EUB/AGS Special Report 73

Regional Groundwater Quality Appraisal, Cold Lake-Beaver River Drainage Basin, Alberta

Alberta Energy and Utilities Board

Alberta Geological Survey

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Acknowledgments

The collection, entry, analysis and interpretation of groundwater quality data, and the determinations of aquifer sensitivity and vulnerabilities for the Cold Lake – Beaver River Basin was undertaken under contract with Alberta Environment. The authors would like to acknowledge the participation of industrial developers, municipalities and counties, cities and towns, industry associations, and government agencies for their data submissions. The authors wish to express their appreciation and thanks to the Cold Lake – Beaver River Basin groundwater quality steering committee for their careful review of the draft report and figures and for providing feedback during the data collection and interpretation phases of the project. Special thanks are due to Erin Kempin, Gordon Jean, Sheila Stewart and Kevin Nipp for their work in assembling and processing the project data; to Natasha Clarke for her assistance and advice in preparing the various GIS figures; to Dan Magee for his assistance in preparing various project figures; and to Maryanne Protz for her assistance in generating the digital version of this report.

Summary

The Alberta Geological Survey (AGS) of the Alberta Energy and Utilities Board (EUB) has partnered with Alberta Environment (AENV) Northern Region to compile and analyse groundwater data in the Cold Lake-Beaver River Drainage Basin. This compilation and analysis will assist AENV and its stakeholders to complete an update of the Beaver River-Cold Lake Water Management Plan. The project completed a fully-digital three-dimensional geological model of the area, compiled a relational database of groundwater well and chemistry details and linked it to a geographic information system (GIS), and constructed a three-dimensional calibrated regional groundwater flow-model of the basin. This report summarizes the groundwater quality assessment portion of the project and presents preliminary results. This report is divided into seven sections:

- Section 1 provides an overview of the study area, discusses groundwater use within the Basin and provides the scope of the report.
- Section 2 provides an overview of the groundwater flow characteristics within the Cold Lake-Beaver River Drainage Basin and discusses means to address data gaps identified in the current state of knowledge.
- Section 3 discusses the geology of the glacial deposits overlying the bedrock in the Cold Lake-Beaver River Drainage Basin, presents maps showing the geological extents of aquifer and aquitards therein and introduces the reader to the geological processes that can affect groundwater quality.
- Section 4 discusses the distribution of potential point and non-point sources of contamination within the Basin.
- Section 5 presents preliminary observations on the groundwater chemical quality within the Basin by formation.
- Section 6 discusses the concepts of intrinsic sensitivity and aquifer vulnerability and the applicability of these concepts within the Basin.
- Section 7 provides recommendations and presents the study conclusions.

The key learnings of this study are as follows:

- The regional groundwater chemical-quality is generally within Canadian drinking water quality guidelines and it has not changed detectably over time.
- A number of areas within the Basin were determined to be potentially sensitive to contamination.
- A number of potential point and non point sources of contamination are located within these sensitive areas. Activities within such areas should be carefully managed so that minimal impacts occur on groundwater quality.

1 Introduction

Groundwater is extensively used in the Cold Lake-Beaver River Drainage Basin for household, agricultural, municipal and industrial purposes. The area economy and population are growing and with this continued growth comes increased demand on the existing groundwater resource. A possible consequence from continued activity in the area is the increased risk of groundwater contamination through anthropogenic means. The fact that chemical constituents of concern have been documented in the area suggests that management of groundwater from a quality perspective will be challenging. The purpose of this report is to document the present state of knowledge of regional groundwater quality in the Cold Lake-Beaver River Basin. The sensitivity of geological materials to contamination is also presented. This report is a companion report to the Regional Groundwater Resource Appraisal of the Cold Lake-Beaver River Drainage Basin, Alberta (Parks et al, 2005). As such, some material is duplicated.

1.1 Study Area Location

The Cold Lake-Beaver River Basin in Alberta is located in east-central Alberta, Canada (Figure 1.1). It extends from approximately 54° North Latitude to 55.5° North Latitude and from 110° West Longitude to 113° West Longitude. In Canadian National Topographic System coordinates, it occupies most of the 73L 1:250,000 map sheet, with parts overflowing into the 73M map sheet and in a more minor way, onto the adjoining sheets. In the Canadian Dominion Land Survey coordinates, the southeast corner of the Basin is at approximately Township 56 Range 1 W4 and extends northward as far as Township 78 and westward as far as Range 19 W4.

1.2 Topography and Physiography

A digital elevation model (DEM) of the land surface topography is shown in Figure 1.2. The colour shade on the DEM indicates elevation above sea level, with darker colours being relatively low and lighter colours being relatively high. Some elements of the topography are immediately evident from inspection of the DEM. First, the basin outline is shaped like a cone lying west to east, opening up to the east. Second, the basin topography is somewhat saddle-shaped. There are two dominant lowland areas (blue colour on Figure 1.2) – a large one in the east and a smaller one in the northwest. There are also two dominant highland areas – a large one in the northeast and a smaller one in the west. Last, there is a bridge of intermediate elevations in the centre of the Basin that forms the “seat” of the saddle.

The Cold Lake-Beaver River Basin lies within the Eastern Alberta Plains and the Moostoos Hills Uplands regional physiographic units (Atlas of Alberta, 1969). The parts of the basin in the Eastern Alberta Plains tend to lie below 600 m elevation (except in the westernmost part of the basin) while the parts of the basin in the Moostoos Hills Uplands tend to lie above 600 m elevation. Pettapiece (1986) further subdivided the Alberta physiographic regions into smaller, sub-regional units based on physiography, local relief, drainage, and elevation. According to the Pettapiece scheme, the Cold Lake-Beaver River Basin is further subdivided into ten physiographic sub-regions. These are shown on Figure 1.3. The main sub-regions include the Moostoos Upland, the Pinehurst Hills, the Beaver River Plain, the Cold Lake Hills, the Elk Point Plain, and the Whitefish Upland. Minor parts of the Christina Lake Plain, the Frog Lake Upland, the Whitford Plain, and the Wandering River Plain are found along the Basin periphery.

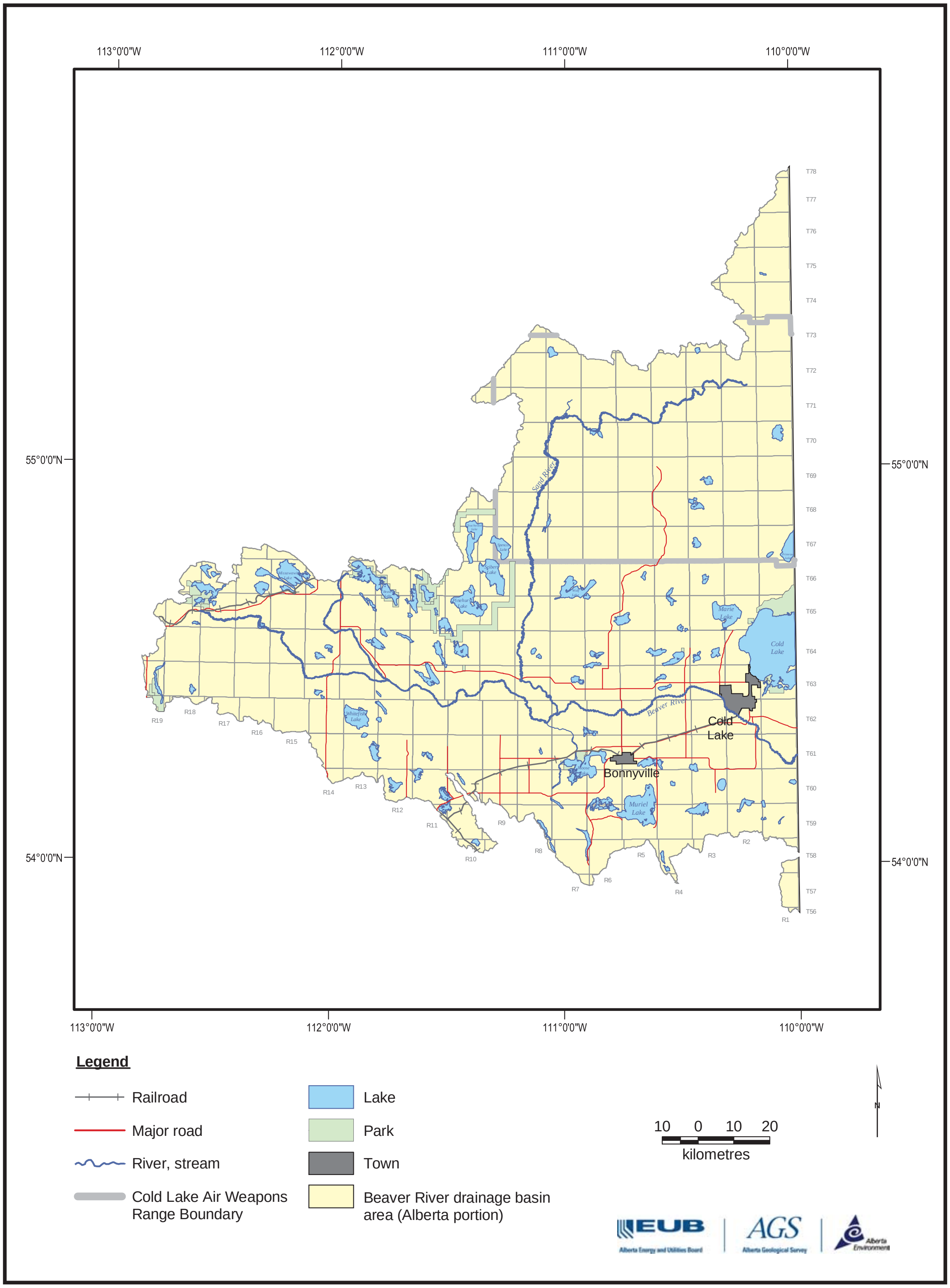
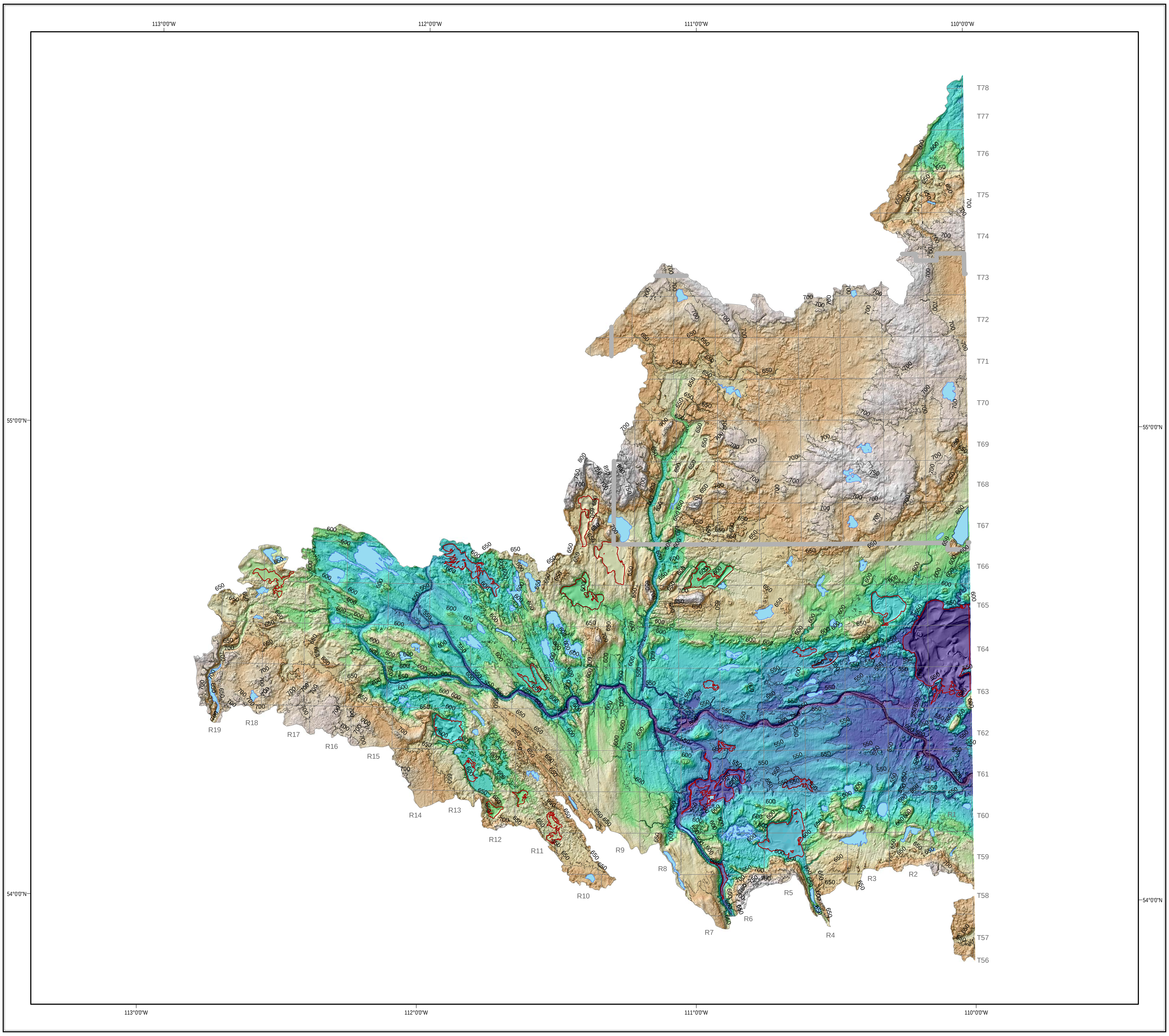
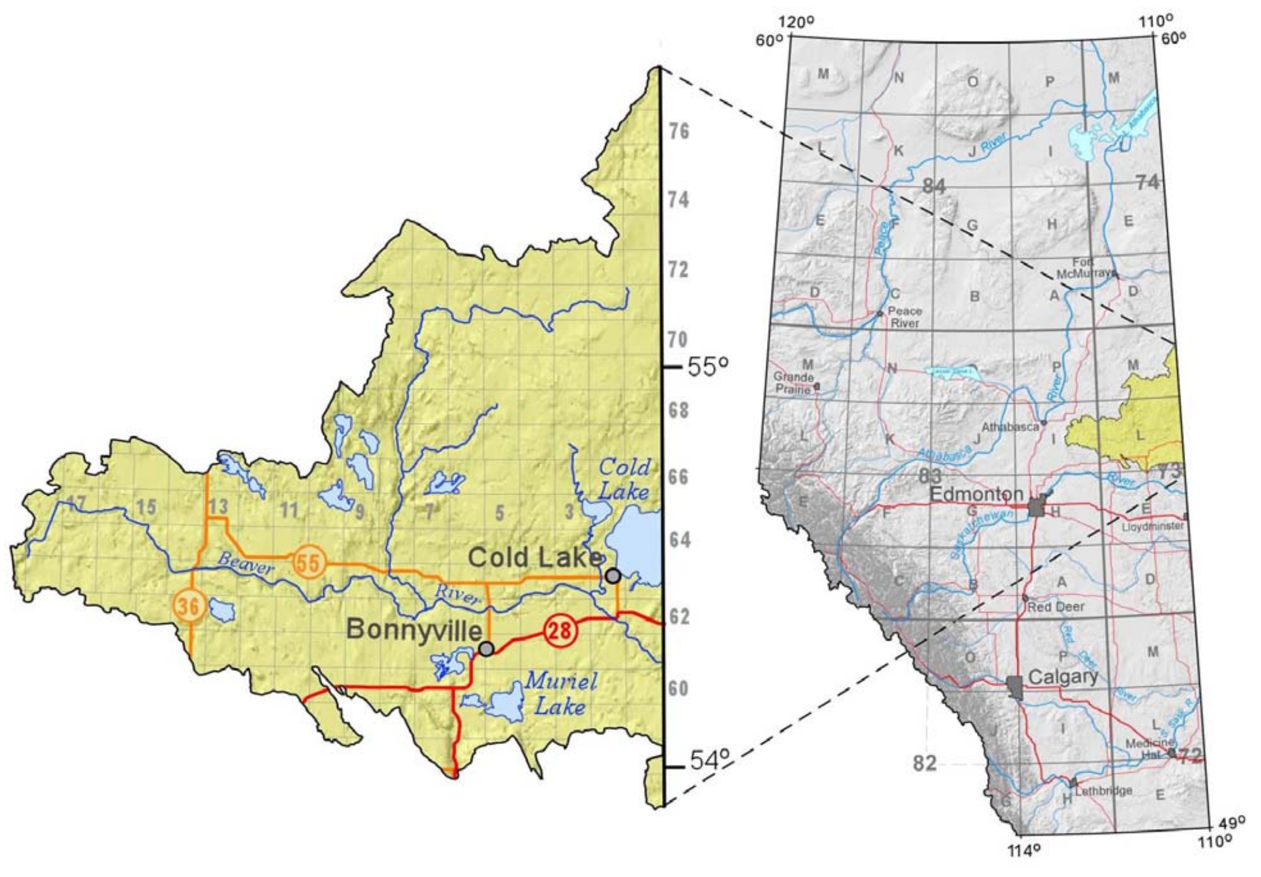


Figure 1.1. Beaver River Basin study area.





Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

4 0 4 8 12 16 20 24 Miles

Projection: UTM Zone 12
Datum: NAD83

▨	High : 700-860
▨	690
▨	670
▨	650
▨	630
▨	620
▨	610
▨	600
▨	580
▨	550
▨	540
▨	530
▨	Low : 435-520 metres above sea level

🟦	Lakes
🟥	Boundary of lakes with bathymetry
―	50m contours on land surface
▬	Cold Lake Air Weapons Range Boundary

October, 2004

Figure 1.2. Digital elevation model of the study area.

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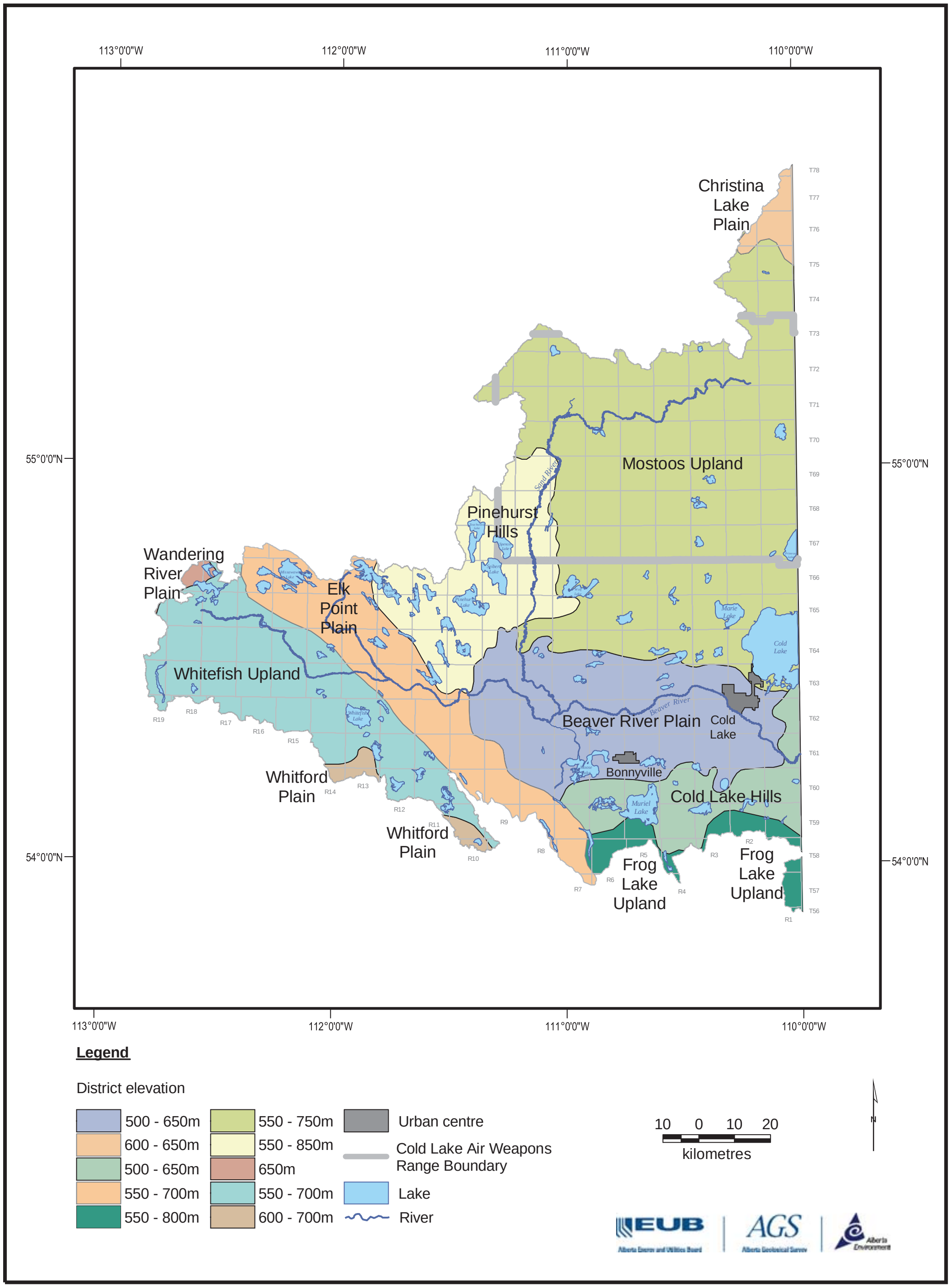


Figure 1.3. Physiographic subdivisions of the Beaver River Basin (from Pettapiece, 1986).

1.3 Climate and Precipitation

Winters in the Beaver River-Cold Lake Basin are cold with an average January daytime temperature of -18^{o}C. Summers are cool with an average July daytime temperature of +18^{o}C. The summer is short with

80 to 100 frost-free days. The average annual precipitation is 400-600 mm. Average annual snowfall in non-drought years is of the order of 1200 mm. Lake or free surface evaporation is 600 mm whereas estimated average annual evapotranspiration is in the order of 400 mm. Total streamflow including runoff and baseflow is in the order of 120 mm/year (Environment Canada, 1978).

1.4 Groundwater Use and Availability of Groundwater Chemistry Data

The use of groundwater can be generally assessed based on the volumes applied for and licensed under the Water Act. Based on the available information, a map of potential water use was produced (Figure 1.4). This map likely overestimates the actual use at these sites, since applied for volumes are not always actually withdrawn. The location of all water wells is presented in Figure 1.5. The distribution of the wells suggests that groundwater is an important resource in the Basin and one that is actively being developed. Not all wells will have associated information on the water chemistry and some that do, will not meet site selection criteria for inclusion into a groundwater quality assessment exercise. The locations of wells that were included in the water chemistry evaluation are presented in Figure 1.5.

1.5 Scope of the Report

An original water management plan for the Basin was completed in 1985. In an effort to update this plan, the Alberta Geological Survey in conjunction with Alberta Environment undertook a study to investigate the physical and chemical hydrogeology of the area. The original management plan did not include groundwater quality information and as such, this report is the first to document the groundwater quality of the Quaternary-Tertiary succession on a basin-wide scale. The primary purpose of this report is to document the results of the groundwater quality assessment. Towards this goal, this report will

- Summarize the existing information available on groundwater quality in the Basin
- Compile the locations of potential point and non-point sources of contamination
- Assess the sensitivity of aquifers in the area to contamination

2 Groundwater Flow in the Cold Lake-Beaver River Drainage Basin

2.1 Potentiometric Surfaces and Horizontal Flow Directions

Regional groundwater flow was mapped for the coarse-grained formations classified as regional aquifers in the Cold Lake-Beaver River Basin using a dataset of regional hydraulic heads compiled from available information from water wells and observations wells in the Cold Lake Beaver River Basin. Maps were produced for the Empress Formation Unit 1, Empress Formation Unit 3, Muriel Lake Formation, Ethel Lake Formation, Sand River Formation, and Grand Centre Formation (Figure 2.1, Figure 2.2 and Figure 2.3). There were not enough static water-level data of acceptable quality in the other formations to map. The geology of these formations is summarized in Section 3.

Regional groundwater flow directions in the horizontal and vertical can be inferred from these static water-level maps. Groundwater will flow from high values of hydraulic head to low values of hydraulic head along paths perpendicular to the iso-head contour lines. Vertical components of groundwater flow can be inferred by stacking hydraulic head maps from the deepest formation to the shallowest formation. Examination of flow directions and hydraulic head distributions in each formation reveals a complex pattern of regional flow with local variations presumed to be caused by geology, local topography, or pumping effects.

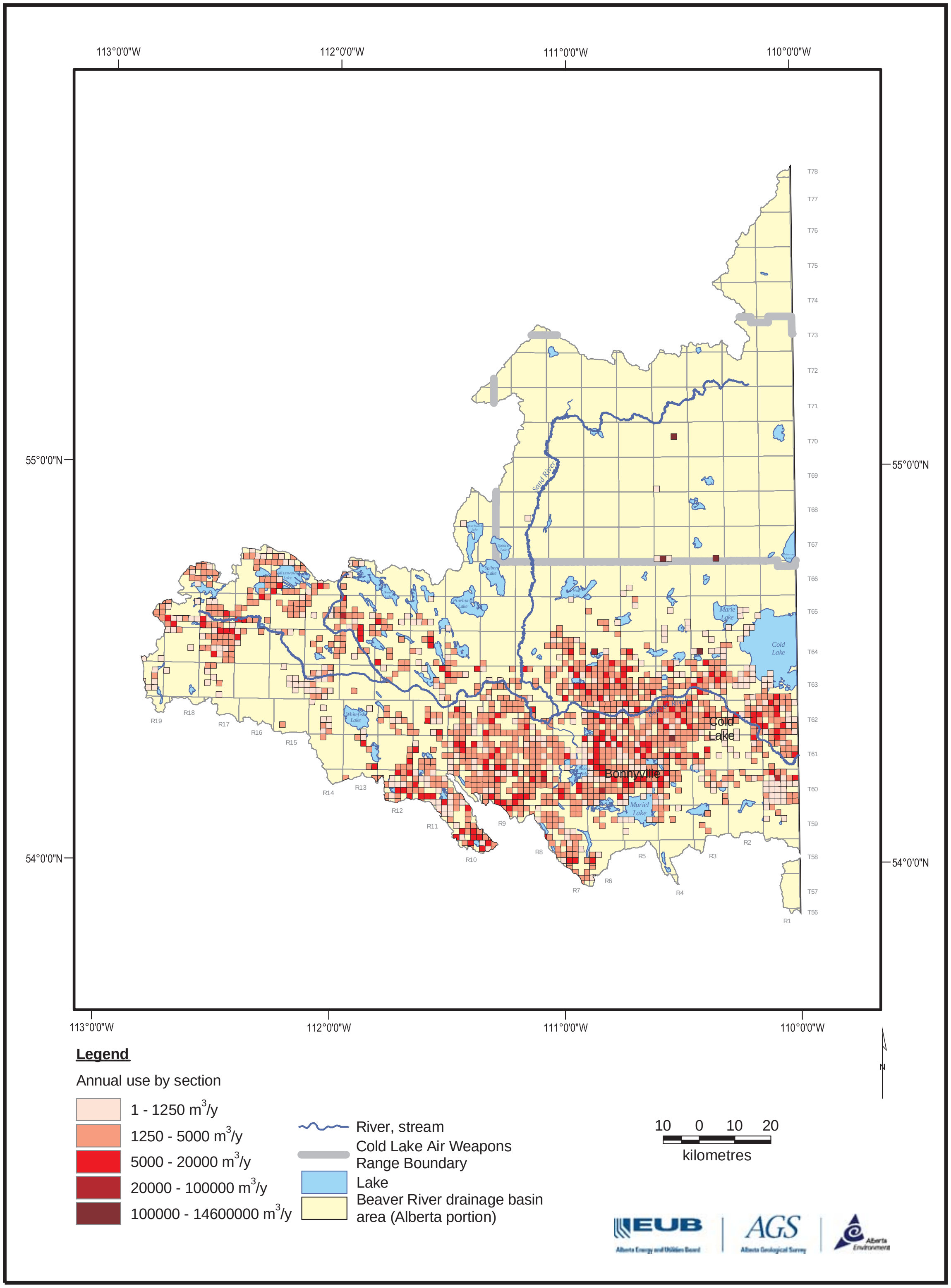


Figure 1.4. Estimated water use in the study area by section.

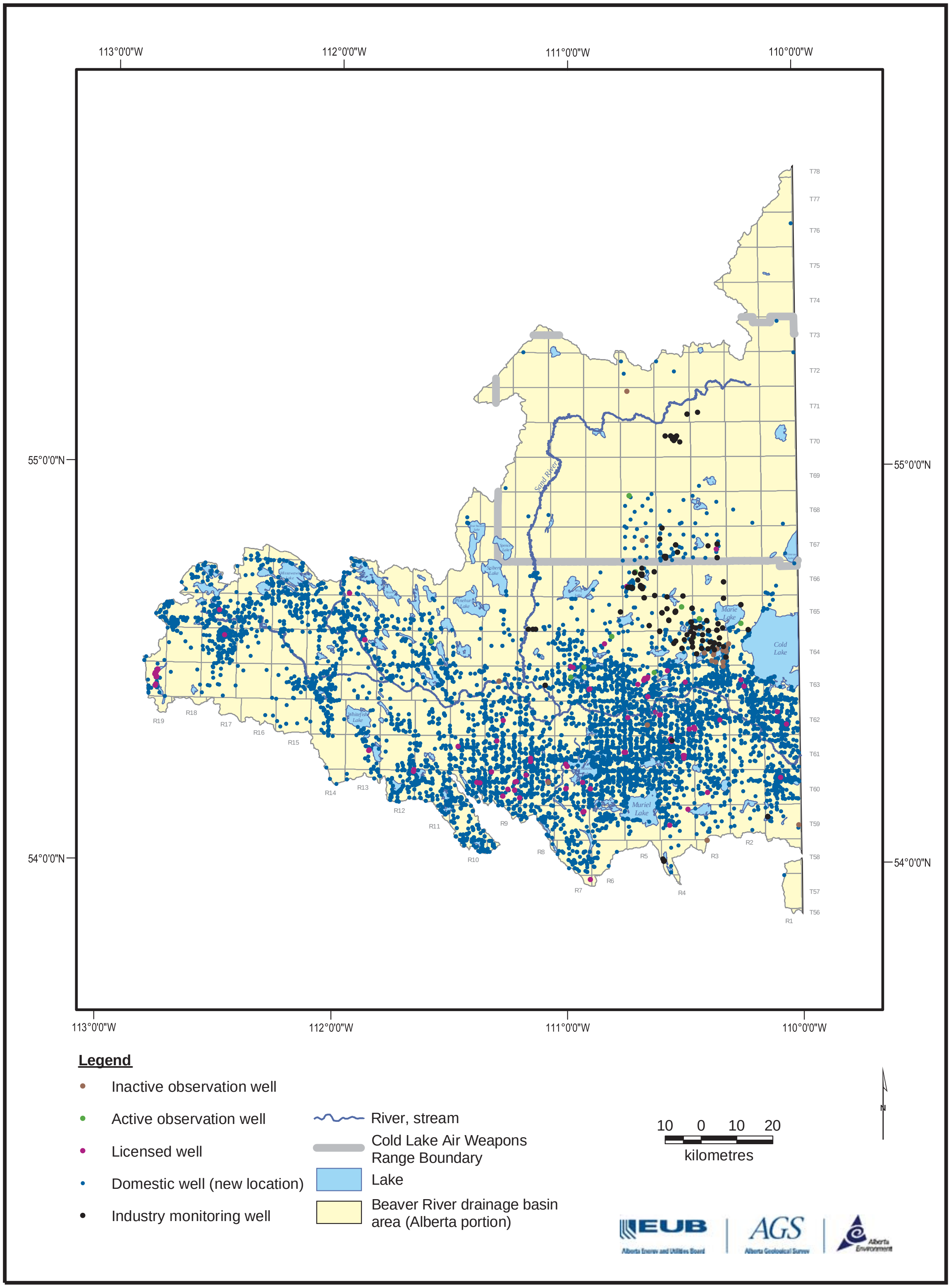


Figure 1.5. Location of water wells (by type).

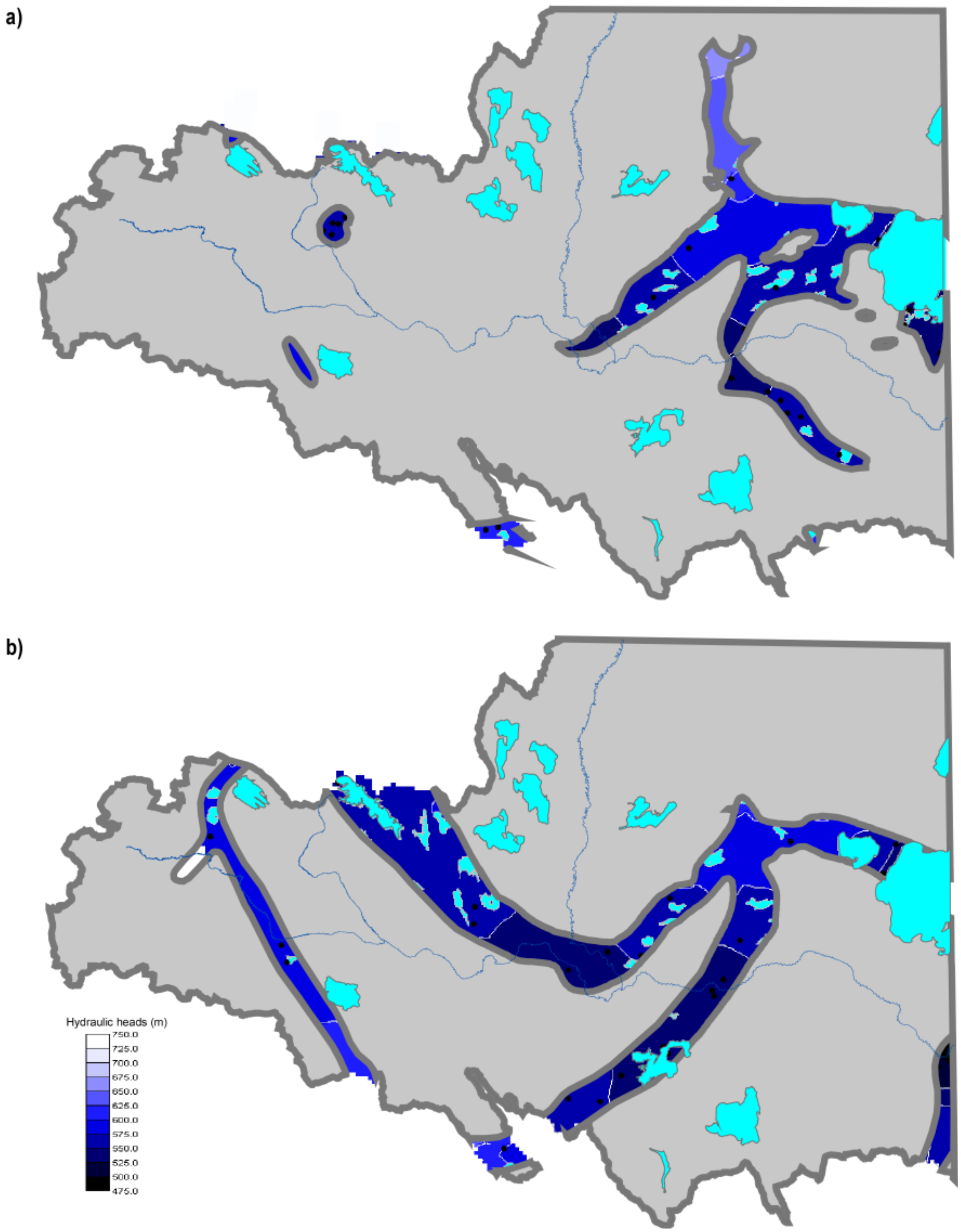


Figure 2.1. Distribution of hydraulic head in: a) the Empress Formation Unit 3; and b) the Empress Formation Unit 1.

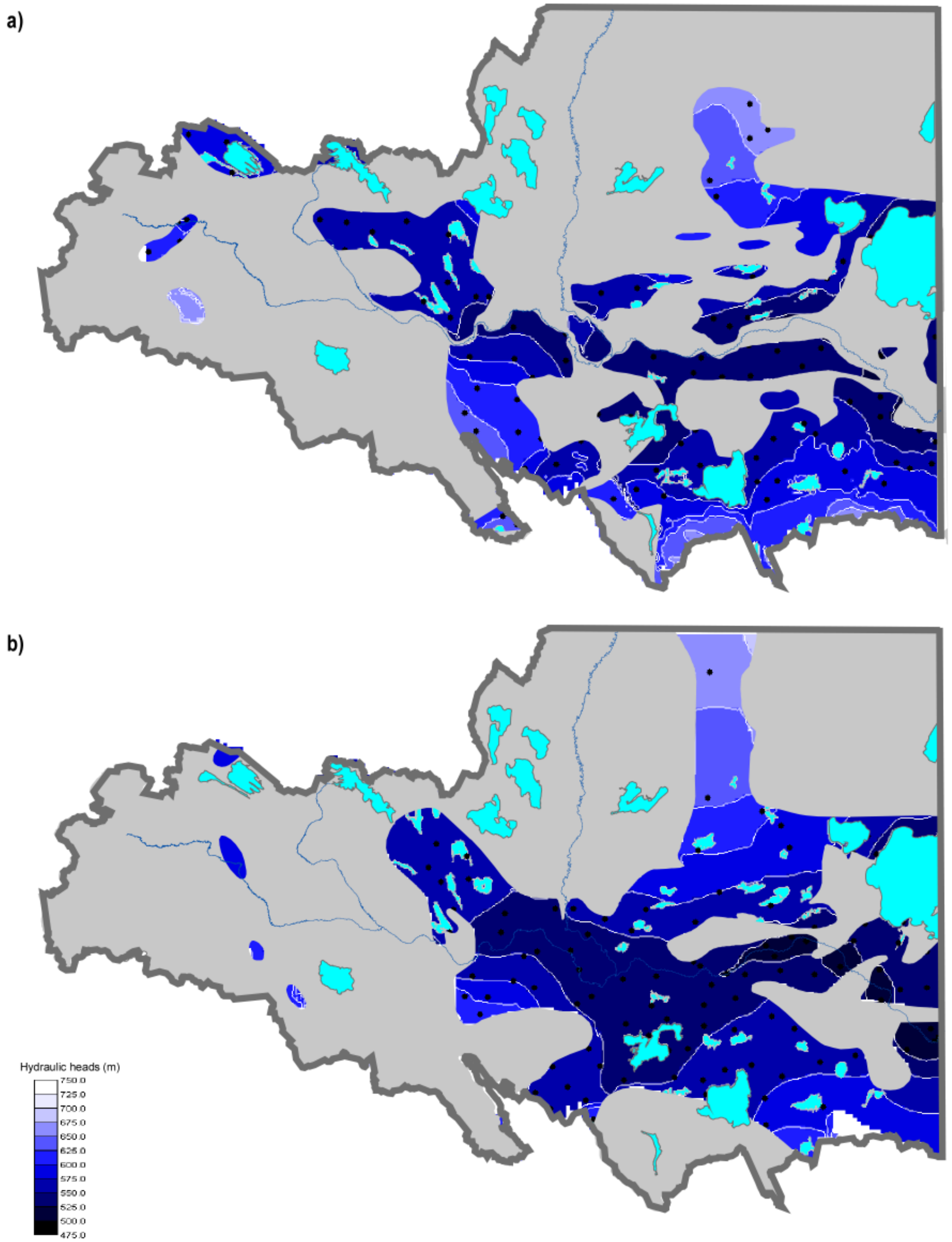


Figure 2.2. Distribution of hydraulic head in: a) the Ethel Lake Formation; and b) the Muriel Lake Formation.

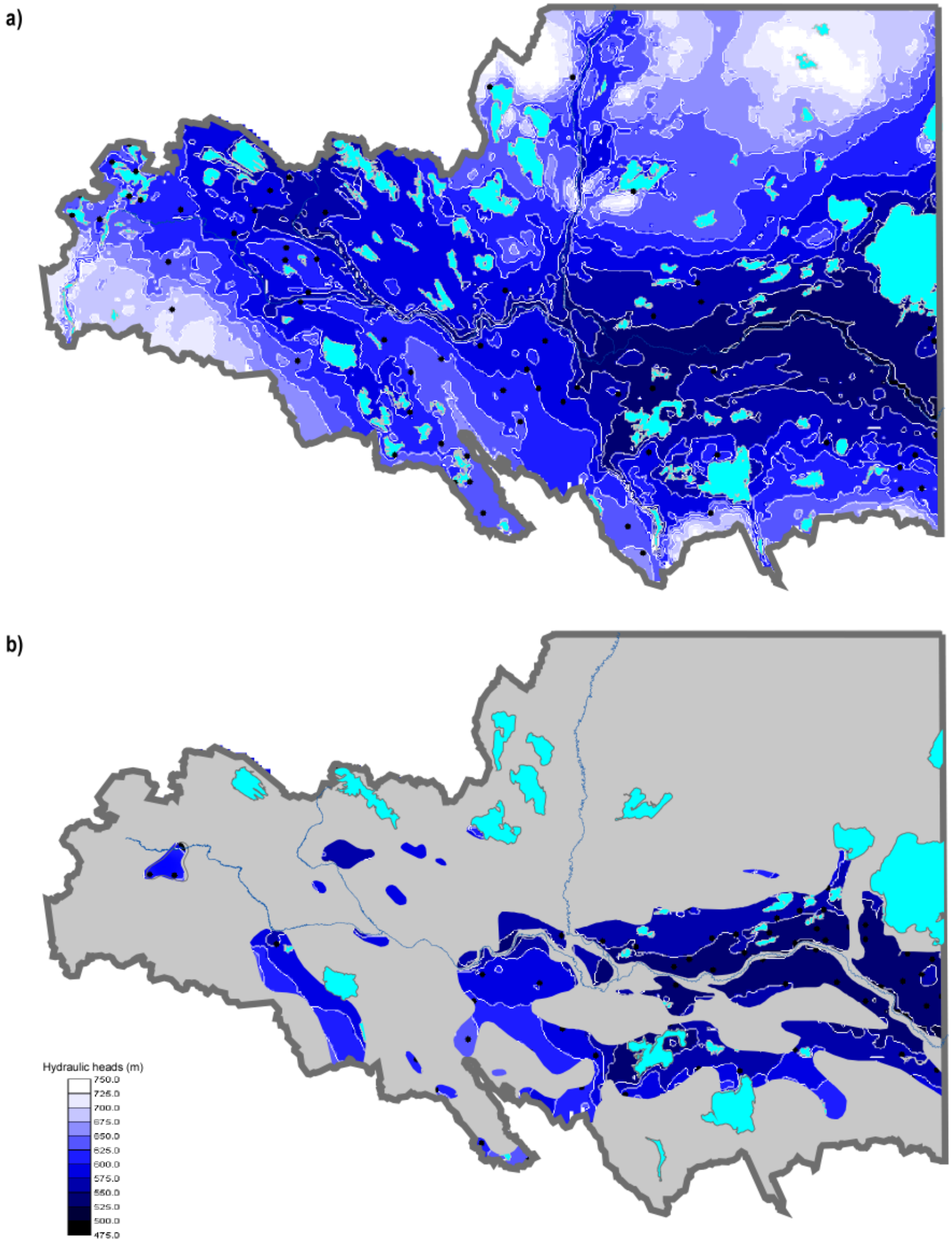


Figure 2.3. Distribution of hydraulic head in: a) the Grand Centre Formation; and b) the Sand River Formation.

