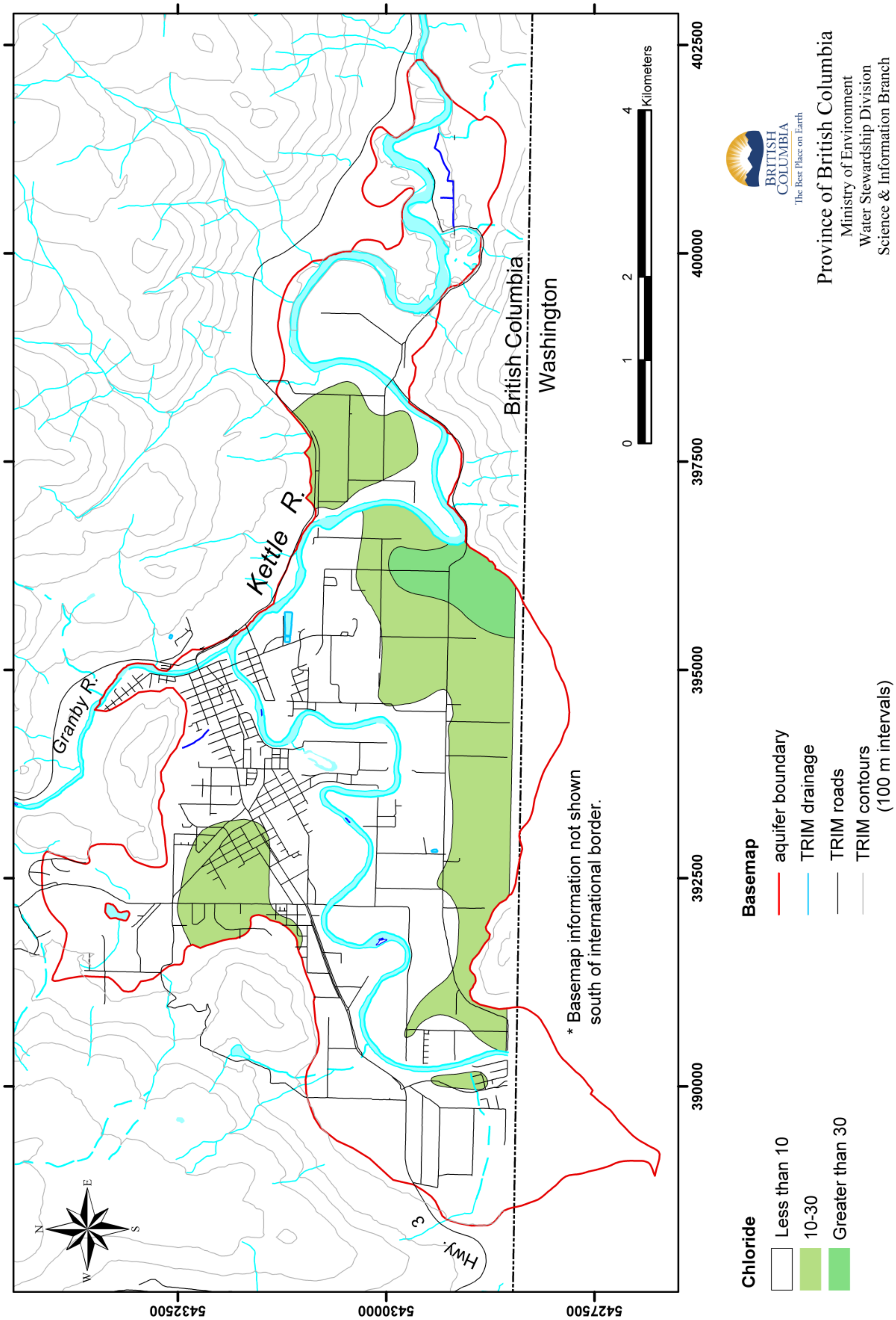


Figure 29 **Map of distribution of chloride in Grand Forks.**

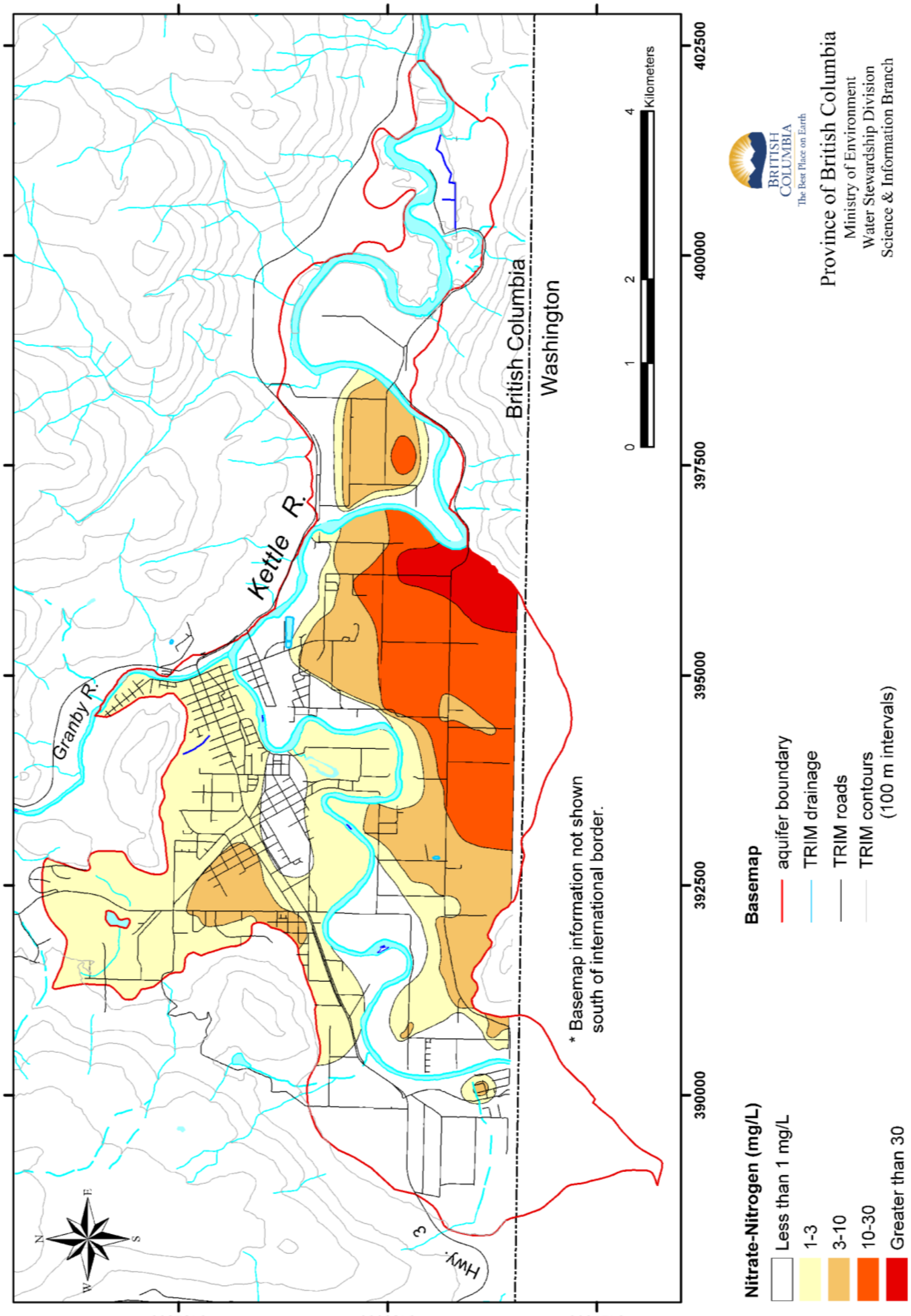


Figure 30 Map of distribution of nitrate-nitrogen in Grand Forks.

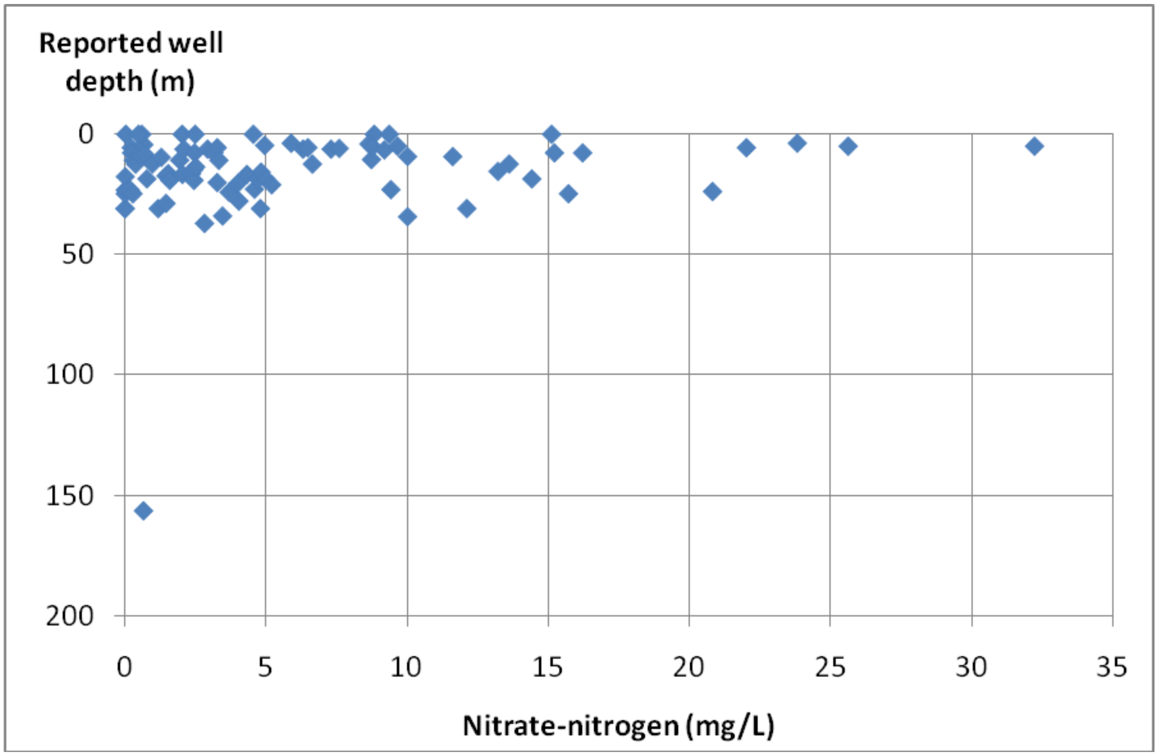


Figure 31 **Plot of nitrate-nitrogen versus reported well depth (adapted from Maxwell et al., 2002).**

However, ^{15}N and ^{18}O isotope[12] results from select samples from 2002 (Allen and Bishop, 2004) and 1993 (Wei, 2001) show that, isotopically, the nitrate in well water samples is slightly more enriched in ^{15}N and more depleted in ^{18}O than what is expected for inorganic fertilizers (see Figure 31). One possible explanation is that because urea fertilizers may be more commonly used, volatilization of NH_4 may occur. Volatilization will result in both the NH_4 and subsequent nitrification product, NO_3, becoming enriched in ^{15}N. Volatilization in combination with ^{18}O contributions from ^{18}O depleted groundwater may provide an explanation as to why the well water samples have an unusual isotopic composition if their source is synthetic fertilizer.

The ^{15}N and the low ^{18}O values are in the right range for a source of N from microbial oxidation of organic N (Dr. Schiff, pers. comm., 2003). In this instance, the nitrate would originate from the decomposition followed by nitrification of a manure source. The low ^{18}O values could be explained by variable contribution of ^{18}O of the groundwater. If the ^{18}O composition of the local groundwater is not the cause, then it has been observed at some locations that the pore waters themselves may be depleted (contrary to expectations). This hypothesis suggests that manure as a significant source of elevated nitrate in the aquifer cannot be ruled out, based on the limited isotopic data available.

[12] Similar to nitrogen, the relative abundance of oxygen with 18 neutrons compared to oxygen with 16 neutrons (in the nitrate) can be used to infer the source of the nitrogen.

To determine the source of elevated nitrate in the aquifer, Allen and Bishop (2004) and Wei (2001) suggest: 1) characterizing the isotopic make-up of fertilizers commonly used in the valley, 2) examining in greater detail, the land use, fertilizer practices and groundwater flow patterns in the piezometer area to better understand the source of nitrate locally, and 3) measuring ^{18}O in water (in addition to ^{18}O in the nitrate) from selected piezometers, to characterize the ^{18}O composition of the groundwater to help interpret the isotopic results.

Although the source of elevated nitrate in the aquifer cannot be conclusively determined, it is generally accepted that the source is from human activities and is not naturally occurring. In the absence of proving up a definitive source, it would be prudent to focus public awareness and education, plus best management practices on both agricultural and sewage disposal activities to generally minimize the overall potential loading of nitrogen into the aquifer from all possible sources.

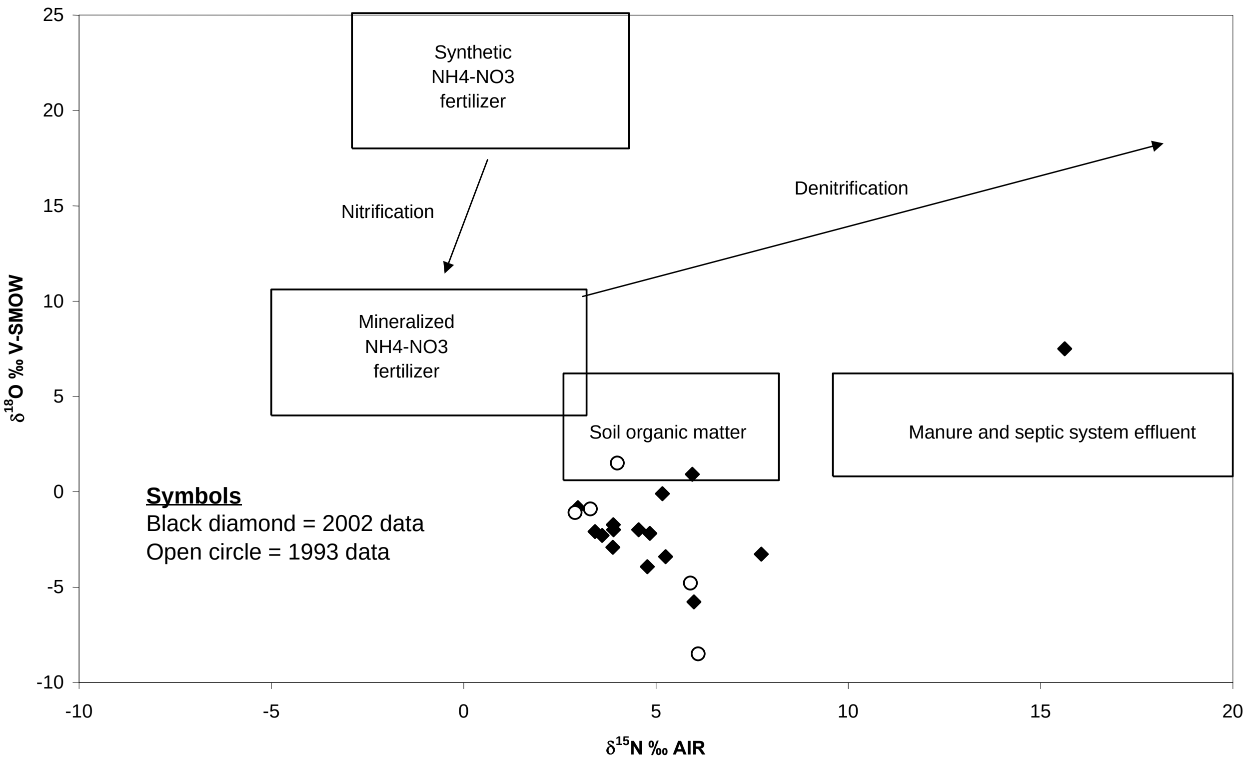


Figure 32 Isotopic composition of Grand Forks well water samples.

3.7 Intrinsic Aquifer Vulnerability

The susceptibility or vulnerability of an aquifer to impacts from human activities at the land surface is governed by the types and thicknesses of sediments overlying the aquifer, the amount of recharge to the aquifer, and the type and intensity of human activities over the aquifer. Human activities can change over time but the types and thicknesses of overlying sediments and the amount of recharge, which govern the degree of vulnerability intrinsic to the aquifer, generally do not change (unless the area is re-landscaped). An aquifer that is confined above by clay, silt or till would be regarded as generally less vulnerable than an aquifer that is unconfined. An aquifer located in an area of high precipitation (and greater recharge) would be considered generally more vulnerable than the same aquifer in a dry climate with little precipitation (and lesser recharge).

The intrinsic vulnerability of the aquifer at Grand Forks was mapped using USEPA's DRASTIC method (Aller et al., 1987). The term "DRASTIC" reflects the seven physical parameters considered by the USEPA in quantifying an aquifer's intrinsic vulnerability:

- **D**epth to the water table or to the aquifer
- **R**echarge
- **A**quifer material
- **S**oil material
- **T**opographic slope
- **I**mpact of the vadose (unsaturated) zone and
- **C**onductivity (hydraulic conductivity) of the aquifer.

The DRASTIC methodology is discussed in Appendix A. Figure 33 shows the DRASTIC vulnerability map for the aquifer. The orange and red colours denote areas where the DRASTIC index is greater than 160 and where the aquifer is considered highly vulnerable to contamination. Areas considered highly vulnerable to contamination occupy much of the aquifer, with the highest DRASTIC areas located east of the Grand Forks Irrigation District and in the Nursery area. The extremely high DRASTIC areas in the eastern portion of the aquifer are thought to be due to shallow depths to groundwater in those areas. The extent of the highly vulnerable area, surrounded by moderately vulnerable areas (DRASTIC index of 120 – 160) is consistent with the overall unconfined nature of the aquifer. Areas of low vulnerability (DRASTIC index of <120) are extremely few and are located just east of Ward Lake and along the western edge of the aquifer where the water table is deep and the land is not irrigated (less recharge from irrigation return flow). The unconfined nature determines the overall high vulnerability of the aquifer because the lack of confinement directly affects Impact of Vadose Zone, Recharge to the aquifer and Soil material in calculating the DRASTIC Index.

The influence of irrigation return flow, depth to water, and topography on the DRASTIC results can be seen from the DRASTIC map. In the Grand Forks Irrigation District area, return flow from irrigation has increased the DRASTIC vulnerability index. For example, the area directly south of the Canada-USA border and the property south of Carson Road and east of Seminoff Road that are not irrigated have a slightly lower DRASTIC vulnerability than the adjacent areas that are irrigated. Clearly this difference in vulnerability is due to increased return flow in irrigated areas. The effect of depth to water is evident in the Covert Irrigation District on the west side of the Kettle River near the Danville border crossing. This portion of the aquifer is characterized by a relatively deep water table, resulting in a slightly lower vulnerability rating than the area east of the Kettle River where the water table is shallower. Finally, there are areas along terrace slopes, such as the slope in the land surface just north of the airport, north of Almond Gardens Road past Cooper Road, or at the south boundary of the aquifer southwest of the Big Y where the vulnerability rating is slightly lower than in adjacent flatter areas. This is due to the fact that sloping areas have a lower "T" Rating, resulting in a lower DRASTIC index.

In interpreting the DRASTIC map, there are several issues to keep in mind. Firstly, because the Recharge rating considered irrigation return flow, the DRASTIC rating is some areas may change slightly, depending on whether irrigation practices change over time. For example, if land use in areas currently being irrigated changes in the future to where irrigation is not practiced, the vulnerability may decrease. Another issue to remember is that data for many of the DRASTIC parameters (i.e., Recharge to the aquifer, Soil material, Topography, hydraulic Conductivity of the aquifer) are derived from regional the mapping or assumed data. Therefore the DRASTIC map should not be used for quantifying vulnerability at the site scale. Finally, the DRASTIC map portrays the intrinsic vulnerability of the aquifer only. In assessing threats to pollution, information on land use, land use practices, and location and nature of potential sources of contamination also need to be assessed (see Section 3.9).

3.8 Capture Zones for Major Community Groundwater Supplies

The location of community wells with their modelled capture zones are shown in Figure 34[13]. A capture zone is defined as the area of the aquifer that provides water to a pumping (community) well. Typically, a well's capture zone does not occupy the entire aquifer, but rather only a smaller portion of the aquifer around or near the pumping well. Although the entire aquifer contains groundwater, only that smaller portion around or near a pumping well typically provides water directly to that particular well. A main factor governing the size of a capture zone is the pumping rate for the well. The greater the pumping rate, the greater the size of the capture zone that pumping well generates (everything else being equal). The capture zones in Figure 34, shows up to three zones – the area within which groundwater takes up to 5 years to reach the pumping well, the area within which groundwater takes 5 to 10 years to reach the pumping well, and the area within which groundwater takes 10 to 25 years to reach the pumping well. These time-of-travel areas show the time it would take for water (or potential non-reactive contaminant) to reach the well. Since the capture zones in Figure 34 were determined based on the numerical groundwater model, they are considered more physically representative than the circular and parabolic capture zones determined using more simplified water balance and analytical calculations by Wei (1999).

[13] The Copper Ridge well was not part of the model and thus, its capture zone is not shown in the figure. Wei (1999) calculated a 10-year fixed radius capture zone for the Copper Ridge well to be 550 m. Also not shown in the figure are the capture zones for the Kettle River Place MHP, Riviera RVP, and West Grand Forks MHP wells (capture zones are too small) and the recently drilled Sion Production Well No. 6.

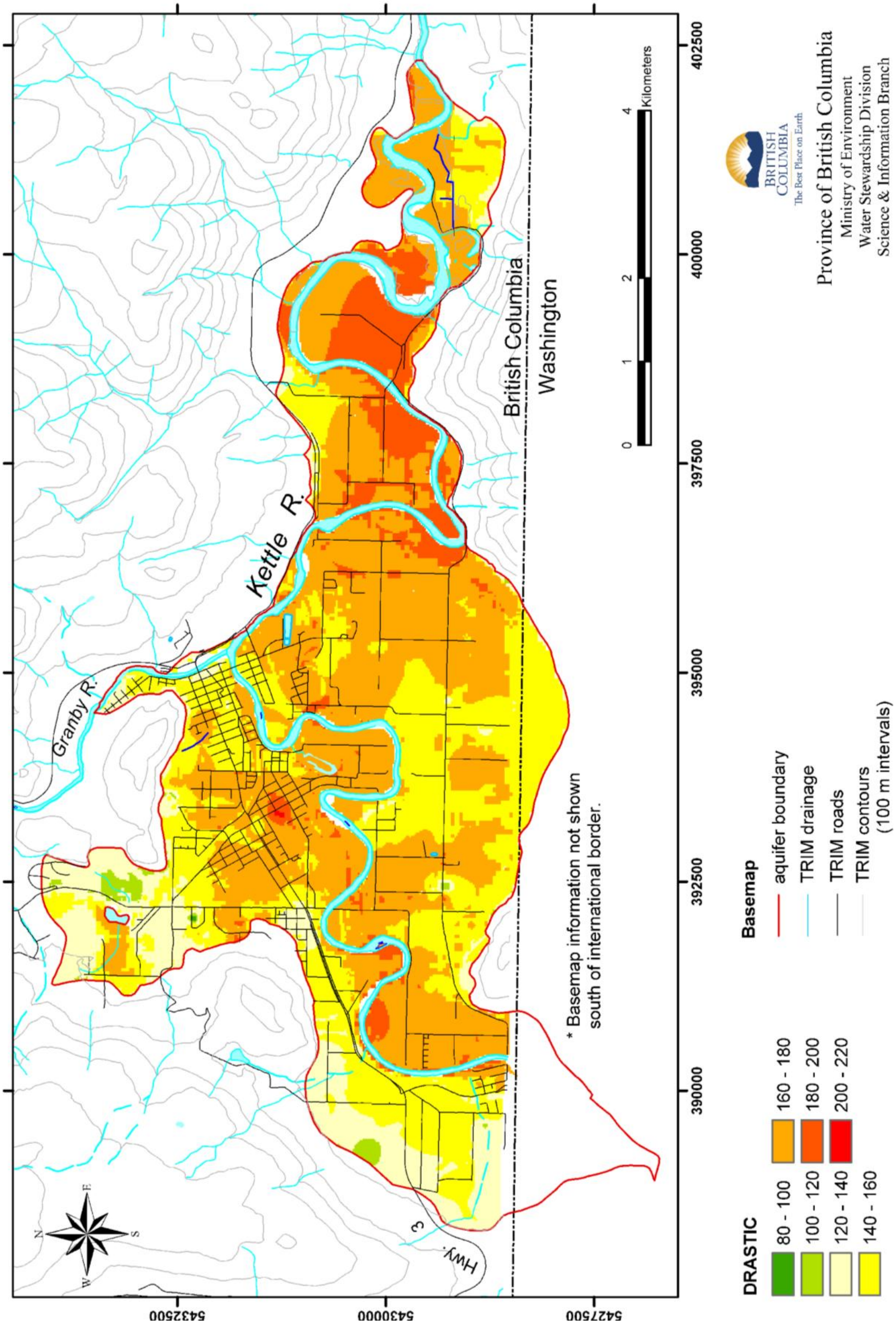


Figure 33 DRASTIC intrinsic aquifer vulnerability map.