2.2 Flow Systems in the Cold Lake-Beaver River Drainage Basin

The natural groundwater flow in the Cold Lake-Beaver River Basin can be divided into five main regional systems. The extents of the five systems are shown in Figure 2.4. They are identified by their geographic location and were determined by the nature of hydraulic head maps of the various formations present within the Basin. They are named for the purpose of this report as the Southwest Beaver River (SWBR) flow-system, the Northwest Beaver River (NWBR) flow-system, the Southeast Beaver River (SEBR) flow-system, the Northeast Beaver River (NEBR) flow-system and the Wiau flow-system.

Flow in the SWBR flow-system originates in the Whitefish Upland and flows northeast into the Amisk River from the southwest. There is however some regional flow within this system that appears to be captured by Whitefish Lake, the largest lake in the area.

Flow in the NWBR flow-system is more complex, with groundwater flow diverging north and south along a topographic high that separates surface drainage going into the Amisk and upper Beaver rivers and also coming westward to the Beaver River from the west side of the Pinehurst Hills. Hydraulic head distributions in all of the formations suggest that some groundwater flow in the NWBR flow-system leaves the basin along the Helina Valley north westward towards Lac La Biche as opposed to leaving the Basin eastward as baseflow or underflow of the Beaver River.

Regional groundwater flow in the SEBR flow-system flows north from the Cold Lake Hills to the Beaver River. Regional groundwater flow in the NEBR flows radially off of the Moostoos uplands into the Sand River to the west, Cold Lake to the southeast and Beaver River to the south.

On the north side of the Moostoos Upland, the limited data suggest that there is regional groundwater flow to the north towards the Wiau Valley. The nature of the regional flow north of the Moostoos Upland requires further investigation before any definitive conclusions can be drawn.

The regional flow systems discussed above should be regarded as a general statement of groundwater flow in large parts of the Cold Lake-Beaver River Basin. Within these regional systems, there will be a multitude of complex local systems that transfer groundwater from recharge areas to lakes, small streams and wetlands. In addition, pumping can alter the natural boundaries of these flow systems and can pirate groundwater from one natural flow system to another.

2.3 Groundwater Pathways

Understanding regional variations in groundwater quality, especially in shallow aquifers, requires knowledge of where groundwater is entering and leaving the natural system, how long it stayed in the ground and what materials were encountered along the flow path.

2.3.1 General Concepts

Water enters groundwater flow systems by downward-directed percolation of infiltrating precipitation, or in some cases, directly from surface water bodies. This flow is termed recharge. Regions where the flow of water is directed downwards with respect to the water table are called recharge areas (Tóth, 1963). Freeze and Witherspoon (1967) indicate that areas of recharge should be expected in the following situations

- Near the topographic divide at the upstream end of a homogeneous isotropic basin with a simple water-table configuration

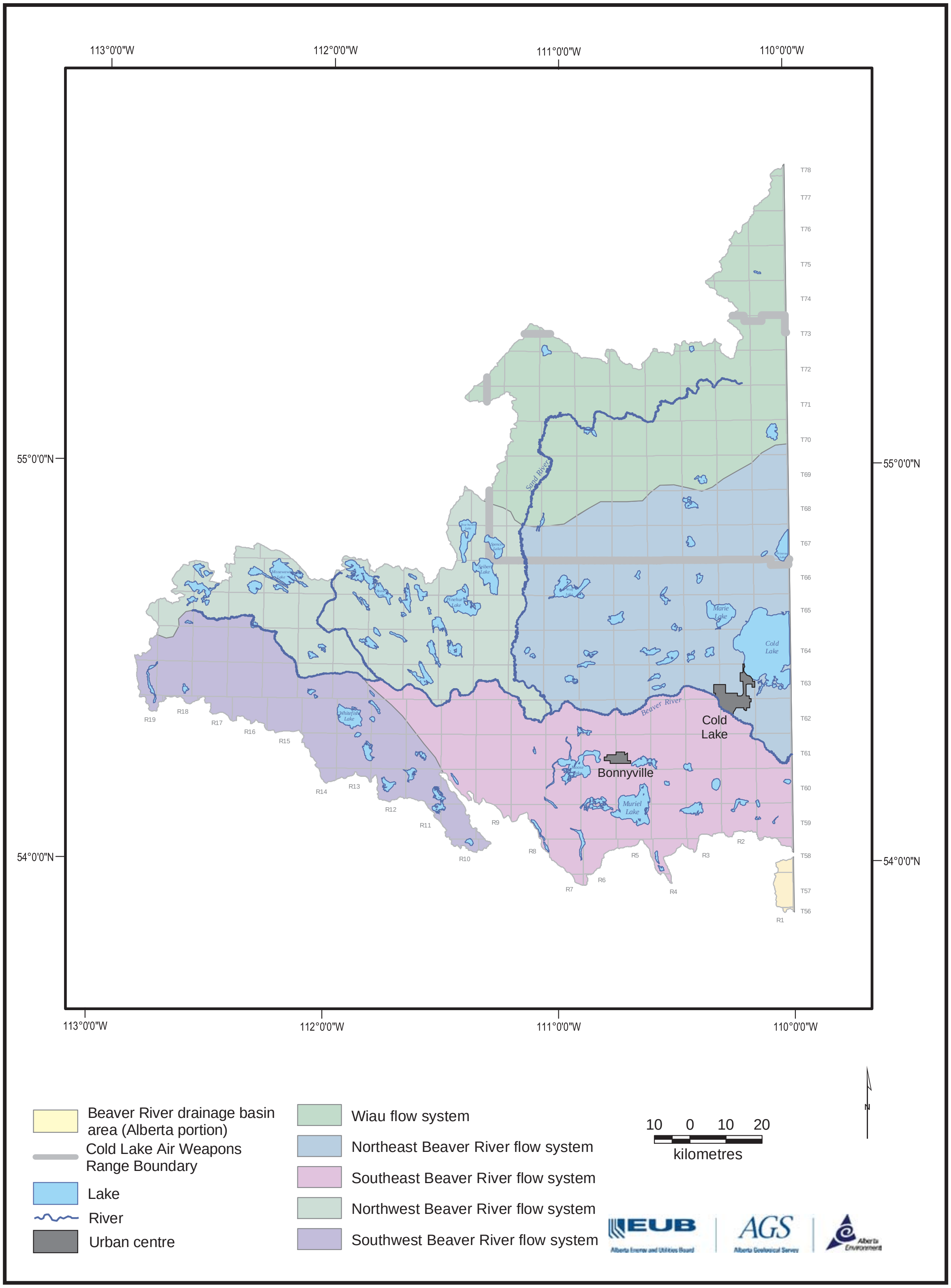


Figure 2.4. Flow systems within the study area.

- In the upstream half of basins with continuous layered stratigraphy
- On and just above steep valley slopes
- On water table highs in regions with a hummocky water table configuration
- In the area overlying the upstream portion of a partial aquifer
- In the outcrop area of a downstream sloping aquifer.

Water exits groundwater flow systems by upward flow into surface water bodies, marshes, wetlands and springs. Upward-oriented, exiting flow is called discharge. Regions where the flow of water is directed upward with respect to the water table are called discharge areas (Tóth, 1963). Freeze and Witherspoon (1967) suggest that areas of groundwater discharge occur under the influence of at least six distinguishable cases of water table configuration and geologic setting, including

- The existence of a valley causing concentrated discharge into the valley
- Minor topographic lows will form discharge areas, potentially capturing significant amounts of basin flow
- A discharge area can occur just below the steep components of a break in slope
- A discharge area can occur at the surface above a pinchout of a high permeability aquifer. The extent and intensity of discharge depends on
    a) The position of the aquifer within the basin
    b) The permeability contrast between the aquifer and the surrounding medium
- A discharge can occur below the outcrop of an upstream sloping aquifer
- A discharge area can occur at the outcrop of an downstream sloping aquifer.

The area that separates the recharge area from the discharge area is termed by Domenico and Schwartz (1990) as the region of lateral flow.

2.3.2 Recharge and Discharge Areas

Recharge and discharge areas were mapped using the groundwater modelling results detailed in (Parks et al., 2005). The recharge and discharges areas were determined by subtracting the ground surface elevation from the hydraulic heads of the first model layer. Values greater than 1 were classified as recharge areas. Values less than -1 were classified as discharge areas. Values between 1 and –1 were classified as areas of lateral flow. Certain model-generated discrepancies created near surface water bodies were dealt with on a case-by-case basis. The various areas are presented in Figure 2.5.

Recharge areas correspond closely to topographic highs, while discharge areas appear related to topographic lows and surface water bodies. Departures from this standard model are likely caused by such factors as those discussed in the previous section, properties of geological materials, or pumping effects. It should be noted that a more detailed analysis of recharge discharge relationships is possible using the groundwater model developed for the Cold Lake Beaver River Basin. However, the calculation method employed is adequate for general purposes such as drawing preliminary conclusions regarding recharge discharge relationships, and intrinsic sensitivity of aquifers with the Basin.

2.3.3 Groundwater Velocity and Age

Depending upon hydrogeologic conditions within recharge areas and along flow paths, water entering

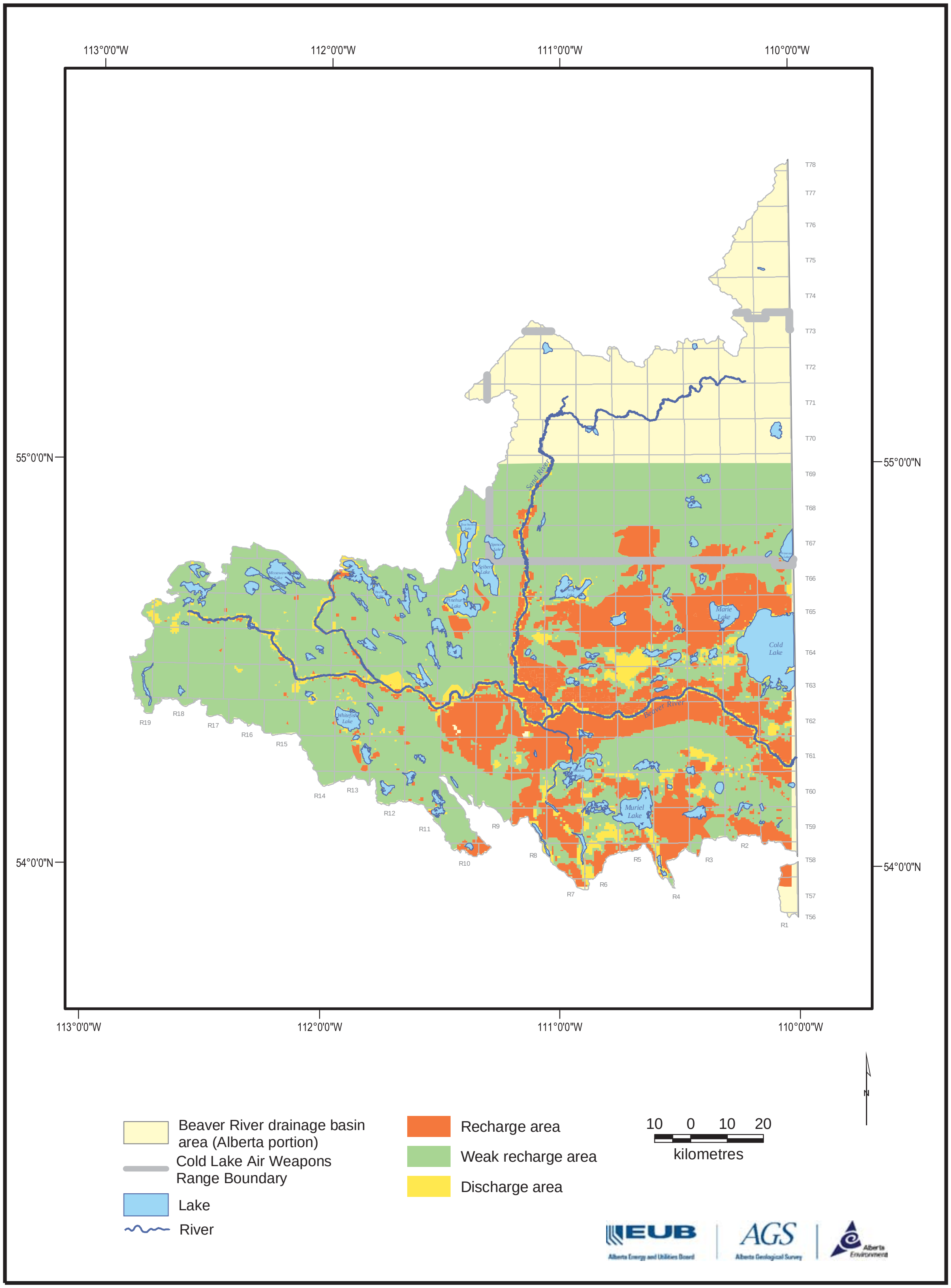


Figure 2.5. Recharge and discharge areas within the study area.

the groundwater system can follow short or long pathways towards discharge areas (Figure 2.6). Considerations such as sustainability of groundwater resources are dependent on recharge-discharge relationships of groundwater flow systems. In turn, recharge-discharge relationships are dependent on groundwater flow velocity within the aquifers that make up the flow system.

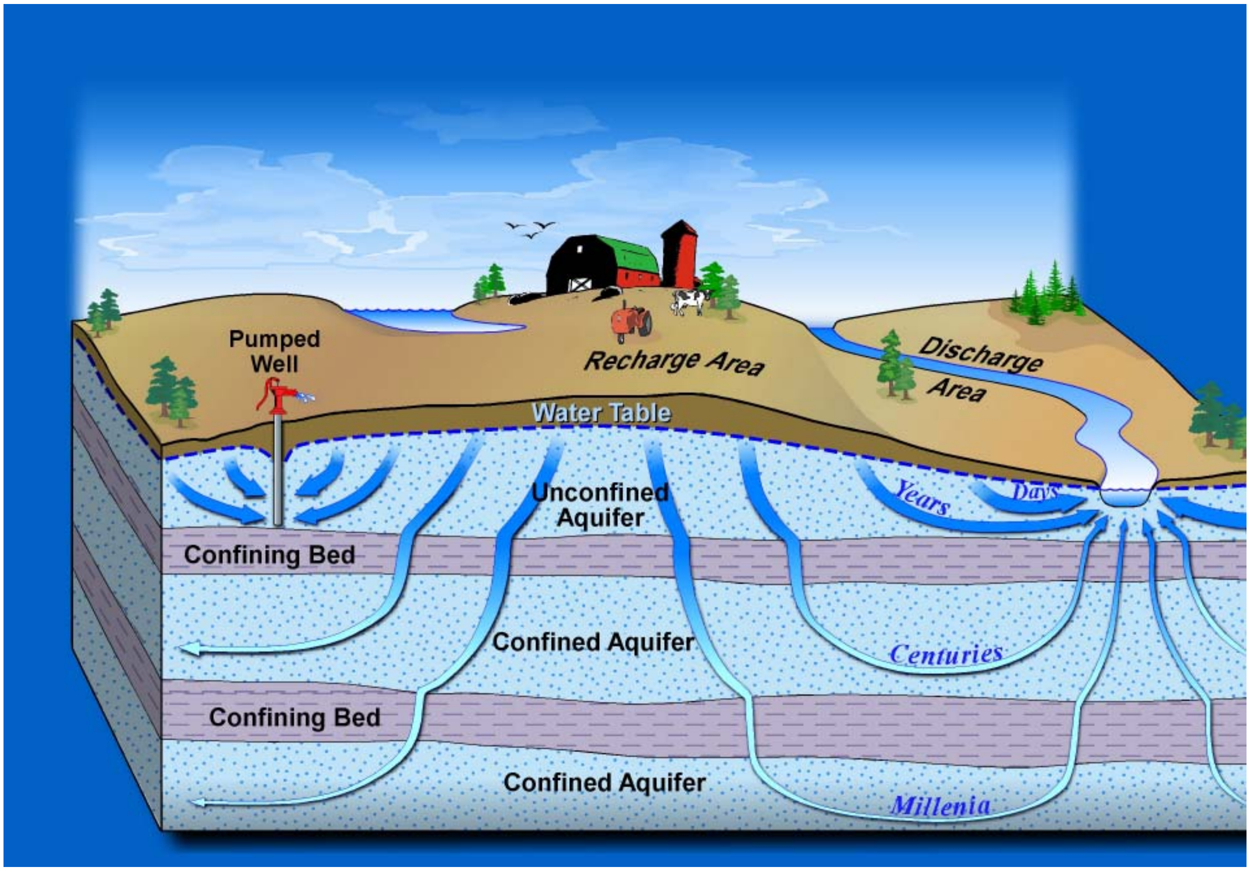


Figure 2.6. Schematic diagram of groundwater flow concepts.

Groundwater moves through the connected pore openings of the aquifer material from regions with high hydraulic head to regions of lower hydraulic head. The velocity is controlled by the porosity of the aquifer, the nature of the aquifer material and the hydraulic gradient according to the equation

$$v = -\left(\frac{K}{n_e}\right)\frac{\partial h}{\partial l} \qquad \text{(Equation 1)}$$

where: v = velocity (volumetric flow rate per unit area of connected pore space)
K = hydraulic conductivity (a property of the medium and of the fluid moving through it)
n_e = effective porosity (amount of connected pore space)

$\frac{\partial h}{\partial l}$ = hydraulic gradient (rate of change of hydraulic head over a given distance)

Although groundwater velocity can be calculated from the above equation, it may not accurately reflect the period of time required for a molecule of water to move from a recharge area towards a discharge area. In order to determine this time value, chemical methods must be applied in the form of tracer studies or through groundwater age dating.

Groundwater age is among the most fundamental parameters describing subsurface flow, and is the conceptual link between flow modeling and radiometric age dating (Bethke and Johnson (2002a). With this information, calculations can be performed to determine: sustainable yields of aquifers, groundwater flow velocities and therefore more accurate representations of groundwater flow. Conceptualizations of groundwater age can be broken down into four separate models: 1) piston flow age; 2) age mass; 3) radiometric age dating; and 4) in-growth from radioactive decay.

2.3.3.1 Piston Flow Age

The idea behind piston flow age is that groundwater age is the distance to the point of recharge divided by groundwater velocity averaged over the flow path (Bethke and Johnson, 2002a). This implies that a mass of water enters at the recharge point and migrates through the aquifer as a distinct mass. Flow is through advection and the assumption is made that the exchange of mass between aquifers and aquitards has little or no effect on the age of the water. Several authors have pointed out deficiencies of this concept including Sudicky and Frind (1981), Walker and Cook (1991), Maloszewski and Zuber (1991), Goode (1996), Bethke and Johnson (2002a, b) and Park and Bethke (2002). Bethke and Johnson (2002b) state that the piston flow model: 1) can provide information only about the rate of advection in one dimension; 2) breaks down when considering any but the simplest flow regimes; 3) produces estimates of age that are unrealistic since water molecules do not move through the subsurface in isolated packets; 4) calculates ages that are inconsistent with dating methods; and 5) does not allow for the analysis of error. However, some successes have been documented using the piston flow age approach. Reilly et al. (1994) used an advective model to show that simulated groundwater age was consistent with the distribution of chlorofluorocarbons and tritium in a shallow sand and gravel aquifer.

Because of these now recognized limitations to piston-flow age determinations, these calculations have not been attempted in the Cold Lake-Beaver River Basin.

2.3.3.2 Age Mass

Future work in the Cold Lake-Beaver River Basin on groundwater age dating must consider conceptual advances in age-mass determinations. Goode (1996) defines groundwater age as the average over its water molecules of the time elapsed since they recharged the subsurface. This suggests that the age of the groundwater is not a measureable physical property, but rather, when different masses of water are mixed, the mean age of the mixture is the mass-weighted average age of the mixed components (Goode, 1996). For example, if 1 kg of 10-year-old water is mixed with 1 kg of 30-year-old water, the result is 2 kg of 20-year-old water (Bethke and Johnson, 2002a). The concept behind the age mass groundwater age is that one water molecule may have migrated from recharge rather directly while another may have been derived from an overlying aquifer while yet another may have entered a confining layer and resided there for a long period of time before returning to the aquifer. All three masses of water combine to give one groundwater age mass. Each component contributes an older or younger age to the entire mass. The most important contributor to the age of the water appears to be the component that flows from the confining units. Bethke and Johnson (2002b) found that the aging of water as it migrates along an aquifer commonly contributes little to its age, but that the mere presence in the subsurface of confining layers and the very old water they contain dominates. In fact, the effect on age does not appear to depend on mixing rate, but rather on the ratio of fluid volume in aquitards in comparison to the fluid volume in aquifers (Bethke and Johnson, 2002a).

This idea appears to contrast completely with the idea of piston flow age, but really it adds to it. Instead of simply accounting for advection, the concept of age mass states that groundwater age is controlled by molecular diffusion, hydrodynamic dispersion, and fluid advection (Bethke and Johnson, 2002a). The distribution of age is therefore controlled by the transport of age in three dimensions (Bethke and Johnson, 2002a).

2.3.3.3 Radiometric Age Dating

A number of radiogenic isotopes are used for the purposes of calculating groundwater age. These include ^{3}H, ^{14}C, ^{32}Si, ^{36}Cl, ^{37}Ar, ^{39}Ar, ^{81}Kr, ^{85}Kr, ^{129}I, ^{222}Rn, ^{226}Ra, ^{232}Th, ^{235}U and ^{238}U. These radionuclides decay at a constant rate according to the equation

$$a_t = a_0 e^{-\lambda t} \qquad \text{(Equation 2)}$$

where: a_t = the activity of the species in question at time t
a_0 = the activity of the species in question at time 0

λ = the decay constant (equal to $\frac{\ln 2}{t_{1/2}}$)

t = time

The half-life ($t_{1/2}$) is the time interval required for the number of atoms or the activity of a radioactive element to fall from any particular value to one half that value (Friedlander et al., 1981, p. 191). With this information, and the determined concentration of the radionuclide in question, age dating of materials can be undertaken using the radioactive decay equation.

These age dates can be affected by some of the points raised in the previous section. Contribution of a radionuclide by molecular diffusion or hydrodynamic dispersion into the aquifer can cause the age of the water to appear younger than it actually is, while molecular diffusion or hydrodynamic dispersion out of the aquifer can cause the age of the water to appear older than it actually is. The decay rate equation is usually modified to try and account for these possibilities.

Age dating has been tried in the Cold Lake area. The results are publicly available (Imperial Oil Resources, 2002) and suggest that water within the Quaternary-Tertiary succession was recharged since the last glaciation. Age dates of groundwater from Quaternary and Quaternary-Tertiary aquifers to the north of the Cold Lake study area (Lemay, 2002a) indicate that the groundwater in most of the aquifers was recharged since the last glaciation. One of the samples had an age date suggesting it was recharge near the onset of the last glaciation.

2.3.4 Knowledge Gaps and Possible Solutions

The nature of the groundwater flow system in the Cold Lake-Beaver River Basin is generally understood and has been well modelled. However, the age and groundwater velocities are poorly constrained. The specifics are controlled by a number of factors that are difficult to characterize given current well densities and available information. Current estimates indicate that groundwater pumping has increased over time, but that present levels appear to be within the sustainable limits of the basin. Groundwater development in all aquifers will likely interact with surface water within five years of initiation of pumping (Parks et al., 2005) suggesting that management of both surface water and groundwater should be considered as a whole. Useful tools in clarifying these sustainability and management questions would be groundwater age dating techniques. Age dating of groundwater can quantitatively describe the length of time water has been isolated from the atmosphere, or since it was recharged. This coupled with groundwater modelling techniques can assist the groundwater management effort through a better capture zone analysis of single wells, a better understanding of recharge-discharge relationships of aquifers and a better understanding of flow paths within and between aquifers.

3 Geology of Aquifers and Aquitards Within the Cold Lake-Beaver River Basin and the Potential Impact on Groundwater Quality

3.1 Description of Major Aquifers and Aquitards

The drift in the Cold Lake-Beaver River Basin is comprised of all of the unconsolidated sediments between the top of the bedrock and the land surface. The drift is generally, but not always, thicker over bedrock lows and thinner over bedrock highs. The drift is composed of a series of regionally distinct and mapable units. These units have been formally recognized as geological formations. A stratigraphic chart showing the names of the drift formations and major glacial events is presented in Figure 3.1.

In order of age from oldest to youngest, and depth from deepest to shallowest, the drift formations in the Cold Lake-Beaver River Basin are as follows: The Empress Formation, the Bronson Lake Formation, the Muriel Lake Formation, the Bonnyville Formation, the Ethel Lake Formation, the Marie Creek Formation, the Sand River Formation, and the Grand Centre Formation. These formations will be described in general terms below. More detailed descriptions of the formation properties within the study area and adjacent areas are given in Parks et al. (2005), Andriashek and Fenton (1989) and Andriashek (2003).

3.1.1 The Empress Formation

The Empress Formation is defined in Alberta as all stratified sediments that overlie the bedrock and underlie glacial till. In the Cold Lake-Beaver River Basin, the Empress Formation is found mostly on the floors and adjoining terraces of preglacial buried valleys. Three distinct stratified units of the Empress have been recognized in the area. The basal unit, the Empress I, is a sand and gravel deposit directly overlying bedrock. The next unit, the Empress II, is a stratified silt and clay unit that overlies much but not the entire Empress I. The third unit, the Empress III, is another stratified sand and gravel unit that overlies the Empress II, but lies below the till of the overlying Bronson Lake Formation. All of the units of the Empress Formation are areally confined to the preglacial valleys. The extent of the Empress Formation is presented in Figure 3.2, 3.3 and 3.4.

3.1.2 The Bronson Lake Formation

The Bronson Lake Formation is a glacial till (or diamict) and diamict mixed with clay. Like the overlying Empress Formation, the Bronson Lake is mainly confined to the buried preglacial valleys but offlaps some of the valley margins onto higher bedrock elevations. The extent of the Bronson Lake Formation is presented in Figure 3.5.

3.1.3 The Muriel Lake Formation

The Muriel Lake Formation is composed of silt, sand and gravel of glaciofluvial origin. The Muriel Lake Formation generally follows the bedrock valleys but like the underlying Bronson Lake Formation, it extends beyond the valley walls. The extent of the Muriel Lake Formation is presented in Figure 3.6.

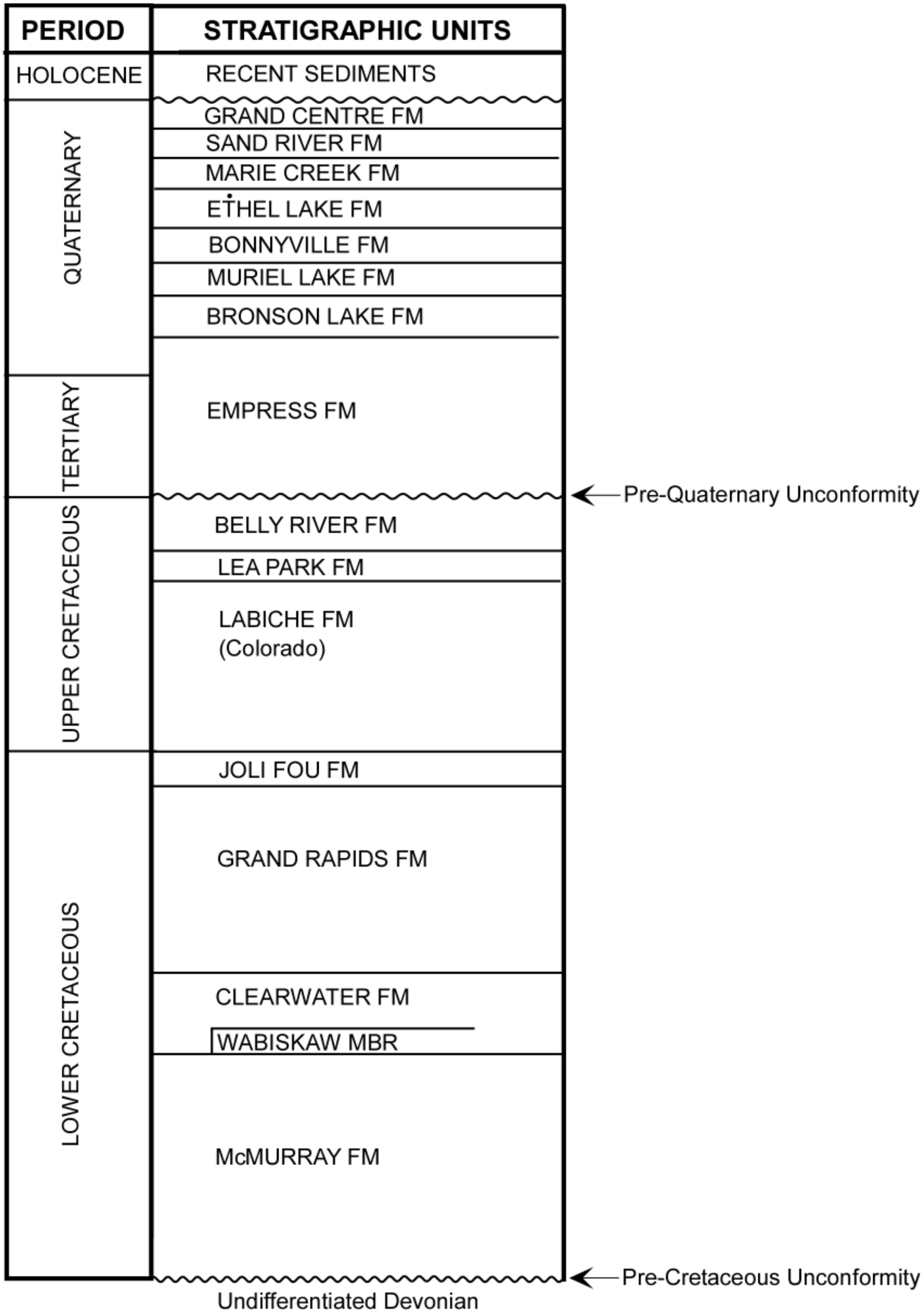


Figure 3.1. Stratigraphic column for the study area.

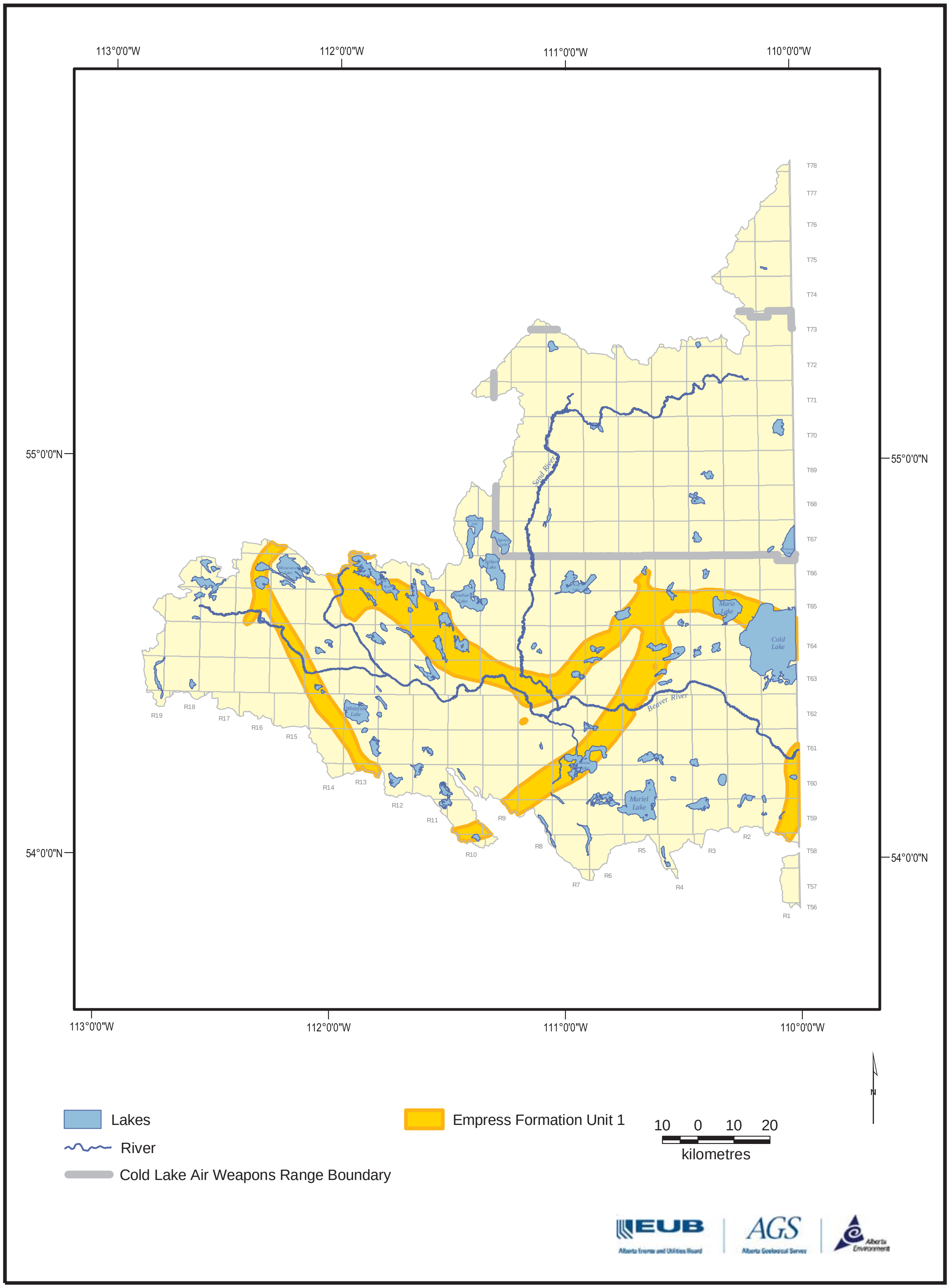


Figure 3.2. Geographic extent of the Empress Formation Unit 1.

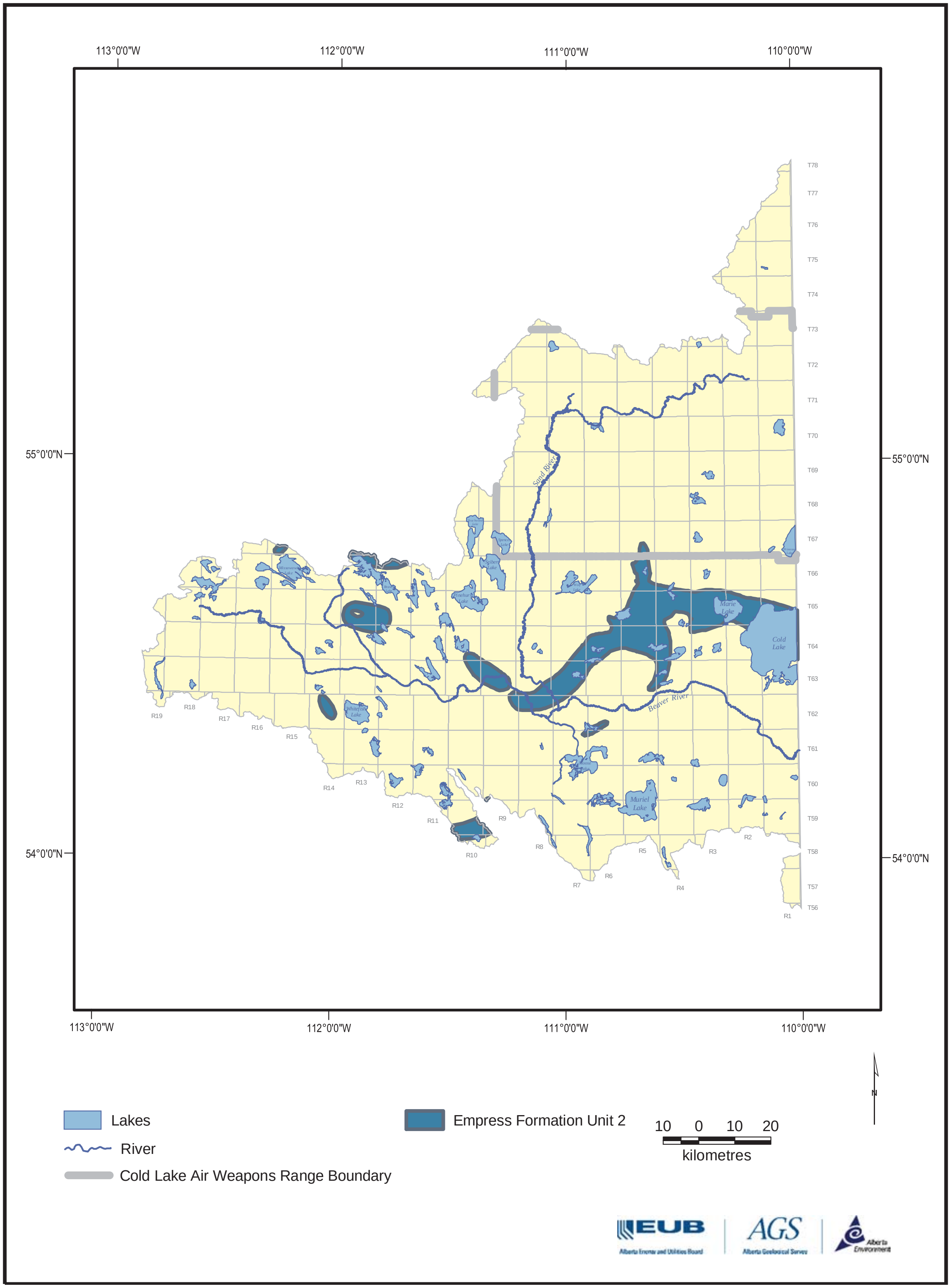


Figure 3.3. Geographic extent of the Empress Formation Unit 2.

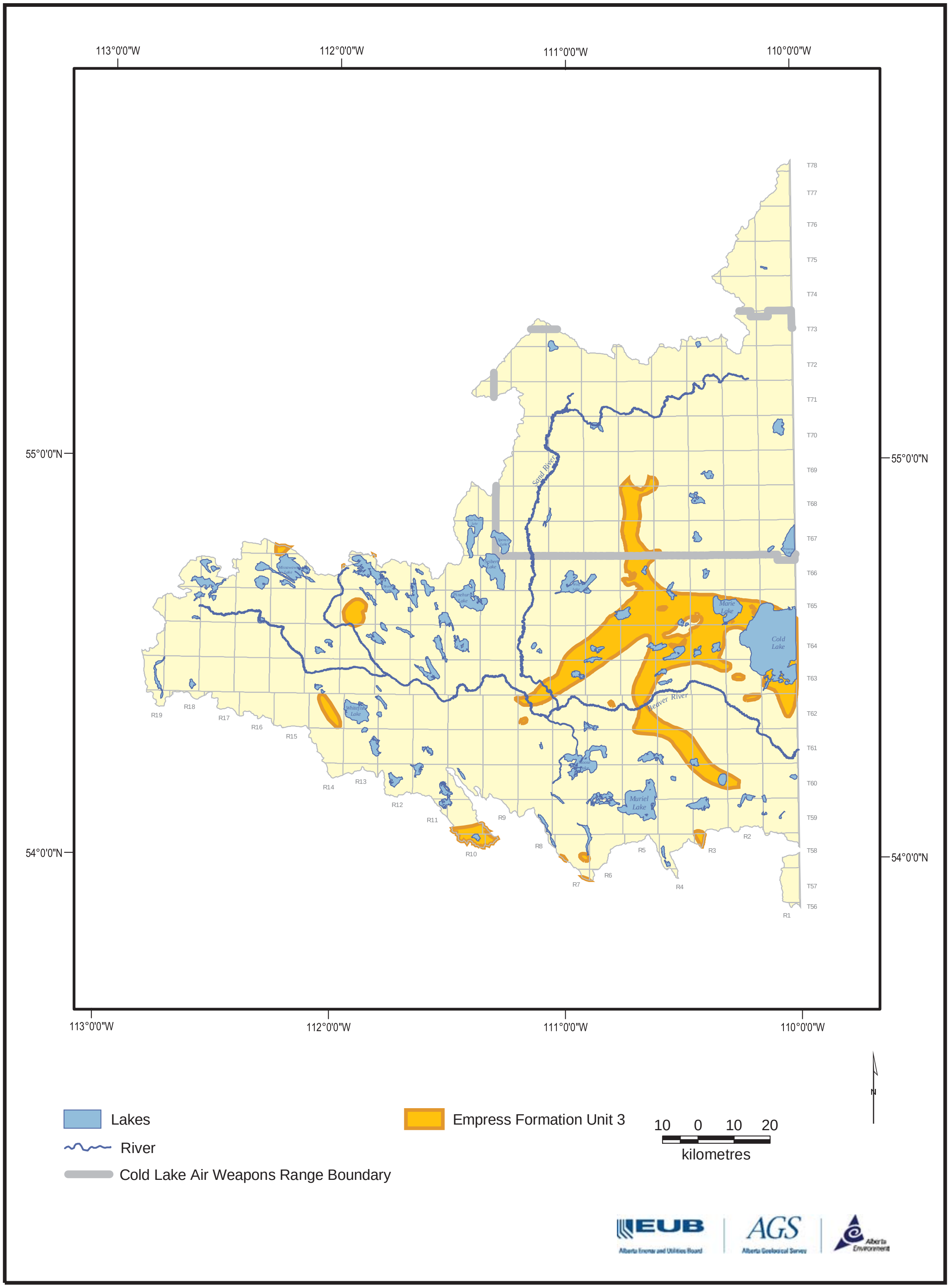


Figure 3.4. Geographic extent of the Empress Formation Unit 3.

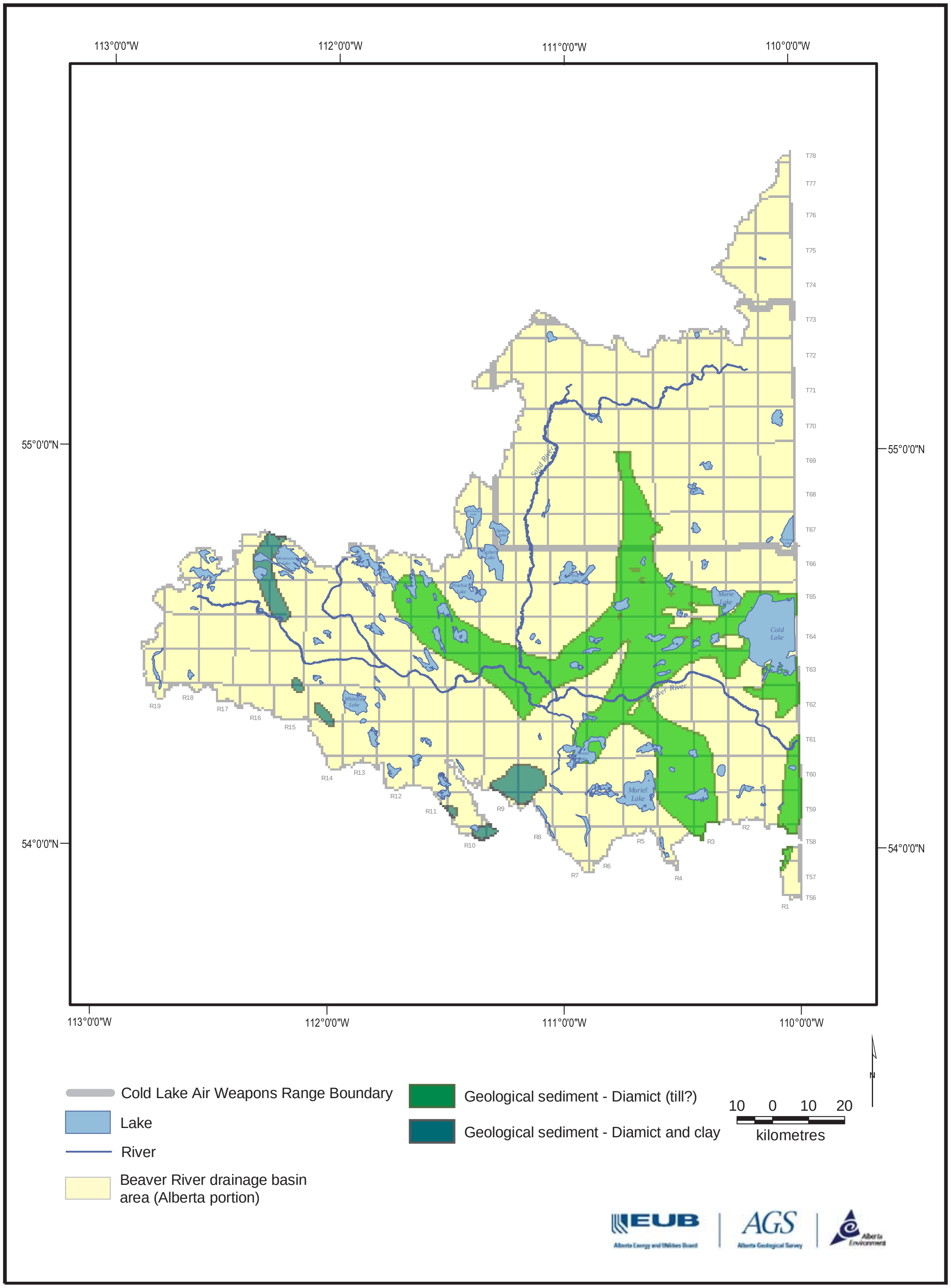


Figure 3.5. Geographic extent of the Bronson Lake Formation.

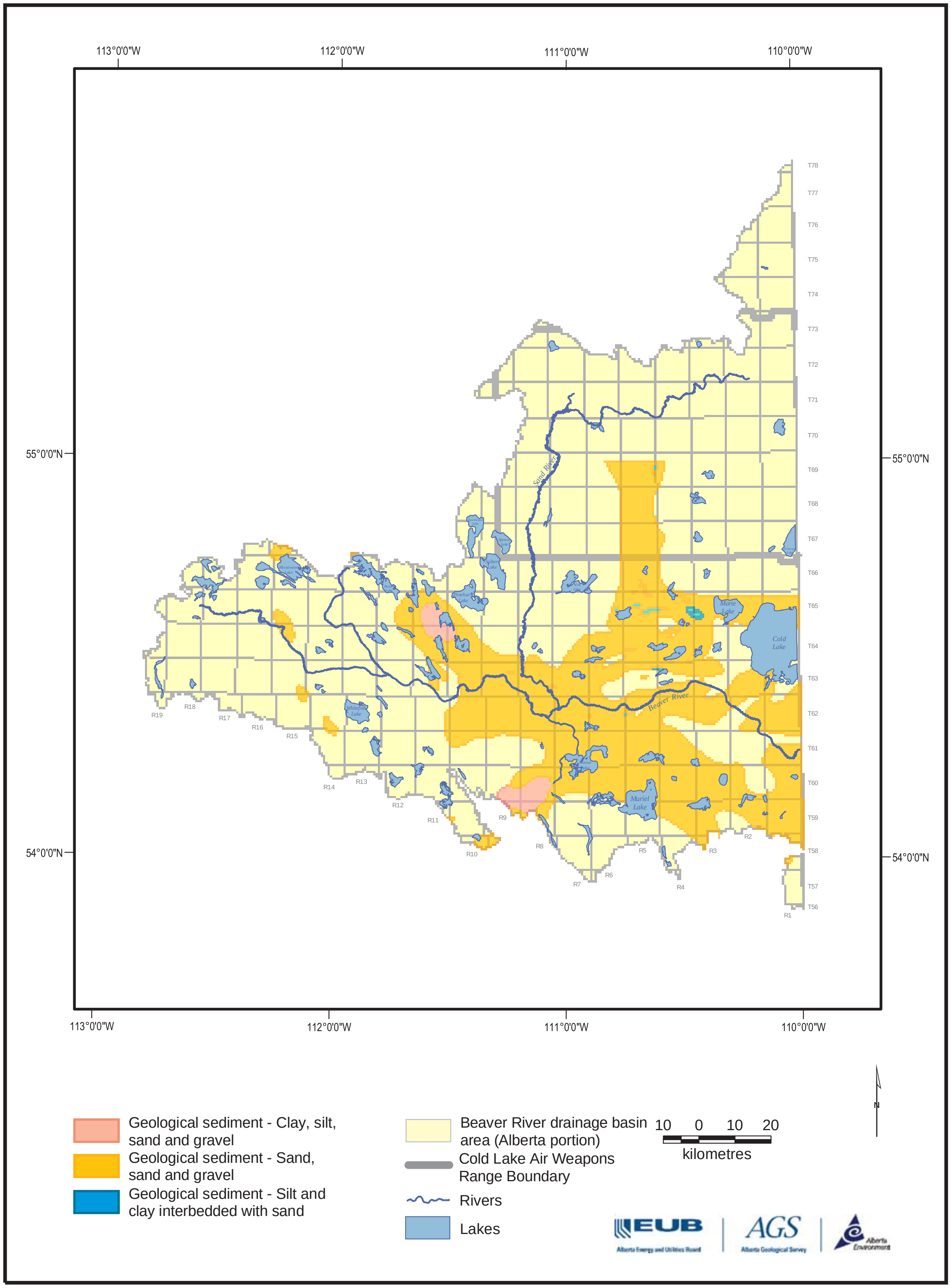


Figure 3.6. Geographic extent of the Muriel Lake Formation.

3.1.4 The Bonnyville Formation

The Bonnyville Formation is the first formation that extends beyond the bounds of the buried valley system. It is subdivided into three units. The Bonnyville I glacial till (or diamict) has an areal extent similar to the underlying Muriel Lake Formation that shows influence of the buried valley morphologies. The medial Bonnyville I sand and gravel has an areal distribution generally restricted to the area of confluence of the Helina and Sinclair valleys. The uppermost Bonnyville II till has a higher proportion of coarse sand than the underlying Bonnyville I till. The Bonnyville II till does become increasingly more clay-rich to the west. The extent of the Bonnyville Formation is presented in Figure 3.7, 3.8 and 3.9.

3.1.5 The Ethel Lake Formation

The Ethel Lake Formation consists of silt and clay with smaller amounts of sand and gravel. Andriashek and Fenton (1989) note that the Ethel Lake Formation tends to be associated with areas of thin Bonnyville Formation sediments, suggesting that the Ethel Lake Formation deposition was associated with regional erosion. The Formation is found primarily in the south and central parts of the Cold Lake-Beaver River Basin. The extent of the Ethel Lake Formation is presented in Figure 3.10.

3.1.6 The Marie Creek Formation

The Marie Creek Formation consists of till characterized by a very coarse sand fraction rich in calcareous fragments. The Marie Creek Formation is found over most of the Cold Lake-Beaver River Basin except in portions of the southwest of the Basin. The extent of the Marie Creek Formation is presented in Figure 3.11.

3.1.7 The Sand River Formation

The Sand River Formation is a stratified sand and gravel formation of glaciofluvial origin. The Sand River Formation, like the Ethel Lake Formation is located in the southern portion of the Basin. The extent of the Sand River Formation is presented in Figure 3.12.

3.1.8 The Grand Centre Formation

The Grand Centre Formation extends completely across the Basin. It is primarily a till, but has locally mapable sand and gravel units within it. Some of these accumulations of sand extend from surface to bedrock along the Sand River Channel. The extent of the Grand Centre Formation is presented in Figure 3.13.

3.2 Relationship Between Geology and Groundwater Quality

The controls on the chemical quality of groundwater are complex and depend on the interplay of a number of factors, including

- The chemical nature of the recharging surface water
- The type of geological material the groundwater comes into contact with along its flow path from recharge to discharge
- The length of time groundwater spends in contact with these materials
- The order of the materials groundwater came into contact with

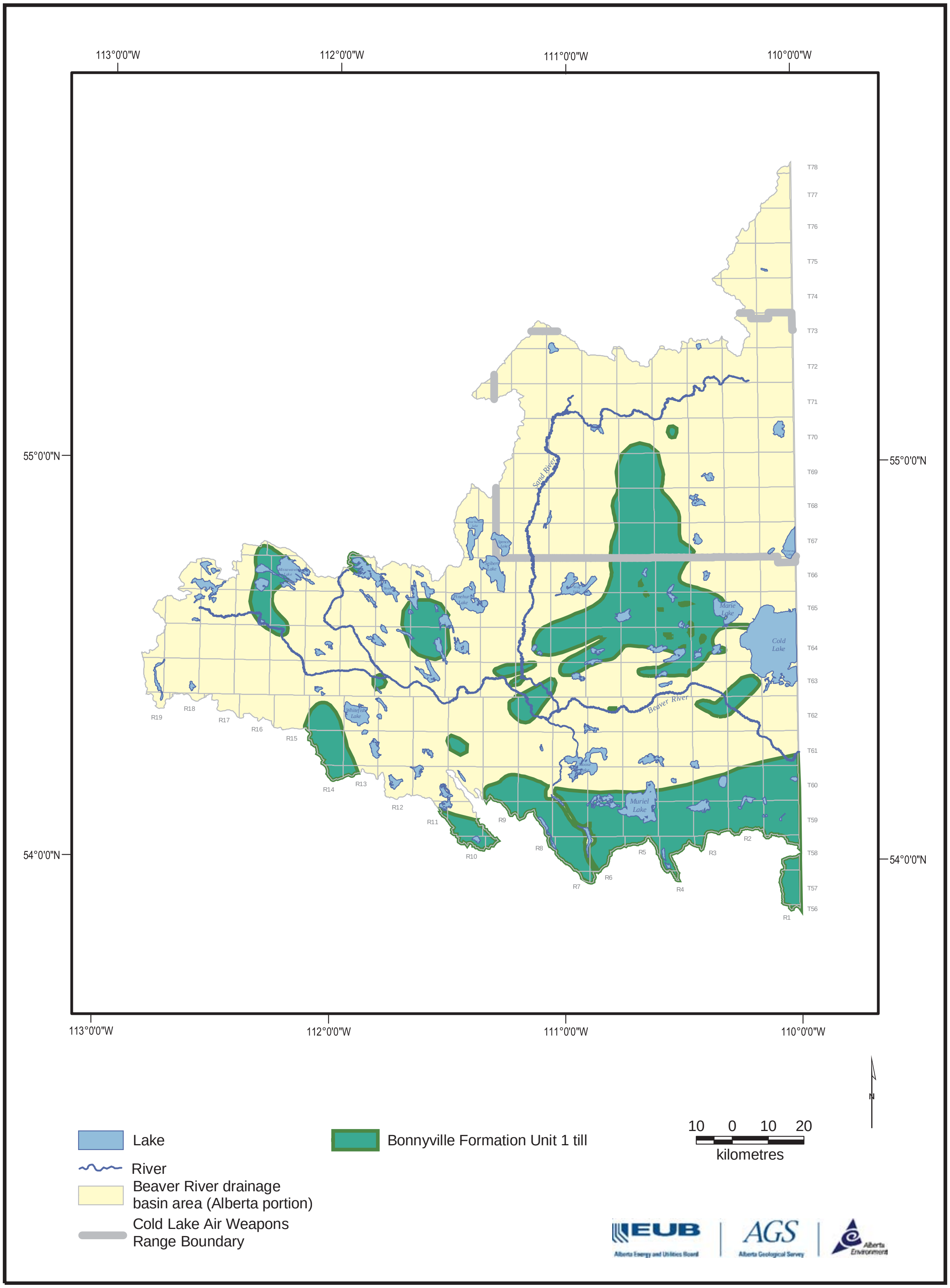


Figure 3.7. Geographic extent of the Bonnyville Formation Unit 1 glacial deposits.

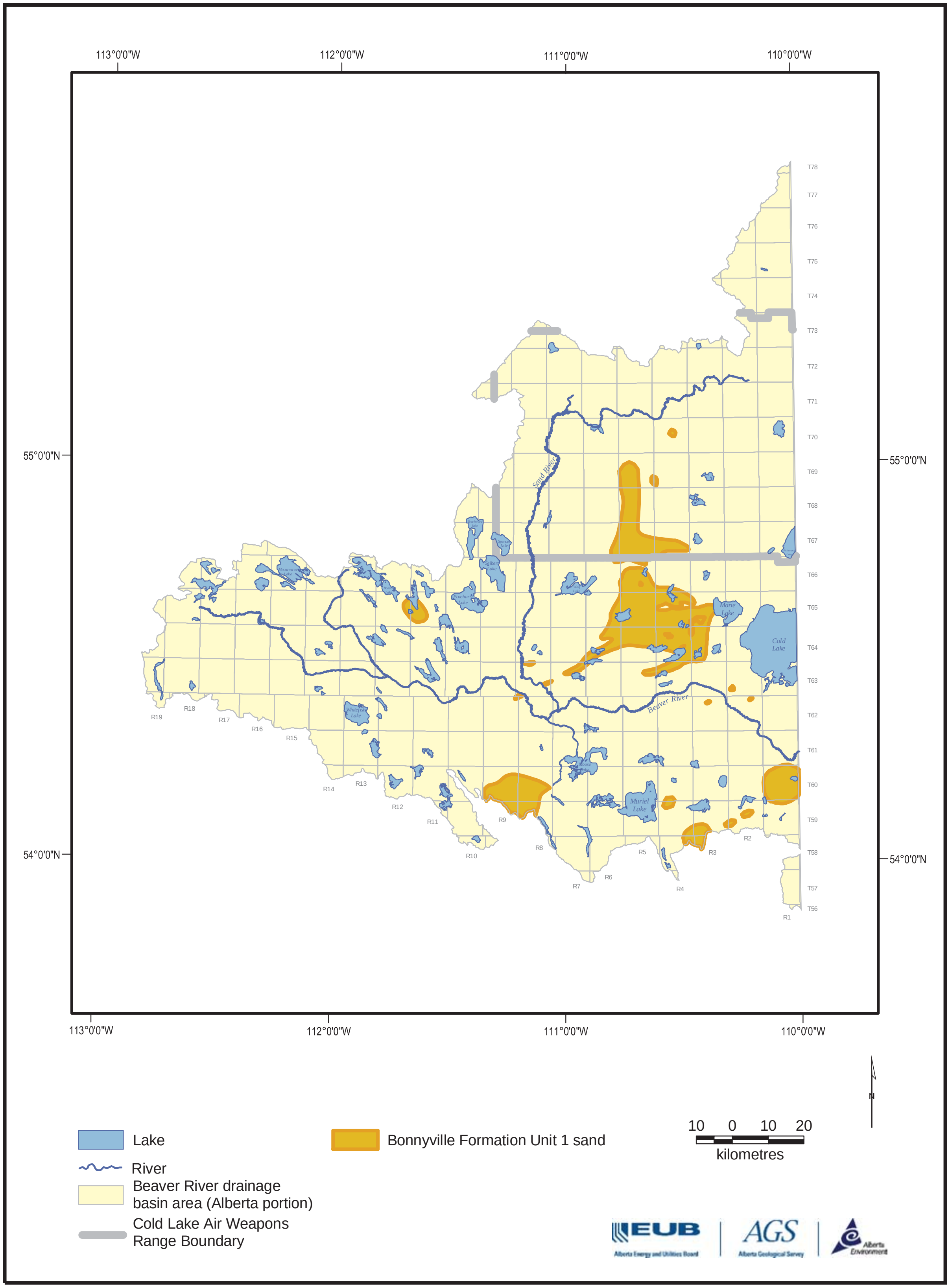


Figure 3.8. Geographic extent of the Bonnyville Formation Unit 1 sand and gravel.

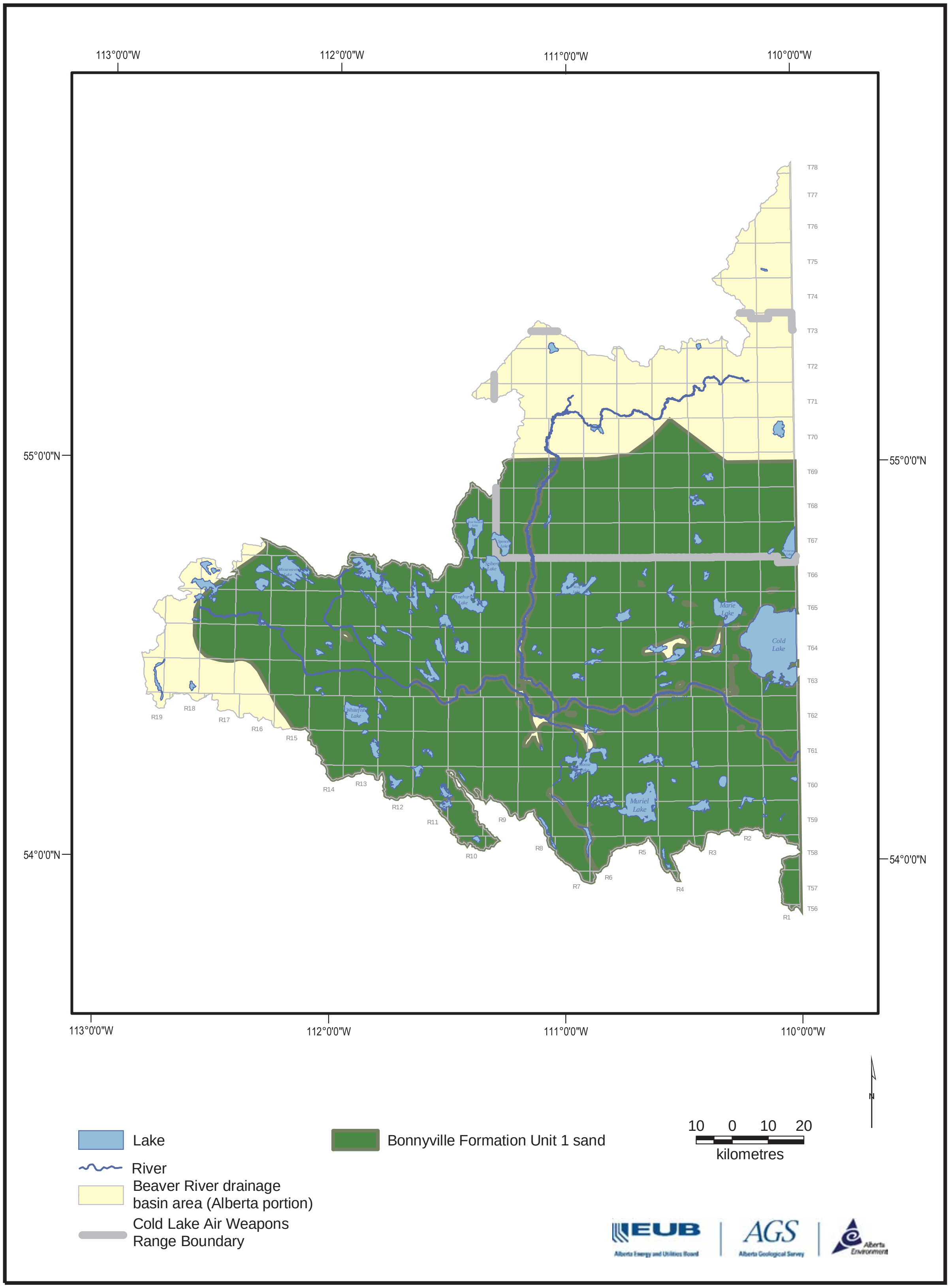


Figure 3.9. Geographic extent of the Bonnyville Formation Unit 2 glacial deposits.

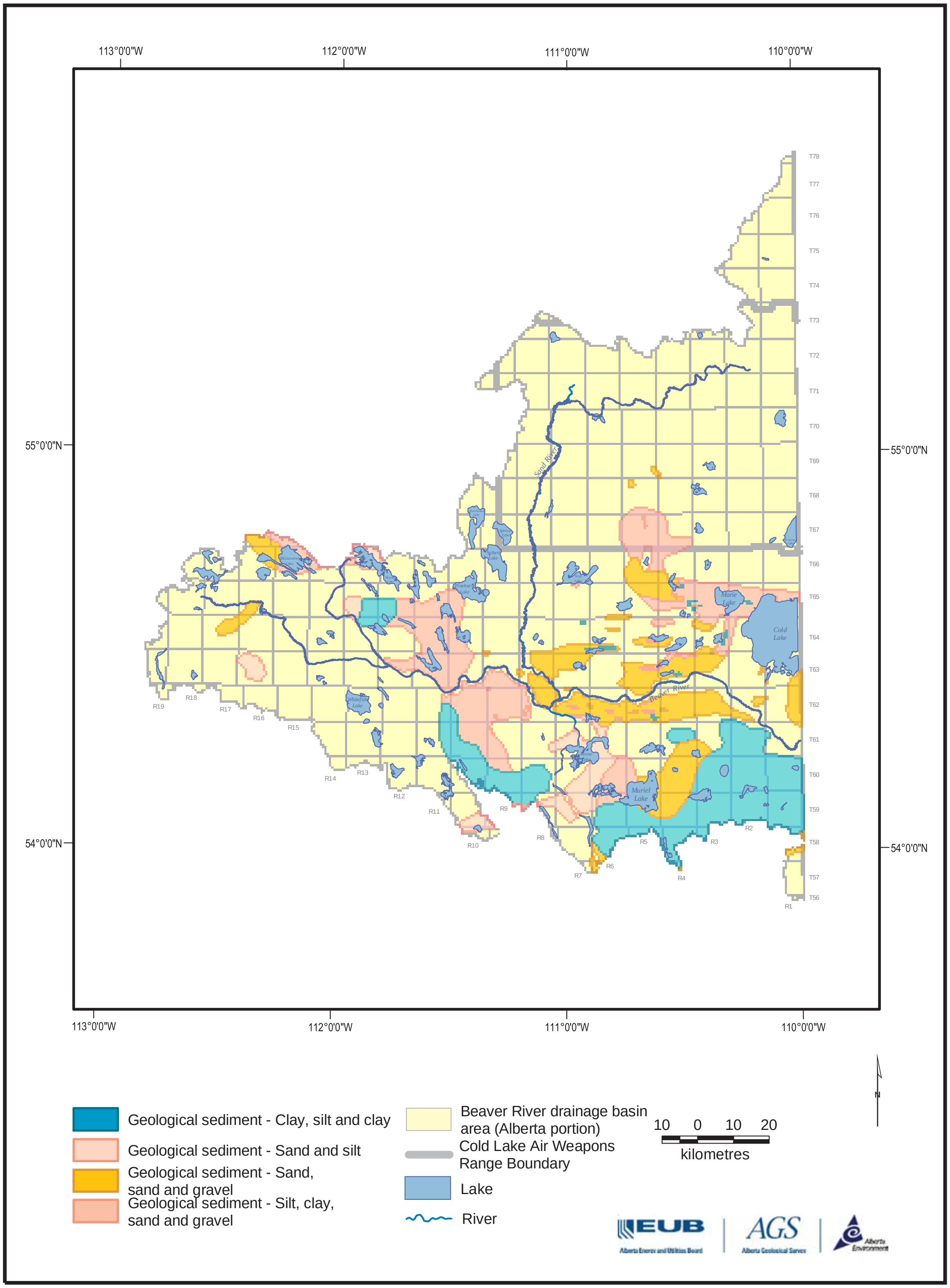


Figure 3.10. Geographic extent of the Ethel Lake Formation.

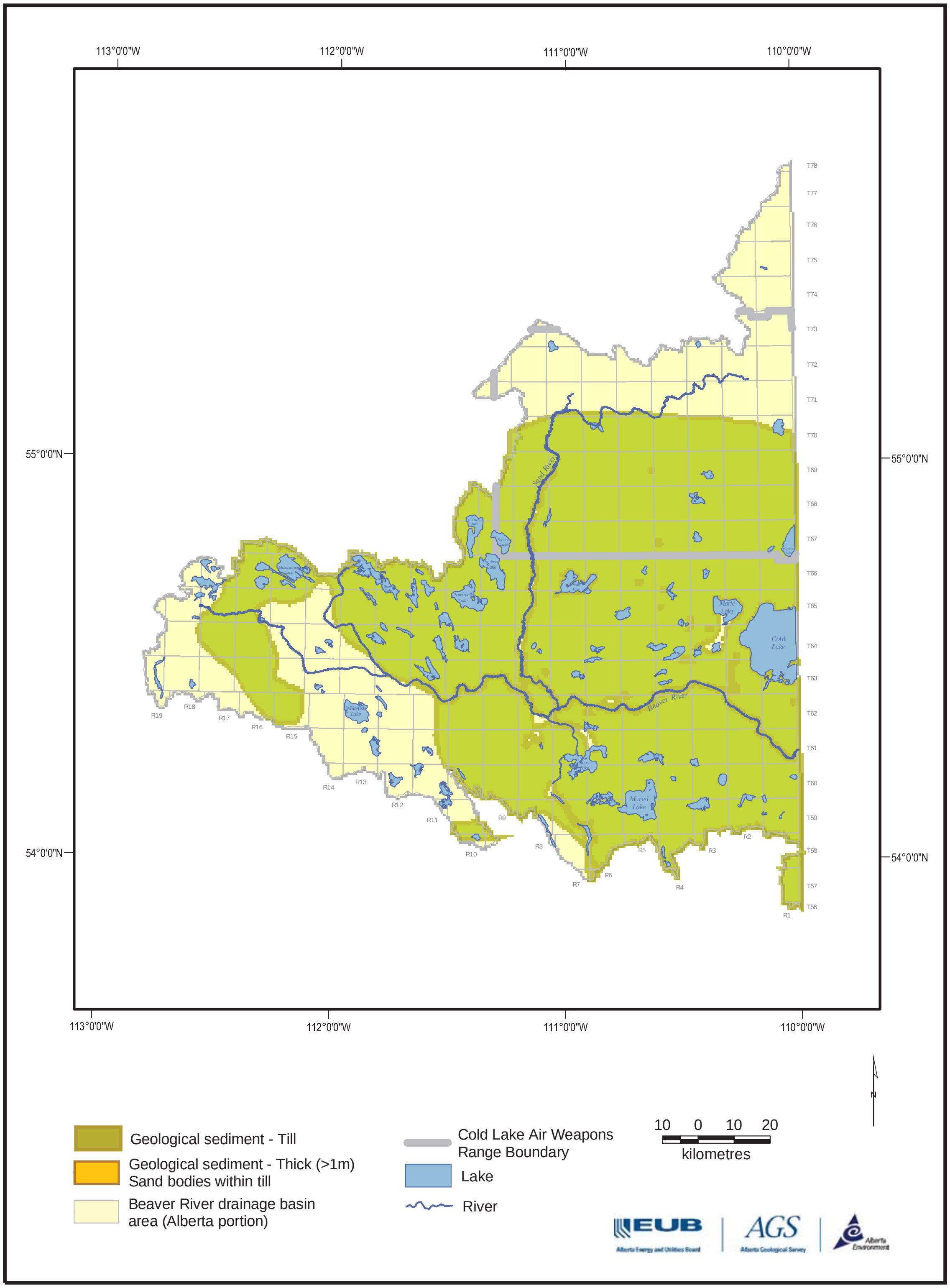


Figure 3.11. Geographic extent of the Marie Creek Formation.

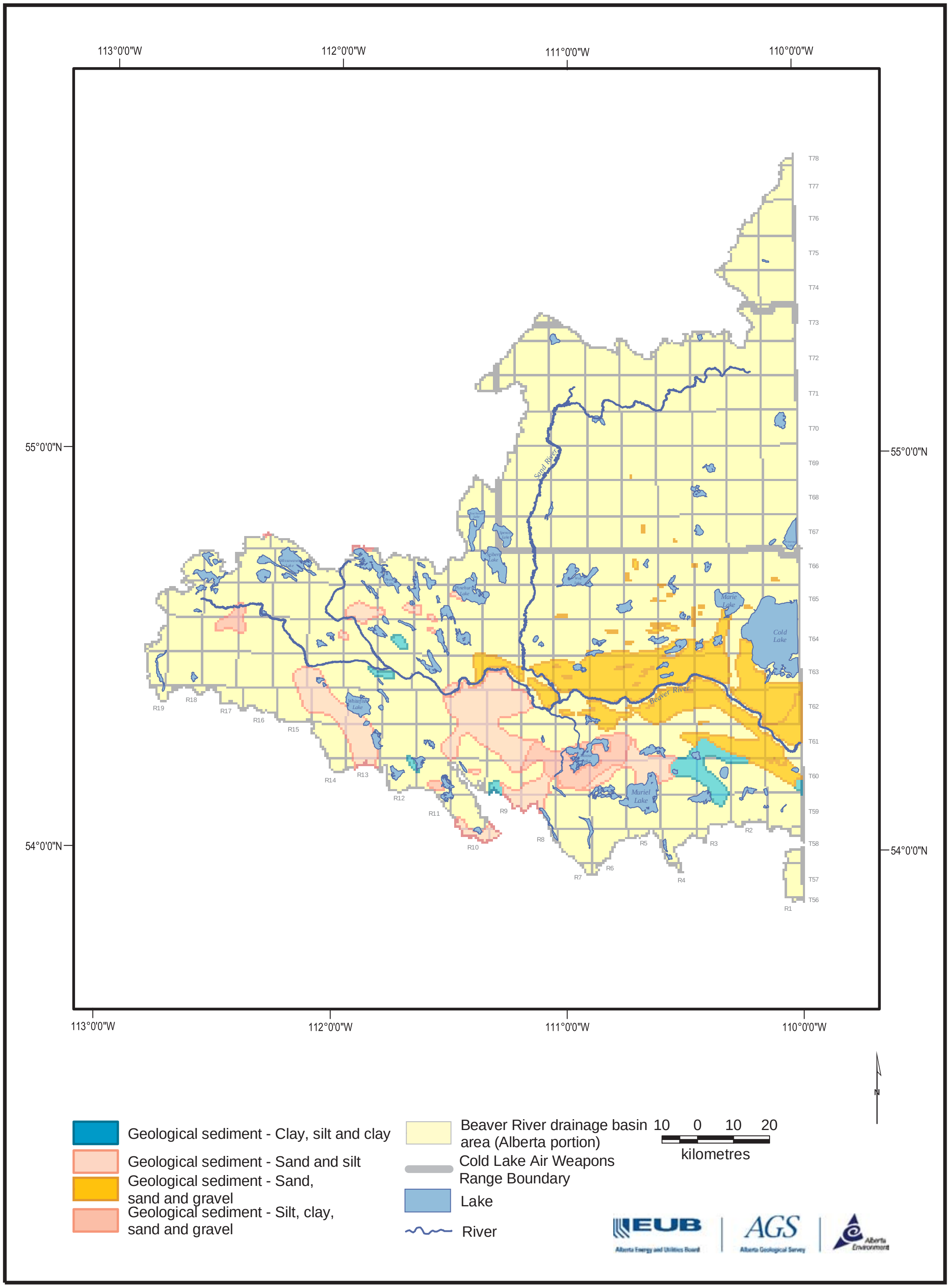


Figure 3.12. Geographic extent of the Sand River Formation.

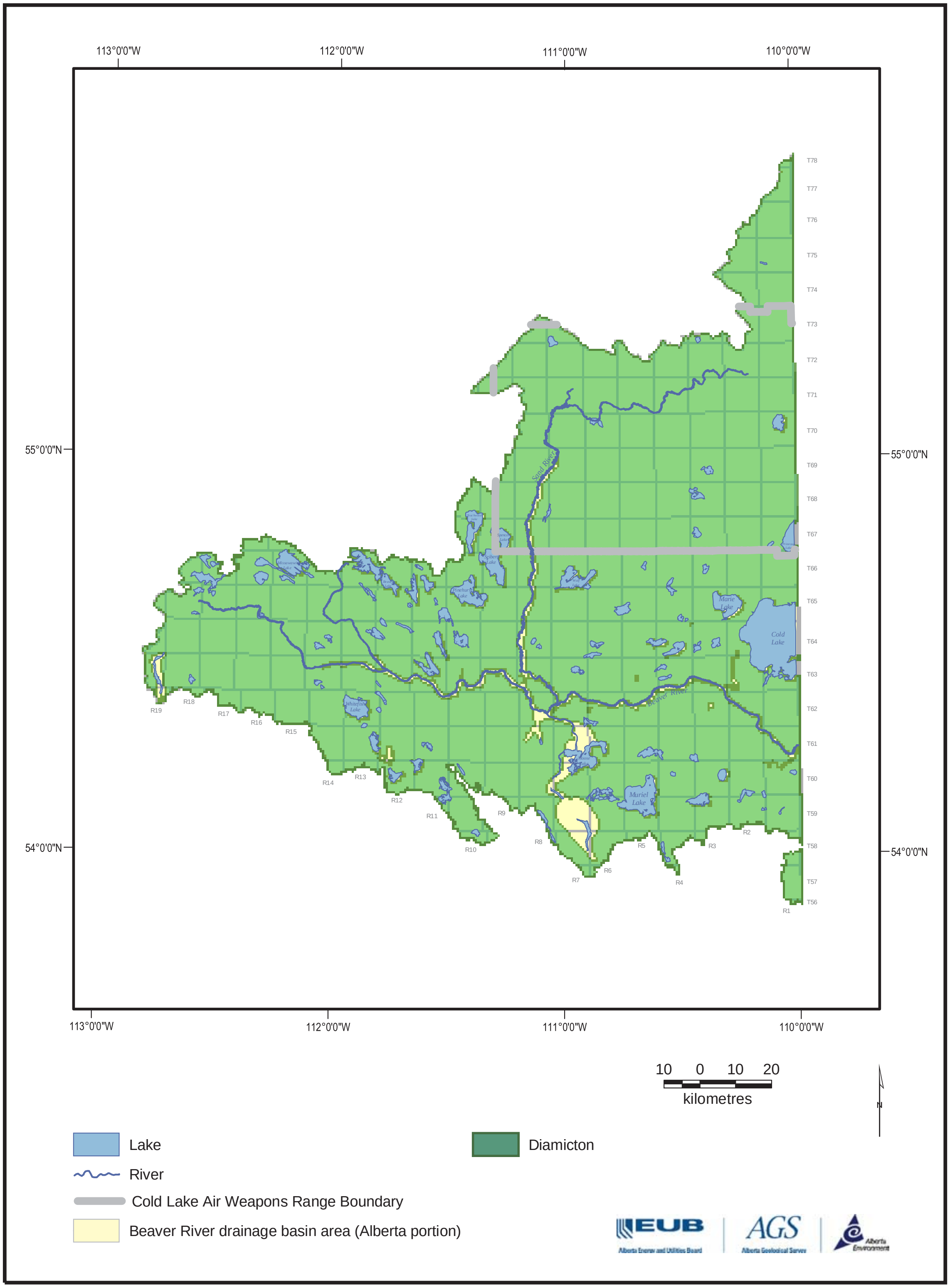


Figure 3.13. Geographic extent of the Grand Centre Formation.

- The degree to which the groundwater mixes with groundwater of other origins or chemical quality along its flow path
- The presence of point or non-point sources of natural and anthropogenic contaminants along the flow-path
- The unique geochemical conditions at the discharge zone, spring, or well where the groundwater returns to surface and comes into contact with the atmosphere

As can be seen from the list above a prime control on groundwater quality is the nature of the geological material water comes into contact with along its flow path from recharge areas to discharge areas and the length of time spent in contact with each geological material. It is important therefore to consider the complexity of the geological architecture of the Cold Lake-Beaver River Basin when analyzing groundwater chemical quality.

3.2.1 Geology and Travel Time in the Cold Lake-Beaver River Basin

3.2.1.1 Surficial Geology

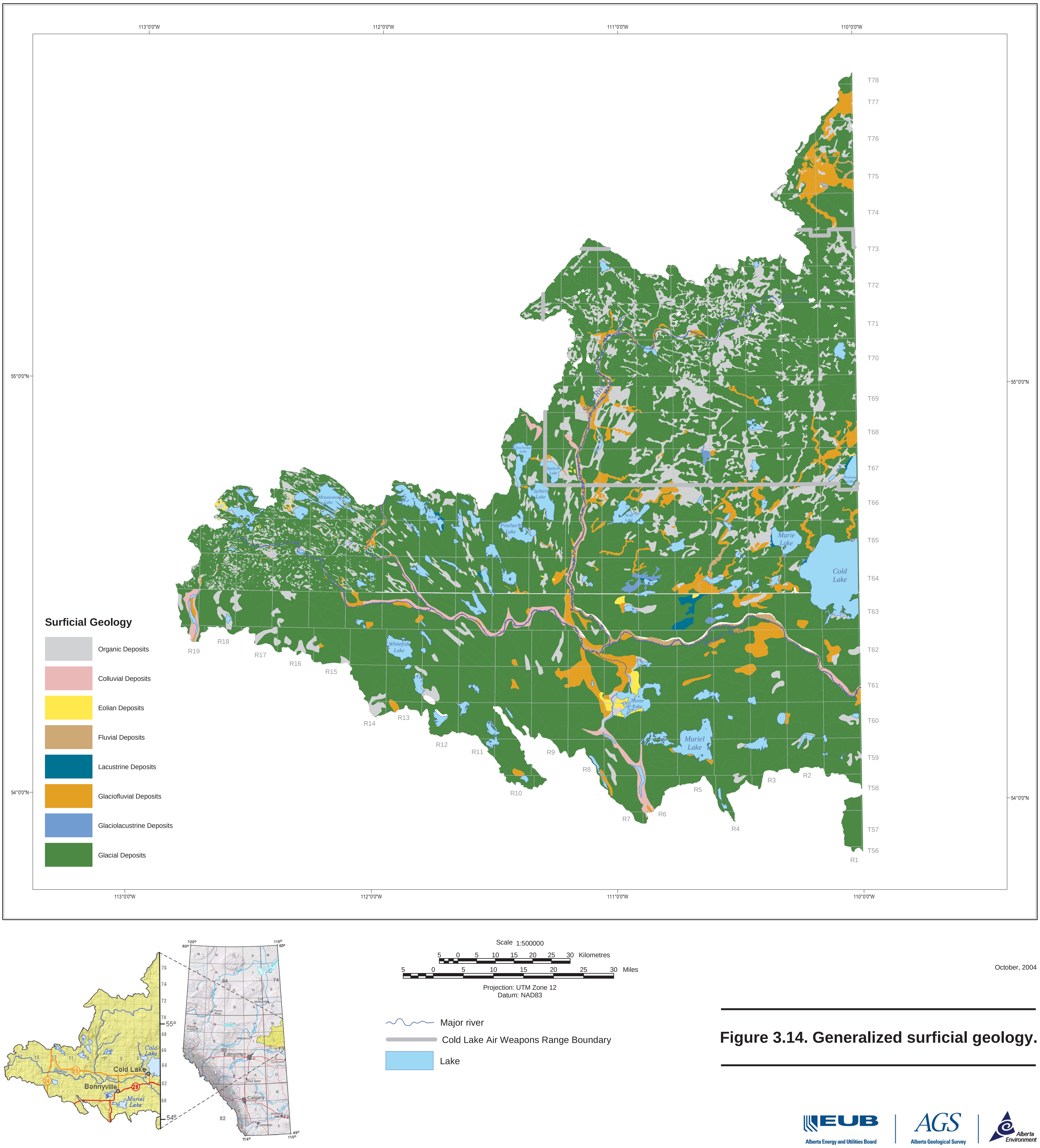
Surficial geology is classified based on an analysis of the surficial materials, aspects of local relief, and morphological characteristics of surface landforms. Andriashek (2003) states that analysis of these classifications forms an integral component in the evaluation of recharge fluxes to regional groundwater flow systems. In addition, since infiltrating groundwater first interacts with the geological materials at the land surface, the first changes in water chemistry will be observed as the water enters the soil zone.