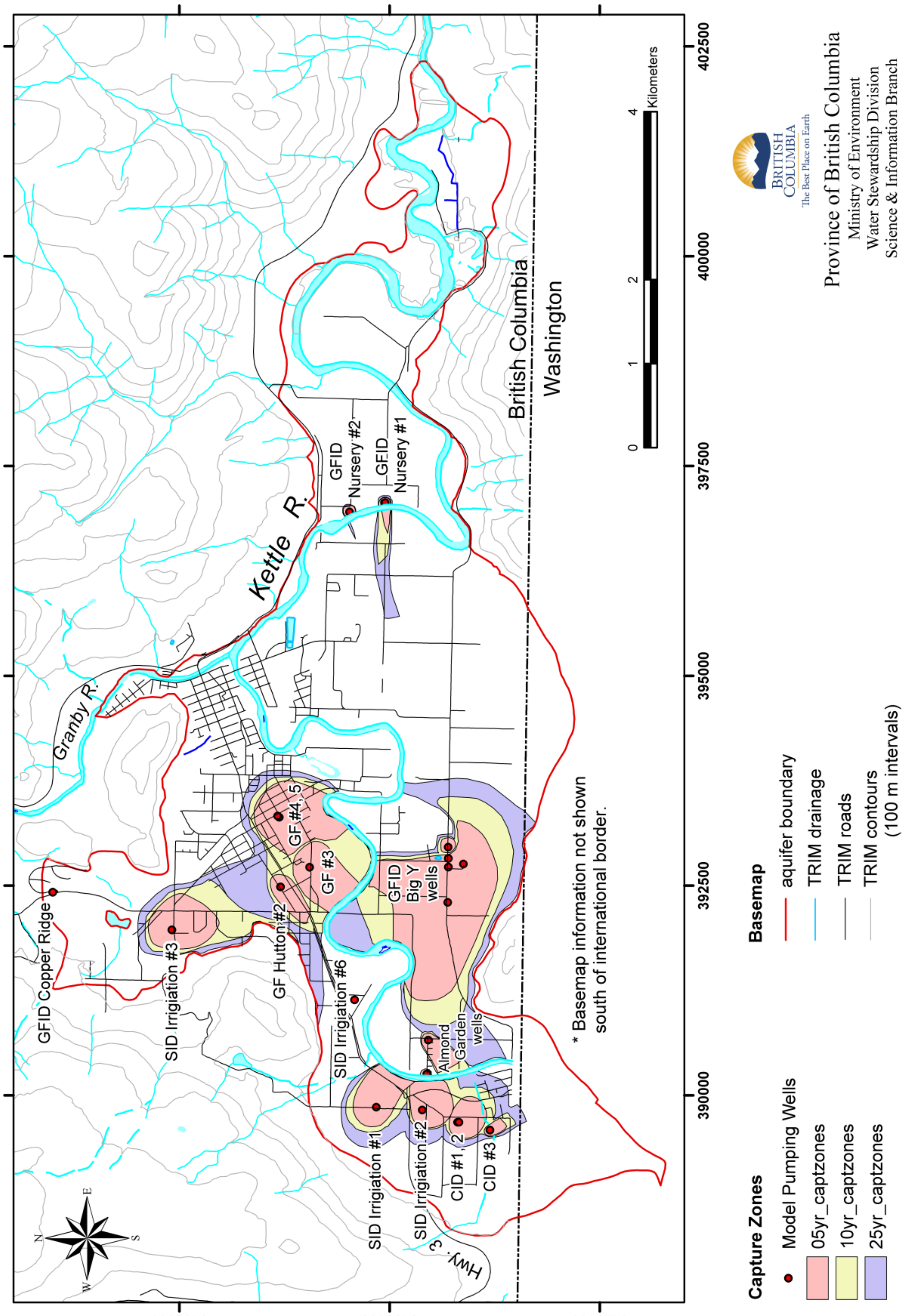


Figure 34 Modelled capture zones for the major community wells in Grand Forks

For the most part, the capture zones are relatively circular in shape and extend predictably in a radial direction away from the well, with a slight tendency to tail back up gradient. The generally circular shape of the capture zones reflects the isotropic nature of the aquifer (in the horizontal direction) and the low ambient hydraulic gradient. For many of the community wells in Grand Forks, the capture zones also extend to the Kettle River and reflects the interpretation that these community wells derive their water directly from induced infiltration of surface water from the Kettle River into the aquifer. The Almond Gardens MHP wells and the GFID Nursery #2 well are so close to the Kettle River that the ultimate travel times of water in those capture zones are less than 25 years, and even less than 5 years. Interestingly, the modelled capture zones for the Grand Forks Irrigation District Nursery wells do not terminate at the Kettle River, but rather, extend underneath the river to the aquifer on the other side. This implies that even though a significant amount of water to the pumping wells is derived from surface water, some groundwater from the other side of the Kettle River can also be drawn underneath the river, toward those pumping wells (see Figure 35).

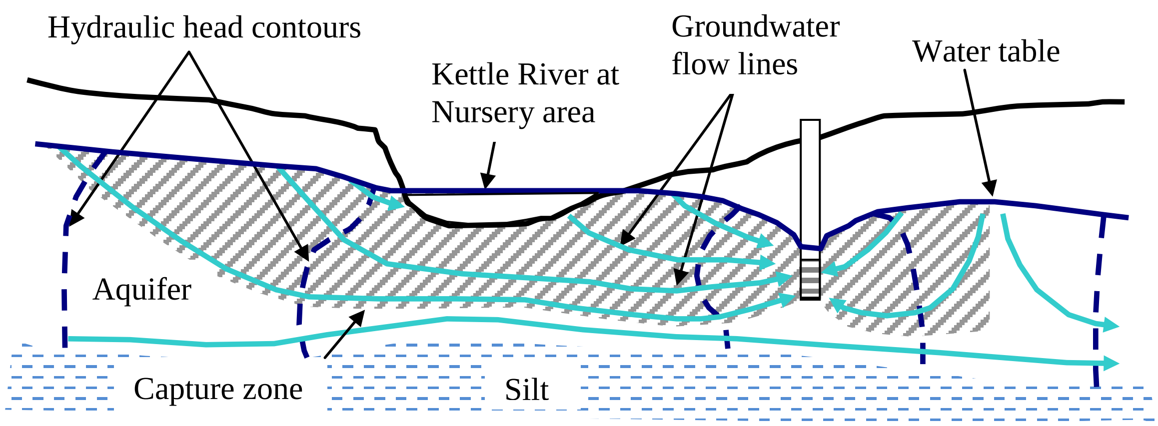


Figure 35 **Schematic cross-section (looking north) at the Nursery area, showing the GFID Nursery well pumping and capturing water from the Kettle River and also some groundwater from the other side of the Kettle River.**

Another observation is that the 25 year time-of-travel boundaries for capture zones for the City of Grand Forks and the Sion Improvement District well no. 3 coalesce and occupy a significant portion of the western half of the aquifer north of the Kettle River. The capture zones for Sion Improvement District well no. 2 and the northernmost Covert Irrigation District wells also coalesce. This suggests that community wells that share common capture zone areas could work cooperatively and pool their energy and resources to protect their well water supplies. As a significant portion of the aquifer is highly vulnerable to contamination from the land surface (see Figure 33), development of protection measures in these capture zone areas should be considered a high priority.

3.9 Groundwater Protection Issues in the Capture Zone Areas

Once the capture zones have been delineated, they help mark protection areas within which groundwater quality issues can then be identified and addressed by the water supply systems. By comparing the DRASTIC vulnerability map in Figure 33 with the capture zones in Figure 34, one can see that the capture zones for the Sion Improvement District and Covert Irrigation District wells occupy areas that are mostly of moderate vulnerability (DRASTIC scores of between 120 and 160 – deeper water table). On the other hand, capture zone areas for the Almond Garden wells, the GFID Nursery wells, and City of Grand Forks well nos. 3, 4 and 5 are mostly high in vulnerability (DRASTIC scores of >160 – shallow water table). Capture zones for the GFID Big Y wells and City of Grand Forks well no. 2 occupy areas of mixed moderate and high vulnerability.

Atkinson and Sacre (2005) conducted a contaminant inventory and subjectively assessed the risk of the various land uses mapped by Sheppard (1995) for the entire aquifer. The subjective risks of the various land uses compiled by Atkinson and Sacre (2005) are shown in Figure 36. Also shown in Figure 36 are the location of wells in the WELLS database and the time of travel boundaries for the modelled capture zones. Although the information in Figure 36 may not be complete with respect to all potential sources of pollution (i.e., inventory of contaminated sites and spills) and may have changed over time (i.e., land use and land use practices and new major wells), the discussion is still useful in illustrating the various issues that exist and how groundwater quality issues vary from one capture zone area to the next. The discussions will focus on four capture zone areas to illustrate the issues and differences: for the Covert Irrigation District and Sion Improvement District wells at the western end of the aquifer, the Sion Improvement District's well no. 3 at the north end of the aquifer, for the City of Grand Forks wells, and for the GFID Big Y wells.

Covert Irrigation District and Sion Improvement District wells at the western end of the aquifer: Inspection of the information within the capture zones for the Covert Irrigation District wells and Sion Improvement District wells 1 and 2 shows the subjective land use risks are mostly low to moderate. The only high risk activities are: a small feedlot, retailing, and area for treating/disposal of solid waste. Since both water systems have relied on community sources of water through its history, the only other water supply wells in the capture zones are in the Danville border crossing area (e.g., there are a total of 21 reported wells within the 5-year time of travel capture zones of the Sion and Covert wells – a well density of 0.27 well/ha), and most of those wells should be still in use.

Sion Improvement District well at the northern end of the aquifer: The subjective land use risks for the Sion well is low to moderate. The aquifer supplying groundwater to this well is also confined. There are 26 reported wells within the 5-year time of travel capture zone of this well, however, these other wells are south of Hardy Mountain Road and east of North Fork Road, outside of the water system boundary and most of those wells should still be in use.

City of Grand Forks wells: The subjective land use risks for the City of Grand Forks wells are mostly low to moderate; the only high risk activity is retailing. The number of private individual wells in the capture zone areas is low and mostly in the low-lying areas adjacent to the Kettle River, south of 66th Avenue (e.g., there are a total of 18 reported wells within the 5-year time of travel capture zones of the City of Grand Forks wells – a well density of 0.15 well/ha). However, a unique issue is there are three contaminated sites associated with former gasoline stations (near 19th Street and Highway 3 – not shown in Figure 36) that exist in the capture zone for the City of Grand Forks wells 4 and 5.

GFID Big Y wells: In contrast with the above areas discussed, the capture zone area for the GFID Big Y wells cover significant areas of land use deemed by Atkinson and Sacre (2005) to be high risk; these include: commercial nurseries (growing ornamental shrubs and trees), storage and assembly areas, and small feedlots. The commercial nurseries take up a significant percentage of the area within the 25-year time-of-travel capture zone boundary. An issue unique to the GFID Big Y capture zone area is the fact that it overlies a part of the aquifer where groundwater contains elevated concentrations of nitrate (actual groundwater quality issue, not just potential risks). The presence of elevated nitrate in groundwater underlines the need to monitor and assess the nitrate concentration in the GFID Big Y wells.

Another issue is the number of private wells in the capture zone area (e.g., there are a total of 70 reported wells within the 5-year time of travel capture zones of the GFID Big Y wells – a well density of 0.38 well/ha). The GFID historically relied on the Kettle River for irrigation supply and residents had dug or drilled wells for their own private domestic supply. That started to change when the GFID wells came into production in the late 1980's. Residents in the GFID area had the opportunity to hook up to the GFID water supply system and over the years, more and more residents did this, especially as some of them became concerned about elevated nitrate in the local groundwater. By comparing the well locations plotted on a cadastral map against information on which property is hooked up to the GFID water supply system, one can then infer which of the private wells may still be in use and which have likely been abandoned. The issue of potential abandoned wells is not only limited to the GFID Big Y capture zone area but also to the GFID areas east of the capture zone, in the GFID Nursery area, and in the Johnson Flats area where residents relied on shallow wells for water supplies. Wells that have been abandoned may not necessarily be properly deactivated or closed in accordance with the Ground Water Protection Regulation. Abandoned wells can provide a direct conduit into the aquifer for any contaminants that may be present at the wellhead (e.g., floodwaters, sewage effluent, toxic chemicals improperly stored in proximity to an abandoned well). If abandoned wells are left without being deactivated or closed, they may become overgrown, partially buried and forgotten over time.

Finally, there may be other risks that cannot be portrayed on maps and require an on-site inspection of the wellhead and capture zone area. Risks such as improperly stored fuels or chemicals in proximity to wells can be identified on the ground via an inspection of the wellhead area.

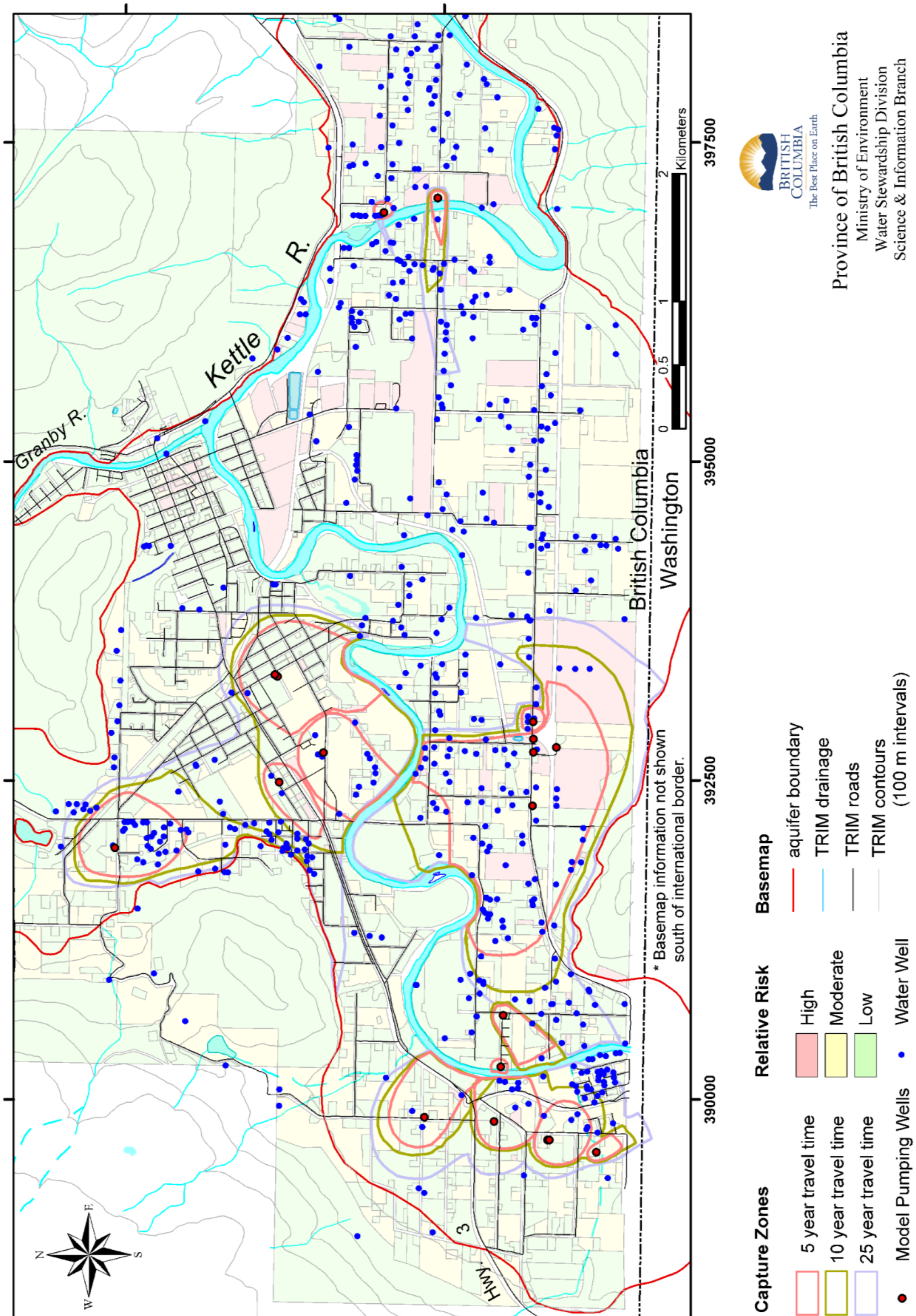


Figure 36 **Map of subjective risks for land use (from Atkinson and Sacre, 2005), reported wells and modelled well capture zones.**

4 Conclusions and Recommendations

A glaciofluvial sand and aquifer underlies the community of Grand Forks and provides good quality groundwater to the residents there for drinking and irrigation water. The use of the aquifer dates back at least 50 years (1960's) and possibly earlier. The aquifer is not only a provincially important aquifer (classified as an IA aquifer[14]) but is a vital part of the natural heritage of the local community and region.

The aquifer is largely unconfined at the top and underlain below by mostly a thick layer of silty sand and clay. The aquifer is highly productive, with a median reported well yield of 220 m^3/d, well specific capacities of up to hundreds to thousands of m^3/d/m and transmissivity values of up to thousands and over 10,000 m^2/d (geometric mean of 3,700 m^2/d - Table 2). Ambient groundwater flow in the aquifer is generally from the west towards the east, the same general direction of flow as the Kettle River (Figure 15). Groundwater flow direction is heavily influenced by large pumping community wells (Figure 17). The aquifer is thickest in the western end of Grand Forks (saturated thickness of up to 100 m) and thins toward the east (saturated thickness of <20 m – Figure 14).

The aquifer is believed to be in close hydraulic connection with the Kettle River. Groundwater level elevations in wells and direction of ambient groundwater flow (under non-pumping conditions) in the aquifer are similar to the Kettle River (Figure 15). Groundwater level fluctuation in Observation Well No. 217 mirror, and lag behind, the fluctuation in Kettle River stage (Figure 24). Pumping test data also suggest drawdown cones can extend to the Kettle River (Figure 23). SFU's numerical model also indicates that the Kettle River supplies a significant amount of water to the aquifer in its western reach, particularly when the community wells are pumping, and there is significant groundwater discharge back to the Kettle River (Figure 21). In addition to the Kettle and Granby Rivers, the other major source of water for the aquifer is precipitation falling directly on the aquifer. The contribution from ephemeral streams from the upland areas is thought to be minimal. Although not considered in this study, mountain block recharge, which is subsurface groundwater flow from the upland areas to the valley bottom, may be an important source of recharge to the valley bottom aquifer.

There is evidence from well records that a confined sand and gravel aquifer also exists at the junction of North Fork and Hardy Mountain roads (Sion Improvement District well #3). It is not known if this buried aquifer extends farther south and east towards the main valley bottom; a deep well drilled in Johnson Flats did not encounter this lower aquifer zone.

The groundwater quality is generally very hard (average hardness of 300 mg/L – Figure 27) and mineralized (average total dissolved solids of 350 mg/L – Figure 25). Groundwater tends to be softer and less mineralized near the Kettle River. Elevated nitrate-nitrogen exists in the eastern part of the aquifer, to historic levels over 30 mg/L NO_3-N (Figure 30). The source of nitrogen cannot be confirmed but is believed to be

[14] For an explanation of the BC Aquifer Classification System, see Kreye and Wei (1994) and Ronneseth and Berrardinucci (2002).

principally from leaching of excessive inorganic fertilizer. The aquifer, on the whole, is considered highly vulnerable to impacts from human activities, particularly in the eastern end where the depth to water table is shallowest (Figure 33).

SFU's numerical model allowed the capture zones for the major community wells to be delineated (Figure 34). The capture zones generally overly moderate to highly vulnerable areas (compare the capture zones in Figure 34 to the DRASTIC map in Figure 33). The land use risks varied from one capture zone area and another. For example, commercial nurseries and the number of potential abandoned wells appear to be the obvious land use threats to groundwater quality in the GFID Big Y capture zone area, while retailing and contaminated sites appear to be the issues in the capture zone area for the City of Grand Forks wells.

Capture zones cover much of the western part of the aquifer, both north and south of the Kettle River and suggest there is an opportunity for the various water supply systems (i.e., Sion Improvement District, Covert Irrigation District, Grand Forks Irrigation District, and City of Grand Forks) to jointly address groundwater protection within the capture zone. Finally, the modelled capture zones all extend up-gradient to or towards the Kettle River, and reflect the concept that the major community wells in Grand Forks ultimately drawdown the groundwater level in the aquifer to induce infiltration of water into the aquifer from the Kettle River.

The following are recommendations, based the current knowledge of the aquifer, to promote decisions that support the sustainable use of the groundwater resource and protection of the groundwater quality of this provincially important aquifer.

Groundwater Quantity

- Before any new large capacity water supply well (e.g., >3,000 m^3/d or 500 gpm) is brought into production in the future, the proponent should engage a Qualified Professional with competency in hydrogeology to: 1) delineate the capture zone for the new well and assess how the capture zones for the existing large production wells have changed as a result of proposed pumping of the new well, and 2) assess how the proposed pumping will affect the aquifer water budget and flow rates and levels of the Kettle and Granby Rivers.
- All water supply systems in Grand Forks should monitor the pumping and non-pumping water levels in their wells, and volumes of water pumped from the wells. This information should be reviewed annually to see if the current pumping rates are sustainable or whether pumping is resulting is a gradual decline in the local groundwater levels. This should be part of the prudent operating practices of water supply systems that rely on wells.
- All water supply systems should conduct controlled short-term pumping tests on their wells annually to determine the wells' specific capacity. Such a controlled short-term pumping test involves pumping the well as a specified rate (e.g., at the rated capacity) and for a specified time (e.g., 1 hour), and measuring the drawdown in the well. The specified pumping rate is divided by the drawdown in the well to calculate the well's *specific capacity*. The short-term pumping test, if

repeated exactly the same way and at the same time of year, will allow the water system to track the performance of each of their wells. If the specific capacity of a well decreases over time by, say more than 10-15%, it is an indication that the well's performance or efficiency is deteriorating and a qualified driller or qualified professional with competency in hydrogeology should be consulted to assess corrective actions to take. Ensuring a well is performing at its maximum efficiency saves pumping costs and promotes the life of the well.

- All the water supply systems should undertake a program to promote conservative use of water to help promote the sustainability of the aquifer and Kettle River flows.
- The Ministry of Environment should review the Observation Well Network in the Grand Forks area to assess whether or not one observation well (Observation Well No. 217) is sufficient to monitor groundwater conditions in the Grand Forks Aquifer. Consideration should be given to establishing one or two additional observation wells, one in the Almond Gardens area to better understand the hydraulic relationship between the aquifer and the Kettle River in the up-gradient area of the aquifer, and possibly another away from the Kettle River, either in the area south of Carson Road, between Seminoff Road and International Road, or in the area along Coalshute Road in the northern end of the City of Grand Forks, to monitor groundwater conditions in the part of the aquifer that is expected to be much less influenced by the Kettle River.

Groundwater Quality Monitoring and Assessment

- All water supply systems should analyze their source water quality and assess how quality varies over time. The GFID, especially, should review the nitrate-nitrogen levels in their Big Y wells annually to assess any trends in the nitrate levels of their well water.
- The Ministry of Environment should review the results of its Ambient Groundwater Quality Monitoring Network sampling program to summarize the water quality status and trend (in particular nitrate) for groundwater in the aquifer and assess whether the current locations and frequency of sampling are appropriate.

Groundwater Quality Protection

- The water supply systems in Grand Forks should develop and implement well protection plans to protect the source of community drinking water. Development of well protection plans were initiated in the 1990's but momentum seems to have faltered in the last 5 years. One suggestion is for Interior Health Authority to bring the water supply systems in Grand Forks together again to progress with this work, including considering requiring implementation and reporting of well protection plans as part of the water supply systems' operating permit.
- The water supply systems, especially the GFID, should seek the help of Ministry of Agriculture and Lands to promote optimal application of nutrients and irrigation practices at farms and nurseries. This type of work may be best undertaken by a person with experience in nutrient and irrigation practices if the advice is to be respected and adapted by farmers and business owners. This type

of promotion work should also have a follow-up component to check whether farmers and business owners are improving their practices.

- The water supply systems, Ministry of Environment, and Interior Health Authority should work together to promote closure of abandoned wells in the Grand Forks area to minimize risk of contamination via abandoned wells. Although regulatory standards for deactivating and closing abandoned wells exist in the Ground Water Protection Regulation, voluntary compliance to regulatory requirements may be helped by promoting the need to close wells at the local level and also in coordinating the work so owners can have wells closed at a bulk discounted cost.
- The City of Grand Forks and GFID should consider adopting a well closure bylaw. There are still a few areas or properties in Grand Forks that rely on individual wells for domestic and non-domestic water supply (e.g., domestic wells in Johnson Flats, some schools and businesses). Adopting a well closure bylaw will provide the City of Grand Forks and GFID the authority within their service boundaries to require: 1) disconnection of the private well from the residential water system to prevent cross-connection with the community water supply and 2) closure of the private well when the property hooks up to the community water supply system. Model well closure by-laws were developed by the Ministry of Community Development and are available at: http://datafind.gov.bc.ca/query.html?qt=model+well+closure+bylaws&style=cd&qp=url%3Awww.cd.gov.bc.ca%2Flgd%2F.
- The Regional District of Kootenay-Boundary and City of Grand Forks should consider using the information and maps in this report, such as the DRASTIC vulnerability map, to assist in decision making regarding local land use (e.g., in developing Regional Growth Strategies and Official Community Plans, in establishing Development Permit Areas for the aquifer). The Okanagan Basin Water Board has developed a *Groundwater Bylaws Toolkit*, a document that should be useful to local governments. The Toolkit is publically available via their website: http://www.obwb.ca/groundwater_bylaws_toolkit/.

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Appendix 1 - Methodologies Used to Generate Map Coverages

In characterizing and assessing the aquifer at Grand Forks, the initial work was to verify the location of the wells of the study area in the WELLS database. The well coordinates were plotted on a base map and each location checked against the detailed location sketches in the original paper well records. Additional wells located in the 1993 land use survey by Sheppard (1995) were also entered into the WELLS database to provide as comprehensive an inventory as possible of the number of wells in Grand Forks. Approximate elevations of the wellheads were also determined from 1:5,000 scale floodplain maps with 1 m contours.

The well records provided the fundamental data to develop a series of map coverages and cross-sections depicting relevant characteristics of the aquifer and of the wells. Table A1-1 shows the series of maps (and cross-sections) produced in this study. The type of hydrogeological information displayed in the maps range from basic data (e.g., map of well types, reported well yield and well depths) to interpretive (e.g., map of capture zone areas for community wells, potential well yield).

Table A1 - 1 Listing of hydrogeological and other maps developed for the Grand Forks Aquifer.

Map themes	Description of maps	How maps were developed
Water well characteristics	Location map of wells, by type of construction (e.g., drilled, dug)	From reported water well record data in WELLS
	Map of reported well depths	From reported water well record data in WELLS
	Map of reported well yields	From reported water well record data in WELLS
	Contour map of potential well yield in the aquifer	From Cooper-Jacob's equation relating allowable well pumping rate to aquifer thickness
Aquifer architecture	Series of contour maps showing the thicknesses and top and bottom elevations of the major surficial geological units in the study area	Interpreted from reported water well record data
	Series of north-south and east-west vertical cross-sections showing the subsurface arrangement of the major surficial geologic units and underlying bedrock surface	Interpreted from reported water well record data
	Contour map of aquifer thickness	Interpreted from reported water well record data
	Contour map of bedrock surface elevation	From Digital Elevation Model and well logs were bedrock was encountered.
Groundwater flow characteristics	A contour map of groundwater level elevation in the aquifer under non-pumping conditions	From numerical model calibrated against reported well water level data
	A contour map of groundwater level elevation in the aquifer under pumping conditions	From numerical model
	A map of the major community wells and their capture zone areas	From numerical model
Groundwater quality characteristics	Six contour maps of relevant groundwater chemistry parameters (TDS, specific conductance, hardness, alkalinity, chloride, nitrate-nitrogen)	From available water chemistry data
	A DRASTIC map of the aquifer's intrinsic vulnerability	Interpreted from reported water well and meterological data, soil mapping, and information on irrigated lands
	A map of areas where groundwater quality has been significantly impacted by human activities	Interpreted from the nitrate-nitrogen map
Other	A map of land use and location of septic systems	From 1993 land use survey by Sheppard (1995)

Specific map coverages and the cross-sections allow us to define the aquifer geologic model (or aquifer architecture) and to develop a conceptual model of the aquifer. This information was then used by Simon Fraser University to develop a finite-difference numerical flow model of the aquifer to determine the direction and rate of groundwater flow and assess the aquifer's water budget, relationship between groundwater in the aquifer and the Kettle and Granby Rivers, and to delineate capture zone areas for the community wells. The transmissivity of the aquifer, which is an input parameter for the numerical model, was based on analysis of pumping test data and grain size distribution of sediment samples by Piteau Associates (1993) for the City of Grand Forks water supply wells.

Wells and Water Use

Information on wells and their uses for the study area was derived primarily from available information in the ~600 well records in the Ministry's WELLS database. Primary information in the well record include: location of the well, well type (drilled versus dug), well depth, estimate of well yield and intended use of the well.