As mentioned in the previous section, the length of time groundwater spends in contact with geological materials will affect its water chemistry. Coarser-grained sediments at the surface will allow water to move through the soil more quickly, minimizing the amount of time the water spends in contact with the sediment. Finer-grained sediments at the surface will firstly allow less infiltration to occur, and secondly necessitate longer time periods for water to move through them, increasing the potential for the water to interact with the soil material. Surficial geology in the Basin has been mapped by a number of researchers including Fenton and Andriashek (1983), Andriashek and Fenton (1989), Shetsen (1990) and Andriashek (2003). The surficial geology of the study area is presented in Figure 3.14.

3.2.1.2 3D Connectivity – Scours, Downcuts and Sand on Sand Contacts

Water moves through the soil zone into the underlying saturated zone along a given flow path towards its discharge area. Water tends to move more easily through coarser-grained materials than finer-grained materials. Subsurface materials are rarely homogeneous, and so the path a water molecule takes as it move towards its discharge area can change as it encounters materials with different hydraulic properties. The subsurface environment is complex hydraulically. Rocks and sediments can have a directional quality to their overall structure (Domenico and Schwartz, 1990, p. 67). In addition, relationships between or within rock or sediment packages can also introduce heterogeneities into an aquifer. Freeze and Cherry (1979) identified three broad classes of heterogeneity. These include

- Trending heterogeneity – a progressive increase or decrease in hydraulic conductivity within one unit
- Layered heterogeneity – a series of internally homogeneous layers that form a heterogeneous whole
- Discontinuous heterogeneity – presence of large contrasts in hydraulic conductivity caused by for example structural features.



October, 2004

Figure 3.14. Generalized surficial geology.

EUB Alberta Energy and Utilities Board

AGS Alberta Geological Survey

Alberta Environment

Given the complexity of the glacial depositional system, heterogeneities are likely.

The most continuous aquifers will likely be those in the sand and gravel deposits between till sheets. Aquifers within the till sheets will probably be very local in extent and not well connected to other aquifers. The till sheets themselves may be sandy enough, especially at their top, to be aquifers in their own right.

There are certain glacial processes can lead to enhanced three-dimensional connectivity between aquifers. Andriashek and Fenton (1989) state that the till and intertill sequence in the Quaternary stratigraphic record indicates that as many as four glaciations occurred within the Basin. Each glaciation was marked by a period of deposition during advance and retreat, and by a period of erosion and weathering during nonglacial periods. If during these nonglacial periods, erosion occurs through aquitards to underlying aquifers, superposition of aquifers can take place. One such mechanism could include downcutting of river systems over time. Catastrophic glacial melt water release as described by Andriashek (2003) could also be capable of creating such sand on sand connections. Such a release could lead to the existence of unpredictable, vertically crosscutting glacial sluiceways that can be in filled with sand and gravel superimposed on older melt water deposits (Andriashek, 2003). Andriashek and Fenton (1989) identified a number of sand on sand contacts (Figure 3.15) within the Cold Lake-Beaver River Basin. One such sand on sand contact extends from the surface through the Sand River Formation to the Ethel Lake Formation and to the Muriel Lake Formation.

These sand on sand contacts are important from a groundwater quality perspective because they provide conduits of flow for groundwater. These conduits can allow recharging water to reach discharge areas more quickly, decreasing the amount of time the water can react with the aquifer material, resulting in water that might be less mineralized than water that would enter the flow system at the same time but follow a less conductive flow path. If such conduits intersect aquifers that contain water that has a higher mineral content, mixing of the water types will lead to a water with a composition somewhere between that of the two end members. An understanding of aquifer interconnectivity is an important consideration in assessing groundwater chemistry.

3.2.1.3 3D Compartmentalization – Ice Thrusting and Lithologic Variation Within Units

While some glacial processes can lead to enhanced connection between aquifers, other processes of glacial sediment deposition and modification can result in three-dimensional compartmentalization of coarse-grained units leading to reduced groundwater velocity along flow paths. These processes involve the deposition of heterogeneous sediments, the isolation of aquifer units between till units, deformation and glaciotectonism.

The extent of aquifer units is usually limited areally and variations in sediment characteristics within aquifer units as a whole can be substantial. Thus there is an intrinsic compartmentalization of some aquifers at a regional scale. In addition, glacial processes can result in complex folding and thickening of sediments, further affecting aquifer properties and interconnection. These complicated heterogeneities and discontinuities affect the velocities of the flow system. This in turn can affect the water quality of groundwater moving through these sediments because more time is available for geochemical reactions such as mineral dissolution.

One extreme example of a glacial process that could introduce heterogeneity into the groundwater flow system is glaciotectonism. Glaciotectonism involves the detachment of bedrock or glacial sediments through the process of deformation of underlying substrate sediments (Eyles and Eyles, 1992). The slab

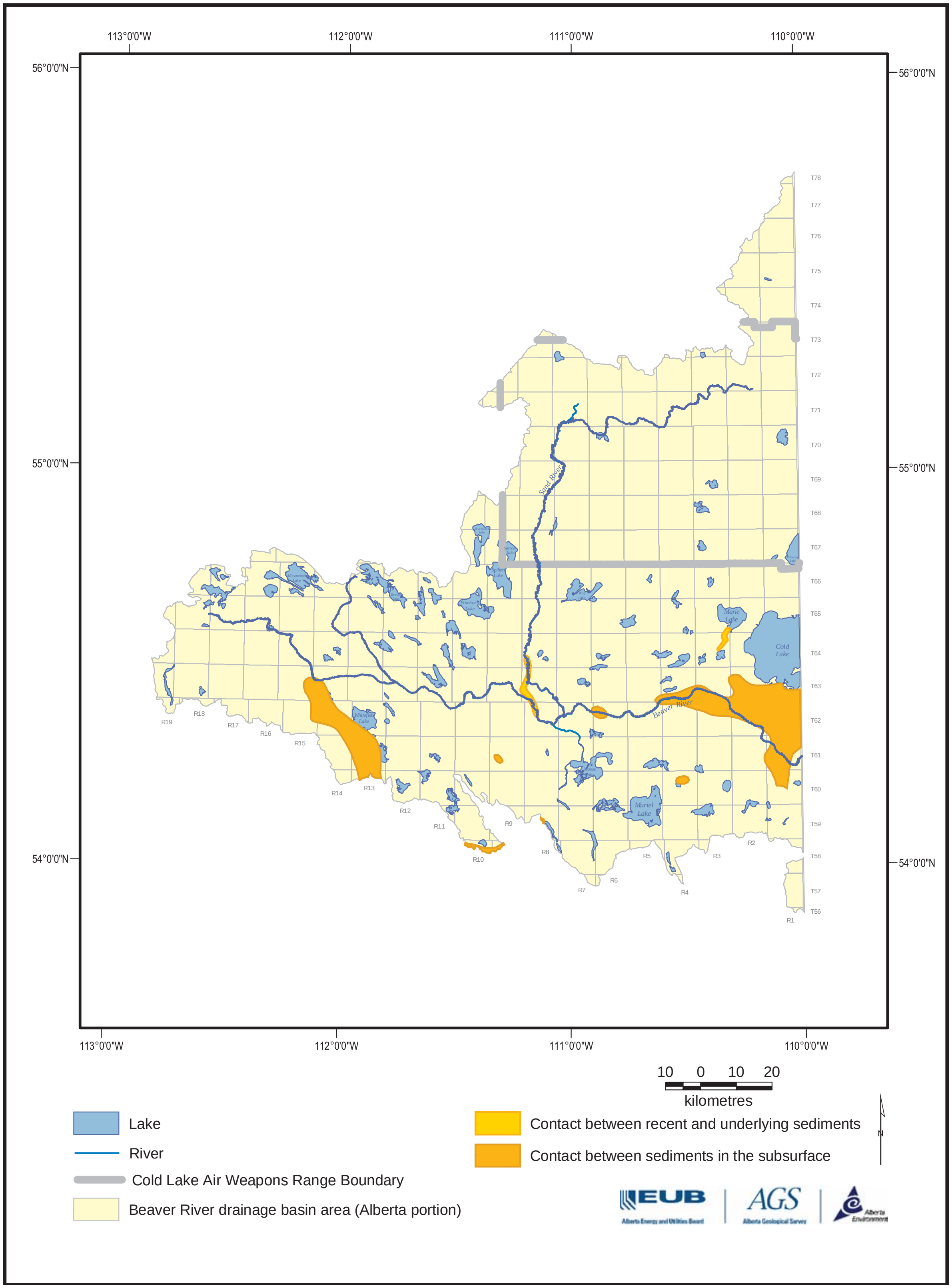


Figure 3.15. Distribution of sand on sand contacts in the subsurface.

of sediment or bedrock is then thrust on top of adjacent sediment or bedrock as the glacier advances. Andriashek and Fenton (1989) have identified a number of glaciotectonic features in the Basin. Andriashek (pers. comm.) has also indicated that there are likely examples of glaciotectonism preserved in the subsurface. Andriashek and Fenton (1989) indicate that the composition of thrust sediment is highly variable and may consist of two or more syngenetic tills, preexisting tills, sand, silt, clay, sandstone, ironstone or mudstone, with the proportion of bedrock in the thrust sediment controlled by the thickness of the preexisting Pleistocene sediment at the time of thrusting. These features vary in area between approximately 0.12 and 140 km^2 (Andriashek and Fenton, 1989). The inclusion of such a feature in the subsurface would undoubtedly affect groundwater flow in the vicinity of the glaciotectonic thrust block. The magnitude of the effect would depend on the characteristics of the block, the characteristics of the material the block was surrounded by and by the nature of the flow system.

The presence of heterogeneities in the framework will affect the groundwater flow system and by extension the groundwater chemistry. An understanding of the nature of the sediments and their interrelationships is therefore important in understanding not only the groundwater flow system, but also the groundwater chemistry.

3.2.1.4 Classification and Permeability of Materials

The geology controls the intrinsic permeability of subsurface materials in the Cold Lake-Beaver River Basin. The permeability of materials can be assessed through a number of means. The most rigourous methods include laboratory analysis of the materials and field determination such as well testing (Figure 3.16) and permeameter testing (Figure 3.17). Permeability can also be approximated based on the sand, silt and clay content of the material. Stephenson et al. (1988) indicated that a strong relationship between laboratory-determined hydraulic conductivity and grain-size distribution exists with the major influence appearing to be the clay content of the sediment (Figure 3.18). Andriashek (2003) noted that based on the work of Stephenson et al. (1988), materials with a sand content less than 40-50% and a clay content generally greater than 20% will have a hydraulic conductivity of approximately 1x10^{-7} cm/s or less. This value becomes significant because the Alberta Energy and Utilities Board (Alberta Energy and Utilities Board, 2001) specifies that clay liners must be constructed of materials, which after being reworked, homogenized and emplaced, have a hydraulic conductivity value of 1x10^{-7} cm/s or less.

Figure 3.16. Photograph of well-testing activities.

Figure 3.17. Photograph of permeameter testing activities.

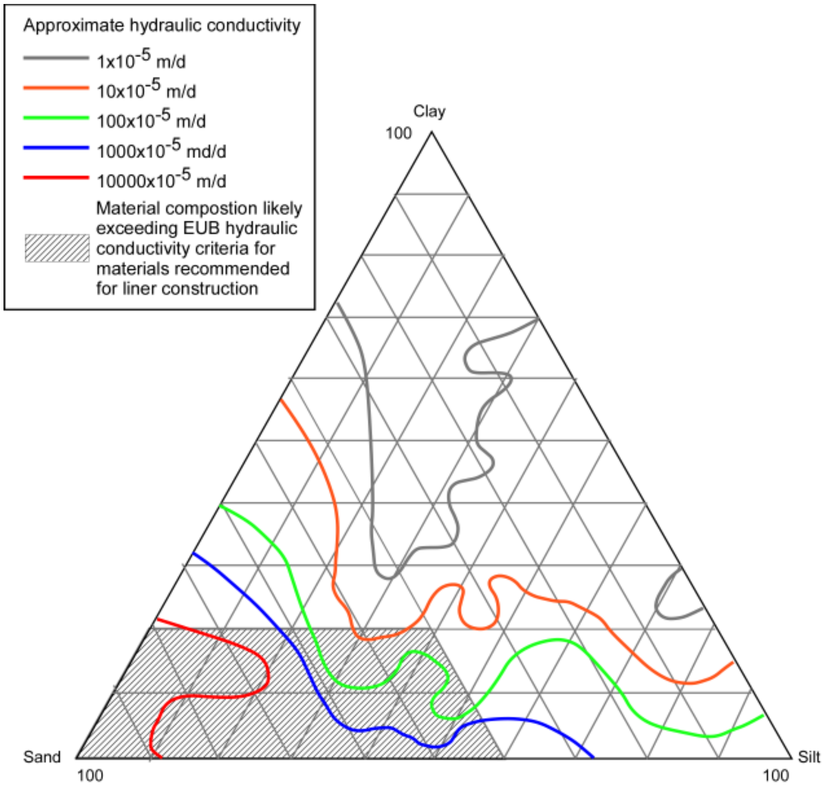


Figure 3.18. Trilinear plot of percent sand, silt and clay, and the relationship to hydraulic conductivity (after Stephenson et al., 1988).

A generic classification can also be applied to materials based on their general properties. A recent assessment of the surficial geology of the province completed by Andriashek et al. (2004) grouped the surficial materials into three dominant classes: 1) sand and gravel; 2) a mixture of coarse and fine-grained material; and 3) till. These simpler classifications were then assessed to be permeable, slightly permeable and relatively impermeable for the purposes of the work being done. This general classification scheme is presented in Figure 3.19. The mapping of surficial geology in the study area was completed by different geologists. As such some differences in interpretation exist and can be seen along the boundaries between mapped areas.

As mentioned in Parks et al. (2005) regional estimates of permeability are needed to parameterize flow models, while local estimates are needed to ascertain deliverability and yield of individual water wells. A better understanding of the distribution of permeability also helps to comprehend the potential changes in water chemistry.

3.2.2 Intrinsic Susceptibility of Cold Lake Beaver River Basin Aquifers

Focazio et al. (2002) provide the following description of the intrinsic susceptibility of an aquifer:

> The intrinsic susceptibility is a measure of the ease with which water enters and moves through and aquifer and is a characteristic of the aquifer and overlying material and hydrologic conditions, and so is independent of the chemical characteristics of contaminants and their sources. The susceptibility of a groundwater system depends on the aquifer properties and the sources of water and stresses for the system. The assessment therefore considers only the physical factors affecting the flow of water to and through the groundwater resource.

A number of methods have been developed for assessing the intrinsic susceptibility of an aquifer. These include subjective rating methods and statistical or process-based methods. The subjective rating methods produce categories of susceptibility whereas the statistical or process-based methods produce delineations of contributing areas or probabilities of exceeding target concentrations. EPA (1993) and Focazio et al. (2002) discuss the fundamentals of the various approaches and provide references to more detailed discussions of the methods. Because of time constraints placed on the completion of the groundwater quality assessment, the method chosen for the assessment of intrinsic sensitivity in the Cold Lake-Beaver River Basin is the subjective rating system.

3.2.2.1 Defining intrinsic sensitivity in the Cold Lake-Beaver River Basin

EPA (1993) indicates that the aquifers characterized by very rapid infiltration and shallow depths to groundwater are typically the most sensitive to contamination. These settings include

- Shallow outcroppings of coarse-grained materials such as consolidated or unconsolidated sand and gravel deposits
- Soils with extensive macroporosity
- Clay soils with high shrinking and swelling potential since cracks may provide a direct conduit for contaminants to reach groundwater.

Surficial material in the Cold Lake-Beaver River Basin that have been categorized as being sensitive to contamination include fluvial and aeolian sand, and any gravel deposits that might be present. Their extent is presented in Figure 3.20.

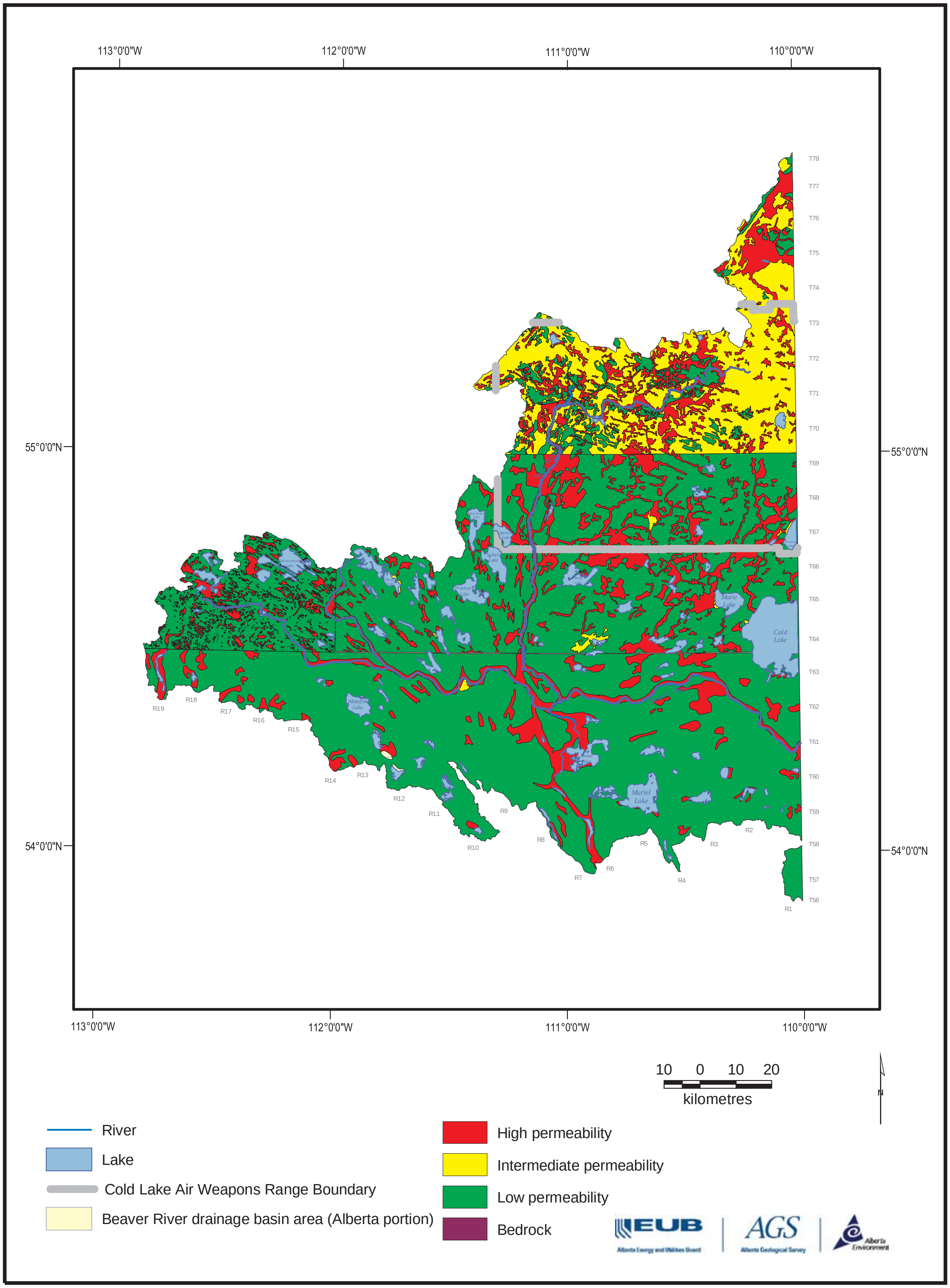


Figure 3.19. Reclassified surficial geology of the study area.

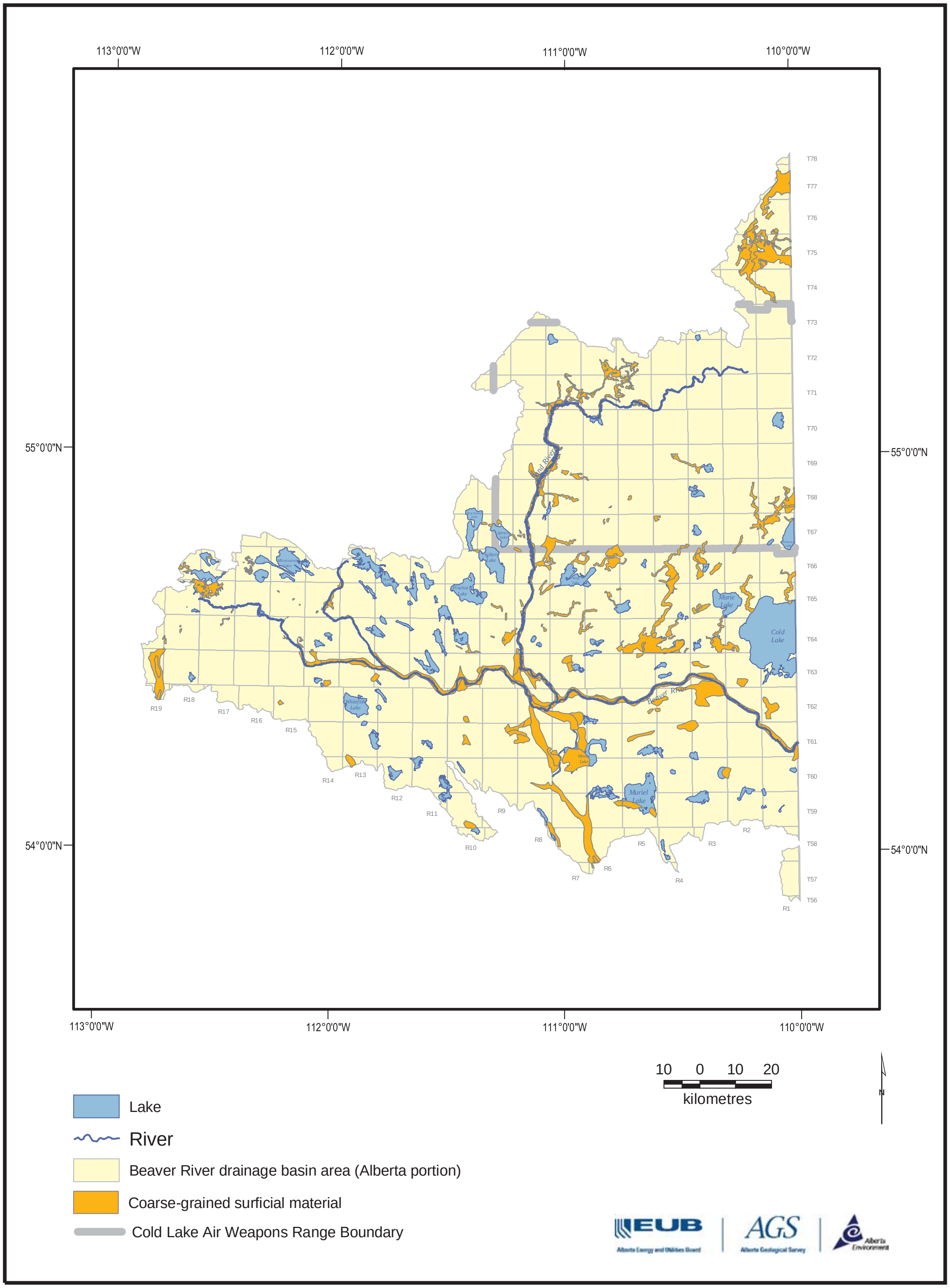


Figure 3.20. Distribution of coarse-grained material at the surface.

Settings that result in a low aquifer sensitivity include

- Thick laterally extensive clayey units or relatively impermeable bedrock overlying a confined aquifer

Surficial materials in the Cold Lake-Beaver River Basin categorized as having a lower sensitivity will include tills and any other fine-grained sediments present within the Basin. The extent of these deposits is presented in Figure 3.21.

While the surficial material contributes to the sensitivity of the aquifer, the material underlying the surficial material will also play an important part in the assessment. The Grand Centre Formation is the first formation encountered below the surface throughout most of the area. The Formation is classified as a till, but contains a number of water wells suggesting that it can be used as a source of water given the proper conditions. The ability of the Formation to transmit water can be estimated from the sand and clay content measured by Andriashek and Fenton (1989). Based on these measurements, maps of the percent sand content (Figure 3.22) and percent clay content (Figure 3.23) can be constructed. Andriashek (2003) suggests that material with a sand content of less than 40% and a clay content of more than 20% will likely meet the Alberta Energy and Utilities Board (AEUB) requirement for materials used as clay liners. The combination of the sand and clay content maps will show the regions that meet this compositional requirement and are therefore relatively insensitive to contamination. Similarly, these figures show areas where the Grand Centre Formation does not meet the compositional requirement and are therefore potentially sensitive to contamination. There are a number of regions within the Basin where the Grand Centre Formation is absent, and other formations will be present beneath the ground surface, or underneath any surficial deposits. Depending on the characteristics of these materials, the potential exists for interaquifer contamination where sandy units of a formation occur underneath sandy surficial materials.

Certain glacial processes can modify the stratigraphic relationships between the various formations, such as creating sand on sand contacts between formations. Sensitive areas will be those areas where connection exists between different coarse-grained sediments units. Potential areas are shown in Figure 3.15. Those areas where sand on sand contacts do not occur and do not have other characteristics that make them potentially sensitive can be considered relatively insensitive.

The combination of these various factors defines the intrinsic sensitivity of the aquifers underlying the Grand Centre Formation as being sensitive or relatively insensitive to contamination by a surface release.

3.2.3 Rock-Water Interactions

Controls on the chemical quality of groundwater involve a number of factors, many of which include the interaction of groundwater with subsurface materials. The first material water interacts with as it infiltrates into the ground surface is the surface soil. Domenico and Schwartz (1990) list common reactions occurring within the soil zone. These include

- CO_2 dissolution and redistribution
- Mineral dissolution reactions
- Sulphide mineral oxidation
- Gypsum precipitation and dissolution reactions
- Cation exchange reactions

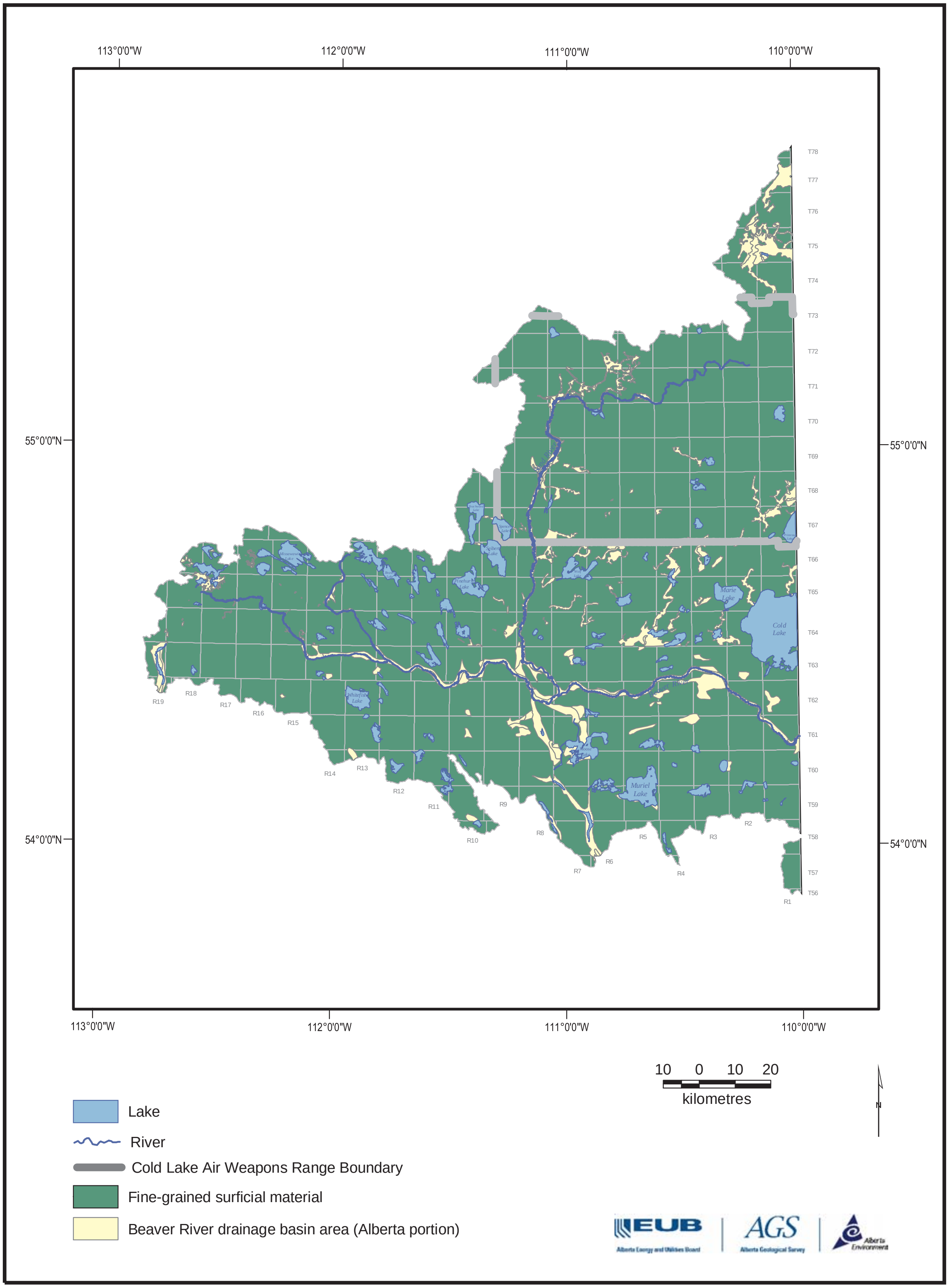


Figure 3.21. Distribution of fine-grained material at the surface.

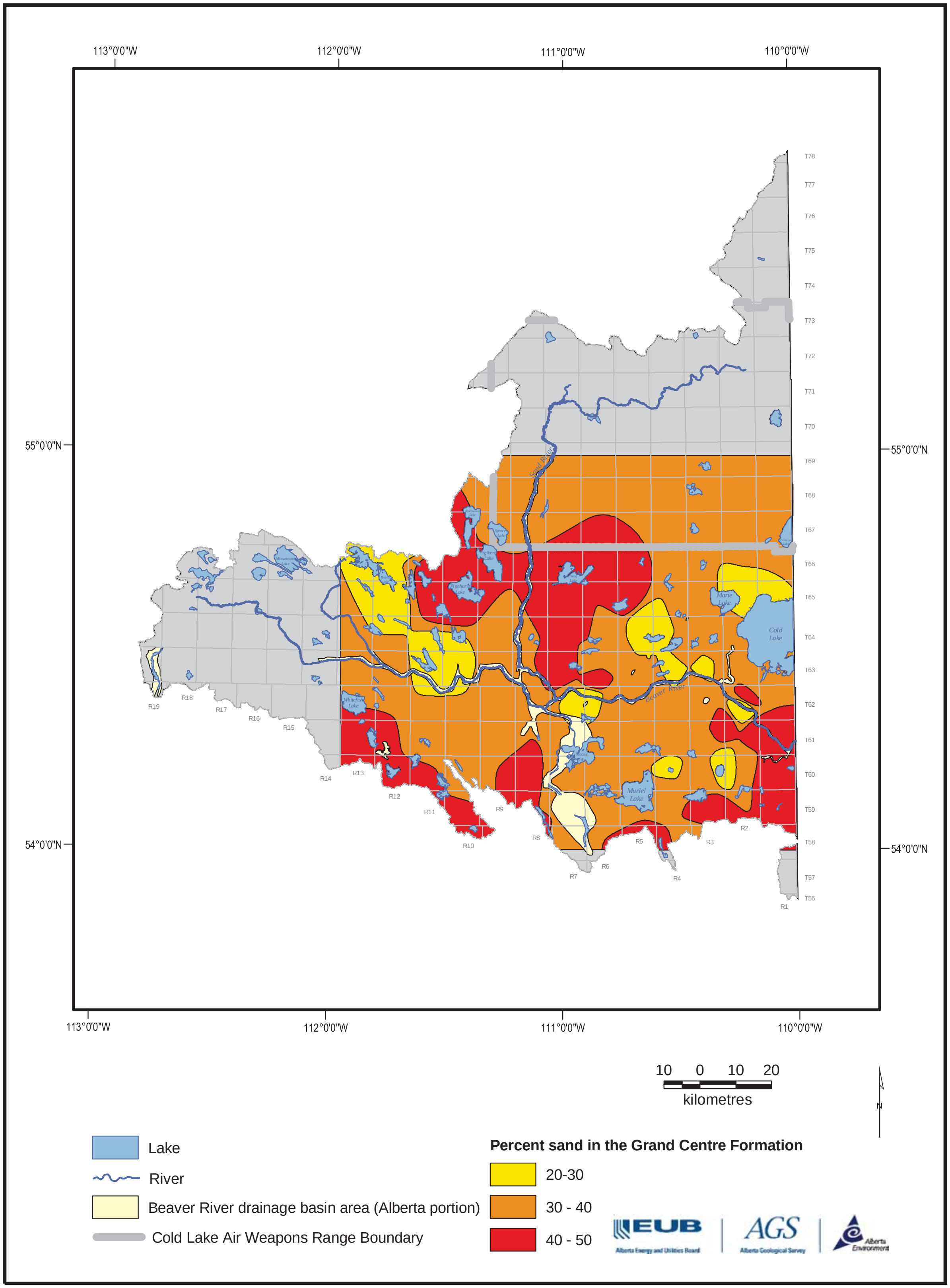


Figure 3.22. Percent sand within the Grand Centre Formation.

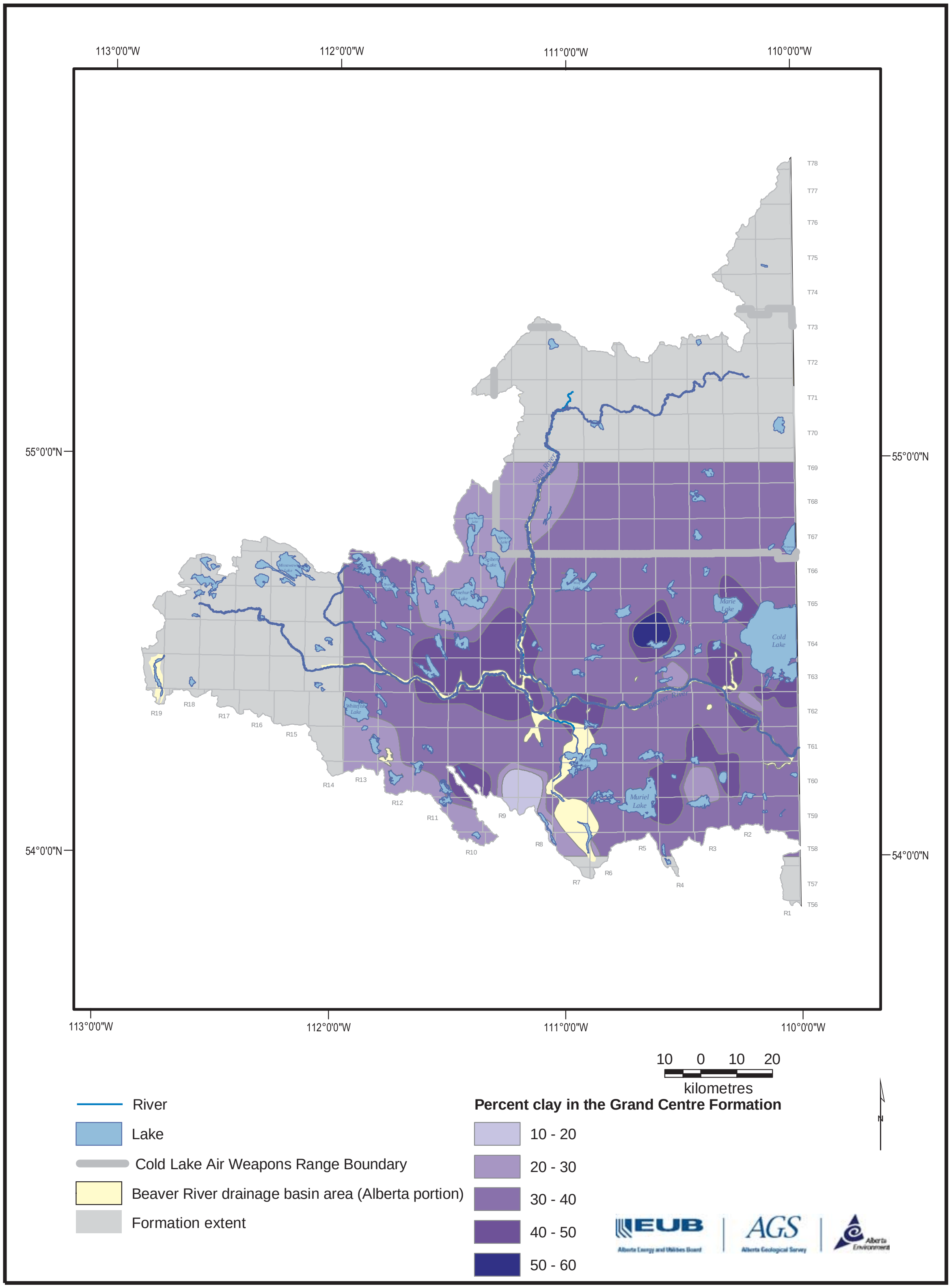


Figure 3.23. Percent clay within the Grand Centre Formation.

- Dissolution of organic litter at the ground surface
- Complexation of iron and aluminum
- Sorption of organic compounds
- Oxidation of organic compounds.

CO_2 dissolution and redistribution results in an increase in the carbonate content of the water. The dissolved CO_2 is subsequently involved in dissolving minerals common in the soil zone including carbonate, silicate and aluminosilicate minerals, potentially introducing calcium, sodium, magnesium and carbonate into the geochemical system. If sulphide minerals such a pyrite (FeS_2) are present, they can be oxidized to produce iron hydroxide and sulphate. Cycles of recharge and evaporation into and from the soil zone can lead to changes in the sulphate concentration in groundwater. As water moves through the soil zone, exchange reactions can occur removing calcium and magnesium and introducing sodium into the water. Dissolution of organic litter is an important source of organic matter such as humic and fulvic acids, tannins and lignins, amino acids and phenolic compounds in shallow groundwater. Organic matter can form complexes with iron and aluminum. This means that a new dissolved species is formed from two or more simpler species, in this case, organic species and iron or aluminum. These complexes allow metals like iron and aluminum that are not particularly mobile to move down through the soil profile. These metals are generally readsorbed further along the flow path. Oxidation reactions of organic matter provide a source of CO_2 that can then be dissolved and potentially participate in mineral dissolution reactions. These oxidation reactions are also thought to introduce sulphate into groundwater (Hendry et al., 1986).

As groundwater continues along its flow path, it enters the saturated zone. Domenico and Schwartz (1990) indicate that geochemical reactions occurring in this zone are more complex than in the unsaturated zone because of the possibilities of dispersive mixing and because geologic, hydrogeologic, and geochemical settings are much more diverse. They state that most of the same processes affecting ion concentrations in the unsaturated zone are also operative in the saturated zone including

- Mineral dissolution reactions
- Redox reactions
- Cation exchange reactions.

Groundwater can continue to dissolve minerals until concentrations of elements in solution are such that precipitation begins to occur. The result is increased quantity of mass dissolved in the water. The electrochemical nature of the water can change as certain geochemical reactions occur. This electrochemical change is important because the change in conditions control the concentrations of metal ions, solids and dissolved gases in solution. Cation exchange reactions will be similar to those described under soil zone groundwater flow conditions.

Groundwater researchers discovered that groundwater compositional changes under certain conditions are systematic. The following description is summarized from Freeze and Cherry (1979, p. 238-253).

Chebotarev (1955), Ignatovich and Souline noted that groundwater tends to evolve toward the composition of seawater accompanied by regional changes in dominant anion species. As travel distance along the flow path increases, the dominant major anion shifts from HCO_3^- to $HCO_3^- + SO_4^{2-}$ to $SO_4^{2-} + HCO_3^-$ to $SO_4^{2-} + Cl^-$ to $Cl^- + SO_4^{2-}$ and finally to Cl^-. A similar progression is seen as the residence time of groundwater increases. A similar evolution sequence for the major cations has not been proposed because of the complications associated with cation movement along flow paths. For example, cation exchange reactions are more prevalent than anion exchange reactions and can commonly cause alterations or reversals in the cation sequences. The process of evolution from stage to stage is controlled by the availability of soluble carbonate, sulphate and chloride minerals along the groundwater flow paths and by mixing with waters of different types. Oxidation-reduction (redox) potentials decrease along the flow path as well as with depth and with residence time. This occurs initially because oxygen introduced during recharge is rapidly consumed by organic matter oxidation forcing the redox potential to decline. Once all of the dissolved oxygen is consumed, reduction of NO_3^- and MnO_2 occurs, followed by the reduction of iron minerals accompanied by incremental decreases in the redox potential of the water. Once sufficiently negative redox potentials are reached, sulphate reduction occurs. The final step in the electrochemical evolution sequence involves the reduction of organic matter to methane. These reactions are biologically catalyzed and it is thought that the evolution sequence is at least partially if not totally controlled by the ability for the necessary redox bacteria to thrive. Important factors controlling the electrochemical evolution of water therefore include the availability of nutrients, the availability of electron acceptors and donors, the pH and the temperature.

Understanding these principles is important to describing geological controls on groundwater quality in the Cold Lake-Beaver River Basin for two reasons. First, they provide a framework for interpretation and prediction. Second, when the predicted quality is contradicted by field data, they give a basis for investigations of the underlying geological causes.

3.2.3.1 Possible Geological and Hydrogeological Controls on Major Ions in the Cold Lake-Beaver River Basin

Recent Environmental Impact Assessments (EIA) submitted by Imperial Oil Resources (IOR) and Canadian Natural Resources Ltd. (CNRL) suggest that major ion chemistry in the drift sediments is in many cases controlled by standard geochemical processes such as mineral and gas dissolution in recharge areas, and cation exchange, mixing and ion diffusion in areas further along flow paths.

Ozoray et al. (1980) suggested that changes in solubility of gypsum and exchange reactions with clay minerals in the drift and shallow bedrock in the Cold Lake area are the dominant geochemical processes affecting the composition of the groundwater in this area. Ozoray et al. (1980) also noted that there was a high seasonal variability of chemical quality of these groundwaters.