Locations for wells in the WELLS database were plotted on 1:5,000 scale base maps, containing cadastral and topographic information (1 m contour interval in the floodplain). Elevation of the wellhead for each well was interpolated using the 1 metre contour lines on the base map. Locations for the wells provided good spatial control of the well data points for interpretation of hydrogeology and development of the numerical model. Basic information on wells, such as well type, well depth and the drillers' estimated well yield are useful information and were summarized in maps.

Water use information was also inferred from the well records in the WELLS database, but also from Sheppard (1995)'s land use survey, and from past knowledge of groundwater development in the Grand Forks area summarized in Wei (1999).

Potential Yield to Wells

A map of potential well yield was developed for the Grand Forks Aquifer to show the potential for the aquifer to yield water to wells for supply. Although a map of the drillers' estimate of well yield provides similar information, the map of drillers' estimates of well yield shows only point data at specific locations in the aquifer for specific wells and not the potential yield that may be possible. The map of potential yield would show the potential across the study area, not just at specific points where there are wells but also in areas where well information is not available. Estimating potential yield in areas where well information is lacking is the main advantage of this type of map over the drillers' estimate of well yield map.

In this study, the map of potential well yield was developed by using the Cooper-Jacob equation to calculate the allowable pumping rate from a well. Information on the spatial variability in aquifer hydraulic parameters (hydraulic conductivity and specific storage) and saturated thickness of the aquifer were used to specify the hydraulic parameters and allowable drawdown in a well to calculate the allowable pumping rate at any location in the aquifer. The main assumption is that drawdown in the aquifer over time can be adequately characterized by the Cooper-Jacob equation[15]:

$$h_o - h = 2.3Q/(4\pi T) \times \log(2.25T \times t/r^2 \times S) \qquad \text{(A1.1)}$$

where

$h_o - h$ is the drawdown of the water level in the aquifer or in the well,
Q is the pumping rate of a well,
T is the transmissivity of the aquifer and is defined as the product of the hydraulic conductivity, K, and the saturated thickness of the aquifer, b,
t is the time since pumping started,
r is the radial distance from the pumping well, and
S is the storativity of the aquifer and is defined as the product of the specific storage, S_s, and the saturated thickness of the aquifer, b.

The Cooper-Jacob equation can be re-arranged to solve for Q as the dependant variable because this is the parameter for well yield:

$$Q = 4\pi T(h_o - h)/2.3 / \log(2.25T \times t/r^2 \times S) \qquad \text{(A1.2)}$$

Substituting $K \times b$ for T, $S_s \times b$ for S and b for $h_o - h$, the equation can be written:

$$Q = 5.464K \times b^2 / \log(2.25K \times t\, r^2 \times S_s) \qquad \text{(A1.3)}$$

The map of the saturated thickness of the aquifer allows the maximum drawdown possible at any given location in the aquifer to be determined. In this study, the maximum drawdown is specified as 70% of the aquifer's saturated thickness. The bottom 30% of saturated thickness would accommodate the well screen and provide a margin of safety.

The aquifer's hydraulic conductivity and specific storage throughout the aquifer can be obtained from the groundwater model (4×10^{-4} m/s and 10^{-5} m^{-1}, respectively; the main aquifer layer in groundwater model is homogeneous).

It is further assumed that drawdown in the aquifer would be calculated for an average well diameter of 8 inches (r = 0.1 m) and the time for pumping would be 100 days, the assumed period of time in British Columbia when an aquifer receives little or no recharge. The above equation can be empirically written for the Grand Forks Aquifer and the potential pumping rate or potential yield from a well varies only with the saturated thickness of the aquifer:

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[15] The Cooper-Jacob equation assumes the aquifer transmissivity is constant. In unconfined aquifers, such as the one in Grand Forks, if the drawdown is significant, this assumption may be violated because the saturated thickness of the aquifer near the pumping well will decrease as drawdown increases and correspondingly, the transmissivity will decrease. This results in an over-estimate of the potential yield to the pumping well.

$Q = 2 \times (10^{-4}) \times b^2$ (A1.4)

where

Q is the potential yield in m3/s and
b is the saturated aquifer thickness in metres

or $Q = 0.3 \times b^2$ (A1.5)
Where:
Q = potential yield (USgpm)
b = aquifer's thickness (in feet)

The saturated aquifer thickness was calculated as the difference between the water table and the bottom of the sand layer. The above empirical equation requires all the assumptions for the Cooper-Jacob equation to be valid. In particular, the following assumptions are relevant:

- The pumping well is 100% efficient
- Borehole storage is not considered
- Essentially horizontal flow
- Drawdown does not appreciably change the saturated thickness of the aquifer.

Aquifer Architecture
Aquifer architecture was defined based on ~600 water well records from the Ministry's WELLS database. Of these ~600 well records, only about 100 had usable lithology information (Scibek and Allen, 2004b). The well record contains information on the geologic materials encountered at different depths during drilling of a well. The accuracy of lithologic descriptions in the well construction reports varies from one well record to another depending on the experience and expertise of each driller, field conditions, drilling method, purpose of drilling, and translation of the lithologic description into the WELLS database.

In order to address the variability of the lithologic descriptions in the well construction reports, the lithology descriptions were standardized to correct errors in syntax, grammar and spelling prior to interpretation. This standardization process utilizing an in-house standardization macro (in MS Excel) was developed at SFU[16]. The standardization process recognizes equivalent terms and classifies the geologic materials into dominant lithologic types.

The aquifer architecture was determined by interpreting the standardized lithologic descriptions in the well construction reports. The lithologic descriptions revealed four distinct layers of surficial geologic sediments that were correlatable from well to well.

[16] This standardization program is based on a set of rules that allow for dominant material types to be identified based on first appearance of the term or by other qualifiers (e.g., silty sand would result in "sand" as the dominant material type, with "silty" as the secondary material type). Grain size and colour, as well as fracturing are descriptors, which are retained in this more advanced standardization code.

Thickness (from the ground surface down) and elevation of the top and bottom of each layer at any well location was determined from the lithologic descriptions in the well record and estimated elevation of the wellhead. The four surficial geology layers are, in order of increasing depth below ground:

- Layer 1 - a thin (up to 10m thick) gravel layer
- Layer 2 - depth-constrained sand layer of variable thickness
- Layer 3 – depth constrained silty sand layer of variable thickness
- Layer 4 – clay layer (extending from the base of the silty sand layer to the bedrock)

Layer 2, the sand unit is the principle aquifer zone. A lower sand layer, present only at depth in the Donaldson Road-North Fork Road area, was identified as a distinct and separate lithology zone for the numerical model.

The bedrock underlying the valley is represented by an impermeable boundary (no flow boundary) in the model, as are the valley walls. Recent research in Okanagan Valley has suggested that the bedrock is not impermeable and may transmit some water from higher elevation to the valley bottom as mountain block recharge. This deep recharge, however, was not included in the model. The bedrock surface underlying the valley was modeled using geostatistical techniques to produce a bedrock digital elevation model (DEM) that constrains the lower bound of the overlying surficial sediments.

Contour maps of elevations of the top and bottom of each surficial geologic layer and of the surface of the underlying bedrock were then developed and used to construct the layers in the numerical model. The aquifer architecture was portrayed by constructing a series of four north-south vertical cross-section and four east-west vertical cross-sections using GMS (version 4.0) and interpolating between well data points to form a solid model.

Groundwater Chemistry

General groundwater chemistry of the aquifer at Grand Forks was characterized using mainly available water chemistry data from historical well water quality surveys conducted by the Ministry in three distinct surveys, in 1989 (Kalyn, 1989), 1993 (Sheppard, 1995) and 2001 (Maxwell et al., 2002):

1. In the fall of 2001, samples from 88 wells were collected and analyzed for nitrate-nitrogen. Objectives of the sampling program and location of the wells sampled are presented in Maxwell et al. (2002). Of the 88 samples, 25 were analyzed in the laboratory for a comprehensive list of inorganic chemical parameters, the remaining 63 wells had laboratory nitrate-nitrogen and nitrite-nitrogen results only.
2. In the summer of 1993, water samples were collected from 83 wells and analyzed in the field as part of a summer-long land use survey (Sheppard, 1995). These data contain field results of nitrate-nitrogen, chloride, hardness, total alkalinity, pH, specific conductance, and iron only. Parameters were analyzed using HACH

field testing kits (model AL-94/AY and NI-11) and Beckman conductivity meters. There were no laboratory analyses performed on any of the samples.

3. In 1989, water samples were collected from 100 wells as part of a survey of nitrate in well water in the Grand Forks area (Kalyn, 1989; Wei et al., 1993). Fourteen of the 100 samples were analyzed in the laboratory for a limited list of inorganic chemical parameters. Field measurements of nitrate-nitrogen, chloride, hardness, total alkalinity, pH, specific conductance, and iron were done for all 100 samples, using HACH field testing kits (model AL-94/AY and NI-11) and Beckman conductivity meters.

Well water chemistry also exists with the Interior Health Authority for the 23 community wells in the Grand Forks area. Some of these data are in the well log files in the WELLS database and the available results were used in characterizing the groundwater quality of the Grand Forks Aquifer, particularly for areas where there was a lack of data. In 2002, water samples were collected by Simon Fraser University for nitrate isotope analysis (Allen and Bishop, 2004).

Mapping groundwater chemistry

The available well water chemistry data were used to develop groundwater quality maps for the aquifer. The purpose of the maps is to show the nature and variation of general water chemistry over the entire aquifer. Based on the data, the following maps were developed:

- A contour map of the Total Dissolved Solids (TDS) of the water in the aquifer. TDS represents the total overall mineralization of the groundwater and therefore, is an indicator of the overall quality of the water;
- A contour map of specific conductance, which represents the ability of the water to conduct electricity and is a direct indicator of TDS;
- A contour map of water hardness which indicates the amount of calcium and magnesium dissolved in groundwater;
- A contour map of total alkalinity which indicates the amount of bicarbonate ions (HCO_3) and the acid buffering capacity of the groundwater;
- A contour map of chloride; and
- A contour map of nitrate-nitrogen which is a specific water quality indicator of impacts from agricultural activities and sewage wastes.

The TDS, specific conductance, hardness, total alkalinity, and chloride maps relied mostly on data from the 1989 survey. The 2001 and 1993 data were not used for these maps. The 2001 data only had these parameters analyzed for 25 of the 88 samples and the 1993 data comprise only field analyses, not calibrated to any laboratory results. For the nitrate-nitrogen map, data from the 2001 survey was used.

There were areas within the City of Grand Forks and in the eastern end of the Nursery area where water chemistry data were lacking. In these areas, laboratory and field water chemistry results from the WELL database for wells sampled in other years were used to help define the contours in those areas, but only those results closest in date to the year of the data (1989 for the TDS, specific conductance, hardness, total alkalinity, and chloride maps and 2001 for the nitrate-nitrogen map) were used.

The microbiological quality of the well water in Grand Forks could not be characterized and mapped at this time because of lack of available data. It is also expected that any fecal coliform bacteria contamination of wells from nearby sewage septic systems would occur very locally and may not be appropriately displayed on maps of this scale.

Because the water chemistry data used to develop the various maps ranged were from 1989 and 2001, there is potentially a concern that the maps developed based on the 1989 data may not be representative of conditions today. To address this concern, results from the 1989 well water samples were checked with laboratory results from the data (from a limited number of wells) in more recent years were compared as a check for overall consistency and to assess whether results have changed appreciably over the years to result in a significant change to the contour maps.

Finally, since wells are completed to various depths within the Grand Forks Aquifer, the resultant groundwater quality maps represent a vertically integrated picture of the water quality in the aquifer. In reality, groundwater quality is expected to vary and change with depth in the aquifer. For example, parameters such as nitrate-nitrogen and chloride, where the main source is believed to be from human activities at the land surface, the concentration for these two parameters is expected to decrease with depth.

The rest of this section describes the data used for each map and how the maps were developed.

<u>TDS:</u> To develop the TDS map, laboratory values of TDS from the 1989 survey were correlated with the field specific conductance values from the same survey. The correlation ($TDS_{laboratory} = 0.7828$ Specific Conductance$_{field}$ -29.713; R=0.962) was then used to calculate TDS for the wells sampled in 1989. These calculated TDS values plus actual TDS values from the 14 laboratory analyzed samples were then plotted and manually contoured to develop the TDS map. A contour interval of 100 mg/L was chosen based on the observed range of TDS values.

<u>Specific conductance:</u> The 1989 data provided the best spatial coverage for specific conductance. The specific conductance was measured in the field using a Beckman conductivity meter. Field specific conductance were plotted and manually contoured to develop the specific conductance map. A contour interval of 250 μS/cm was chosen based on the range of specific conductance values measured.

<u>Hardness:</u> The 1989 data provided the best spatial coverage for hardness. Hardness concentrations were measured in the field using a Hach model AL-94/AY test kit. Field hardness concentrations were plotted and manually contoured to develop the water hardness map theme. A contour interval of 100 mg/L was chosen as opposed to the intervals based on Health Canada's classification for water hardness (<60 mg/L, 60-120

mg/L, 120-180 mg/L, and >180 mg/L) because regular contour intervals worked best to show the spatial variability of water hardness across the aquifer.

Total Alkalinity: The 1989 field data were used to develop the alkalinity map. Total alkalinity was measured in the field with a Hach model AL-94/AY test kit. Total alkalinity measured in the field was correlated with the total alkalinity measured in the laboratory of the 14 well water samples. The correlation (Total Alkalinity $_{laboratory}$ = 0.933 Total Alkalinity $_{field}$ -35.867; R=0.975 if one anomaly was ignored) was used to calculate total alkalinity for the 100 wells sampled in 1989. These calculated total alkalinity values plus actual total alkalinity values from the 14 laboratory analyzed samples were then plotted and manually contoured to develop the alkalinity map. A contour interval of 100 mg/L was chosen based on the range of alkalinity values.

Chloride: The 1989 field data was used to develop the chloride map. Chloride was measured in the field with a Hach model AL-94/AY test kit. Chloride measured in the field were correlated with the chloride measured in the laboratory of the 14 water samples (correlation: Chloride $_{laboratory}$ = 0.6374 Chloride $_{field}$ -4.242; R=0.880) and chloride values were calculated for the wells sampled in 1989. These calculated chloride values plus actual chloride values from the 14 laboratory analyzed samples were then plotted and manually contoured to develop the chloride map. Contour intervals for chloride were selected based on half orders of magnitude for chloride concentrations above 10 mg/L (i.e., 10-30, >30 mg/L) because of two reasons: the occurrence of chloride in groundwater at Grand Forks appears to be log normally distributed and the field measurements limited the minimum detection for chloride to above 3 mg/L.

Nitrate-nitrogen: For the nitrate-nitrogen map, the 2001 laboratory results were used. Nitrate-nitrogen concentrations were determined in the laboratory by calculating the difference between nitrite and nitrate + nitrate. Diazotization was used to analyze for nitrite and Cadmium Reduction was used to analyze for nitrite + nitrate. Nitrate-nitrogen concentrations were then plotted and manually contoured to develop the nitrate-nitrogen map theme. The 2001 data did not cover the Nursery area and, for that area, 2001 nitrate-nitrogen concentrations were calculated by linearly correlating 1989 laboratory results with 2001 results for the same wells sampled (NO_3-N $_{2001\ laboratory}$ = 1.2105 NO_3-N $_{1989\ field}$ -1.8674; R=0.9585; minus 2 anomalies). Contour intervals for nitrate-nitrogen were selected based on half orders of magnitude (i.e., <1, 1-3, 3-10, 10-30, 30-100 mg/L) because the occurrence of nitrate-nitrogen is generally assumed to be log normally distributed.

Statistical analyses of groundwater quality

In addition to using the well water chemistry data to develop maps of groundwater quality, the data used for the maps were also analyzed statistically. Specifically, probability plots for TDS, specific conductance, hardness, total alkalinity, chloride, and nitrate-nitrogen data were developed to determine the statistical nature of occurrence of a given water chemistry parameter (i.e., does a given parameter occur normally or log-normally distributed?) and the following statistics were determined for each parameter:

- Minimum concentration,

- Maximum concentration,
- Range of concentration, and
- Median or average concentration.

Intrinsic Aquifer Vulnerability

The aquifer at Grand Forks has been classified by the Ministry as an "IA", heavily developed, highly vulnerable aquifer[17]. The designation of "highly vulnerable" was based on two main factors:

- well log data show the aquifer is generally unconfined, and
- well water quality results indicate that the aquifer has already been impacted locally by human activities.

However, it is recognized that the Ministry's vulnerability classification is subjective and applies to the entire aquifer and ignores the fact that the aquifer's vulnerability may be different in different places. Characterizing the aquifer's vulnerability in greater detail is desirable to show how vulnerability may vary spatially across the aquifer area.

The term "aquifer vulnerability" refers to the degree of sensitivity of an aquifer to be contaminated, usually from human activities at the land surface. An aquifer's vulnerability is defined here as solely a function of the hydrogeologic characteristics of the aquifer (for example, whether an aquifer is confined or unconfined and the amount of recharge the aquifer receives), and does not consider the type and intensity of human activities at the land surface (which can change over time). The term "specific or integrated vulnerability" has been used (Vrba and Zoporozec, 1994) to describe an aquifer's vulnerability to contamination based not only on hydrogeologic factors but also on land use factors.

In developing a map of vulnerability of the aquifer, we chose to characterize the intrinsic vulnerability of the aquifer, governed solely by hydrogeologic factors because it is expected that hydrogeologic factors would not change appreciably over time, whereas land use would. In this study, DRASTIC was the methodology used to determine aquifer vulnerability. DRASTIC was developed by the U.S. Environmental Protection Agency to be a standardized system for evaluating groundwater vulnerability (Aller et al., 1987). The following seven hydrogeologic parameters are considered in DRASTIC:

1. **D**epth to water
2. net **R**echarge
3. **A**quifer media
4. **S**oil media
5. **T**opography (slope)
6. **I**mpact of the vadose zone media
7. hydraulic **C**onductivity of the aquifer

The equation for determining the DRASTIC index is:

[17] For an explanation of the BC Aquifer Classification System, see Ronneseth and Berrardinucci (2002) or Kreye and Wei (1994).

$$\text{DRASTIC Index} = D_wD_r + R_wR_r + A_wA_r + S_wS_r + T_rT_w + I_wI_r + C_wC_r \qquad (A1.6)$$

where the letters D, R, A, S, T, I, C represent the 7 hydrogeologic factors (see above), *w* represents the weighting (values from 1 to 5 are used where the most significant factors have a weighting of 5 and the least significant factors have a weight of 1 – see Table A1-2) for each parameter, and *r* represents the rating (values from 1 to 10 are used). The DRASTIC Index ranges from a possible minimum value of 23 to a possible maximum value of 230 and represents a relative measure of groundwater vulnerability. The higher the DRASTIC index value, the more vulnerable the aquifer to contamination.

DRASTIC provides a screening tool to be used with other information (e.g., land use, potential sources of contamination, and beneficial uses of the aquifer) to identify areas where special attention or protection efforts are warranted. DRASTIC can be used to set priorities for activities such as where to conduct groundwater quality monitoring or assessments.

The following section discusses the sources of data/information used to estimate the ratings for the 7 hydrogeologic factors used in DRASTIC, as well as the data/information limitations:

Table A1 - 2 Assigned weights for DRASTIC hydrogeologic factors.

Hydrogeologic Factor	Weight (w)
D – Depth to Water	5
R – Net Recharge	4
A – Aquifer Media	3
S - Soil Media	2
T – Topography	1
I – Impact of Vadose Zone Media	5
C – Aquifer Hydraulic Conductivity	3

Depth to water

The depth to water is the distance (in feet) from the ground surface to the water table. It determines the depth of material through which a contaminant must travel before reaching the water table. Thus, the shallower the water depth, the more vulnerable the aquifer is to sources of contamination at surface.

Depth to water was estimated for the Grand Forks aquifer directly from the historic static water levels recorded in drillers' logs. The static water level reported in the well records was assumed to be the depth to the water table. Normally, the static water level is measured immediately following drilling. This can potentially result in a lower than actual water table reading due to the well not having enough time to re-equilibrate with the surrounding aquifer water levels. However, the Grand Forks aquifer is highly permeable and the hydraulic disturbance during drilling activities can be expected to dissipate quickly. In this respect, it is reasonable to assume that post-drilling measurements of water level may be similar to those of the surrounding undisturbed aquifer. In addition to drilling disturbance, water levels in an aquifer fluctuate throughout the year due to seasonal factors (e.g., changes in recharge and changes in storage). As a result, the depth to water at any location is expected to vary seasonally from the static water level measured in the well at that location. Data from Observation Well No. 217 show that groundwater levels can fluctuate between 1 m and 1.5 m seasonally but this magnitude of fluctuation is not expected to significantly affect the depth to water rating at each well location.

Values of static water level (recorded as depth to water in a well in feet), were imported into ARCGIS as point values. A composite depth to water surface was calculated using a geostatistical analysis involving interpolation between points, and extrapolation to the boundary of the aquifer[18]. The resulting composite "depth to water map" was reclassified according to categories in Table A1-3 (DRASTIC indices for Depth to Water) and converted to a rastor map that represents the D Rating in DRASTIC.

Table A1 - 3 Depth to Water (D) Index Table.

Depth to water (ft) Categories	D Rating
0-5	10
5-15	9
15-30	7
30-50	5
50-75	3
75-100	2
100+	1

Recharge

Recharge in DRASTIC analysis is typically estimated in one of two ways. Often it is assumed that the same amount of recharge is applied to the entire map area and precipitation is assumed to be the primary source of recharge. However, a more accurate representation of recharge takes into account the amount of water that is returned to the aquifer when the land is irrigated. This is commonly referred to as return flow (from the aquifer perspective) or deep percolation losses (from an irrigation perspective). In this study recharge from both precipitation and irrigation return flows were considered.

Recharge from precipitation

The primary source of recharge is precipitation, which infiltrates through the ground surface and percolates to the water table. Net recharge is the total quantity of water per unit area, in inches per year, which reaches the water table. Because recharge is the principle means for leaching and transporting contaminants to the water table, the more recharge the greater the chance for contaminants to reach the water table.

[18] Aquifer Boundary: the boundary or the extent of the Grand Forks aquifer was determined by the BC Ministry of Environment based on visual estimates of the extend of surficial materials that constitute the aquifer media in the valley.

For DRASTIC mapping, a uniform spatial recharge value is needed. This value is often determined by taking a fixed percentage of the precipitation, or using the results of a global water balance. In this study, recharge was modeled using the HELP code (US EPA) within UnSat Suite (Waterloo Hydrogeologic Inc., 1997). Using the climate input data, estimates of recharge are determined by setting up representative aquifer media columns and modelling one-dimension unsaturated water flow in the column. The resulting water balance provides estimates of evapotranspiration, runoff, percolation to the base of the vadose zone (i.e., recharge), and change in storage in the column.

For recharge estimation for DRASTIC mapping, representative soil columns were assumed based on the average soil depth, soil media, aquifer media and depth to water table across the aquifer. Simulations were run for a 10-year period using a climate data series representing the historic climate (Allen, 2001). The average recharge over this time period was calculated. Only one value was estimated for the entire aquifer. A sensitivity analysis was conducted to determine the range of recharge for different input conditions (e.g., material type, vegetation cover, etc.).

The range of recharge from precipitation determined for the aquifer at Grand Forks is 77 mm/year to 166 mm/year, with a "representative" recharge[19] of 136 mm/year. This range of values was converted to inches/year and assigned an R rating number according to the recharge categories in Table A1-4. However, because the range of recharge is relatively small and recharge is not expected to vary significantly across the aquifer, a single rating number of "6" was assigned to the entire aquifer. This rating number was assigned to the aquifer outline polygon in ARCGIS, and a rastor map was generated.

Table A1 - 4 Net Recharge (R) Index Table.

Recharge (inches/yr) Categories	**R Rating**
0-2	1
2-4	3
4-7	6
7-10	8
10+	9

Recharge from Irrigation Return Flows

Estimates of return flow were obtained through consultation with experts in the field of irrigation as no studies have been done in Grand Forks to estimate irrigation return flows (Pat Brisbin and John Parsons, 2003; personal communication). There are two main issues regarding the volume of return flow in Grand Forks. First, is the issue of inefficient sprinkler systems, and second is the issue of excess application.

[19] "representative" recharge was determined from the dominant aquifer media used in the soil column in HELP. This representative value was ultimately used by Allen (2001) as the base case for climate change impact modeling.

Sprinkler systems can be inefficient due to the non-uniformity of area of application. Basically, water is applied over a circular area, but typically the required land area is square. Additional irrigation water must be applied to the circular area in order to provide enough water to the outer edges (outside the circle). This results in excess water going into groundwater storage. It is estimated that approximately 25-28% of applied water will go below the root zone in the central area of the valley and of this amount; approximately 3% is lost to evaporation (Pat Brisbin, 2003; personal communication). Therefore it is estimated that approximately 22-25% of applied irrigation water could be attributed to return flow due to sprinkler system inefficiency.

It has also been estimated that most farmers are likely to over-irrigate because they cannot anticipate rainfall events. A farmer will apply a certain amount of irrigation water so as to fill up the soil profile, and then find that it rains the next day. The irrigation water cannot be used by the plants and therefore, the water infiltrates below the root zone and is added to the groundwater. It is estimated that approximately 50% of water could be lost through such practices (Pat Brisbin, 2003; personal communication).

Varying nitrate concentrations in areas of where agriculture is known to take place, lead to the assumption that there is return flow to the aquifer. Most of this return flow is related to cultivated crops that are grown such as tree nurseries and potato fields, where puddling of irrigation water has been observed (John Parson, 2003; personal communication). Pasture and hay fields that are irrigated on 24 hour sets may also experience some return flow. Return flows on forage fields has been estimated at 5% and cultivated fields at 10-15%, as plant use and evaporation would utilize the rest of the water (John Parson, 2003; personal communication). These estimates would apply to fields that do not have an impervious layer at a depth of 10 feet or lower.

In consideration of both of these estimates for losses of irrigation water, an average irrigation return flow percent of 30% has been assumed.

In order to estimate irrigation flows, the following large scale groundwater users were contacted and asked to provide information on their water use:

- City of Grand Forks
- Grand Forks Irrigation District (Big Y and Nursery Areas)
- Sion Improvement District
- Covert Irrigation District

From existing hardcopy maps areas, irrigation and water districts as well as the individual lots (where these were provided) were delineated. This approach was considered acceptable because the only other major rural areas outside of the City and districts where there is irrigation are the Almond Gardens Road and Darcy Road areas.

As the City of Grand Forks provides water for both domestic and irrigation use, certain assumptions were made:

- No irrigation takes place during the winter months and that water use over this period represents domestic use only and that any increase in water use during summer would represent water used for irrigation;
- Domestic water use remains relatively constant over the year and that seasonal variations such as filling swimming pools during summer, are insignificant; and
- The majority of active irrigation in Grand Forks is performed during June through August as these months have the highest temperatures and least precipitation – this assumption is supported by the City of Grand Forks water use records.

For the Grand Forks Irrigation District, Sion Improvement District and Covert Irrigation District it has been assumed that the water extracted is used for irrigation purposes. Water extracted in these districts are also used for domestic purposes but is assumed to be minor in comparison.

Aquifer media

Aquifer media refers to the consolidated rocks or unconsolidated sediments that comprise an aquifer. The larger the grain size, or in the case of bedrock, the more fractures and openings within an aquifer, the higher the permeability, and thus vulnerability, of the aquifer. In unconsolidated aquifers, the rating is governed by the lithology of the aquifer. In consolidated aquifers, the rating is governed by the amount of primary porosity, and secondary porosity along fractures and bedding planes.