Freeze and Cherry (1979, p. 284-286) classified water composition in glacial deposits into three types. Type I water is typical of glacial deposits in parts of the Precambrian Shield. It generally has TDS values < 100 mg/L. The dominant cations in solution are Na^+, Ca^{2+} or Mg^{2+}, while the dominant anion in solution is HCO_3^-. Type II water is typical in southern Ontario and in the midwestern region of the United States, but is also found in the Interior Plains region of Canada and the United States. Type II water has a TDS < 1000 mg/L. The dominant cations are Ca^{2+} and Mg^{2+} and the dominant anion is HCO_3^-. Type II water is the results of carbonate dissolution reactions involving dissolved CO_2. Subsequent cation exchange reactions can modify the major cation concentration from a dominantly Ca^{2+} and Mg^{2+} composition to a dominantly Na^+ composition. Type III water occurs in the Interior Plains region of Canada and the United States and has TDS values between approximately 1000 mg/L and 10000 mg/L. Na^+, Mg^{2+}, Ca^{2+}, HCO_3^- and SO_4^{2-} occur in major concentrations. Freeze and Cherry (1979, p. 284-286) state that Type III water is produced from a combination of reactions including: 1) carbonate mineral dissolution by water charged with CO_2 from the soil zone; 2) dissolution of small amounts of gypsum; and 3) exchange of Ca^{2+} for Na^+ and Mg^{2+} on montorillonite clays. On this basis, the groundwater in the Cold Lake-Beaver River Basin is best categorized as a Type III water that is consistent with the area geology.

3.2.3.2 Geological and Hydrogeological Controls on Natural Elements or Compounds of Concern in the Cold Lake-Beaver River Basin

Certain elements or compounds of concern have been identified in groundwater samples in the Cold Lake-Beaver River Basin. These include: chloride, fluoride, nitrogen, sodium, sulphur, total phenols, F2 hydrocarbon fraction (C_{11} to C_{30+}), petroleum distillates and certain dissolved metals such as aluminum, antimony, arsenic, barium, boron, cadmium, chromium, cobalt, copper, iron, lead, manganese, mercury, molybdenum, nickel, selenium, silver, thallium, uranium, vanadium and zinc. Some of the observed concentrations exceed water quality guidelines for human health, freshwater aquatic life health, livestock health, irrigation water, or aesthetic considerations. These elements or compounds have both natural and anthropogenic sources making the understanding of their sources important in devising groundwater management strategies for the area. The focus of this section is on the potential geological sources of these elements. Actual concentrations and locations of occurrence in the Cold Lake-Beaver River Basin are reported in Section 5. Not all of the elements discussed below are present at detectable levels everywhere in the Basin. They are included here for completeness because they are reported routinely in groundwater chemical analysis reports.

Chloride (Cl^-)

All elements except the inert gases form chlorides (Brehler, 1973). Chloride can replace hydroxide groups in igneous rocks such as hornblende, apatite and mica. Chloride is also present in certain metamorphic rocks. Dissolution of minerals containing chloride can results in the incorporation of chloride in groundwater. Komex (1997) suggested some chloride concentrations in groundwater from drift aquifers might be the result of diffusion of Cl from underlying bedrock. Mixing of waters of different compositions will also change elemental concentrations. The glacial depositional process is complex, generating connected aquifers in some cases, while isolating others through depositional or glaciotectonic processes. The resulting aquifer-aquitard architecture and material properties could have a significant effect on groundwater chemistry.

Fluoride (F^-)

Fluorine forms simple halide minerals with Na, K, Mg, Ca and Pb. It also forms halides with fluoro anions, oxides, carbonates, borates, sulphates, phosphates and silicates. Because of the similar ionic radii of F^- and OH^-, F^- and OH^- will substitute for one another in crystal structures. This substitution is controlled by the nature of the bond the OH^- molecules are involved in, as well as the H_2O and HF fugacities of the environment (Allman, 1974). Under certain conditions, a complete solid solution series between OH^- and F^- end members is observed (Allman, 1974).

Fluorine is almost all tied up in rock minerals, and only a small percentage of the total is contained in water. Weathering of fluorine containing minerals is a source of fluoride to groundwater. The substitution of F^- by OH^- under appropriate pH conditions can also contribute F^- to groundwater (Hem, 1989). The dominant form of fluoride in groundwater is F^-, while at $pH < 3.5$, the HF form will occur (Hem, 1989). Fluoride will form complexes with aluminum, beryllium, ferric iron, boron and silica (Hem, 1989) depending on pH conditions. Dissolved fluoride is controlled by fluoride mineral solubility as well as by adsorption onto clay minerals (Hem, 1989).

Nitrogen (NH_4^+, NH_3, NO_3^-, NO_2^-, N_2O, N_2)

NO_3^- is the principle form in which nitrogen occurs in groundwater. Dissolved nitrogen is also present as ammonium (NH_4^+), ammonia (NH_3), nitrite (NO_2^-), nitrogen (N_2), nitrous oxide (N_2O) and organic nitrogen. Nitrate consists of one N atom and three oxygen atoms arranged around the N atom in threefold coordination. It can enter the hydrosphere through a number of mechanisms. Nitrogen oxides occur in the atmosphere naturally and in part because of the combustion of fossil fuels. These oxides undergo various chemical reactions that eventually form NO_3^- and ammonia. The nitrate can then be introduced into groundwater through precipitation and aquifer recharge. Nitrate can be directly introduced into groundwater systems from nitrate sources on the land surface, in the soil zone or in shallow subsoil zones through the application of wastes or fertilizers. It can also enter through the ammonification conversion process of organic nitrogen to NH_4^+ followed by the nitrification conversion process of the NH_4^+ to NO_3^-. Ammonification and nitrification generally occur above the water table with the produced NO_3^- leached into groundwater as water migrates through the soil zone to the water table. Nitrate can be removed from groundwater through the reduction of NO_3^- by bacteria to nitrous oxide or nitrogen gas.

Sodium (Na^+)

Sodium occurs only in coordination with oxygen and halogen atoms (Cocco et al., 1970). A close relationship exists between sodium and calcium with substitution of Na for Ca and Ca for Na common. The result of this is a number of solid solution series between Na and Ca end members of various minerals. Because both Na and Ca are abundant within the lithosphere, this potential for substitution can affect a large number of natural compounds. Substitution of Na with Li and K takes place only to a very limited extent unless the reactions occur at elevated temperatures at which point substitution reactions are enhanced (Cocco et al., 1970). Na is introduced into the hydrosphere through weathering reactions of Na-bearing minerals such as feldspars, by the dissolution of evaporite minerals such as halite, and by ionic substitution for Ca on clay minerals.

Sulphur (S^{2-}, SO_4^{2-})

In most natural water, sulphur is present as dissolved sulphate depending on Eh and pH conditions. Sulphate is introduced into the hydrosphere through the oxidation of sulphide minerals as aerated water comes into contact with these minerals. Reduced sulphur may be volatilized and released in volcanic regions and subsequently oxidized and introduced into groundwater through precipitation, dry fallout or water-rock interaction. Dissolution of evaporite minerals such as gypsum, anhydrite, barite, celestite and anglesite can also introduce sulphate into the groundwater system. Under suitable Eh, pH and temperature conditions, sulphate can be removed from the system by reduction to H_2S or HS^-, either through the action of sulphate reducing bacteria or through thermogenic sulphate reduction. Sulphate can also be removed by precipitation of insoluble sulphate minerals such as barite. A detailed study of a large perennial spring just northwest of the study area discusses natural sulphate in shallow groundwater in more detail (Stewart, 2002).

Organic Carbon Compounds

Naturally occurring organic compounds include fulvic acid, humic acid, chlorophyll, xanthophylls, enzymes, amino acids, carboxylic acids, phenols, ketones, aldehydes, alcohols, ethers, polycyclic aromatic hydrocarbons, and petroleum hydrocarbons. Most of these compounds are present only in small concentrations because of solubility factors, biodegradation and adsorption to aquifer materials.
Three classes of organic compounds have been identified in the Basin: 1) petroleum distillates; 2) phenols; and 3) petroleum hydrocarbons. Petroleum distillates are generally not associated with natural sources. The other two classes do have potential natural sources. Phenols can be derived from the decay of organic matter and petroliferous rocks. Longer chain hydrocarbons could likewise be introduced through interaction of water with petroliferous rocks. Andriashek (2003) noted the presence of an odour described as a bitumen odour from core recovered within northeastern Alberta as well as a hydrocarbon emulsion observed in the drilling mud tank during drilling. Andriashek and Pawlowicz (2002) also described various other occurrences of hydrocarbons in Quaternary materials in Alberta. A hydrocarbon

source for both hydrocarbons and phenols might therefore be present in the Quaternary materials present in the Basin.

Aluminum (Al^{3+}, $Al(OH)_3$, $Al(OH)^-_4$)

Al is found in all silicate minerals types, as well as some hydroxides, oxides, sulphates, phosphates and fluoroaluminates (Moore, 1971). The ionic radius of Al^{3+} allows for substitution into a number of crystal structures (Moore, 1971). Al^{3+} commonly substitutes for Cr^{3+}, Fe^{3+} and Si^{4+}, less commonly for As^{5+}, Be^{2+}, Mn^{2+}, Mn^{3+}, Nb^{5+}, Ti^{4+}, V^{3+}, and rarely for Mg^{2+}, Mo^{6+}, Sn^{4+} and W^{6+} (Moore, 1971). Elements that will substitute for Al^{3+} include B^{3+}, Cr^{3+}, Fe^{3+}, Ga^{3+}, Ge^{4+}, Li^+, Mg^{2+}, Mn^{3+}, Sc^{3+}, Si^{4+}, Ti^{4+}, and V^{3+} (Moore, 1971). Weathering of Al-bearing minerals will introduce Al into natural water. However, Al is mostly retained in new solid species such as Al-hydroxides and clay minerals. In solutions with $pH < 4$, aluminum occurs as Al^{3+} surrounded by six water molecules (Hem, 1989). At $4 > pH < 4.5$, one of the water molecules is replaced by an OH^- molecule (Hem, 1989). Between pH 4.5 and 6.5, polymerization of Al^{3+} and OH^- begins. These polymers will form hexagonal rings of aluminum and hydroxide molecules stretching up to a few hundredths of a micrometer in size (Hem, 1989). Above pH 6.5, Al is present predominantly as $Al(OH_4)^-$ (Hem, 1989). In the presence of sufficient silica, aluminum will precipitate to form poorly crystallized clay minerals (Hem, 1989). If in addition, an organic complexing agent is also present, kaolinite can form (Hem, 1989). Al complexes can occur in the presence of fluoride, phosphate, sulphate and organic compounds such as humic acid. Colloidal and polymerized forms of Al are small enough to pass through 0.45 µm and even 0.1µm filters making absolute determination of dissolved Al in solution difficult (Hem, 1989; Hitchon et al., 1999).

Antimony (SbO_2^-, SbO_3^-, Sb^{5+})

Antimony is found as metallic antimony, metal alloys, antimonides, sulphides, sulphosalts, sulpho-oxides, sulpho-halogenides and oxygen containing compounds (Kupčík, 1974). The ionic radii of +3 and +5 Sb allows for limited substitution of Sb for Fe^{2+}, Fe^{3+}, As^{3+}, Pb^{2+}, Zn^{2+} and Cu^{2+} in rock forming minerals (Kupčík, 1974). Weathering of Sb-containing minerals will release Sb to water. In addition, Sb is thought to possess volatilization tendencies and so could be transported atmospherically (Hem, 1989). In water, under reducing conditions and $4 < pH < 6.5$, Sb can be found as SbO^+ and Sb^{3+}. In the range of natural waters, under reducing conditions with $6.5 < pH < 8$, Sb appears to occur as SbO_2^- or Sb^{5+}. Under oxidizing conditions and $0 < pH < 8$, Sb_2O_5 and SbO^+ appear to be dominant. At pH greater than 8 Sb can exist in a number of forms depending on the extent of the reducing conditions. Under very reducing conditions, Sb^{5+} and SbO_2^- are likely. At pH's greater than 8 and under moderately reducing to oxidizing conditions, Sb is found as SbO_3^-.

Arsenic (H_3AsO_3, $HAsO_4^{2-}$)

Sources of arsenic are varied and include minerals, rocks, sediments, soil, anthropogenic sources and the atmosphere. Because of its ionic radii in both the As^{3+} and As^{5+} forms, arsenic can substitute for Si^{4+}, Al^{3+}, Fe^{3+} Ti^{4+} and S in numerous minerals (Smedley and Kinniburgh, 2002). Common mineral types include arsenates, sulphides, sulphosalts, arsenides, arsenites, oxides and native arsenic. Two of the most abundant arsenic bearing minerals are arsenopyrite (Smedley and Kinniburgh, 2002) and arsenian pyrite (Nordstrom, 2000). Arsenic is released into the atmosphere through sources such as volcanic gases and geothermal vents.

Processes that lead to release of arsenic into the groundwater system include

- arsenic-bearing mineral dissolution
- desorption of arsenic from soil material

- chemical transformation of arsenic through redox or other processes
- ion exchange between arsenic and other elements
- release of arsenic through biological activity.

Important factors affecting these processes include

- pH and Eh
- solution composition
- competing and complexing ions concentrations
- aquifer mineralogy
- reaction kinetics
- rate of diffusion of gases through the sediment
- rate of sedimentation
- hydraulics of the groundwater system.

Arsenic is removed from the aqueous system through a number of mechanisms, including

- adsorption or co-precipitation by or with oxides of Fe, Al and Mn
- adsorption onto clay, carbonate and phosphate minerals
- adsorption onto organic material
- co-precipitation with sulphide minerals
- oxidation of the more mobile As(III) to the less mobile As(V) by Mn(IV) with subsequent adsorption to oxide or clay minerals

Komex (1997) suggest that weathering of sulphide minerals, such as arsenopyrite, believed to be present in the local glacial deposits might provide an explanation for the presence of arsenic in groundwater. Andriashek (2003) identified elevated concentrations in core samples from Quaternary sediments in northeastern Alberta indicating that arsenic is naturally occurring in sediments of the region. A detailed study of the occurrence of arsenic in groundwater from drift sediments north of the Cold Lake-Beaver River Basin is found in Lemay (2002b).

Barium (Ba^{2+})

Barium forms a variety of minerals, including oxides, halides, nitrates, carbonates, borates, sulphates, phosphates and silicates. Weathering of Ba-minerals will release Ba into water. In dilute solutions barium will be present as Ba^{2+}. As ionic strength increases, ion pairs and complexes form between barium and CO_3^{2-}, HCO_3^-, OH^-, SO_4^{2-}, acetate, oxalate and succinate (Hitchon et al., 1999). Its concentration in water is controlled to a large extent by the solubility of $BaSO_4$ and $BaCO_3$ (Hem, 1989). The solubility of $BaSO_4$ is very low, on the order of 10^{-10}, while the solubility of $BaCO_3$ is similar to that of calcite. In addition, clays, hydroxides and organic matter can adsorb barium (Hitchon et al., 1999).

Boron (BO_3^{3-}, H_2BO_3, $B(OH)_3$)

Although it possesses a positive valency, boron never behaves as a cation (Christ, 1968). With the exception of two minerals that contain BF_4- tetrahedra, boron always occurs in chemical combination with oxygen such as BO_3^{3-}, $H_2BO_3^-$ or $B(OH)_3$ (Hitchon et al., 1999). As such, boron does not substitute for cations in crystal structures and instead enters as a boron-oxygen group (Christ, 1968). On their own, these groups can polymerize to form polyanions of various complexities possibly including boron species of different coordinations (Christ, 1968). These crystal structures can contain silicate, phosphate, arsenate, or carbonate groups. The resulting minerals are termed borosilicates, borophosphates, boroarsenates or borocarbonates of which the borosilicates form the largest group (Christ, 1968). Boron can enter the hydrosphere through the weathering of boron-containing minerals such as feldspars, micas, and evaporite minerals. Boron is volatile and may be liberated in volcanic gases and through hydrothermal systems (Hem, 1989). The concentration of boron in water is primarily controlled by adsorption or incorporation into clay minerals (Harder, 1973).

Cadmium (Cd^{2+})

Cadmium can replace Zn and possibly Ca in minerals structures and forms a number of crystal molecules and complexes including, halogenides, hydroxides, chalcogenides, silicates, complexes with oxygen, water and organic compounds, and metal alloys (Brehler, 1972). In solution, cadmium is present as Cd^{2+} or forms complex ions with ammonium, cyanide, halide, sulphide, carbonate, hydroxide or oxygen depending on Eh pH conditions (Wakita, 1969). In the range of natural waters, Cd^{2+} tends to be favoured (Wakita, 1969). Cadmium enters the hydrosphere through weathering of Cd-bearing minerals, through industrial wastes and vaporization through metallurgical processes and combustion of fossil fuels (Hem, 1989). Cadmium concentration in solution appear to be controlled by solubility of $CdCO_3$, coprecipitation with manganese oxides or can be adsorbed on mineral surfaces (Hem, 1989).

Chromium ($CrOH^{2+}$, $Cr(OH)_2^+$)

Chromium minerals fall into seven categories. These are oxides, hydroxides, carbonates, sulphides, chromates and silicates (Matzat, 1970). Because of its ionic size and chemical properties, the Cr^{3+} released through weathering of chromium-bearing minerals is effectively fixed in its residual weathering products (Shiraki, 1975a). Under continued oxidation, Cr^{3+} will form the soluble anion CrO_4^{2-} (Shiraki, 1975a). Six different ionic forms of chromium are considered stable under aqueous conditions. The reduced forms are Cr^{3+}, $CrOH^{2+}$, $Cr(OH)_2^+$ and $Cr(OH)_4^-$ (Hem, 1989). The oxidized forms are $Cr_2O_7^{2-}$ and CrO_4^{2-} (Hem, 1989). In the range of natural waters, $CrOH^{2+}$ and $Cr(OH)_2^+$ are thought to be the dominant forms (Hem, 1989). Chromium concentrations in water are controlled by the solubility of $Cr(OH)_3$ and CrO_4^{2-}, as well as adsorption onto Fe and Mn-oxides, hydrous Fe and Mn-oxides, apatite, clay and organic matter (Shiraki, 1975b).

Cobalt (Co^{2+}, Co^{3+})

In the Co^{2+} form, cobalt can substitute for Mg^{2+} and Fe^{2+} in several silicate minerals (Burns and Burns, 1973). Co forms metal alloys, sulphides, arsenides and sulphosalt minerals (Burns and Burns, 1973). The crystal chemistry of Co closely resembles that of nickel and cobalt frequently occurs with nickel in a number of minerals (Burns and Burns, 1973). Cobalt is easily solubilized during weathering and can therefore easily enter the hydrosphere (Turekian, 1976a). Control of cobalt in aqueous solutions appears to be by coprecipitation or adsorption of cobalt by oxides of manganese and iron, the solubilities of $CoCO_3$, cobalt phosphates and hydroxides and the adsorption of Co onto clays (Turekian, 1976b; Hem, 1989).

Copper ($Cu(OH)_3^-$)

Copper will form metallic copper, alloy-like phases, sulphides, sulphosalts, selenides, tellurides, arsenides, oxides, hydroxides, oxygen-containing salts, halides, arsenites, tellurites, selenites, iodates, carbonates, sulphates, nitrates, phosphates, arsenates, vanadates, chromates, molybdates, selenates and silicates as well as organic complexes (Zemann, 1971). Copper is extracted from silicates, sulphides and oxides during rock weathering (Wedepohl, 1973a). Depending on CO_3, Fe and S concentrations a variety of Cu complexes are likely to make up the copper species present under most natural water conditions. Copper concentration in solution is therefore controlled by the solubility of the various mineral phases as well as by adsorption onto clays and organic matter (Wedepohl, 1973b).

Iron (Fe^{2+}, $Fe(OH)_3$, FeO)

Iron occurs in coordination with oxygen, halides and sulphur and is present in a wide variety of mineral classes including, oxides, halides, sulphides, phosphates, arsenates and silicates (Ghose, 1968). Redox reactions occurring in the sedimentary environment therefore influence the state and concentration of Fe. These include oxidation of ferrous minerals to form ferric oxides, reduction of ferric oxides to form iron sulphides, carbonates or glauconites, and adsorption of Fe onto clay minerals (Berner, 1969). Iron generally enters the hydrosphere through the weathering of ferromagnesian minerals and is commonly redeposited as pyrite, siderite, or iron hydroxides depending on redox conditions and ions in solution. Komex (1997) suggest that any anomalous concentrations of iron in the Cold Lake-Beaver River Basin could be the results of weathering of iron rich oxide minerals and the subsequent release of this metal into groundwater.

Lead (Pb^{2+})

Lead is the most abundant heavy element (atomic number greater than 60) in the Earth's crust (Hitchon et al., 1999). Lead forms sulphide, selenide, telluride, sulphosalt, oxide, hydroxide, halogenide, arsenite, selenite, iodate, carbonate, sulphate, tellurate, selenate, chromate, wolframate, molybdate, arsenate, phosphate, vanadate and silicate minerals as well as metallic Pb (Sahl, 1968). Pb^{2+} will substitute for K+ in feldspar and mica and is the dominant form of Pb in the hydrosphere (Wedepohl, 1974). Lead is mobilized during chemical weathering of Pb-bearing minerals. However most if not all the released lead is adsorbed by the also-generated clay minerals (Wedepohl, 1974). Lead is present in solution principally as Pb^{2+}, hydroxide complexes, carbonate-sulphate ion pairs and most probably organic complexes (Hem, 1989). The concentration of lead in natural water is controlled by the low solubility of lead compounds, the adsorption of lead onto organic surfaces and clays, and the coprecipitation of lead with manganese dioxide (Hem, 1989). Komex (1997) suggest that the lead occurrences in the Cold Lake-Beaver River Basin could be the results of weathering of lead sulphide minerals believed to be present in the local glacial deposits.

Manganese (Mn^{2+}, $MnOH^{+}$)

Manganese forms oxides, sulphides, hydroxides, tellurides, selenides, halides, arsenates and silicates. The ionic radius of Mn^{2+} is similar to that of Fe^{2+}, Mg^{2+} and Ca^{2+}. Substitution between Mn and Fe, Mg and Ca is observed in igneous and metamorphic minerals (Peacor, 1970). Substitution can also be seen between Mn and Fe, Mg and Ca in sedimentary rocks such as calcites and dolomites (Peacor, 1970). Manganese enters the hydrosphere through normal rock-weathering reactions. Komex (1997) suggest that any anomalous concentrations of manganese in the Cold Lake-Beaver River Basin could be the results of weathering of manganese rich oxide minerals and the subsequent release of this metal into groundwater.

Mercury (Hg)

Mercury forms solid mercury, metal alloys, halogenides, oxides, hydroxides, sulphides, sulphates and organic complexes (Grdenić, 1967). Mercury can also be found in trace amounts in rock-forming minerals such as feldspars, pyroxenes, amphiboles, calcite and apatite. Weathering of mercury-bearing minerals can introduce Hg into the hydrosphere. Organic complexes are produced by methane-generating bacteria as well as by man (Hem, 1989). Although rare, mercury is well distributed because of its volatile nature. In aqueous solution, under natural water conditions, Hg is present predominantly as Hg_{aq} (Hem, 1989). If sulphur is also present then the possibility of forming HgS in solution is probable. Mercury will also react with organic material and form complexes. The concentration of Hg in solution is controlled by the solubility of HgS, the potential for mercury to volatilize, adsorption onto clay particles and bioconcentration along aquatic food chains (Hem, 1989).

Molybdenum (MoO_4^{2-})

Molybdenum forms the following mineral types, oxides, sulphides, selenides and molybdates. Mo does appear to substitute into other mineral crystals. Solid solution systems have been observed between Mo^{6+}-bearing minerals and W^{6+}-minerals (Evans, 1973). In addition, minor traces of Mo can be found in feldspars, pyroxenes, amphiboles, biotite and sulphide minerals and ores such as sphalerite, pyrite, chalcopyrite, pyrrhotite and galena (Evans, 1973). Under oxidizing conditions, Mo-bearing minerals will undergo oxidation to more soluble Mo^{6+} or molybdates and these compounds will then be leached from the rock and can potentially reach the hydrosphere (Manheim and Landergren, 1978). Controls on concentration include metal molybdate solubility, adsorption to ferric oxyhydroxides and bioaccumulation in plants (Hem, 1989).

Nickel (Ni^{2+})

Nickel forms metal alloys, phosphides, carbides, sulphides, selenides, tellurides, arsenides, antimonides, sulphosalts, chlorides, selenites, carbonates, sulphates, arsenates, phosphates and silicates (Burns and Burns, 1977). Nickel will substitute for iron in ferrous sulphides and ferromagnesian minerals such as olivine, hornblende, biotite and chlorite (Burns and Burns, 1977). Nickel can also be found as a minor constituent in feldspars and spinel (Burns and Burns, 1977). Nickel is easily mobilized during weathering reactions, but many times it is re-precipitated shortly after dissolution (Turekian, 1977a). Ni concentrations in aqueous solution appear to be controlled by the solubility of nickel phosphate, carbonate, sulphide and hydroxide, as well as by the potential for nickel to coprecipitate with manganese oxides (Turekian, 1977b).

Selenium (Se, SeO_3^{2-}, SeO_4^{2-})

Selenium forms the following mineral types, native selenium, selenides, sulphosalts, oxides, selenates and selenites (Fischer and Zemann, 1973). Selenium substitutes for sulphur in many sulphide minerals including galena, sphalerite, pyrite, chalcopyrite, pyrrhotite, arsenopyrite and marcasite (Fischer and Zemann, 1973). Weathering reactions will oxidize selenium-bearing minerals releasing Se in its +6 form. In this form, Se is highly mobile and is not readily adsorbed onto iron oxyhydroxide surfaces (Hitchon et al., 1999). Controls on selenium concentration in aqueous solutions include coprecipitation as pyrite (if iron is present in solution), the low solubilities of elemental Se and SeO_3^{2-} species, the potential of the SeO_3^{2-} to be adsorbed to iron oxyhydroxides and the uptake and concentration by plant material (Hem, 1989).

Silver (Ag^+, $Ag(OH)^{2-}$)

Silver mineral types include, tellurides, selenides, arsenides, antimonides, sulphides, sulphosalts, halides, carbonates, sulphates, phosphates, oxides, native silver and metal alloys (Frueh, 1967). It is most commonly found in its univalent state in nature and as a sulphide or a sulphosalt mineral forming distorted polyhedra (Frueh, 1967). Silver can also be found as a minor constituent in feldspars, micas, hornblende and pyroxenes (Frueh, 1967). Weathering of silver containing minerals can introduce silver into the environment. However, most silver salts are insoluble and Ag^+ is rapidly adsorbed by oxides and organic matter (Vincent, 1974).

Thallium (Tl^+, Tl^{3+})

Thallium forms oxide, sulphide and selenide minerals (Sahl, 1972). Tl can also be found in trace amounts in feldspars, olivine, pyroxenes, micas, amphiboles, apatite, garnet, tourmaline, beryl, leucite and even opal (Sahl, 1972). Thallium appears to be largely retained during the weathering process (de Albuquerque and Shaw, 1970a). The thallium concentration in aqueous solutions appears to be principally controlled by adsorption onto clays (de Albuquerque and Shaw, 1970b).

Uranium (U^{4+}, UO_2^{2+}, $U6^+$)

Uraninite (UO_2) is an important uranium ore. It occurs as a primary constituent of granitic rocks and pegmatites (Klein and Hurlbut, 1985). Uraninite is also found in association with cassiterite, chalcopyrite, pyrite, arsenopyrite, native silver and Co-Ni-As minerals in hydrothermal vein deposits (Klein and Hurlbut, 1985). Complex formation between uranium, phosphate, fluoride and sulphate along with pH and Eh, are the likely controls on solubility of uranium in natural water (Drever, 1997; Clark and Fritz, 1997; Hem, 1989).

Vanadium (V^{3+}, V^{4+}, V^{5+})

Vanadium does not form primary magmatic minerals (Evans, 1967). All vanadium-bearing minerals are secondary and were formed under surface conditions at low temperature (Evans, 1967). These minerals include vanadium sulphide compounds, secondary vanadates, vanadium micas and oxide deposits (Evans, 1967). V^{3+} has a similar ionic radius to that of Fe^{3+} and will substitute for the Fe^{3+} ion in magnetite, pyroxene, amphibole and biotite (Evans, 1967). Vanadium can also be found in trace amounts in other rock forming minerals such as olivine, feldspars, apatite and garnet (Evans, 1967). Vanadium is present in plants, coal and petroleum (Hem, 1989). The low solubility of metal vanadates, adsorption onto clay minerals and metal oxides, coprecipitation with other mineral phases such as metal sulphides and uptake by plants can control V concentrations in natural waters (Landergren, 1974; Hem, 1989).

Zinc (Zn^{2+})

Zinc forms metallic zinc, sulphides, selenides, sulphosalts, oxides, hydroxides, tellurides, carbonates, sulphates, phosphates, arsenites, arsenates, vanadates, tungstates and silicates (Brehler, 1968). Zinc is also found in trace amounts in other rock-forming minerals such as magnetite, olivine, garnet, pyroxenes, amphiboles, biotite, feldspars and quartz (Brehler, 1968). Zn^{2+} has a similar ionic radius to those of Mg^{2+}, Fe^{2+}, Co^{2+}, Ni^{2+} and Mn^{2+}, partially explaining its presence in the above rock-forming minerals (Brehler, 1968). Zinc is introduced primarily through the weathering of zinc silicates and oxides (Wedepohl, 1972a). Zinc concentration in aqueous solutions is controlled by the solubility of zinc sulphide, phosphate, hydroxide, oxide and carbonate, as well as ion exchange and adsorption onto clays, organic matter and various metal oxides (Wedepohl, 1972b; Hem, 1989).

4 Distribution of Non-Point and Point Sources by Type in the Cold Lake-Beaver River Basin

A number of non-point and point sources have been identified in the Basin. These include: 1) urban areas; 2) wastewater treatment sites; 3) landfills; 4) confined feeding operations; 5) agricultural land use other than confined feeding operations; 6) transportation infrastructure; 7) oil and gas wells; 8) oil and gas facilities; 9) oil and gas related spills; and 10) storage tanks.

4.1 Urban Areas

The two major urban areas in the Basin are the town of Bonnyville and the city of Cold Lake (Figure 4.1). Point and non point source contamination can occur through various human activities such as industrial activity. In addition the burning of fossil fuels can introduce contaminants into the atmosphere that can fall in other portions of the Basin.

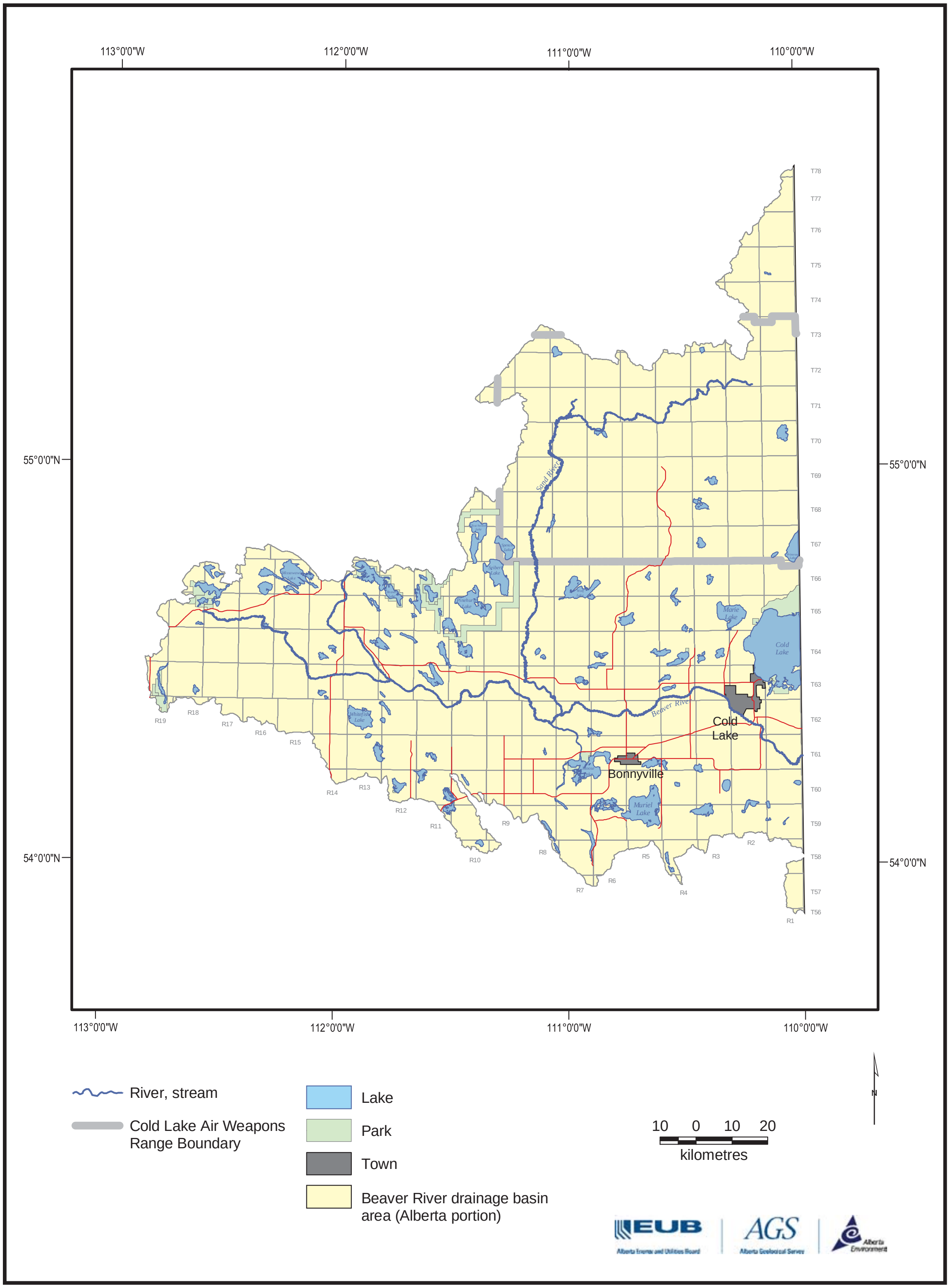


Figure 4.1. Urban areas within the study area.

4.2 Wastewater Treatment Sites

Wastewater treatment plants are located throughout the Basin in urbanized areas (Figure 4.2). The information was gathered from Alberta Environment and the various counties and municipal districts within the Basin. The ponds and lagoons associated with treatment plants have the potential to introduce contaminants into the groundwater system, including microorganisms. The associate disposal of the residual sludge or biowaste will likely be at facilities away from these plants.

4.3 Landfills

The location of landfills within the Basin is presented in Figure 4.3. The information was gathered from the various counties and municipal districts within the Basin. Refuse in landfills is subject to leaching by percolating water derived from rain or snowmelt. Freeze and Cherry (1979) indicate that the liquid derived from the process can contain large numbers of inorganic and organic contaminants with a very high TDS. Migration of this leachate can degrade groundwater quality. Locations of abandoned or so called "orphan landfill sites" where not collected in this study.

4.4 Confined Feeding Operations

Twenty-five confined feeding operations were identified in the Basin (Figure 4.4). The information was gathered from the Natural Resources Conservation Board. Animal waste has the potential to impact groundwater by introducing nitrate, pharmaceuticals, hormones and animal pathogens into the system.

4.5 Agricultural Land Use

The cropland or land used as forage is identified in Figure 4.4. The information was gathered from the Prairie Farm Rehabilitation Agency. Concerns with respect to groundwater quality and agricultural land use centre around the application of fertilizers and pesticides, and the storage and handling of animal wastes. Widespread, dispersed introduction of potential contaminants are referred to as "non-point sources".

4.6 Transportation Infrastructure

The road and rail network as well as the associated transportation maintenance yards are identified in Figure 4.5. The location information for the yards was provided by the various counties and municipal districts and urban centres within the Basin as well as by the highway maintenance contractor for the area. Salt used for highway maintenance during the winter is highly soluble. Freeze and Cherry (1979, p. 456) indicate that contamination of shallow aquifers along roads that receive salt is not uncommon. The highway maintenance yards where the salt is stored can also be a potential site of concern for salt contamination as well as other transportation related chemicals.

4.7 Oil and Gas Wells

Oil and gas wells within the Basin have been classified into four groups: 1) active; 2) inactive; 3) currently being used for injection or disposal purposes; and 4) previously used for injection or disposal purposes. The information was provided by the Alberta Energy and Utilities Board (EUB). The drilling process, well maintenance, abandonment process and injection activities all have the potential to affect groundwater quality in the vicinity of the wells. It should be noted that oil and gas operators adhering to EUB guidelines and regulations will minimize the opportunity for any adverse effects on groundwater.

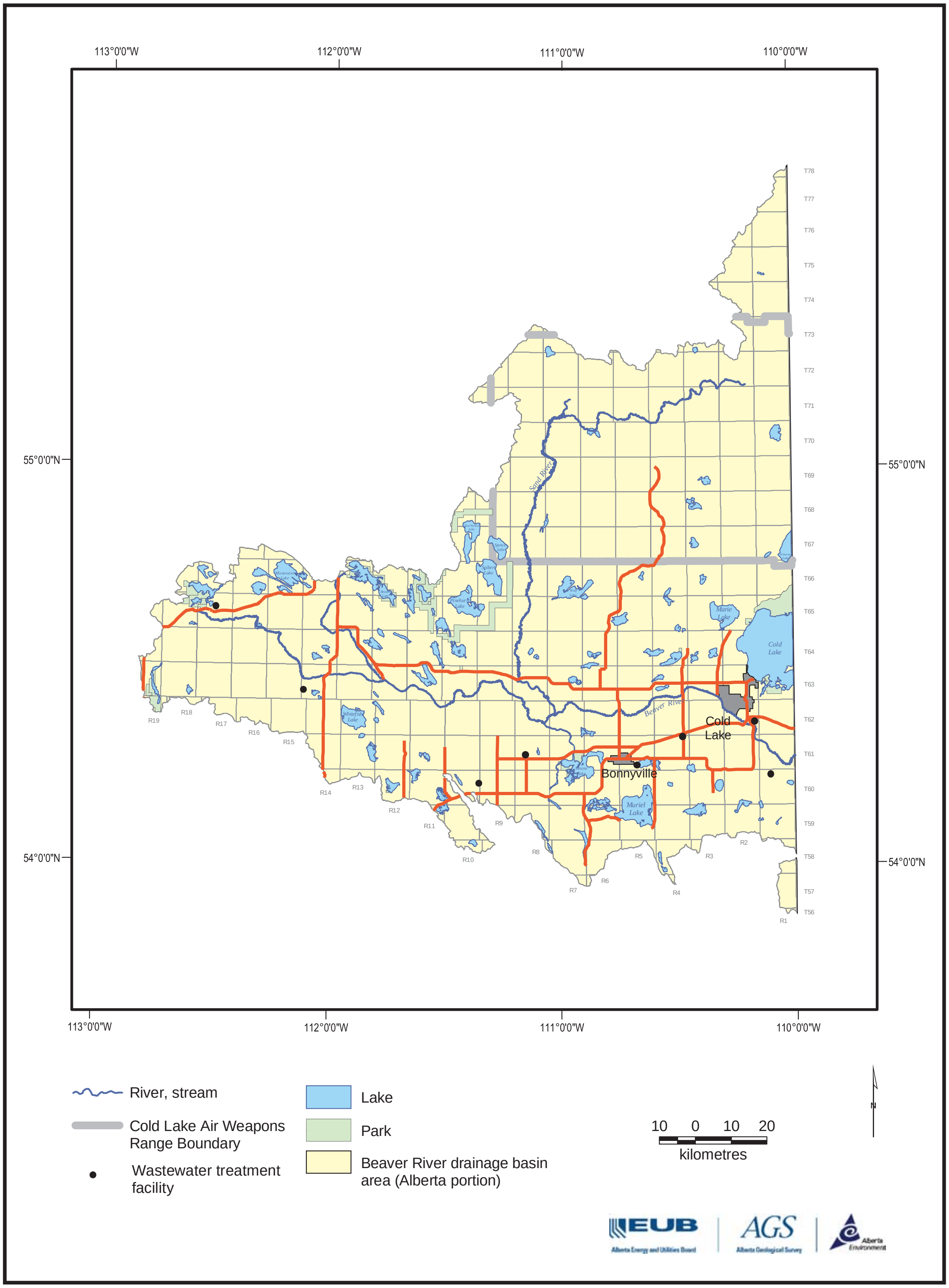


Figure 4.2. Wastewater treatment facilities within the study area.