The Grand Forks aquifer is an unconsolidated aquifer. The aquifer media ranking is determined on the basis of the lithology of the geologic formation encountered at the water table. In some cases, aquifer media is considered as the lithology of the geologic formation over the screen interval of the well. For this study, the former characterization is used.

Using the standardized well logs, a Visual Basic program was written to extract the unit that coincides with the water table depth. This resulted in a single layer for each well. Up to three material descriptions, as described earlier under standardization, were retained. A table recording values of saturated hydraulic conductivity (K_{sat}), specific storage (S_s) and specific yield (S_y) for each material type was created, based on estimates used in previous vulnerability mapping studies in the Fraser Valley (Wei, 1998; Ronneseth et al., 1995) as well as published values (see Table A1-5 for K_{sat} values used). The geometric means of the K_{sat} values were calculated for each well where more than one material type was recorded. Where only a single material type was recorded in the standardized well log, a single K_{sat} value for that layer was generated.

Table A1 - 5 Standardized Aquifer Lithologies and Ksat Values for Automated Calculation of Aquifer Media Properties.

Standardized Lithology	K_{sat} (m/day)
Gravel	1000
Pebbles = Gravel	1000
Cobbles = Gravel	1000
Boulders = Gravel	1000
Sand and Gravel	100
Sand	10
Silt	1.0e-1
Clay silt	1.0e-5
Clay	1.0e-6

Table A1-6 shows the lithologic descriptions and the K_{sat} values for various material types, including dominant material types with qualifiers (e.g., silty sand). A manual examination of the output data was carried out in order to ensure that the calculated hydraulic conductivities were consistent with the original well log descriptions. In only a few cases (<10) were modifications made as a result of the standardization scheme not correctly identifying the dominant material types. Only the two first material types were considered in this manual adjustment of K_{sat} values.

The lithologic unit encountered at the water table was determined on the basis of its calculated K_{sat} value, and was then assigned an A Ranking according to material type as specified in Table A1-6. These ranking values were analyzed using geostatistical methods in ARCGIS and a surface contour map of the ranking values for aquifer media generated. Finally, a rastor map of the A Ranking in DRASTIC was created.

Table A1 - 6 Aquifer Media (A) Index Table.

Lithologic Description	K_{ave}	logK	A Rating
Gravel	1000	3	9
Sand and gravel, gravelly sand, sandy gravel, coarse sand	100	2	8
Gravel, sand and silt, medium sand, sand	10	1	7
Fine sand, silty sand and gravel, very fine sand, silty sand	1	0	6
Gravelly silt, sandy silt, silt, clayey gravel, clayey sand, loam	0.1	-1	5
Clayey silt, gravel till, sandy till, bedrock	0.001	-3	4
Clayey till, till, hardpan	0.00001	-5	3
Clay, gravelly clay, sandy clay, silty clay	0.000001	-6	1

Soil material
Soil media is the upper weathered zones of the earth, which averages a depth of 6 feet or less from the ground surface (Osborn et al., 1998). Soil has a significant impact on the amount of recharge that can infiltrate into the ground. In general, the less the clay shrinks and swells, and the smaller the grain size of the soil, the less likely contaminants will reach the water table.

Soil maps for the Kettle River Valley (Sprout and Kelly, 1964) were digitized and are available as a separate coverage for the aquifer and surrounding area. Attributes assigned to the soil polygons included the soil symbol, which was ultimately linked to soil name, soil description and drainage characteristics. S Ranking values were assigned to each soil polygon. Comparisons to other vulnerability studies in the Fraser Valley (Wei, 1998; Ronneseth et al., 1995) were made to ensure that similar soil characteristics were assigned similar S Ranking values in the DRASTIC method. The S Rating values were then converted to a rastor map.

Topography
Topography refers to the slope of the land surface. Topography helps to control the likelihood that a pollutant will run off or remain long enough to infiltrate below the ground surface. Where slopes are low, there is little runoff, and the potential for pollution is greater.

There are two methods for evaluating topography. One is to use a digital elevation model (DEM) and calculate slope (in percent) directly from the surface. Alternatively, soil maps can be used because these record the soil slope across the mapped area. Because detailed soil maps were available and had been digitized for Grand Forks, the latter approach was used in this study. Attributes assigned to the soil polygons included the soil topography, which was ultimately linked to soil slope (as a percent). A DRASTIC index rating was then assigned to each slope value. The T Rating values were then converted to a rastor map.

Impact of vadose zone
The vadose zone is the unsaturated zone above the water table. The lithology and porosity characteristics of the geologic materials in the vadose zone govern the time of travel of a contaminant through it and the potential for attenuation of the contaminants.

The impact of vadose zone ranking is typically determined on the basis of the lithology of the geologic formations encountered above the water table. However, sole reliance on lithological descriptions for assigning the C value can be problematic. For example, a thin layer of low permeability material like clay, which may appear to be an insignificant layer in the vadose zone, can have a significant effect on the vertical permeability of the vadose zone. In determining the ranking for the vadose zone, the equivalent vertical hydraulic conductivity was calculated based on the well log description to better assess the impact of the vadose zone. Using the standardized well logs, a Visual Basic program was written to extract the units that occur above the water table and record the depths of each layer. The unsaturated thickness was calculated for units that extended above and below the water table. This often resulted in more than one layer for each well. An equivalent vertical hydraulic conductivity (K_z) was determined for each well according to the expression:

$$K_z = \frac{d_{total}}{\sum_{i=1}^{n} \frac{d_i}{K_i}} \qquad \text{(A1.7)}$$

where K_z is the equivalent vertical hydraulic conductivity, d_{total} is the total depth of the vadose zone (depth to water table in each well), d_i is the thickness of each individual layer, and K_i is the saturated hydraulic conductivity of each individual layer. Table A1-6 shows the K_{sat} values for each standardized lithology.

A manual examination of the output data was carried out in order to ensure that the calculated hydraulic conductivities were consistent with the original well log descriptions. A geostatistical analysis within ARCGIS was then undertaken to generate a surface contour map of the ranking value. Finally, a rastor map was generated from the contour map.

Conductivity

Hydraulic conductivity refers to the rate at which water flows through an aquifer. The higher the hydraulic conductivity, the more vulnerable the aquifer is to contamination. The hydraulic conductivity ranking is determined on the basis of the saturated hydraulic conductivity values for the aquifer media encountered at the water table. The K_{sat} values for each well were then assigned DRASTIC rankings. A geostatistical analysis within ARCGIS was then undertaken to generate a surface contour map of the ranking value. Finally, a rastor map was generated from the contour map.

Vulnerability Map

The final DRASTIC vulnerability map was generated by summing the product of the DRASTIC index and its respective weight at each cell. This was done in GIS by calculating a DRASTIC index from the individual weighted rastor maps.

Appendix 2 – Methodologies Used to Generate Conceptual and Numerical Models of the Grand Forks Aquifer

Numerical Model Development for the Grand Forks Aquifer

A three-dimensional finite-difference numerical groundwater flow model was developed of the aquifer at Grand Forks to quantitatively assess groundwater flow directions, velocities, and rates, water balance, to gain a better understanding of surface water-groundwater interaction, to delineate capture zones for the community wells and to better understand the climatic, hydrologic and geologic controls on the aquifer. The original model for Grand Forks was constructed to delineate well capture zones for municipal and irrigation wells (Allen, 2000). The aquifer geometry was determined solely on the basis of data supplied from the BC Ministry of Environment. The source data included estimates of the depth to the base of the upper aquifer unit (base of sand) as determined from available water well records. No information was available on the depth of the other geologic units that fill the valley. Consequently, a simple 4 layer model was assumed to consist of a thin (10m thick) gravel layer, overlying the depth-constrained sand unit (variable thickness), followed by a silt layer (taken to be uniform thickness of 40m). The bottom unit, a lower sand, was assumed to be present throughout the valley as a uniformly thick layer. However, it was speculated at that time that this lower sand may only be present in isolated regions at depth. The presence or absence of a lower sand aquifer was not expected to be important, nor did it prove important in the model, to the overall flow in the aquifer, which is largely in the upper gravel and sand units.

That first modeling work was followed by a numerical study to determine the sensitivity of the aquifer to climate change (Allen, 2001). In this later study, recharge modeling using HELP (UnSat Suite, Waterloo Hydrogeologic Inc.) was undertaken to arrive at more reliable estimates of recharge to the aquifer, and thus, to the model. In this respect, the new estimate of recharge to the model was modified for the current climate, and was in fact, significantly lower than that used in the original well capture zone analysis effort. Recharge was assumed to be uniform across the aquifer surface (135 mm/yr), but the model did allow for slightly elevated recharge around the perimeter of the model domain (i.e., adjacent to the bedrock mountains) to account for recharge from overland flow. The actual model domain and the aquifer geometry remained unchanged in the revised model that was used for climate change sensitivity analysis.

In the current study, some modifications were made to the model as documented by Scibek and Allen (2003, 2004a, 2004b). The model refinements were undertaken to 1) update the aquifer geometry, 2) model spatially distributed recharge, and 3) generate transient aquifer responses to climate change through shifts in recharge and Kettle River discharge (not discussed here).

Aquifer Geometry
Following a more comprehensive analysis and interpretation of bedrock topography underneath the valley, and including the results of standardized well log lithologies, the aquifer architecture has been refined considerably for that previously reported by Allen (2000, 2001). The lower layer of the aquifer was determined to be a clay unit of variable thickness. This clay is overlain by the silt, followed by the upper sand, and then gravel. A lower sand unit was identified in isolated portions of the aquifer, especially to the north of the valley, and is assumed to be related to fan deposits at the flanks of the valley.

The top and bottom elevations of each layer were determined by constructing cross-sections within GMS (version 4.0) and interpolating between points to generate a solid model. The layer elevations were then imported into the existing Grand Forks aquifer model that was generated in Visual MODFLOW. The resulting aquifer architecture is significantly more complex than that used in the original model. The lower discontinuous sand unit is not represented in the model.

Hydraulic Properties
The aquifer hydraulic properties used in the model were the same as those used previously by Allen (2000, 2001) and are consistent with values obtained from hydraulic testing conducted in water wells by various consultants (Table A2.1). Horizontal K values were assigned values one order of magnitude higher than vertical K values for all layers in accordance with previous modeling (Allen, 2000; Piteau Associates, 1988). Values for clay and silt were estimated from the literature on account of there being no values from hydraulic tests conducted in those units. K values for the upper portion of the aquifer (gravel and upper sand) provide a good model calibration under steady-state conditions (see model calibration results below).

Table A2 - 1 Values of K used in the Groundwater Flow Model for Grand Forks.

Layer	K_x (m/s)	K_y (m/s)	K_z (m/s)
gravel	1.0E-3	1.0E-3	1.0E-4
sand	1.5E-4	1.5E-4	1.5E-5
silt	7.0E-7	7.0E-7	7.0E-8
clay	1.0E-7	1.0E-8	1.0E-8

Recharge
Precipitation was assumed to be uniform over the entire surface area of the aquifer and climate data for recharge modeling were based on the Grand Forks climate station. Modifications to the Grand Forks model were made to include spatially-distributed recharge depending on two factors:

1) Type of soil cover, slope and vegetation. The range of recharge for different surface conditions was assessed using the HELP hydrologic model (Scibek and Allen, 2004a).
2) Occurrence of return flow to the aquifer from irrigation. A portion of the pumped water (approximately 30% of the water used for irrigation) is thought to return to the aquifer. The spatial distribution of recharge to the aquifer that accounts for

this return flow was included in the vulnerability map coverage for the aquifer and in the updated groundwater flow model.

In addition, it was determined through a hydrologic interpretation of the watershed (Scibek and Allen, 2003) that overland flow would be concentrated in ephemeral streams around the perimeter of the valley, and that the amount of water supplied annually to the aquifer from these ephemeral streams can considered to be minimal. Therefore, additional recharge to the model around the perimeter of the domain is now thought not to be important.

Rivers

The numerical flow model BRANCH (Schaffranek et al, 1981) and associated channel geometry analysis program CGAP (Regan and Schaffranek, 1985) of Kettle and Granby Rivers showed that channel geometry is variable and affects stage-discharge relation along the river channel. The calculated rating curves, together with an automated mapping of river water elevations to groundwater flow model of the valley aquifer allowed for modeling of seasonal variation of groundwater levels and their sensitivity of changed river hydrographs.

The hydraulic connection of the Kettle and Granby Rivers to the shallow aquifer appears to be good as there does not appear to be any till or low permeability silt material overlying the highly permeable sand and gravel in the river beds. In addtion, the water balance and the relation of water levels in the observation well and the Kettle River, established that the valley aquifer is hydraulically linked to the Kettle River.

The rivers have been treated in the model as specified head boundary conditions. The rivers are best represented as specified head nodes in the model because the bottom sediments of the rivers are largely gravel, ensuring good hydraulic connection with the underlying aquifer. Modifications to the specified head boundary conditions (i.e., the rivers) had to be made to account for slight variations in the surface topography of the model, as this upper elevation had been modified as part of this study. Nevertheless, the only significant change to these boundary conditions was the layer to which the specified head was associated.

Hydrograph (Obs Well #217)

The shallow, more permeable portion of the upper unit (i.e., the gravel layer), appears to be closely linked with the Granby and Kettle Rivers as evidenced by the corresponding rising and falling of water levels in shallow wells situated close to the rivers (Piteau and Associates, 1993). All wells completed in this shallow layer exhibit a static level approximately at river elevation, indicating that the groundwater regime is likely strongly linked to the surface water regime.

In the Grand Forks valley, observation well #217 (well tag number 14947) is drilled into a shallow unconfined aquifer, several hundred meters north of Kettle River. The well has depth of 8.83 m and the lithology log indicates gravel to this depth. Records in this well were usually taken on the last or second last day of each month. The monthly average water table elevation varied only by about 1 metre, with standard deviation of 0.2 m. The hydrograph in well 217 displays regular seasonal pattern, similar to stage hydrograph of the Kettle River (Figure A2.1). The maximum groundwater level generally corresponds to maximum river stage during the spring freshet, while the lowest water tables occur during the winter months. However, the peak water level apparently is at end of July, rather than at end of June. However, the actual date of highest water level in well 217 is uncertain to at least 15 days, since the measurements are taken only once each month. For example, if well soundings were taken in the middle of the month, the peak would probably occur in the middle of June. The phase shift of the well hydrograph as induced by river hydrograph is at least 15 days, but could be up to 30 days (Figure A2.2).

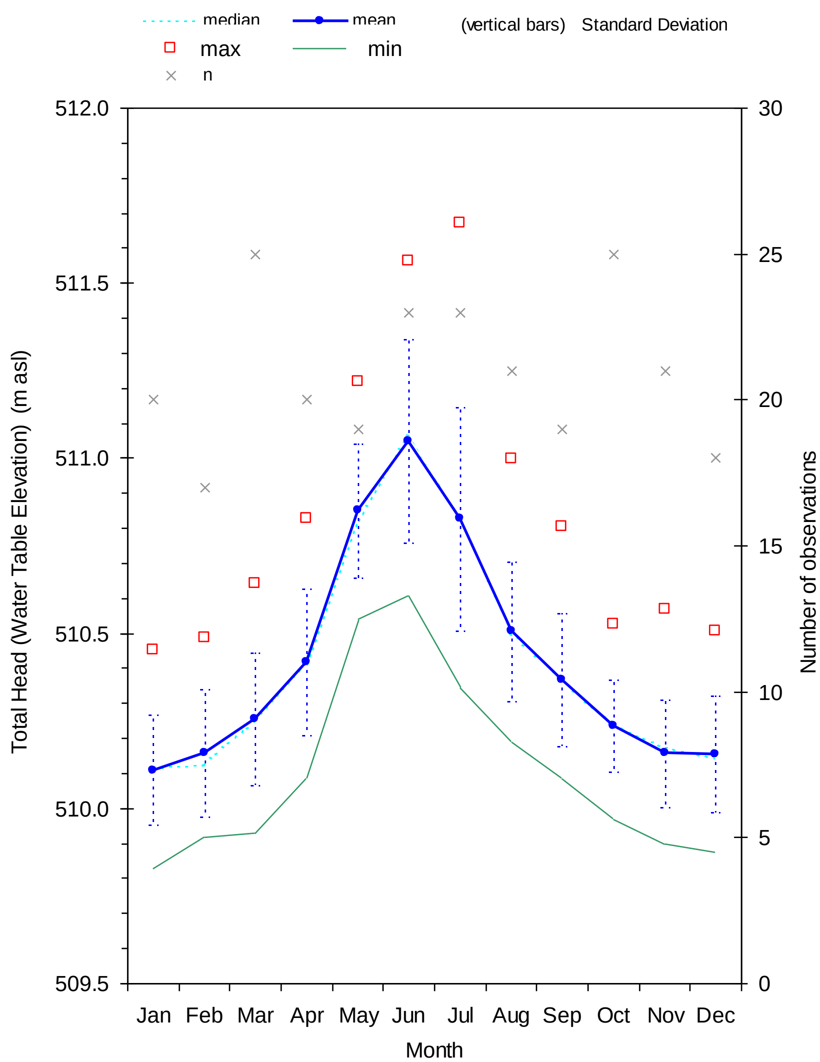

Figure A-2- 1 Observation well 217 at Grand Forks mean monthly water table elevation (total head in unconfined aquifer layer) statistics calculated for Period of Record of 1974 - 1996.

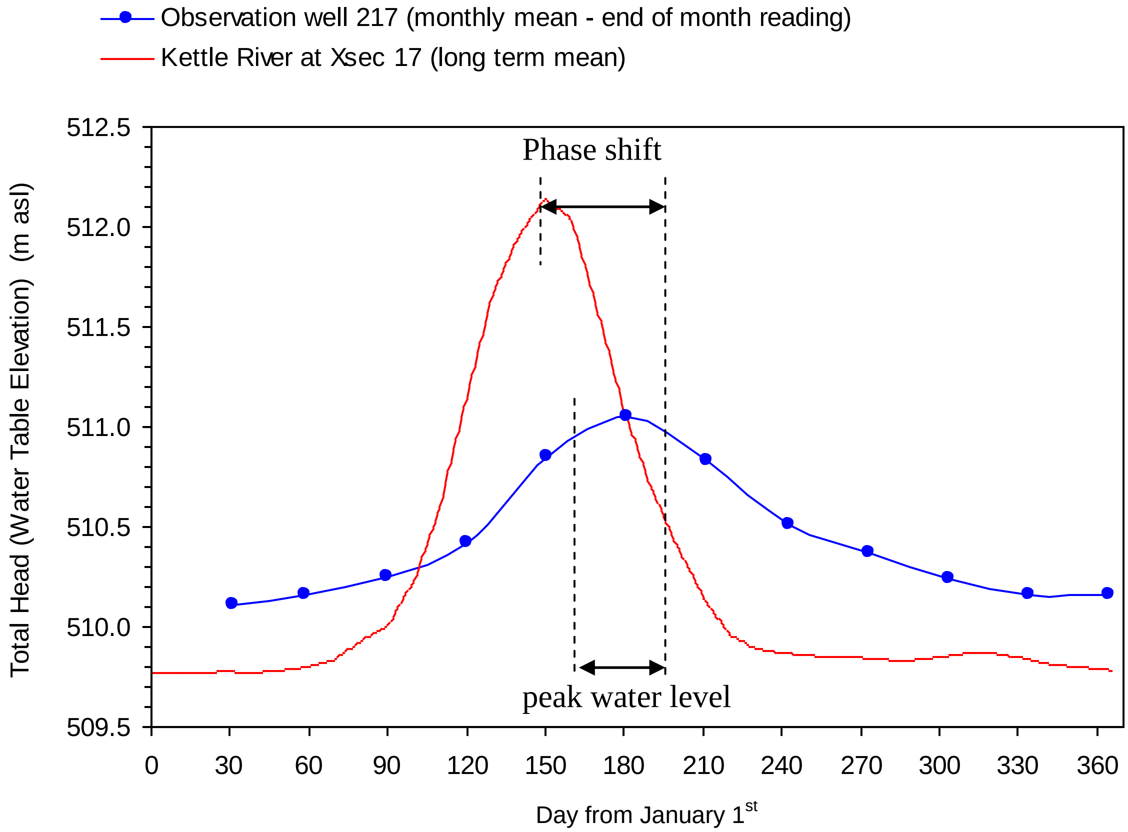

Figure A-2- 2 Mean hydrograph of water table elevation (total head) in Observation Well 217 in Grand Forks aquifer and water surface elevation of Kettle River 400 m from well 217.

Pumping Wells

The major production wells in the Grand Forks aquifer include Sion Improvement District (Sion#1, #2, and #3); Covert Improvement District (CID#1, #2 and #3); City of Grand Forks (GF#2, #3, #4, and #5); Grand Forks Irrigation District (BigY#1, #2, #3, #4, and 87-2) as well as the two Nursery wells (#1 and #2). These wells were assigned pumping rates based on values reported by the various operators for summer peak operating conditions. In most cases, the values were similar to those used in the previous modeling study (Allen, 2000). These pumping rates are provided in Table 2.

Table A2 - 2 Pumping Rates for Major Production Wells in Grand Forks.

Well	Reported Well Yield (m^3/s)	Average Winter Q (m^3/s)	Average Summer Q (m^3/s)	Q used for irrigation (m^3/s)	Theoretical Max Yearly Use ($m^3/year$)	Actual Yearly Use ($m^3/year$)
City of Grand Forks Hutton Well #2	0.0379	0.0089	0.0167	0.0078	1,195,214	338,499
City of Grand Forks Well #3	0.0757	0.0023	0.0633	0.0610	2,387,275	546,007
City of Grand Forks Well #4	0.0303	0.0069	0.0117	0.0048	955,541	252,915
City of Grand Forks Well #5	0.0908	0.0465	0.0696	0.0231	2,863,469	1,626,228
GFID Big Y #1	0.0513	0.0000	0.0522	0.0522	1,617,797	405,540
GFID Big Y#2	0.0421	0.0000	0.0570	0.0570	1,327,666	443,340
GFID Big Y#3	0.0513	0.0000	0.0429	0.0429	1,617,797	333,720
GFID Big Y#4	0.1893	0.0000	0.1077	0.1077	5,969,765	837,540
GFID Nursery #1	0.0757	0.0000	0.0483	0.0483	2,387,275	375,300
GFID Nursery #2	0.0268	0.0000	0.0181	0.0181	845,165	140,940
CID #1 (125hp)	0.0757	0.0000	0.0265	0.0265	2,387,275	206,116
CID #3 (50hp)	0.0606	0.0000	0.0002	0.0002	1,911,082	1,759
SID Irrigation Well #1	0.0505	0.0000	0.0861	0.0861	1,592,568	669,224
SID Irrigation Well #2	0.0394	0.0000	0.0671	0.0671	1,242,518	522,128
SID Irrigation Well #3	0.0325	0.0000	0.0411	0.0411	1,024,920	319,486

Note: GFID=Grand Forks Irrigation District; CID=Covert Irrigation District; SID=Sion Improvement District

Model Calibration

The groundwater model, particle tracking and zone budget calculations were run under steady-state conditions. To this end, the static water level elevations, as obtained from the original well records for the valley, were used for calibration. Despite significant changes to the aquifer geometry in the revised model, the calibration accuracy did not change to any large degree. The NRMS error is roughly 9% and there are no clusters of data points that can be associated with any particular portion of the aquifer. Most of the data points are for wells completed in the gravel or upper sand unit.

Well Capture Zones

Capture zones for the major production wells in the aquifer were delineated using backward particle tracking. A total of 10 particles were placed at a radial distance of 50m around the well cell within the layer intersected by the screen. The capture zones for 5, 10 and 25 years were digitized and provided as GIS coverages. These capture zones represent a projected view of the individual well capture zones (i.e., they show the capture zones for all layers of the model on a single surface). In reality, the capture zones for the shallow wells (Almond Gardens East and West) extend into Layer 1; the capture zones for BigY4, Nursery 1 and Grand Forks #4 and #5 extend into Layer 3; the remaining majority of the wells have capture zones that extend into Layer 2.

For the most part, the capture zones are relatively circular in shape and extend predictably in a radial direction away from the well, with a slight tendency to tail back upgradient. In a few cases, the capture zones extend to the Kettle River, supporting the conclusion that some wells derive their water directly from the Kettle River. Of significance is the fact that the 25 year capture zones for all the major production wells in the valley coalesce and influence a major portion of the aquifer.

Groundwater-Surface Water Interaction

Interaction between the Kettle and Granby Rivers and the aquifer were not modeled specifically. This is because in a groundwater flow model, the rivers are normally treated as having some specified head (or head-dependent) boundary condition which is essentially unaffected by the groundwater regime. Unless a specialized code, such as ModBranch (USGS) is used, the feedback from the aquifer to the river cannot be simulated. It is assumed that the head in the river is held at a specified value regardless of how much water is taken from that surface water body. In the case of the Kettle and Granby Rivers, there is sufficient flow on a year-round basis to justify this assumption, and therefore, no need to implement a coupled flow code such as ModBranch.

In the current study, the river stage elevations were determined from survey data for the rivers and generally correspond to baseflow conditions (August values). Model calibration and all simulations have therefore been conducted under baseflow conditions. In this respect, maximum pumping, minimum river stage and zero return flow from irrigation are represented in the model. The results therefore provide somewhat of a conservative estimate of river levels in the aquifer under the most stressed conditions.

Generally, the Kettle River is influent (feed the aquifer) in the western portion of the valley and effluent (receives groundwater from the aquifer) in the eastern portion of the valley. The water balance calculated for different zones in the model (West, Central, North and East) confirm the nature of the connection. In the west, a large percentage of groundwater is derived from constant head nodes (i.e., the river), and in the east, a large percentage of groundwater exits the model via the constant head nodes.

Groundwater Flow and Gradients

Groundwater flow in the aquifer is predominantly from west to east, in the same direction as Kettle River flow. The water level map is for the second layer of the aquifer, because the first layer is dry in some portions. The range in hydraulic head values is 490m a.s.l. to 530 m as.l..

An average hydraulic gradient was calculated in a horizontal direction by measuring the separation between equipotential lines on the output water level contour map. The average horizontal hydraulic gradient through the central region of the aquifer is 2.25E-3 m^{-1}. The same gradient is measured in all layers (i.e., the equipotential lines are roughly vertical in cross-section). Using the K_x values in Table A2.1, the average groundwater velocity (flux) in layer 1 is (0.001 x 2.25E-3 = 2.25E-6 m/s) while the average groundwater velocity (flux) in layer 2 is (1.5E-4 x 2.25E-3 = 3.38E-7 m/s).

Groundwater flux in the vertical direction was calculated by Visual Modflow. The range of vertical flux through the top layer of the model (Layer 1) is 0 to ~20 m/day. Unrealistically high values were obtained to the west along the edge of the model domain as well as to the north near Copper Ridge. The values are suspicious and thought to be related to edge effects in the model solution.

Of interest with the flux map is the slightly elevated vertical region to the south of the City of Grand Forks. This is also the area where high levels of nitrate contamination have been measured. Using the K_z value for layer 1 (0.0001 m/s) and a flux of 5-10 m/day, the range of gradient in this region is roughly 0.58 to 1.16 m^{-1}, considerably higher than that measured in a horizontal direction.