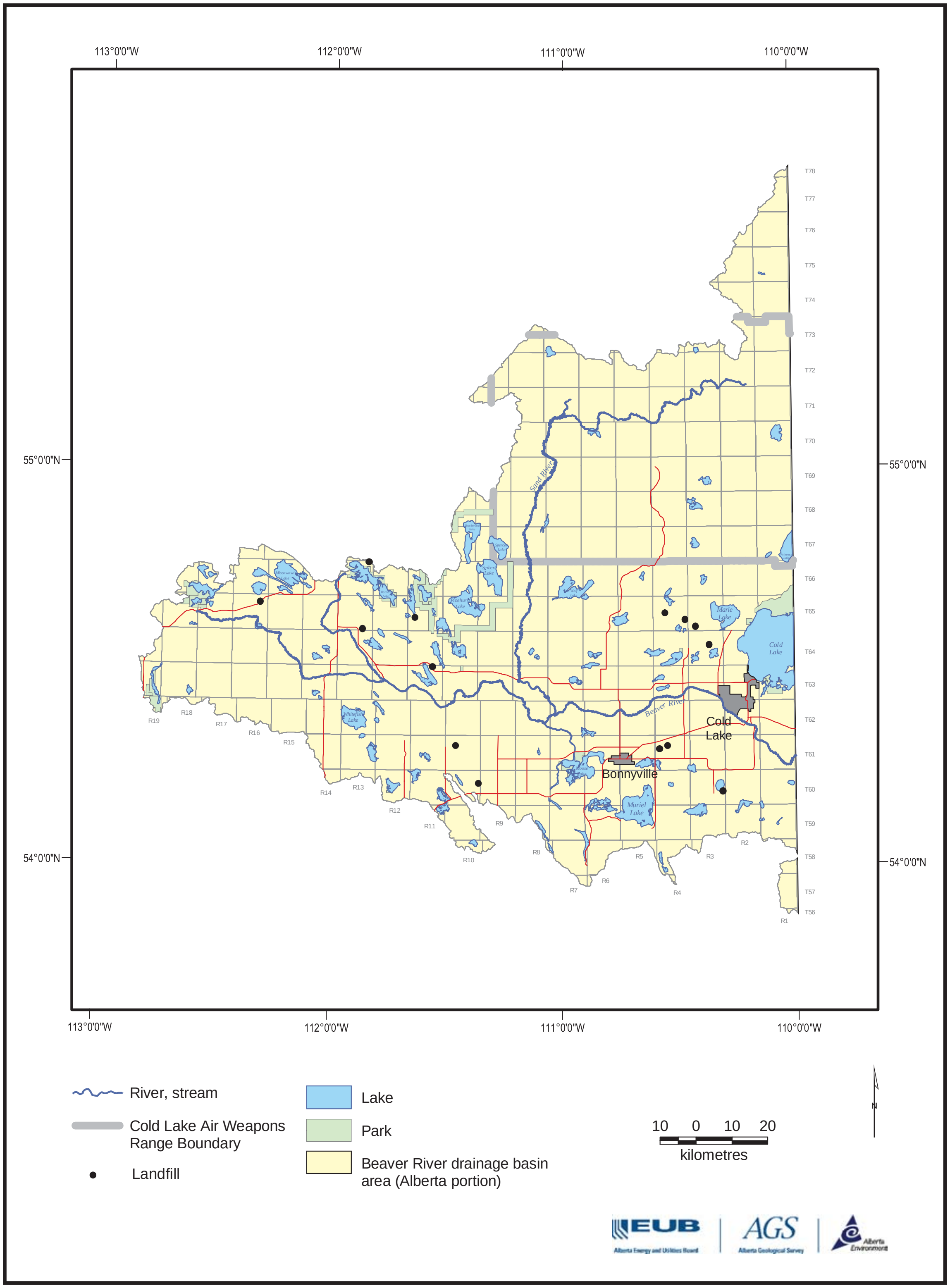


Figure 4.3. Landfills within the study area.

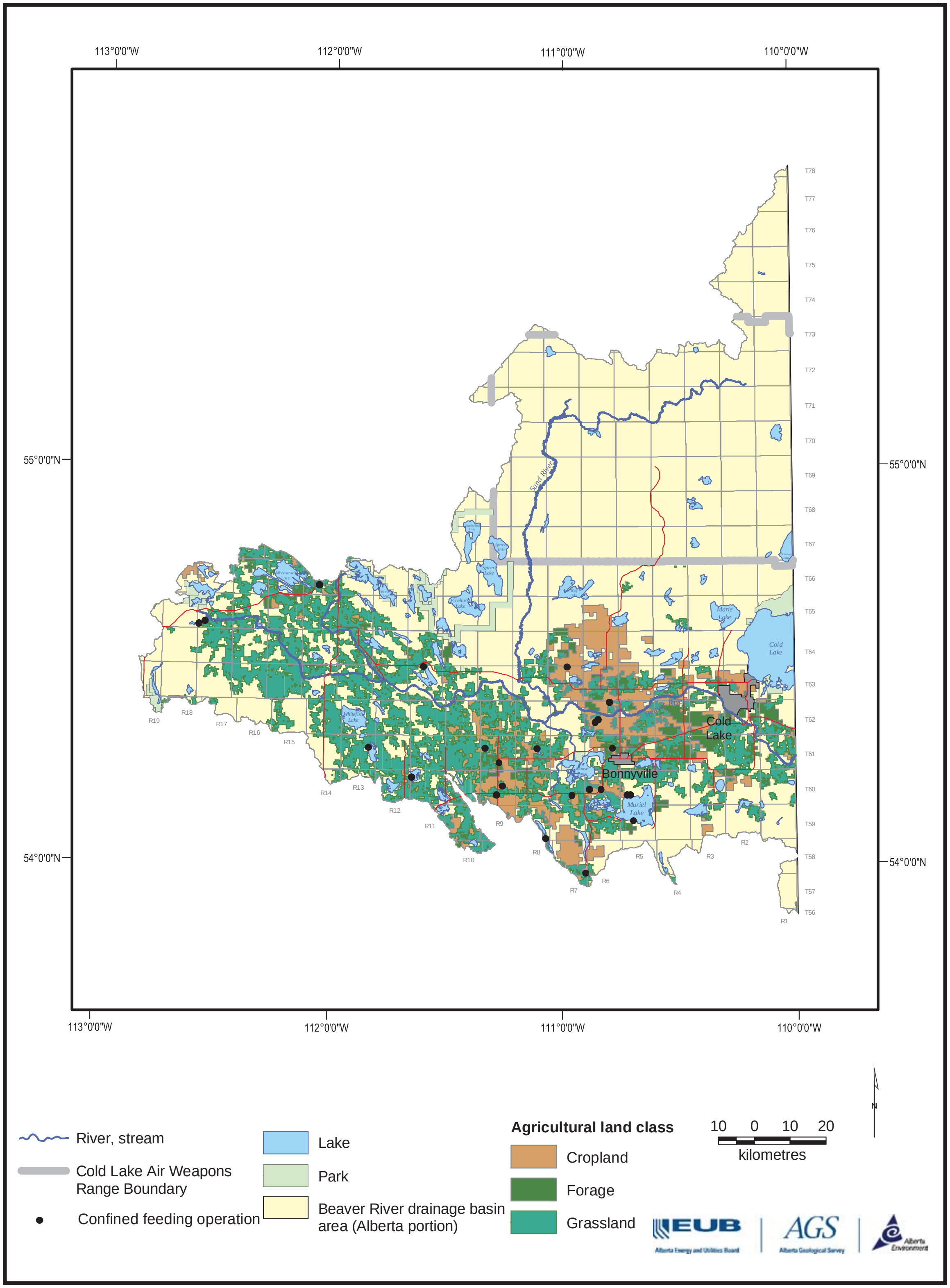


Figure 4.4. Confined feeding operations and agricultural land use within the study area.

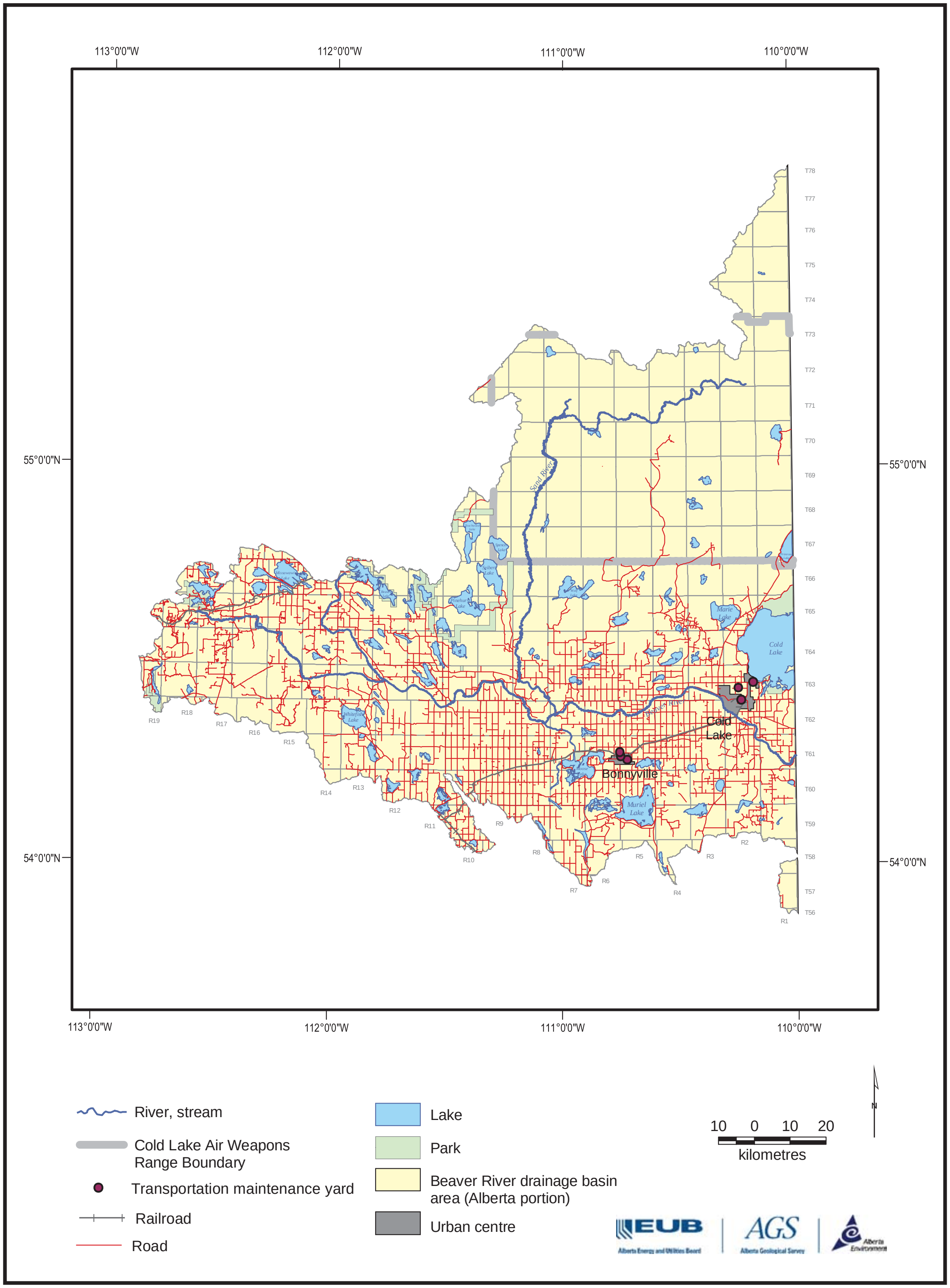


Figure 4.5. Transportation infrastructure within the study area.

4.7.1 Active Oil and Gas Wells

Active oil and gas wells were those wells identified as: 1) drilled and cased; 2) flowing gas; 3) flowing oil; 4) licensed; 5) miscellaneous; 6) pumping oil; 7) suspended gas; 8) suspended oil; and 9) water supply. The distribution of the wells is presented in Figure 4.6.

4.7.2 Inactive Oil and Gas Wells

Inactive oil and gas wells were those wells identified as abandoned gas or oil wells. The distribution of the wells is presented in Figure 4.7.

4.7.3 Current Injection or Disposal Wells

Current injection wells are those wells identified as: 1) steam injection wells; 2) water injection wells; and 3) water disposal wells. The distribution of the wells is presented in Figure 4.8. All of these wells will be completed below the regulated Alberta Base of Groundwater Protection.

4.7.4 Previous Injection or Disposal Wells

Previous injection or disposal wells are those wells that were at some point used for injection or disposal purposes. The distribution of the wells is presented in Figure 4.9. All of these wells will be completed below the regulated Alberta Base of Groundwater Protection.

4.8 Oil and Gas Infrastructure

The facilities and pipelines associated with oil and gas development have the potential to impact groundwater quality in the Basin through potential releases to the environment. The location information for the facilities and pipelines was obtained from the Alberta Energy and Utilities Board. Facility and pipeline locations are identified in Figure 4.10.

4.9 Documented Oil and Gas Related Spills

Oil and gas related surface releases must be reported to Alberta Environment if there is a potential for adverse affects associated with the release and to the Alberta Energy and Utilities Board. These releases can include, but are not limited to, water releases, chemical spills, or oil or bitumen spills. The potential impact of such occurrences on groundwater quality is probably localized. Information on the spills was obtained from the Alberta Energy and Utilities Board. The distribution of the spills is presented in Figure 4.11.

4.10 Storage Tanks

Storage tanks can hold any number of different solutions and can be located above or below ground. In the event of a leak developing in the tank, groundwater can be put at risk. Information on above and below ground storage tanks was obtained from the Petroleum Tank Management Association of Alberta. The distribution of storage tanks within the area is presented in Figure 4.12. This map does not show abandoned underground storage tank locations, nor does it show sites of formerly leaking underground storage tanks.

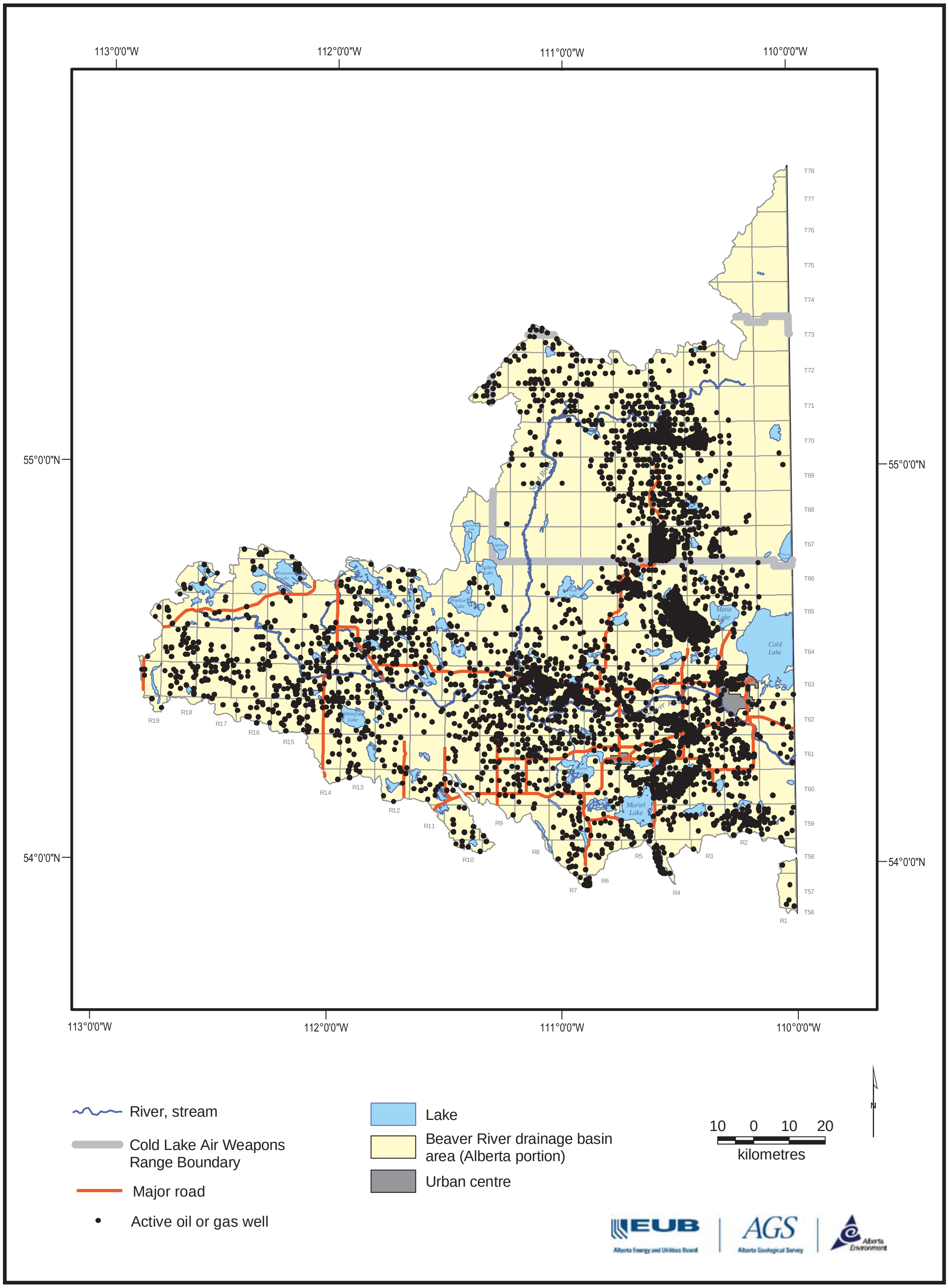


Figure 4.6. Active oil and gas wells within the study area.

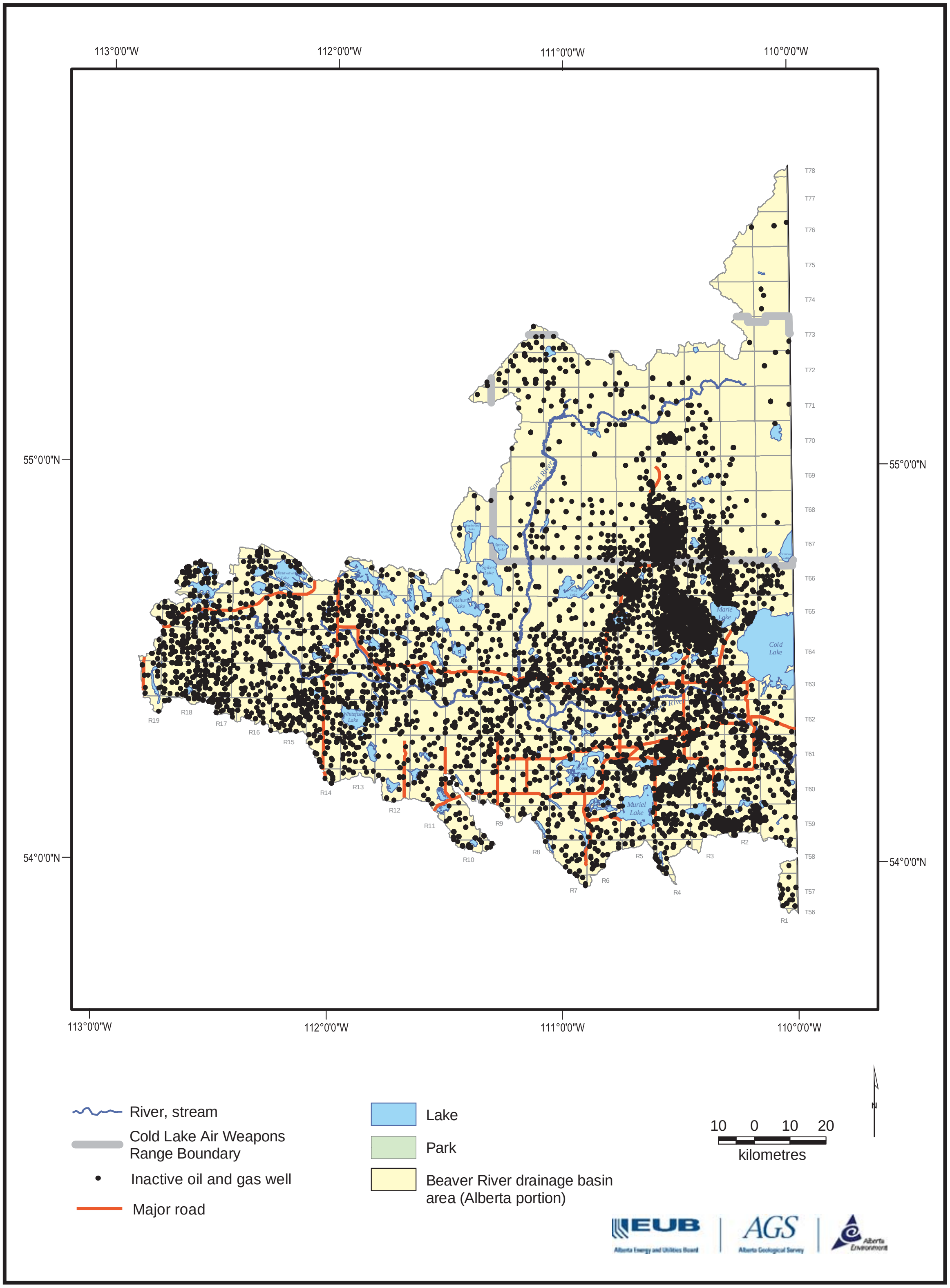


Figure 4.7. Inactive oil and gas wells within the study area.

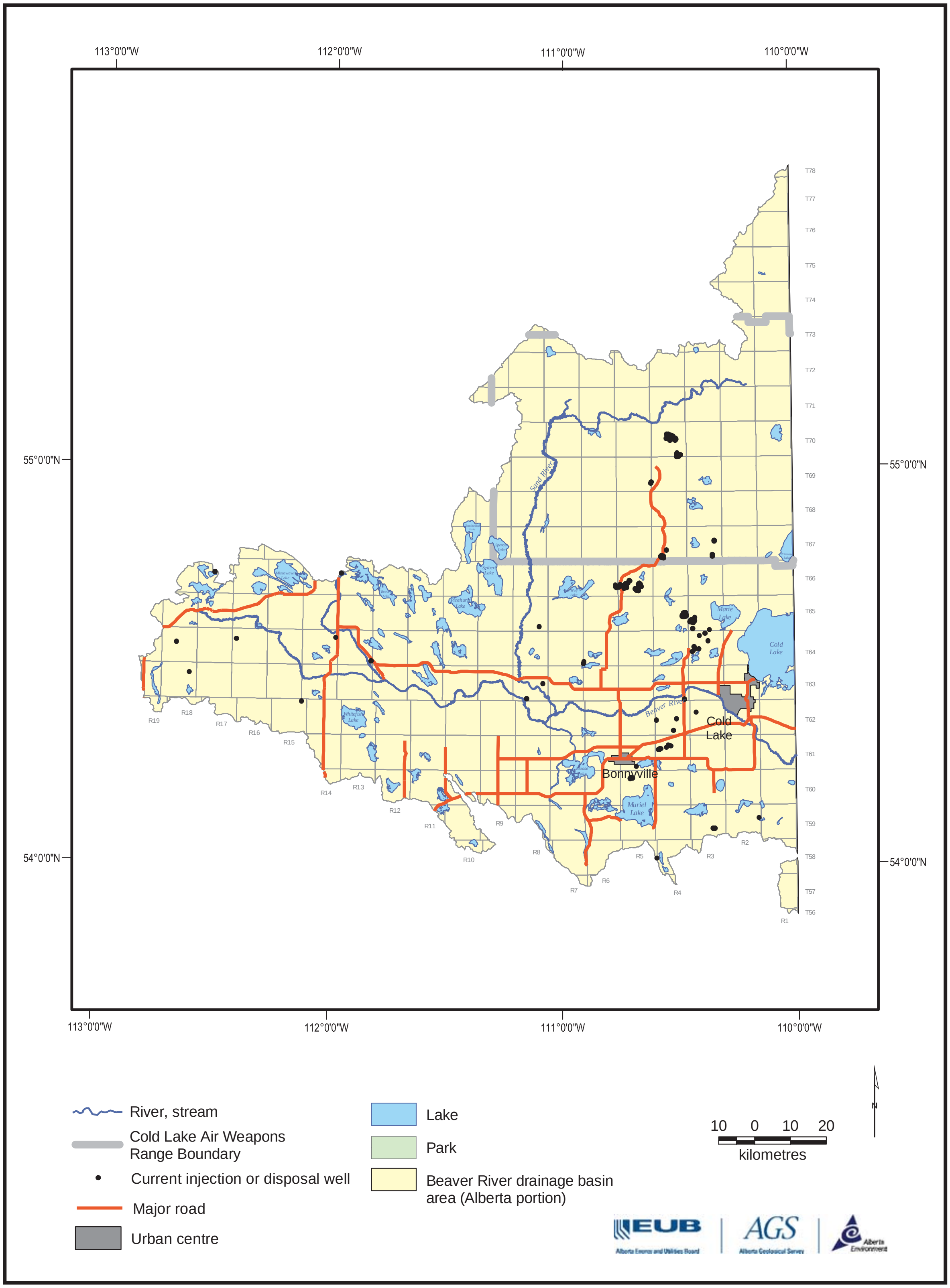


Figure 4.8. Wells currently used for injection or disposal within the study area.

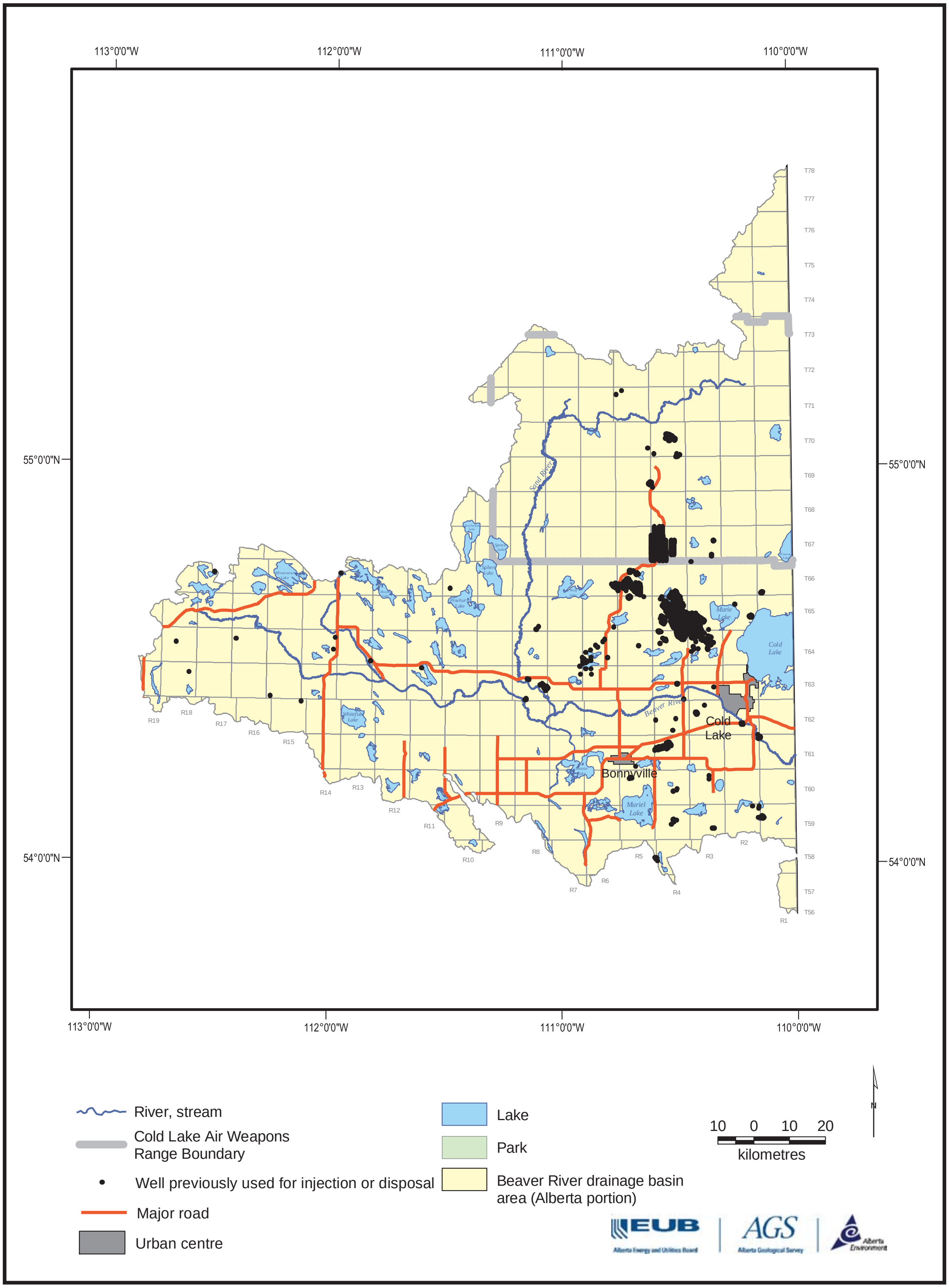


Figure 4.9. Wells that have been used for injection or disposal purposes in the past within the study area.

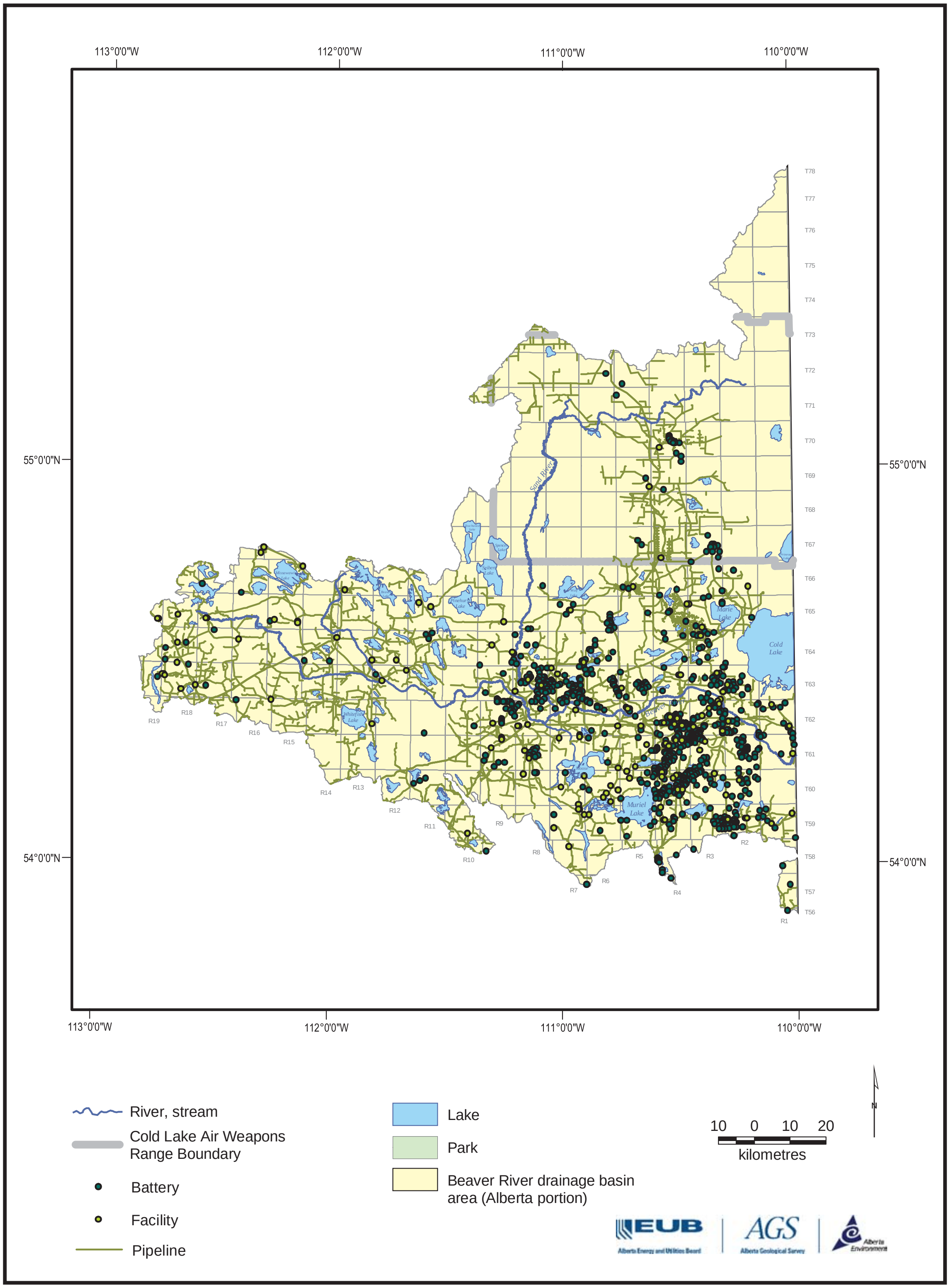


Figure 4.10. Oil and gas infrastructure within the study area.

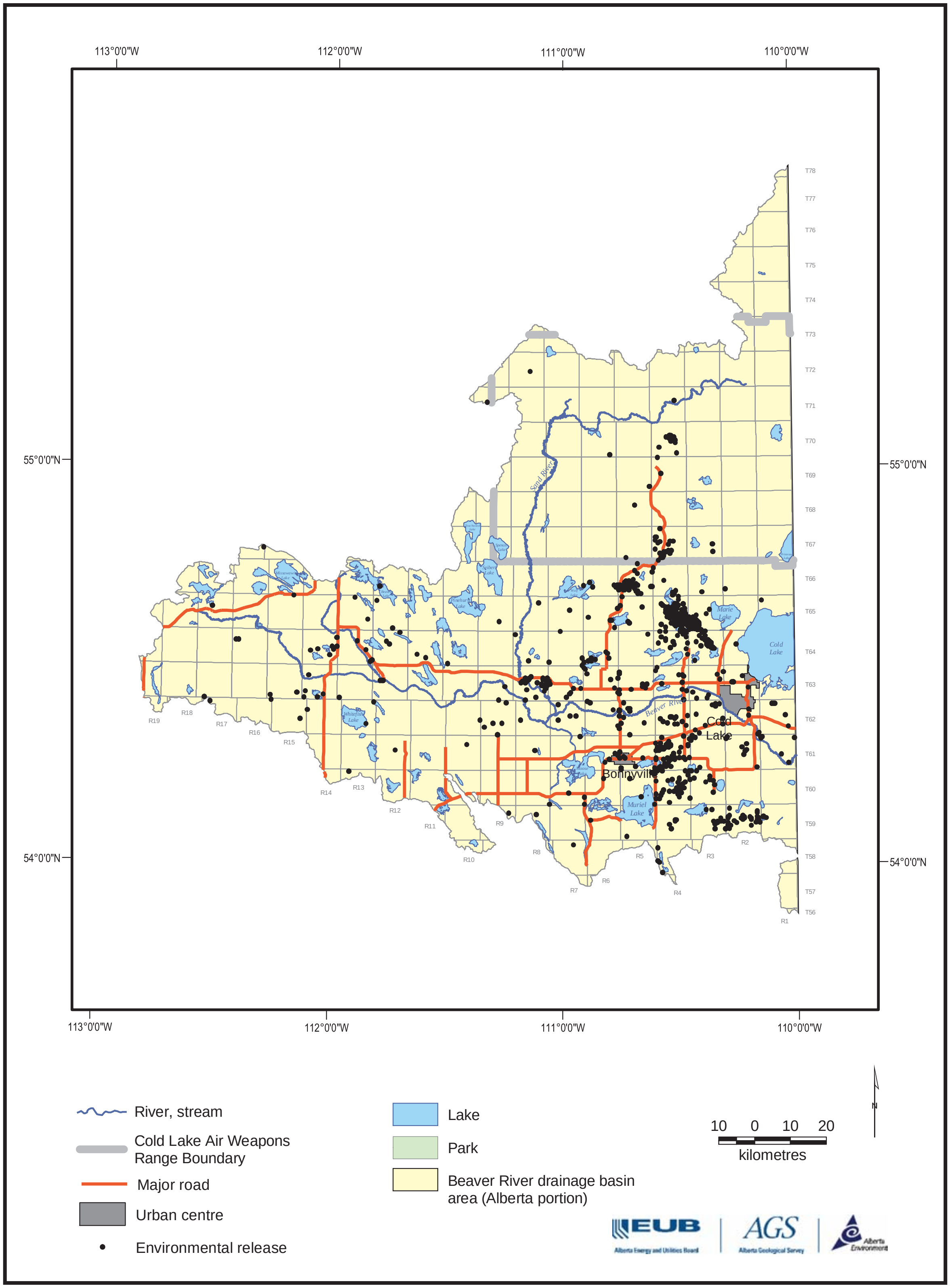


Figure 4.11. Environmental releases related to the oil and gas industry within the study area.

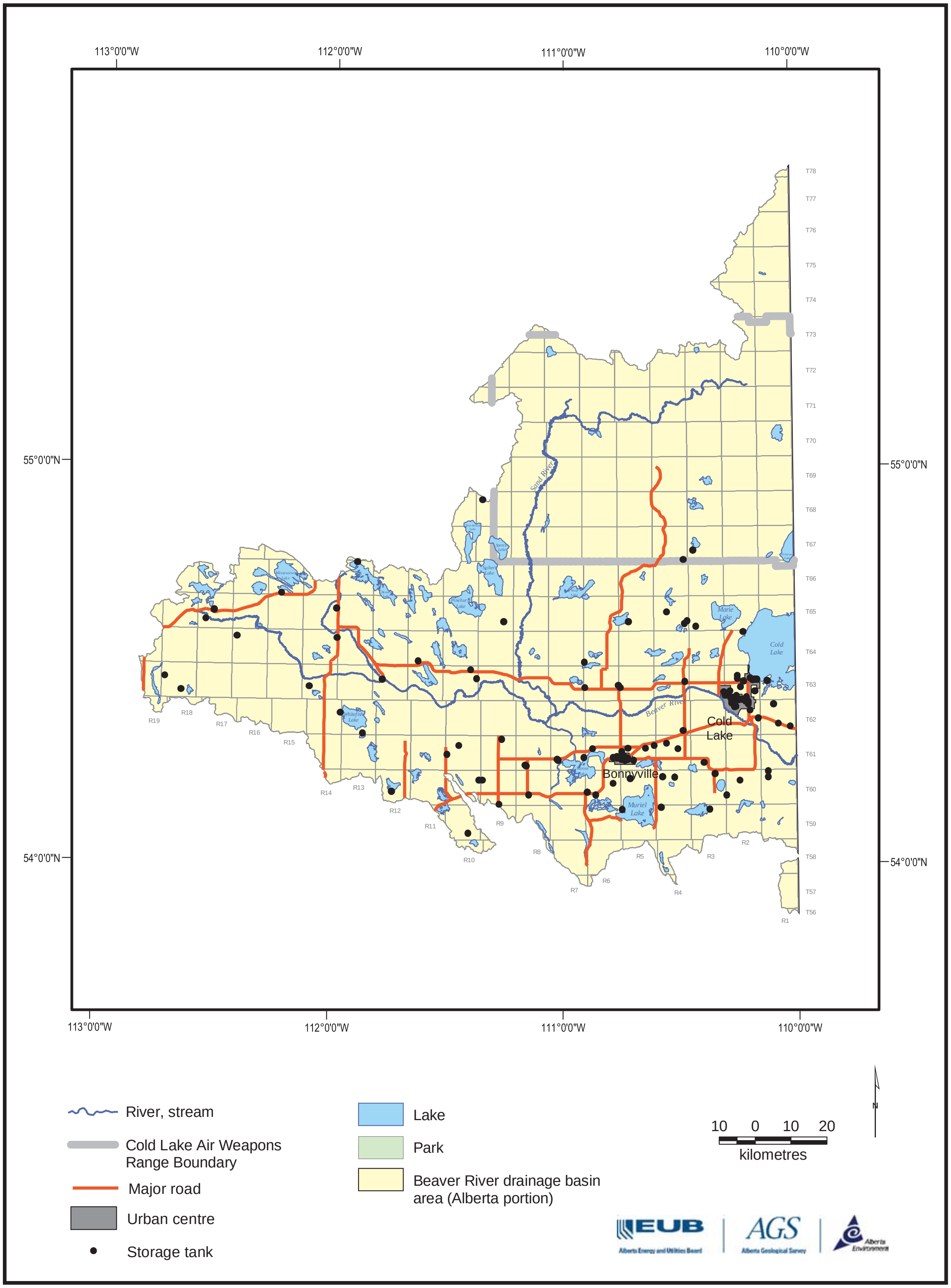


Figure 4.12. Locations of aboveground and underground storage tanks in the study area.

5 Groundwater Quality in the Drift Formations, Cold Lake-Beaver River Basin

Water well and groundwater-chemistry data were obtained, sorted, and compiled into a normalized database capable of being utilized with geographic information system (GIS) technology. These data came from government sources such as: documents and databases owned and maintained by the Alberta Geological Survey, the water-well completion and water-chemistry databases maintained by Alberta Environment, and groundwater water-license data plus supporting documentation on file with Alberta Environment. These data were supplemented by voluntary submissions of monitoring well records and water-chemistry data from industrial facilities, mostly bitumen operators.

All the original data were compiled in the database on an as-received basis. Various quality-control filters were created in the form of database queries in order to use the data to make maps discussed in this section.

All of the groundwater data needed geospatial co-ordinates and formation assignments in order to be of use to this study or future study. If the elevation of the land-surface at the well is known, the subsurface data on various files reported as depths can be converted to subsurface elevations and interpreted by geologists and hydrogeologists.

The water-well completion and water-chemistry database comprises the largest part of the database but the locations are only reported to the nearest quarter section in Dominion Land Survey co-ordinates. The co-ordinates of each centroid of each quarter section in Alberta are known so an initial elevation has been assigned from a DEM to each approximate location. The initial formation assignments using elevations equal to the centroid of each quarter section were found to be unsatisfactory. AGS obtained an improved estimate of ground surface elevation by comparing the initially assigned well locations to air photographs. Where a dwelling or structure existed on a quarter-section of land with a well record, the location of the well was reassigned to the dwelling or structure and a revised estimate of ground elevation was made from the DEM. The original assigned locations of the wells are still recorded in the database to facilitate backward comparisons should they ever become necessary. As well, quality codes were assigned by the operator doing the location reassignment to qualify the certainty associated with the location reassignment.

Once all of the wells in AENV's dataset plus all industry wells voluntarily submitted to AGS were either reassigned or accepted as submitted in terms of location, an elevation was generated by matching the final surface co-ordinate with the DEM. Then all well records with completion details were mapped into the geological framework discussed in Section 3 and assigned to a formation. For a water chemistry-record to be useful in a hydrogeological appraisal, several minimal criteria must be met: the location of the sampled well needs to be known; the date of the sample needs to be known; the completion details of the well must be known; the well needs to have a screen or perforated interval that can be assigned to a formation; and the chemical analysis itself must have a calculated charge-balance error of less than 5%. It must be underscored that the screening criteria for a regional resource appraisal are different than for a human health assessment of drinking-water quality or investigation of groundwater contamination. In the former, there would be much more emphasis on the type and nature of the drinking-water source and treatment technology rather than emphasis of the geological formation of origin. In the latter, there would be much stricter attention to sampling methodology, laboratory analysis, and the methods used to normalize or "level" data to facilitate comparison of results from different methods or different sampling events, mainly because the concentrations in question are in the part-per-billion or part-per-trillion range (1 mg/l roughly equates to one part-per-million). Thus the results of this analysis should not be interpreted in terms applied to investigations of drinking-water quality or groundwater contamination.

This section discusses regional groundwater chemistry based on these data. All of the maps presented herein are GIS-generated views of the database and represent only a fraction of the groundwater information that can be extracted from the database. The discussion will be limited to those parameters that Alberta Environment has indicated are of particular interest. These parameters include TDS, major ions, arsenic and phenols. The database view used to generate the maps was a view of the most current analyses submitted for a given well that passed the various screening criteria.

5.1 Regional Distribution of Total Dissolved Solids

Drever (1997, p. 13) defines salinity or total dissolved solids (TDS) as the sum of all dissolved constituents in water. Water within the hydrosphere can be classified based on TDS concentrations. The following general categories of water quality have been defined (Drever, 1997, p. 13):

- Fresh water – less than about 1000 mg/L
- Brackish water – between 1000 mg/L and 20000 mg/L
- Seawater – approximately 35000 mg/L
- Brines – significantly more saline than seawater

In addition, Alberta Environment defines brackish water to have a TDS concentration greater than or equal to 4000 mg/L. This value is used to define the base of groundwater protection within the Province and is used by both Alberta Environment and the Energy and Utilities Board in regulating the oil and gas industry. Environmental quality guidelines have been established for the TDS concentration in water for various uses and are presented in the following table (Table 1).

Table 1. Canadian environmental quality guidelines for TDS concentrations in water (CCME, 2003).

Water – Community Use		**Freshwater Aquatic Life**	**Water – Agricultural Use**		
			Irrigation		Livestock
MAC, IMAC	AO		Lower value	Upper value	
(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
-	≤ 500	-	500	3500	3000

Some of the TDS concentrations in the drift aquifers in the Basin exceed some or all of the environmental quality guidelines. The following table (Table 2) contains a summary of the exceedances of environmental water quality guidelines for TDS concentrations captured in the water quality database. The first column (Formation) lists the drift formations. The second column (Range of Values) presents the minimum and maximum values for the Formation. The third column (N) presents the total number of records for a given Formation. The fourth column (Water-Community Use) presents the number of records that exceed the water for community use guideline value where AO is the aesthetic objective. The fifth column (Freshwater Aquatic Life) presents the number of samples that exceed the freshwater aquatic life guideline values. The sixth column (Water-Agricultural Use) presents the number of records that exceed agricultural water use guideline values. In the case of water for irrigation use, a range of TDS values is presented. The column is split into two with the first subcolumn representing the number of records that exceed the lowest value of the range, and the second subcolumn representing the number of records that exceed the highest value of the range.

Table 2. TDS exceedances summary.

Formation	**Range of Values**		**N**	**Water – Community Use**	**Freshwater Aquatic Life**		**Water – Agricultural Use**		
							Irrigation		Livestock
	Min (mg/L)	Max (mg/L)		AO			Lower value	Upper value	
Grand Centre	39.5	3960	641	396	-	-	396	2	5
Sand River	87	10529	326	236	-	-	236	1	1
Marie Creek	133	3467	293	202	-	-	202	0	4
Ethel Lake	151.5	3967	301	235	-	-	235	1	1
Bonnyville	152.2	3776	364	248	-	-	248	1	3
Muriel Lake	227	6846	486	428	-	-	428	2	2
Bronson Lake	218	3182	21	20	-	-	20	0	1
Empress	29	4870	569	502	-	-	502	8	8

While the values above summarize the database contents, the following table describes the exceedances of the most recently collected data on TDS concentrations (Table 3).

Table 3. TDS exceedances summary - most recent values.

Formation	**Range of Values**		**N**	**Water – Community Use**	**Freshwater Aquatic Life**		**Water – Agricultural Use**		
							Irrigation		Livestock
	Min (mg/L)	Max (mg/L)		AO	Lower value	Upper value	Lower value	Upper value	
Grand Centre	39.5	3960	273	189	-	-	189	2	4
Sand River	87	10529	251	179	-	-	179	1	1
Marie Creek	133	3092	166	125	-	-	125	0	3
Ethel Lake	151.5	3967	204	173	-	-	173	1	1
Bonnyville	152.2	3776	143	107	-	-	107	1	3
Muriel Lake	292.6	6846	237	219	-	-	219	1	1
Bronson Lake	218	3182	14	13	-	-	13	0	1
Empress	28.6	4690	139	119	-	-	119	1	1

The distribution of the most recently collected data on TDS concentrations in the various formations is presented in Figure 5.1, Figure 5.2, Figure 5.3, Figure 5.4, Figure 5.5, Figure 5.6, Figure 5.7 and Figure 5.8.

5.1.1 Empress Formation

TDS information is available for the all five flow systems within the Basin, but most of the data is located within the NEBR and SEBR flow systems. The most recent TDS values of groundwater from the Empress Formation appear to increase towards Cold Lake and Moose Lake (Figure 5.1). These areas correspond to discharge areas as presented in Figure 2.5. An increase in TDS towards discharge areas is consistent with typical geochemical processes occurring along groundwater flowpaths. The relationship between recharge and discharge areas and TDS is less clear in other portions of the Basin. The highest TDS value was obtained from a well that based on its completion details would be completed just about bedrock. This might imply a connection to bedrock resulting in the observed TDS. Drever (1997) classifies fresh water as having a TDS value of approximately 1000 mg/L or less. Sixty-three percent of the samples collected from the Empress Formation fall within this range. The remaining samples are considered brackish. The TDS values are consistent with those proposed by Freeze and Cherry (1979) for water from glacial deposits.

5.1.2 Bronson Lake Formation

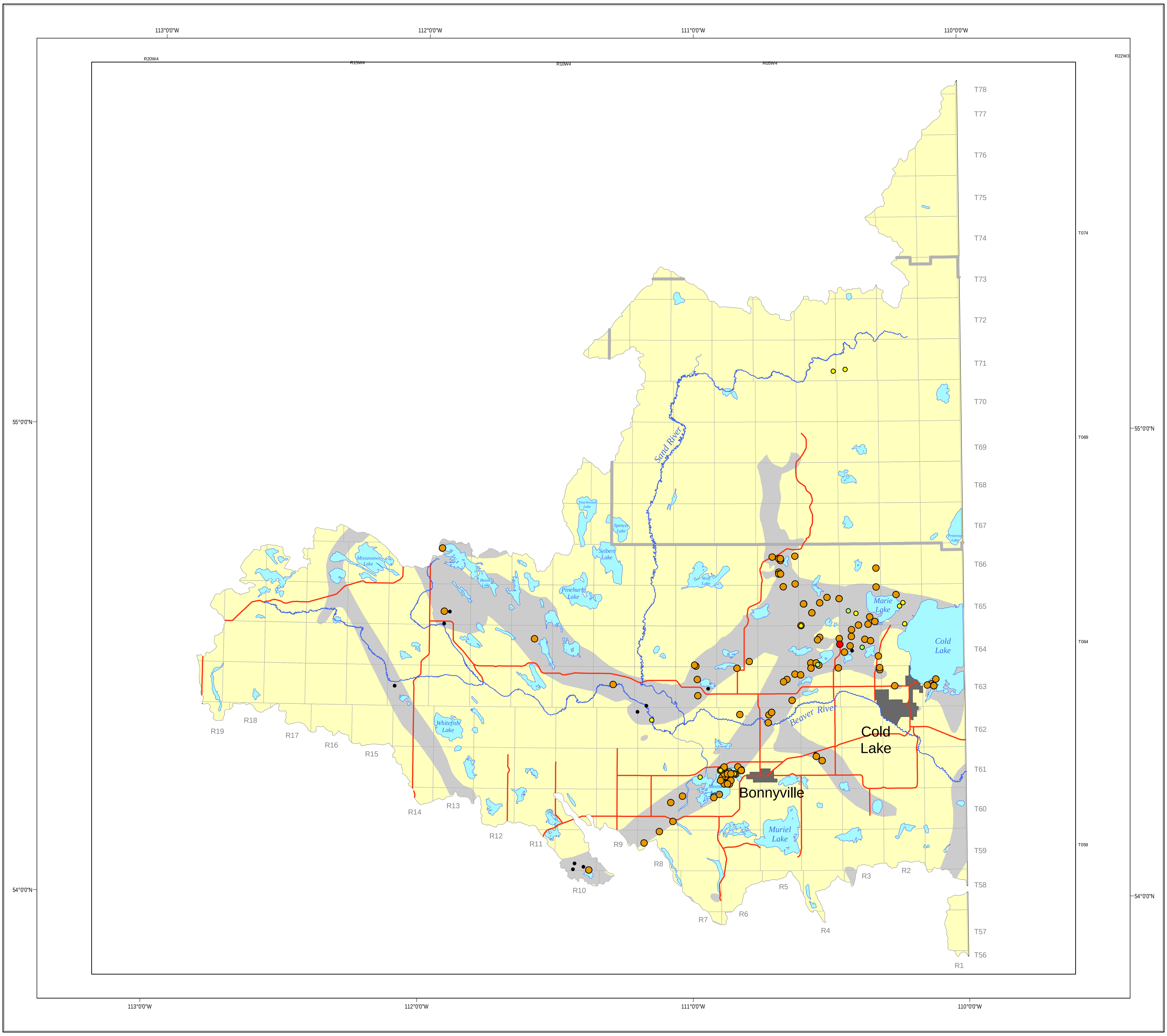
Information is available for the SEBR and NEBR flow systems. Because of the small number of sample points it is difficult to assess any trends in TDS in the Bronson Lake Formation (Figure 5.2). In general however, the groundwater samples located within discharge areas appear to have the higher TDS values while the samples located in recharge areas appear to have the lower TDS values (Figure 2.5). Twenty-nine percent of the samples (71%) have TDS values that would class them as fresh according to Drever (1997). The remainder would be considered brackish. TDS values fall within the TDS range proposed by Freeze and Cherry (1979) for water from glacial deposits.

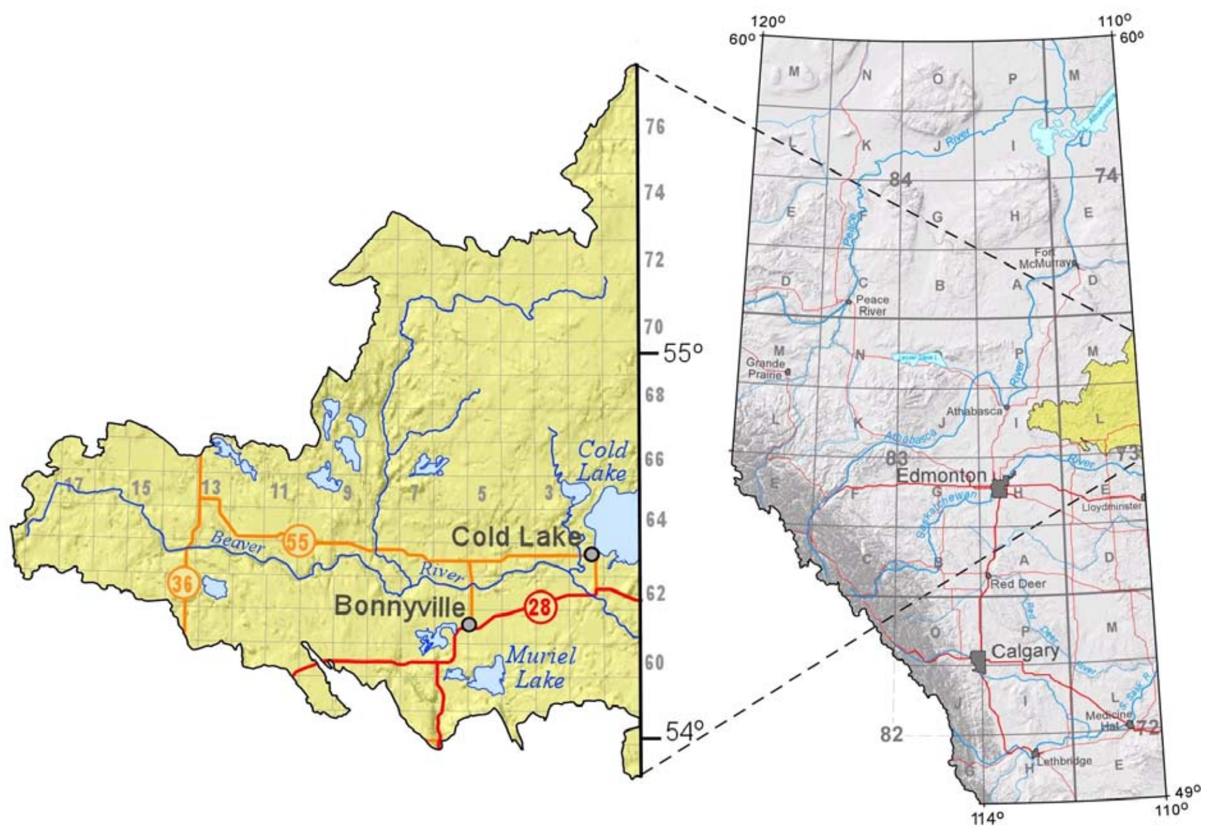
5.1.3 Muriel Lake Formation

TDS values appear to be similar regardless of which portion of the aquifer samples are collected from (Figure 5.3). Information is available for the NEBR, NWBR, Wiau and SEBR flow systems. The TDS values do not appear to have any obvious relationship to recharge or discharge areas (Figure 2.5) although samples collected around certain lakes appear to have some of the higher TDS values. For example, the highest TDS value was measured in a sample located near Muriel Lake and is located within what is defined as a discharge area. Most of the samples (59%) would be classified as fresh water based on the value put forward by Drever (1997) for fresh water. The remainder would be considered brackish. Based on TDS values, the samples are consistent with the water types listed by Freeze and Cherry (1979) for water in glacial deposits.

5.1.4 Bonnyville Formation

TDS values are available for all five-flow systems. Possible relationships exist between recharge and discharge areas, but they are by no means absolute. Many of the lower TDS values are found in the recharge areas, while higher TDS values are found in discharge areas (Figure 5.4 and Figure 2.5). Sixty-nine percent of the samples have TDS values less than 1000 mg/L, the cut off value proposed by Drever (1997) for fresh water. The values are also consistent with the glacial deposit water types detailed by Freeze and Cherry (1979).





Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

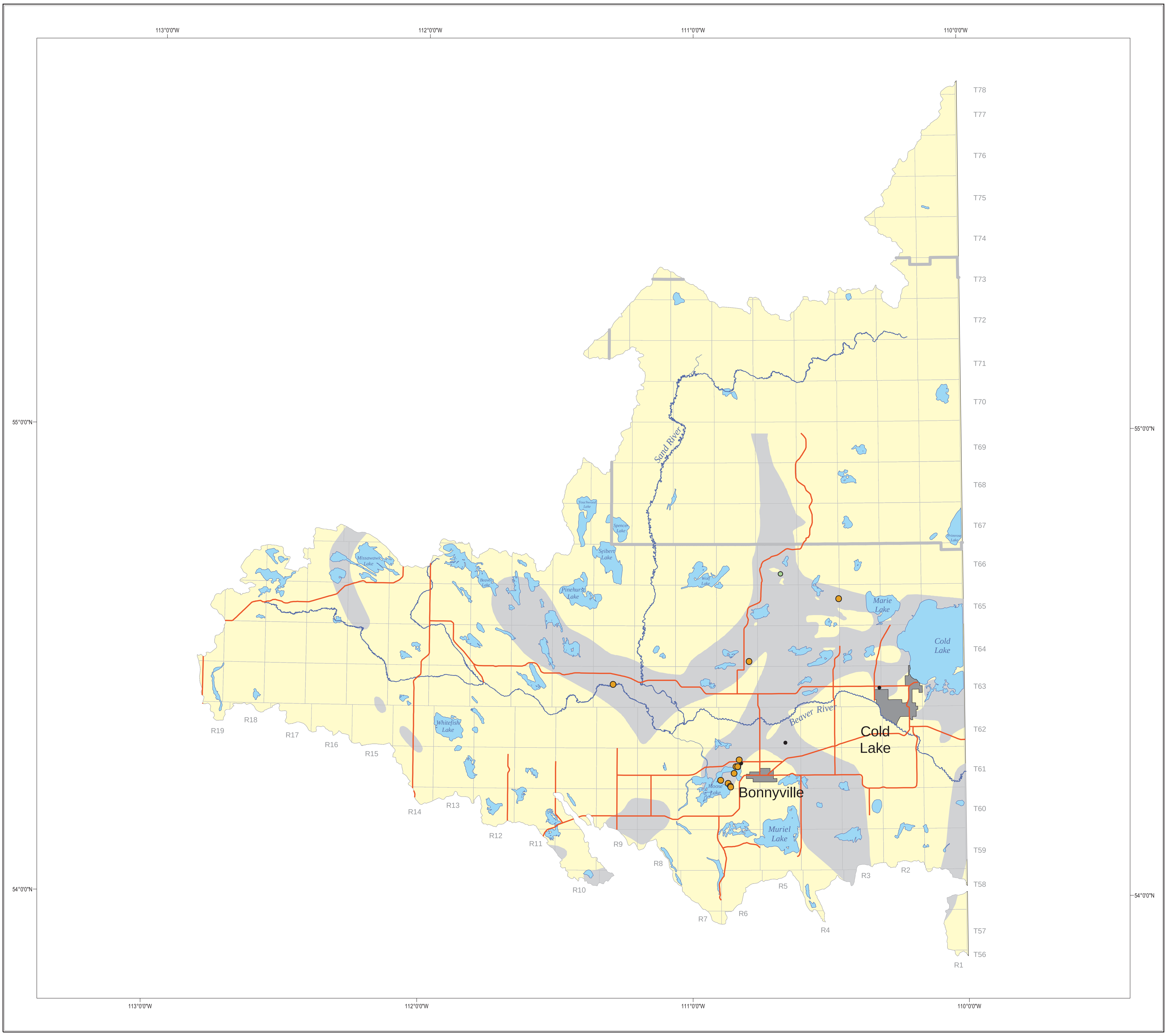
- Major river
- Major road
- Cold Lake Air Weapons Range Boundary
- Lake
- Town
- Approximate Formation extent
- Beaver River drainage basin area (Alberta portion)

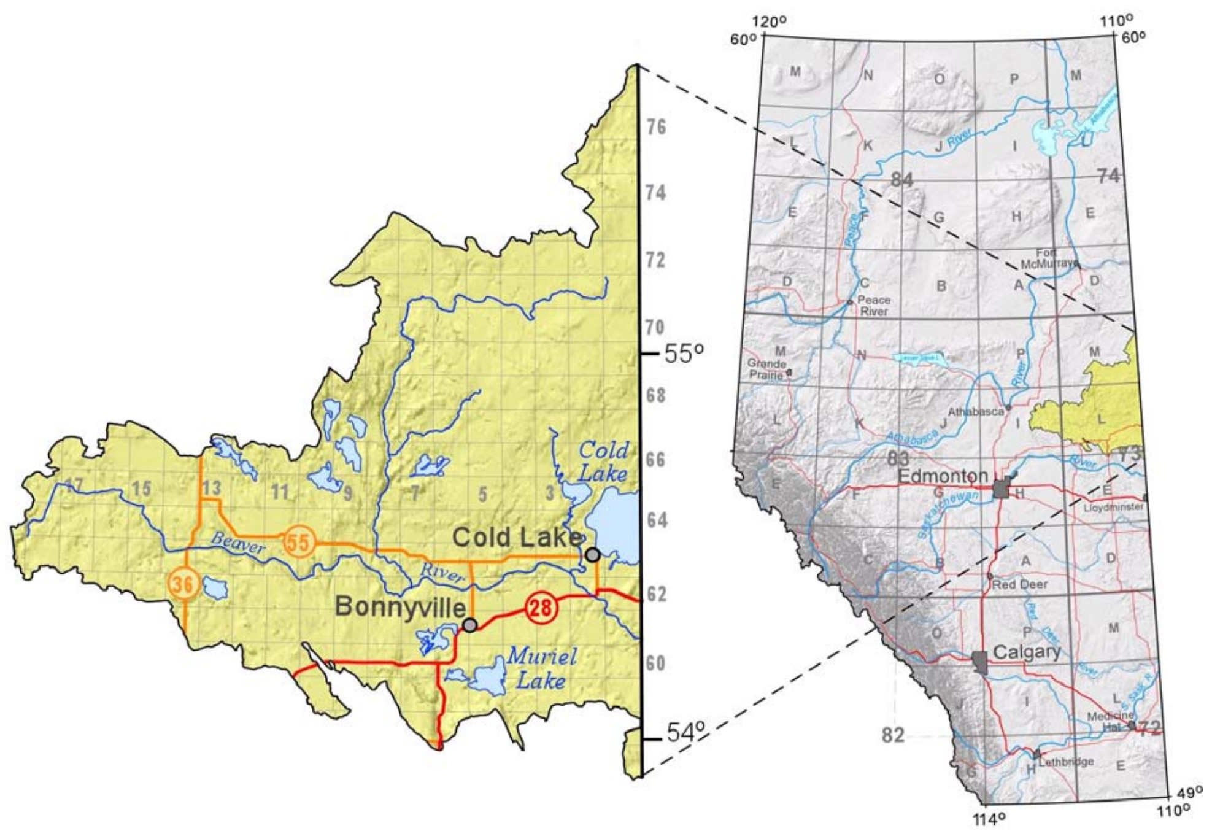
Total Dissolved Solids (mg/L)

- ● 0 - 250
- ● 250 - 500
- ● 500 - 4000
- ● > 4000
- ● Well completed in the Formation without TDS information or with suspect chemical analysis

Figure 5.1. Total dissolved solids concentration in the Empress Formation.

Alberta Energy and Utilities Board
Alberta Geological Survey
Alberta Environment





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5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

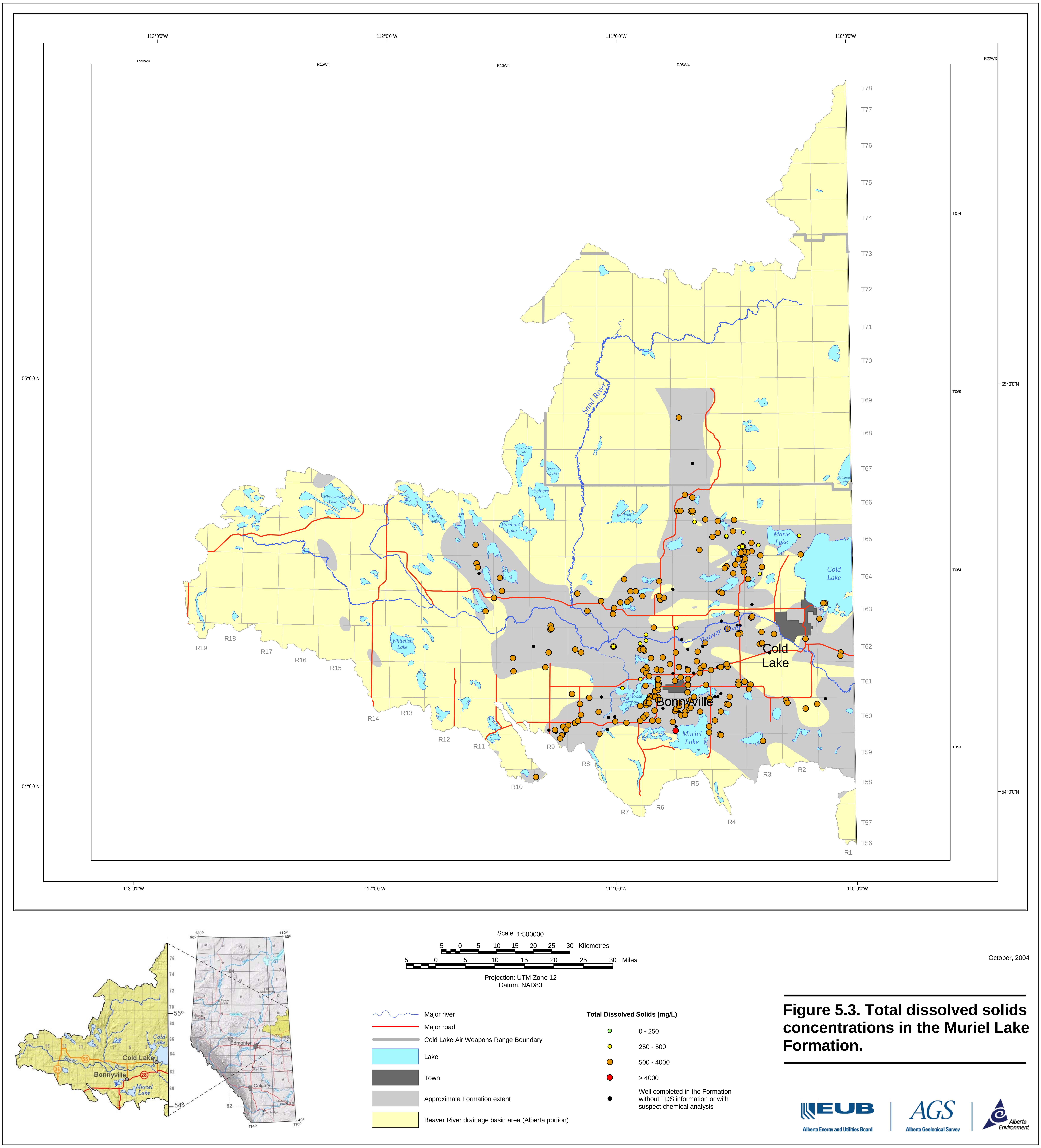
Figure 5.2. Total dissolved solids concentrations in the Bronson Lake Formation.

〰	Major river
—	Major road
▬	Cold Lake Air Weapons Range Boundary
🟦	Lake
⬛	Town
▨	Approximate Formation extent
🟨	Beaver River drainage basin area (Alberta portion)

Total Dissolved Solids (mg/L)

●	0 - 250
●	250 - 500
●	500 - 4000
●	> 4000
●	Wells completed in the Formation without TDS information or with suspect chemical analysis

EUB Alberta Energy and Utilities Board
AGS Alberta Geological Survey
Alberta Environment



Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

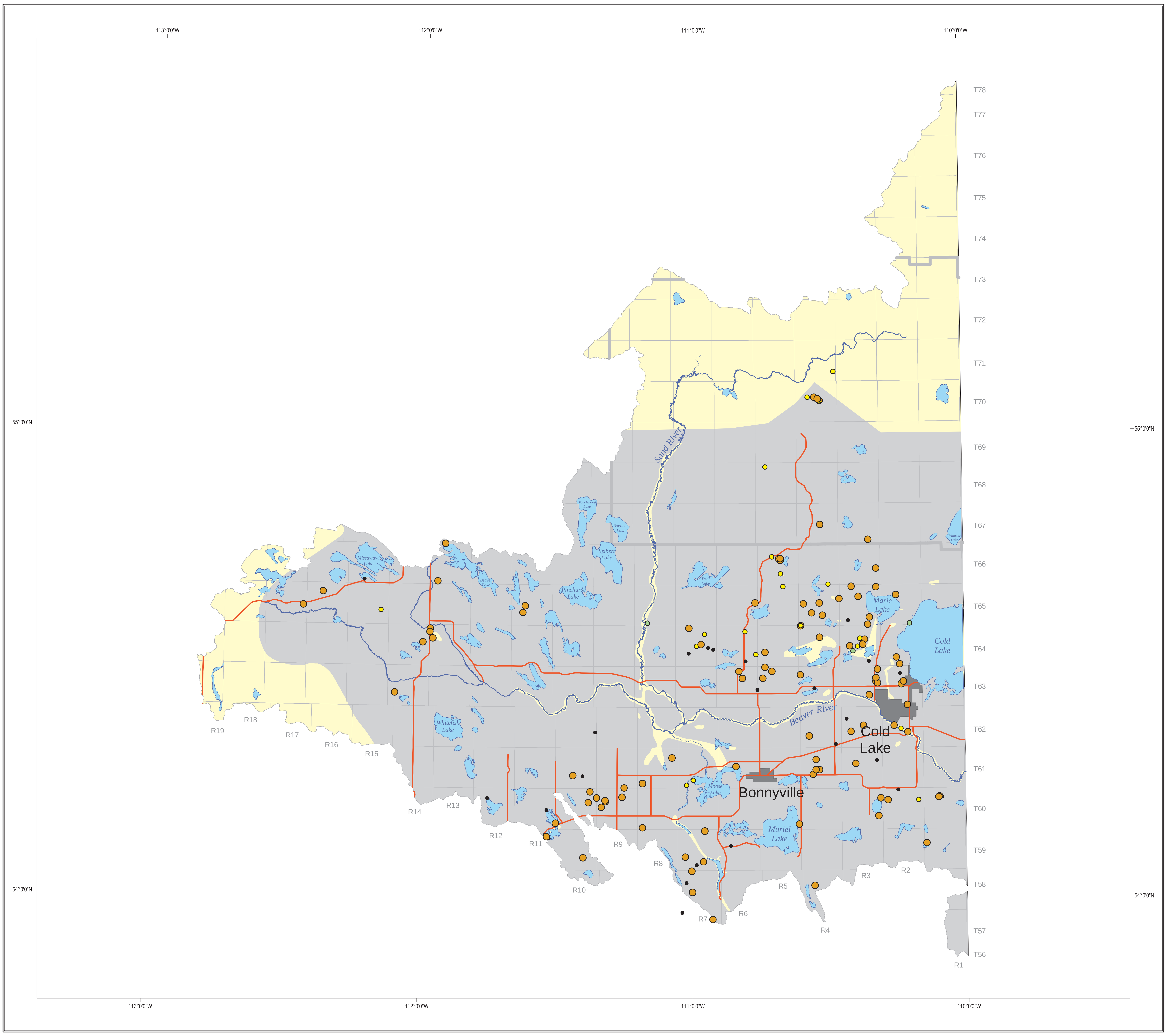
- Major river
- Major road
- Cold Lake Air Weapons Range Boundary
- Lake
- Town
- Approximate Formation extent
- Beaver River drainage basin area (Alberta portion)

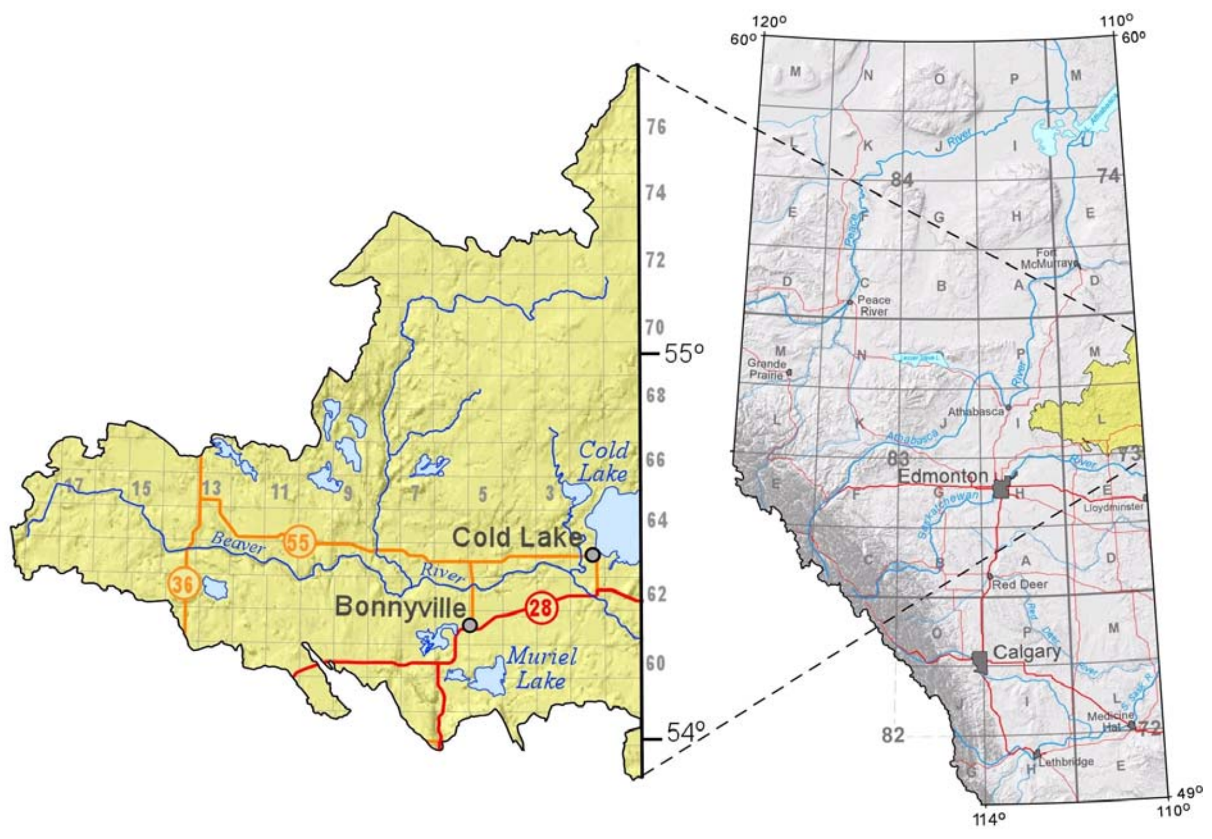
Total Dissolved Solids (mg/L)

- ● 0 - 250
- ● 250 - 500
- ● 500 - 4000
- ● > 4000
- ● Well completed in the Formation without TDS information or with suspect chemical analysis

Figure 5.3. Total dissolved solids concentrations in the Muriel Lake Formation.

EUB Alberta Energy and Utilities Board | AGS Alberta Geological Survey | Alberta Environment





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5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

Major river
Major road
Cold Lake Air Weapons Range Boundary
🟦 Lake
⬛ Town
▨ Approximate Formation extent
🟨 Beaver River drainage basin area (Alberta portion)

Total Dissolved Solids (mg/L)
🟢 0 - 250
🟡 250 - 500
🟠 500 - 4000
🔴 > 4000
● Well completed in the Formation without TDS information or with suspect chemical analysis

Figure 5.4. Total dissolved solids concentrations in the Bonnyville Formation.

EUB Alberta Energy and Utilities Board
AGS Alberta Geological Survey
Alberta Environment

5.1.5 Ethel Lake Formation

TDS concentrations were measured at locations within all five-flow systems. Many of the lower TDS values are related to recharge areas and many of the higher TDS values appear to correspond to discharge areas (Figure 5.5 and Figure 2.5). Exceptions are present however. The majority of samples (61%) would be classified as fresh based on the general classification put forward by Drever (1997). The TDS values are also consistent with the glacial deposit water types put forward by Freeze and Cherry (1979).

5.1.6 Marie Creek Formation

Seventy-five percent of the water samples collected from the Marie Creek Formation would be classified as fresh according to Drever (1997). The remaining samples would be considered brackish. Samples were collected from all five-flow systems. The samples with lower TDS values appear related with recharge areas and those samples with higher TDS values appear related to discharge areas (Figure 5.6 and Figure 2.5). The TDS values are also consistent with the values reported by Freeze and Cherry (1979) for water from glacial deposits typical of the Interior Plains of Canada.

5.1.7 Sand River Formation

TDS values were collected for four of the five regional flow system including the SEBR, NEBR, NWBR and SWBR flow systems. Many of the observed TDS values appear related to recharge and discharge areas (Figure 5.7 and Figure 2.5) with lower values more common in recharge areas and higher values generally associated with discharge areas. The majority of samples (75%) would be classified as fresh based on the general classification put forward by Drever (1997). All but one of the remaining samples falls within the brackish water classification. This one sample exceeds the upper limit classification value. The samples, with the exception of the one sample with the highest TDS value, fall within the range of TDS values put forward by Freeze and Cherry (1979) for water from glacial deposits.

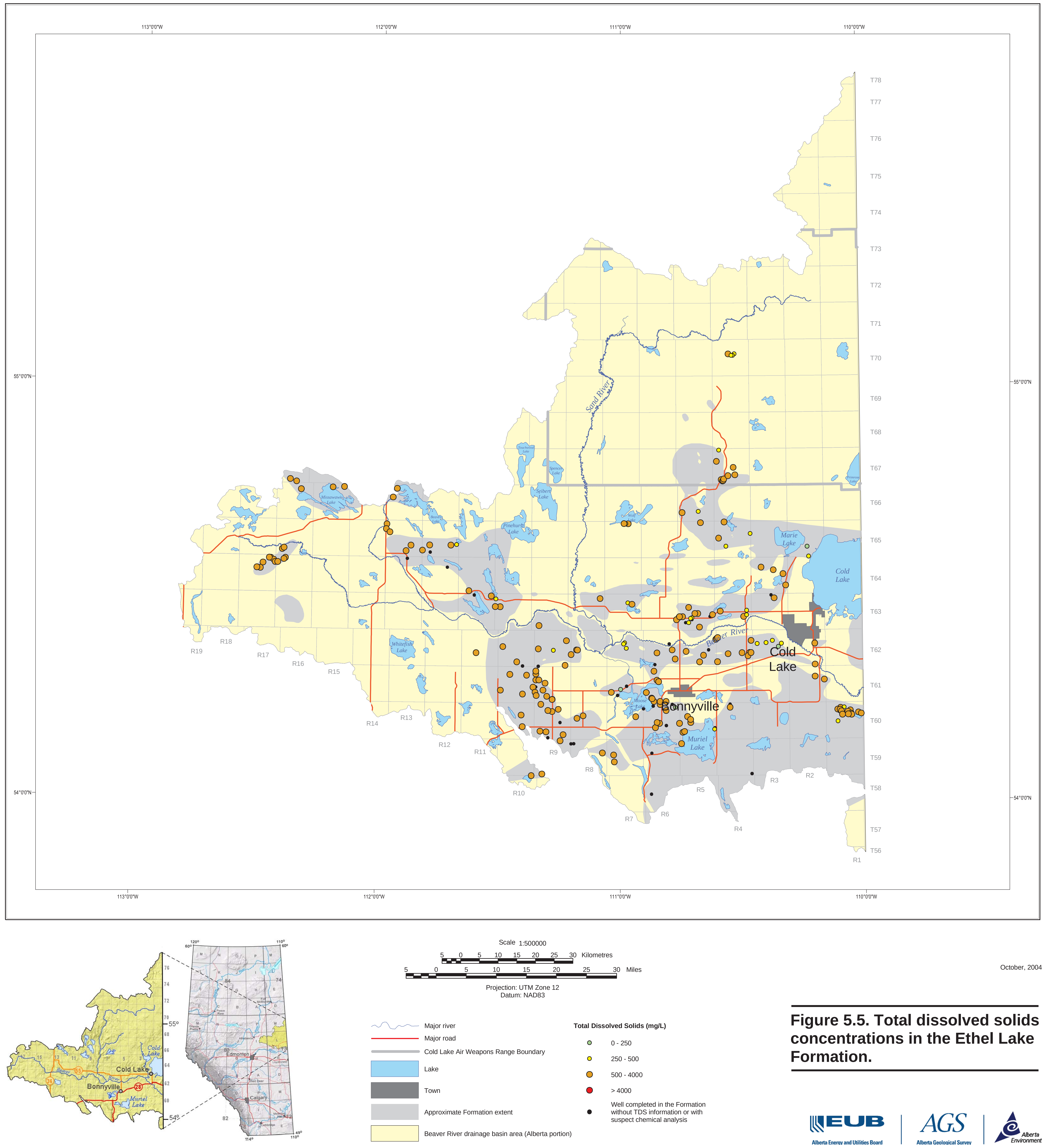
5.1.8 Grand Centre Formation

Seventy-nine percent of the water samples collected from the Grand Centre Formation would be classified as fresh according to Drever (1997). The remaining samples would be considered brackish. Samples were collected from all five-flow systems. Many of the lower TDS values are found in the recharge areas, while higher TDS values are found in discharge areas (Figure 5.8 and Figure 2.5). The reported TDS values fall within the range of values reported by Freeze and Cherry (1979) for water in glacial deposits in the Interior Plains region of Canada.

5.2 Distribution of Geochemical Composition Categories

Freeze and Cherry (1979, p. 252) define hydrochemical facies as distinct zones that have cation and anion concentrations describable within defined composition categories with the definition of a composition category commonly based on subdivisions of the trilinear diagram. One such diagram is presented in Figure 5.9. Compositions can also be summarized using other types of plots such as pie charts, where each segment of the pie represents one of the major ions or ion groups in solution (Figure 5.10). Such classifications can then be plotted on maps to describe the distribution of hydrochemical facies. These distributions are displayed in Figure 5.12, Figure 5.14, Figure 5.16, Figure 5.18, Figure 5.20, Figure 5.22, Figure 5.24 and Figure 5.26.

In general, the geochemical composition categories of groundwater samples from the Cold Lake-Beaver



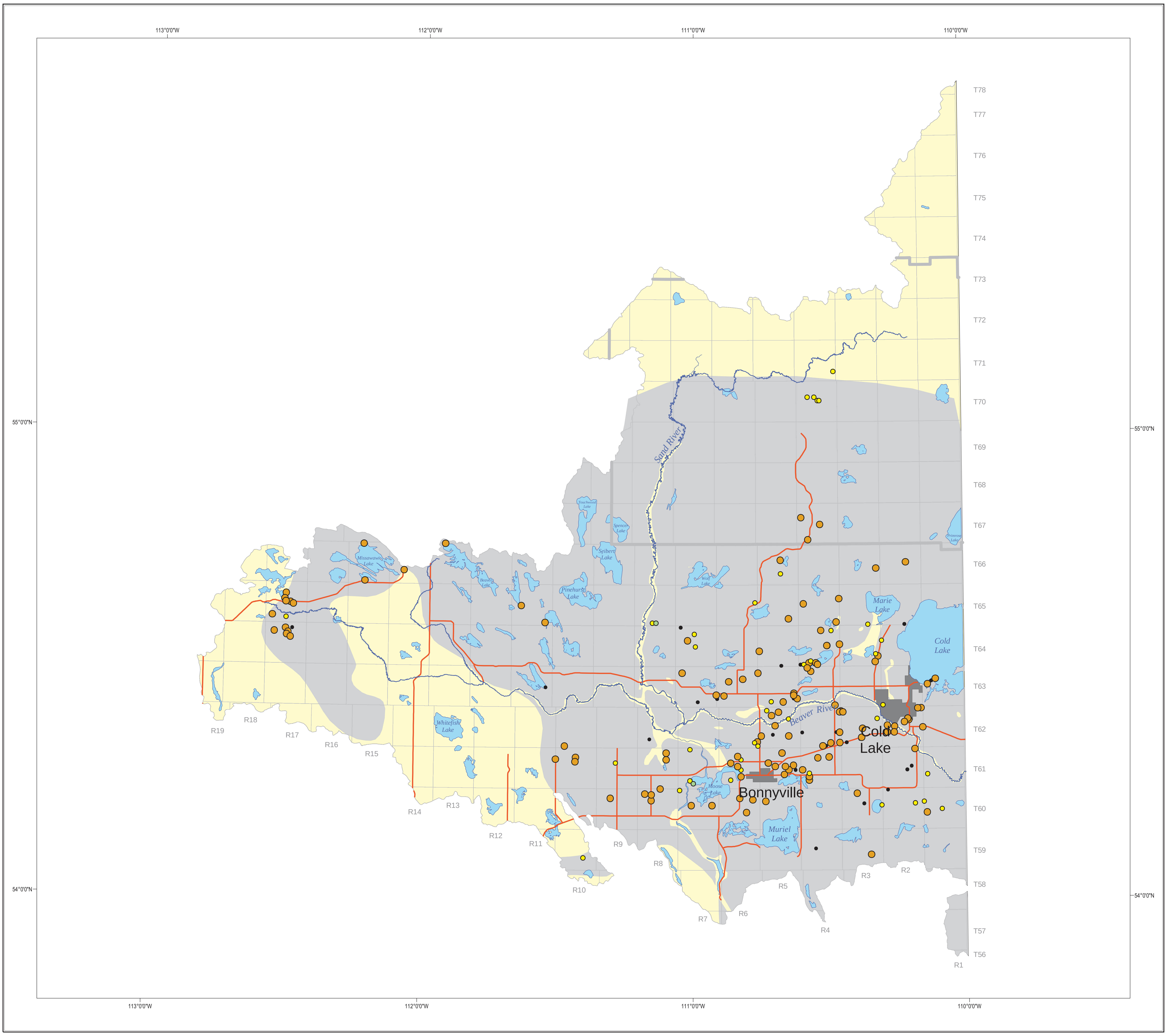
October, 2004

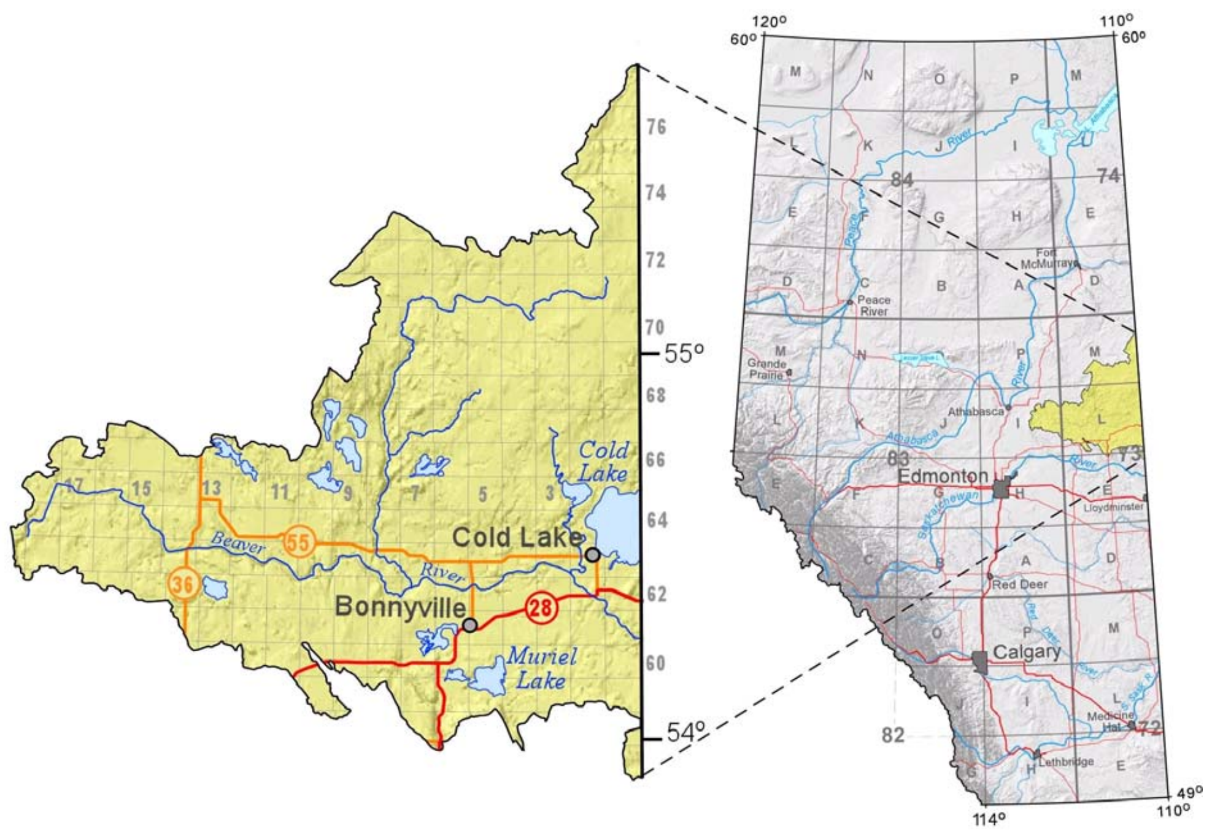
Figure 5.5. Total dissolved solids concentrations in the Ethel Lake Formation.

Alberta Energy and Utilities Board

Alberta Geological Survey

Alberta Environment





Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

〰	Major river
―	Major road
▬	Cold Lake Air Weapons Range Boundary
🟦	Lake
■	Town
▨	Approximate Formation extent
🟨	Beaver River drainage basin area (Alberta portion)

Total Dissolved Solids (mg/L)

🟢	0 - 250
🟡	250 - 500
🟠	500 - 4000
🔴	> 4000
●	Well completed in the Formation without TDS information or with suspect chemical analysis

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Figure 5.6. Total dissolved solids concentrations in the Marie Creek Formation.

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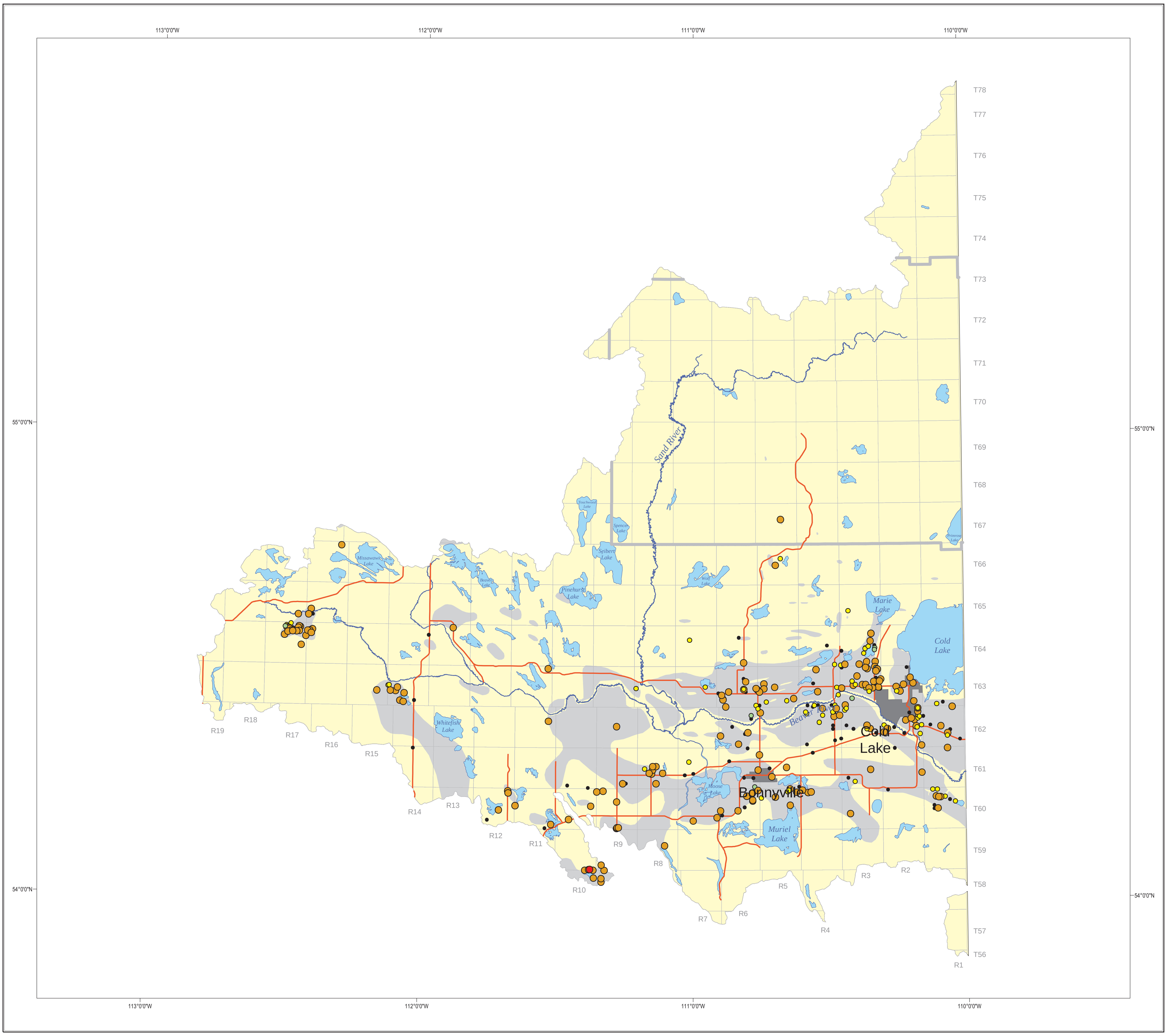

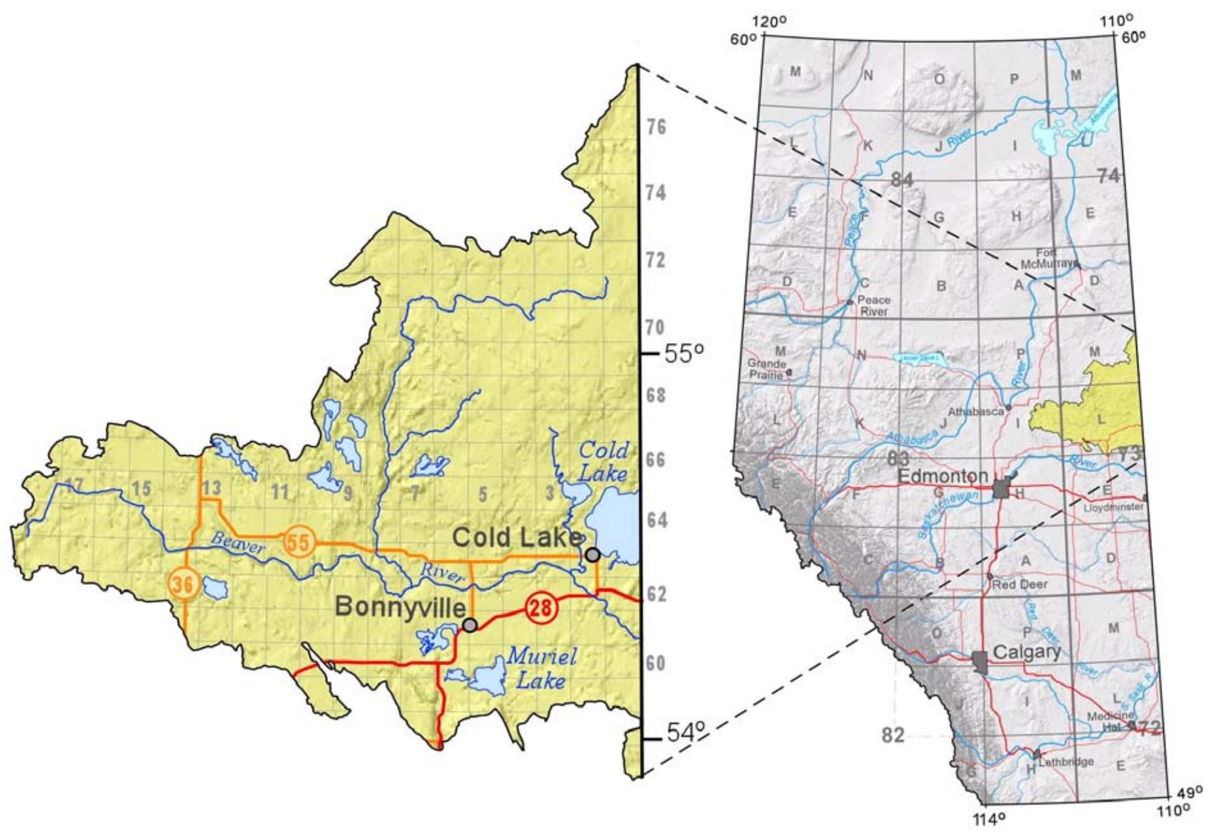

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5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

- 〰 Major river
- — Major road
- — Cold Lake Air Weapons Range Boundary
- 🟦 Lake
- ⬛ Town
- ⬜ Approximate Formation extent
- 🟨 Beaver River drainage basin area (Alberta portion)

Total Dissolved Solids (mg/L)

- ● 0 - 250
- ● 250 - 500
- ● 500 - 4000
- ● > 4000
- ● Well completed in the Formation without TDS information or with suspect chemistry

Figure 5.7. Total dissolved solids concentrations in the Sand River Formation.

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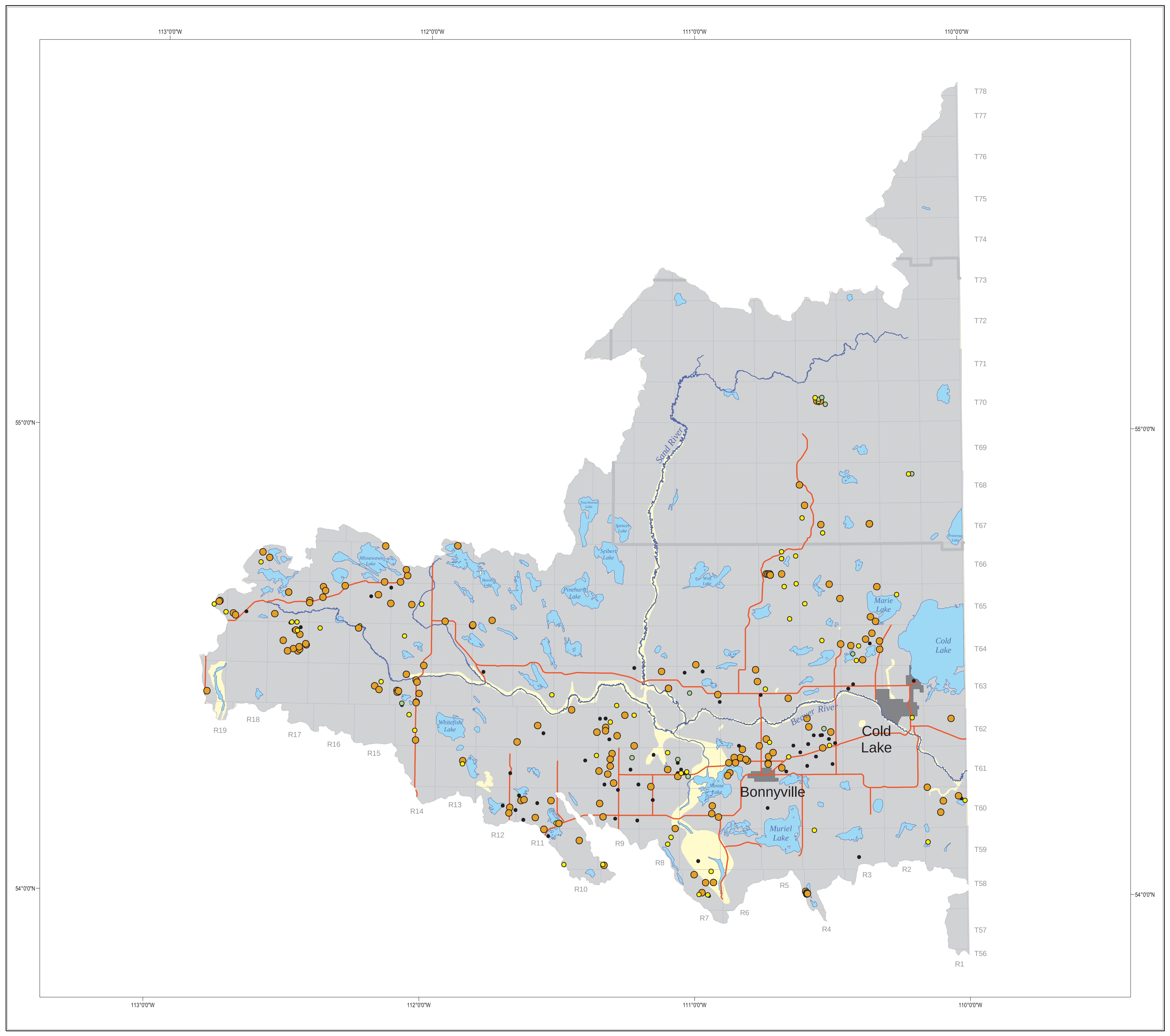
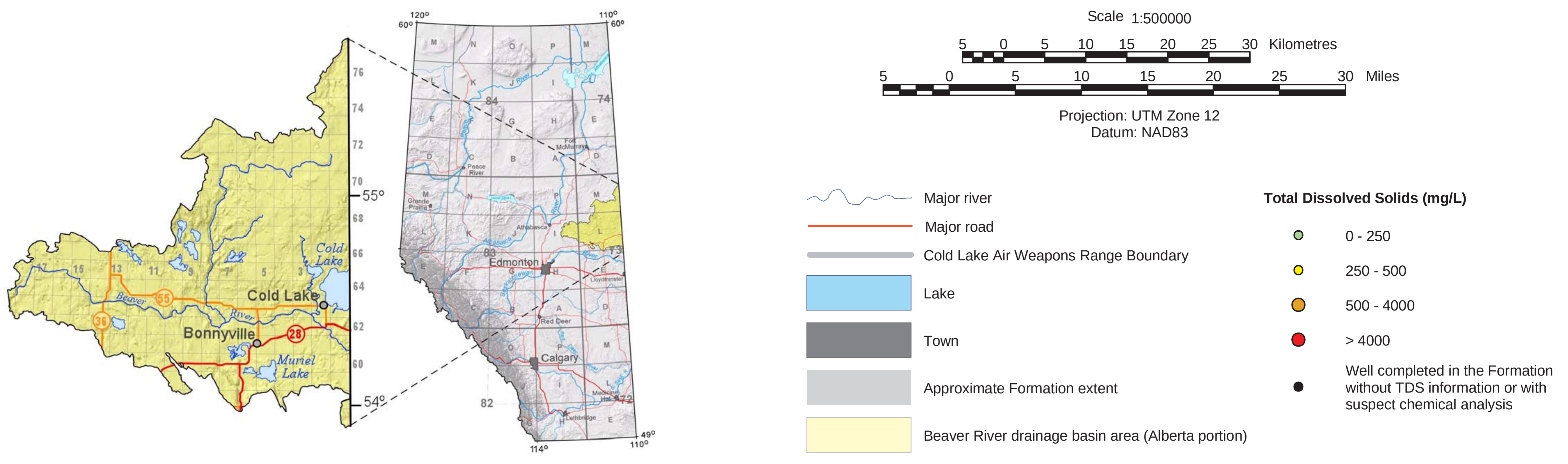
Alberta Environment





October, 2004

Figure 5.8. Total dissolved solids concentrations in the Grand Centre Formation.

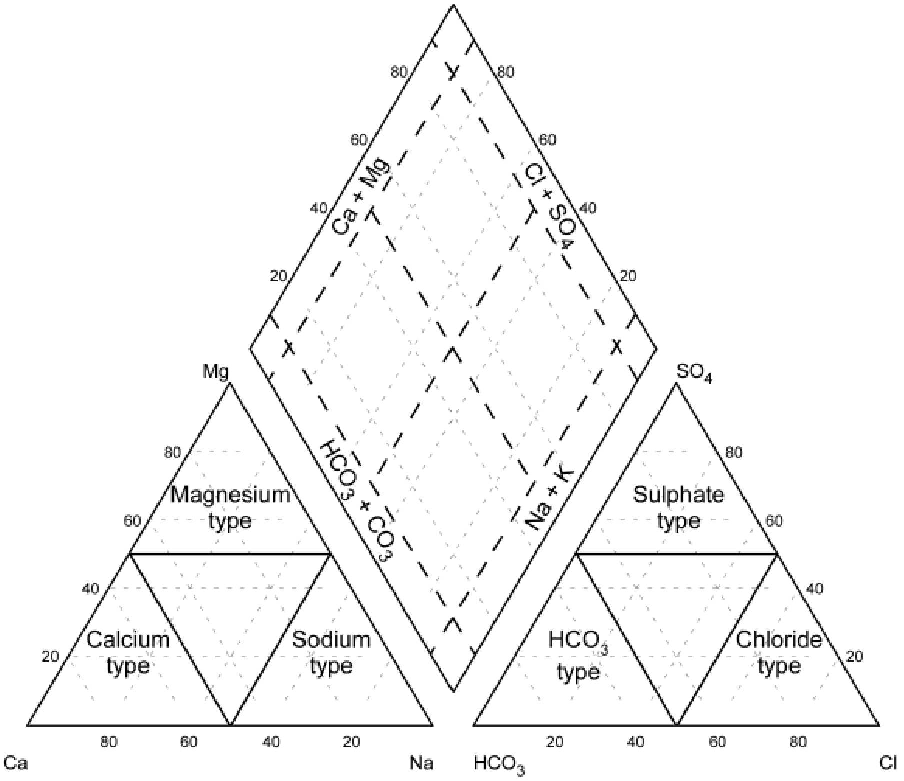


Figure 5.9. Geochemical classification of groundwater using a Piper trilinear plot.

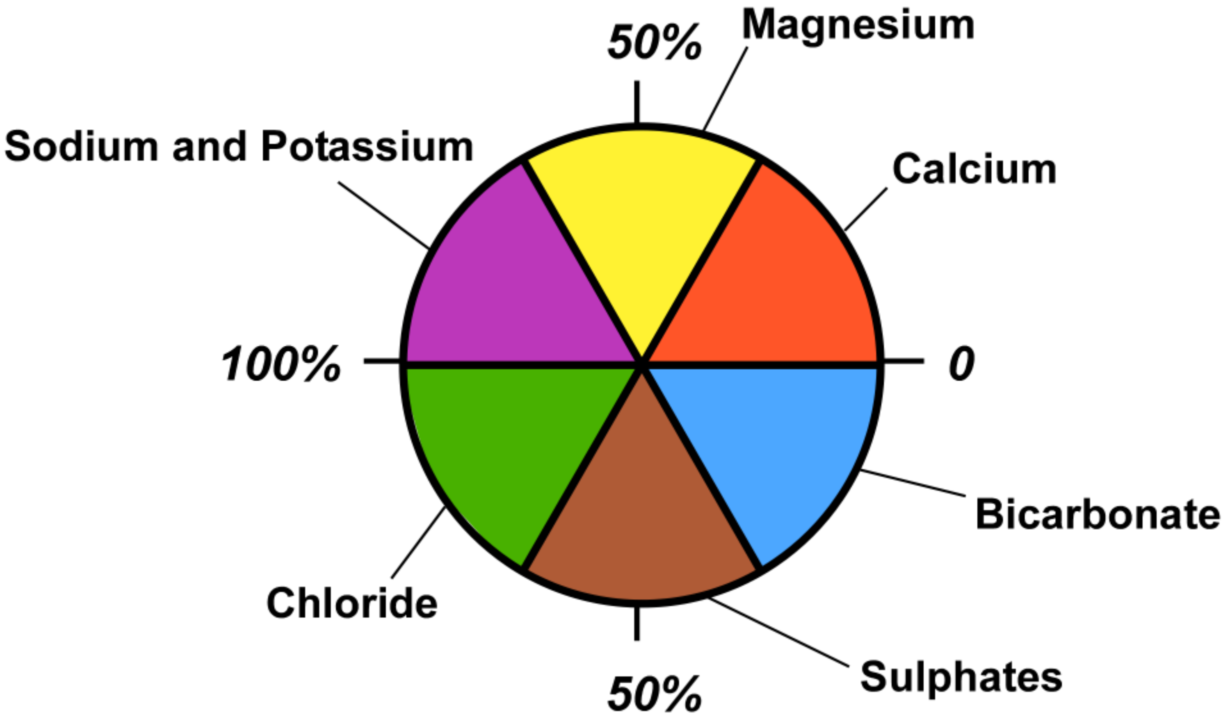


Figure 5.10. Geochemical classification of groundwater using a pie chart.

River Basin are consistent with the processes laid out by Freeze and Cherry (1979) for the generation of Type III glacial deposit waters, with the exception of some of the chloride concentrations. As mentioned previously, chloride is likely a naturally occurring component of the groundwater chemistry regime, incorporated through diffusion or mixing of groundwater from different aquifers. However, there are a number of potential point and non-point sources that have been identified in the Basin that could contribute chloride to groundwater. Recharge areas and discharge areas are categorized by Ca-Mg-HCO3 type water and dominantly Na and HCO_3 or SO_4 type water respectively. The following sections discuss the distribution of the hydrochemical composition categories within each of the drift formations within the Basin.

5.2.1 Empress Formation

The piper plot for the Empress Formation (Figure 5.11) shows that the dominant geochemical compositions vary between flow systems. The NWBR, SEBR, SWBR and Wiau flow systems exhibit a trend consistent with that of ion exchange between calcium and sodium. No trend can be discerned from the one point available in the SWBR flow system. There could be two trends evident in the major anion field. The first is a trend from bicarbonate type water towards sulphate type water. This trend is manifested in the SEBR and SWBR flow systems. A trend from bicarbonate type water to chloride type water is present within the NEBR flow system. Trends in the anion composition for the SWBR, NWBR and Wiau flow systems are difficult to assess based on the available data.

The distribution of the major ions in the Empress Formation is presented in Figure 5.12. In the Wiau flow system the dominant ions are calcium and bicarbonate. In the northern third of the NEBR flow system the dominant cation appears to vary between calcium and sodium, with the dominant anion being bicarbonate. Towards the central-southern third of the flow system the dominant anion appears to be chloride, while the dominant cation is generally sodium. Based on the modeled groundwater flow directions within the Empress Formation, it appears that the trend of increasing chloride concentrations relative to bicarbonate concentrations coincides with the general groundwater flow directions in the in the central-southern NEBR flow system. This kind of change is consistent with geochemical processes expected to occur along groundwater flowpaths from recharge areas to discharge areas. Closer to the town of Bonnyville, sulphate becomes more important. Within the SEBR flow system the dominant cation is generally sodium, with some occurrences of calcium and magnesium as the dominant cations. The dominant anion in solution is bicarbonate, with some occurrences of sulphate within the portions of the aquifer that pass underneath Moose Lake. This continues the trend of increasing sulphate as the Empress Formation passes from the NEBR flow system into the SEBR flow system. The dominant cation in the one sample from the SWBR flow system is sodium while the dominant anion is bicarbonate. The dominant cation in the NWBR flow system is sodium and the dominant anion is bicarbonate.

5.2.2 Bronson Lake Formation

The piper plot for the Bronson lake Formation (Figure 5.13) shows that the dominant changes in water chemistry are consistent with ion exchange reactions between calcium and sodium and processes introducing sulphate into solution. These trends are most obvious from the data available for the SEBR flow system.

The distribution of the major ions in the Bronson Lake Formation is presented in Figure 5.14. Calcium and magnesium are the dominant cations in the NEBR flow system. Bicarbonate is the dominant anion in solution, but sulphate appears to increase in concentration towards the southern portion of the flow system. The sample from the NWBR flow system appears to have a similar composition as the southern

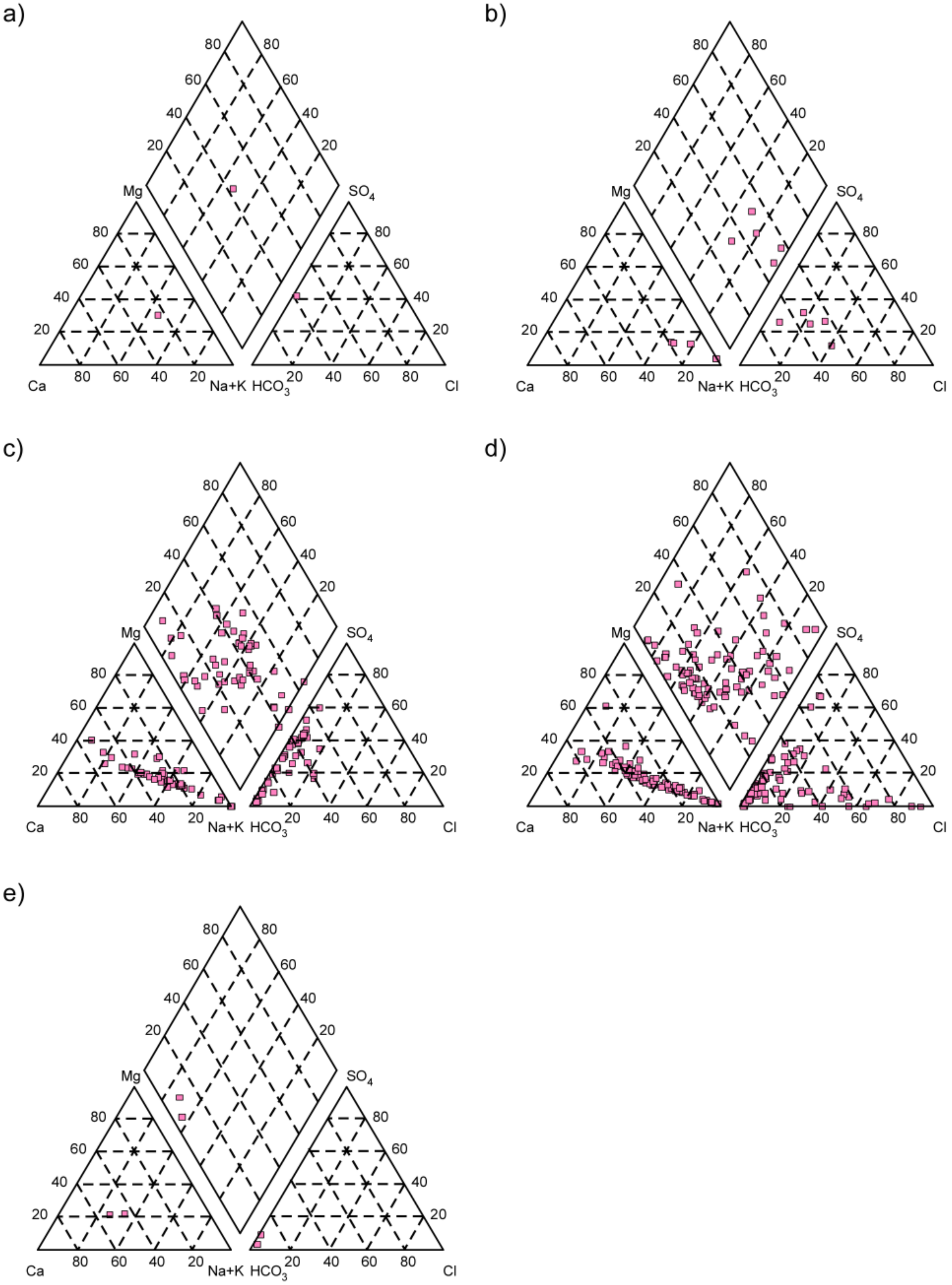


Figure 5.11. Piper plot for the Empress Formation.

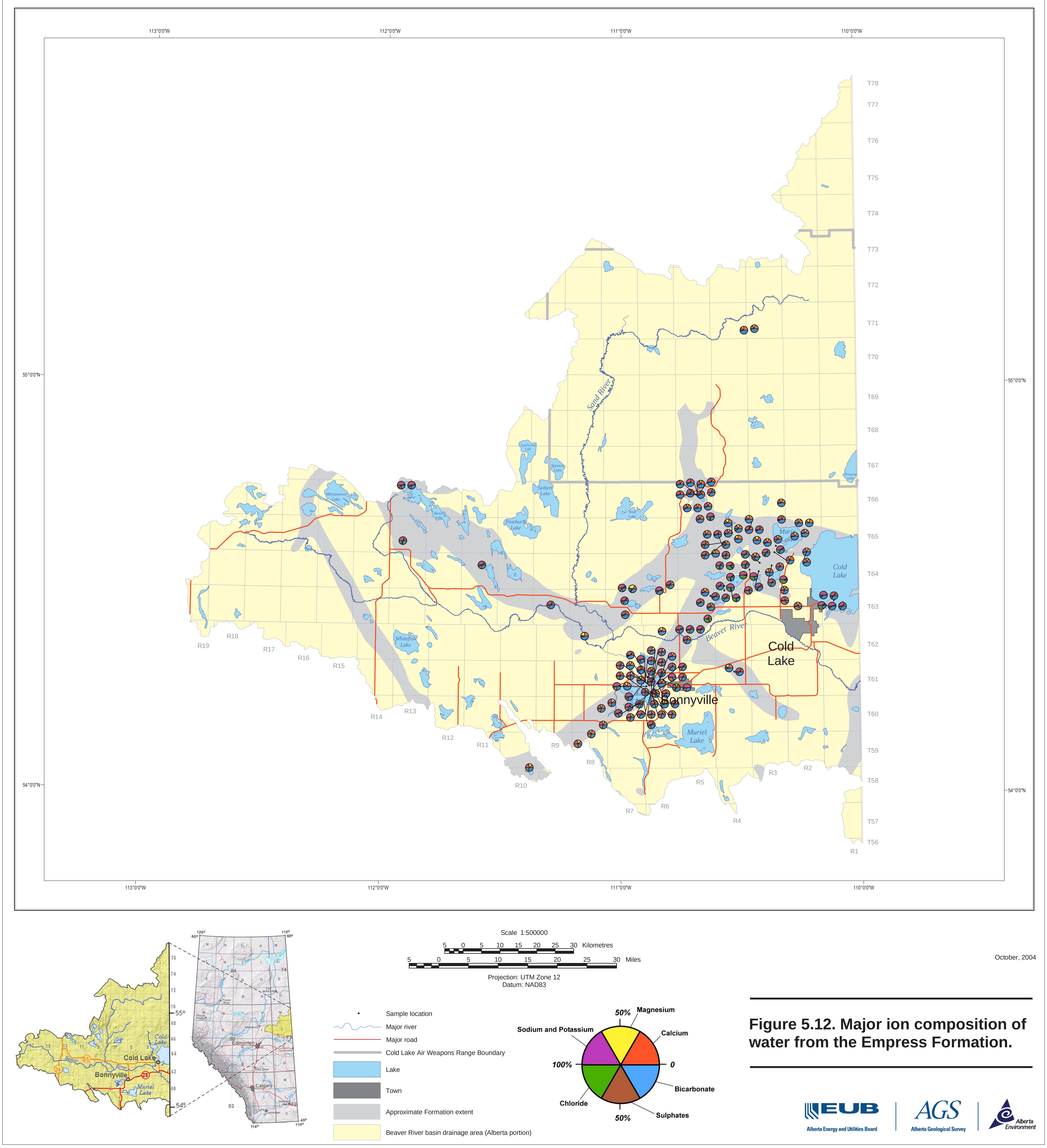


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Figure 5.12. Major ion composition of water from the Empress Formation.

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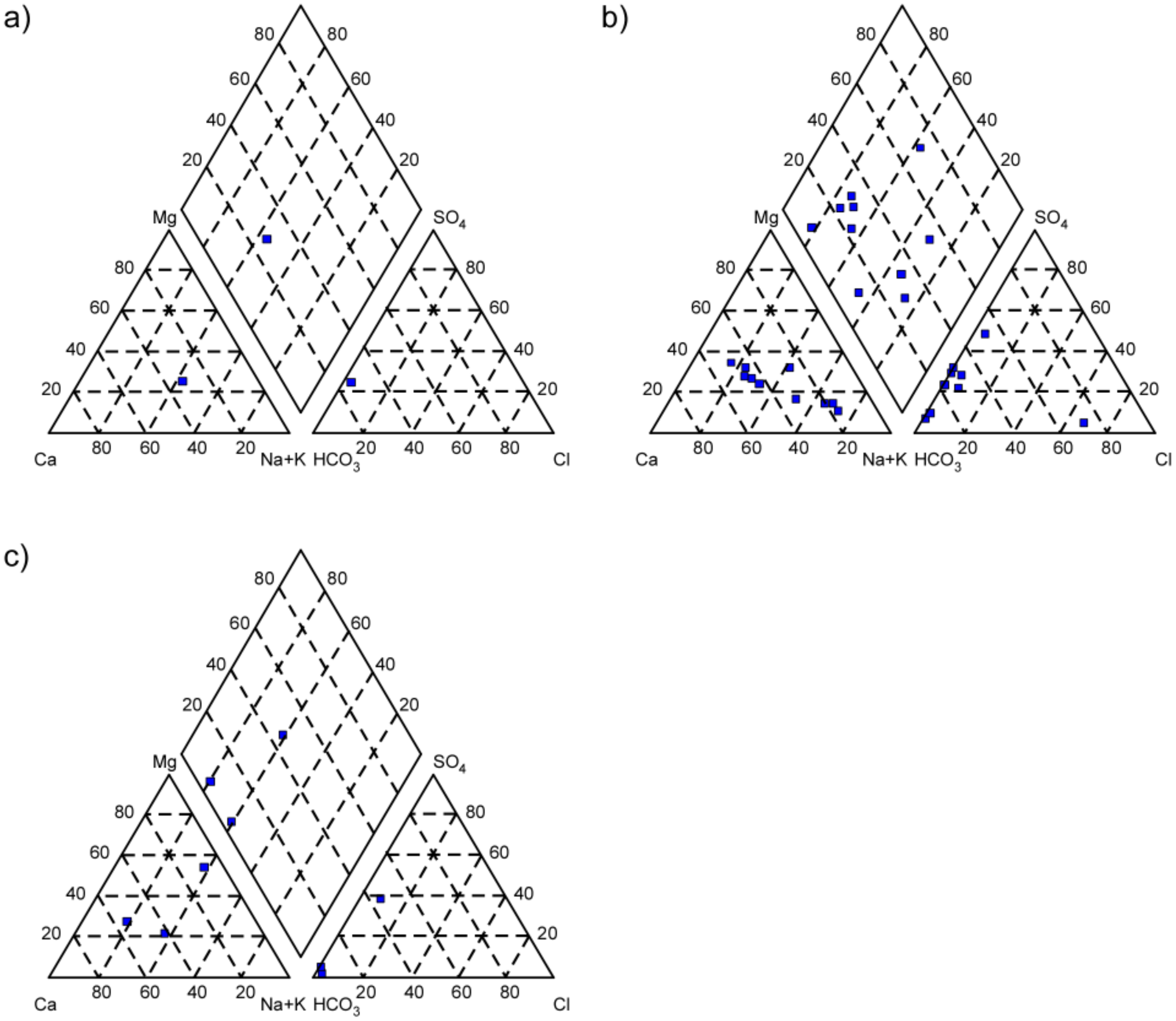
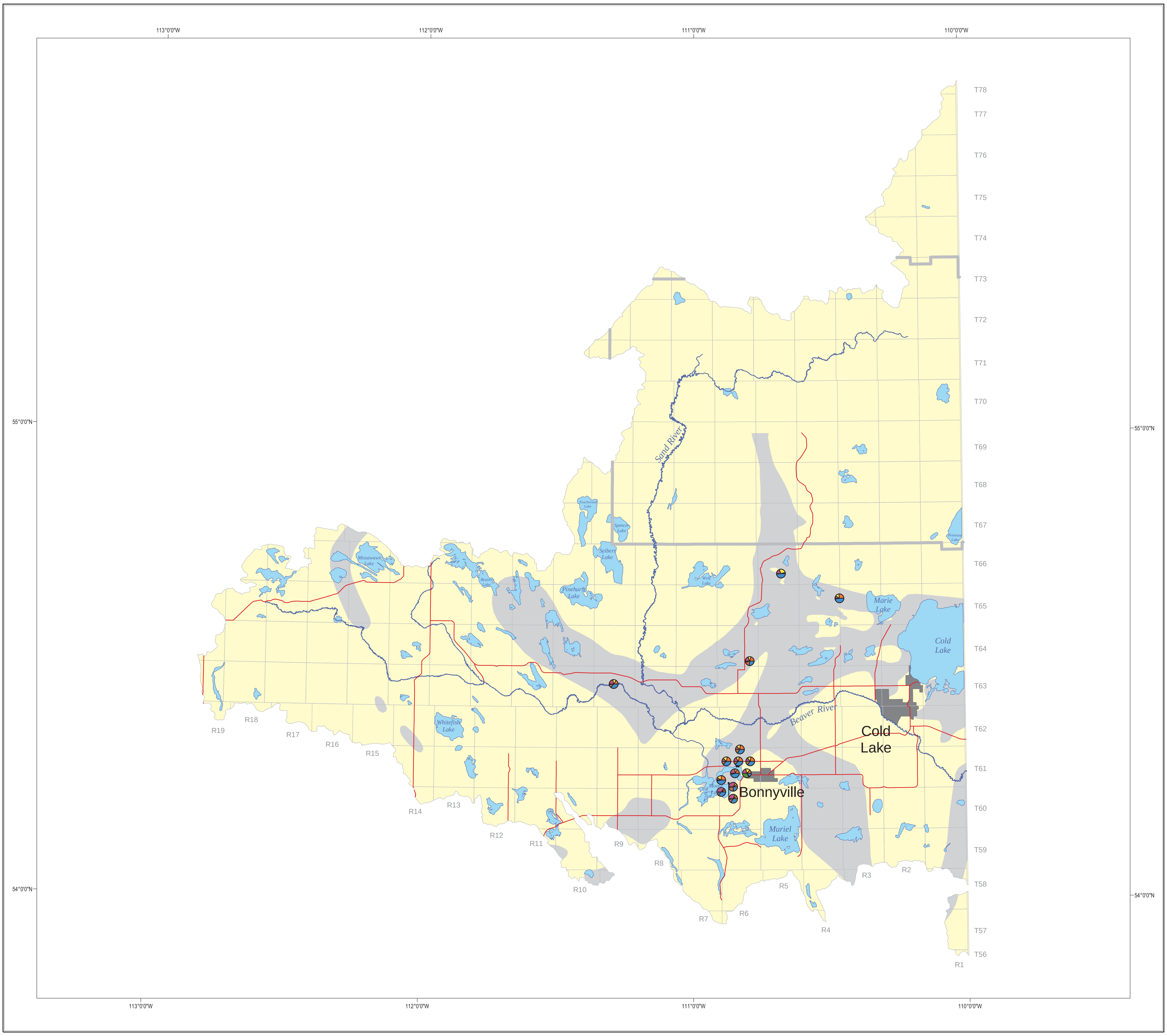


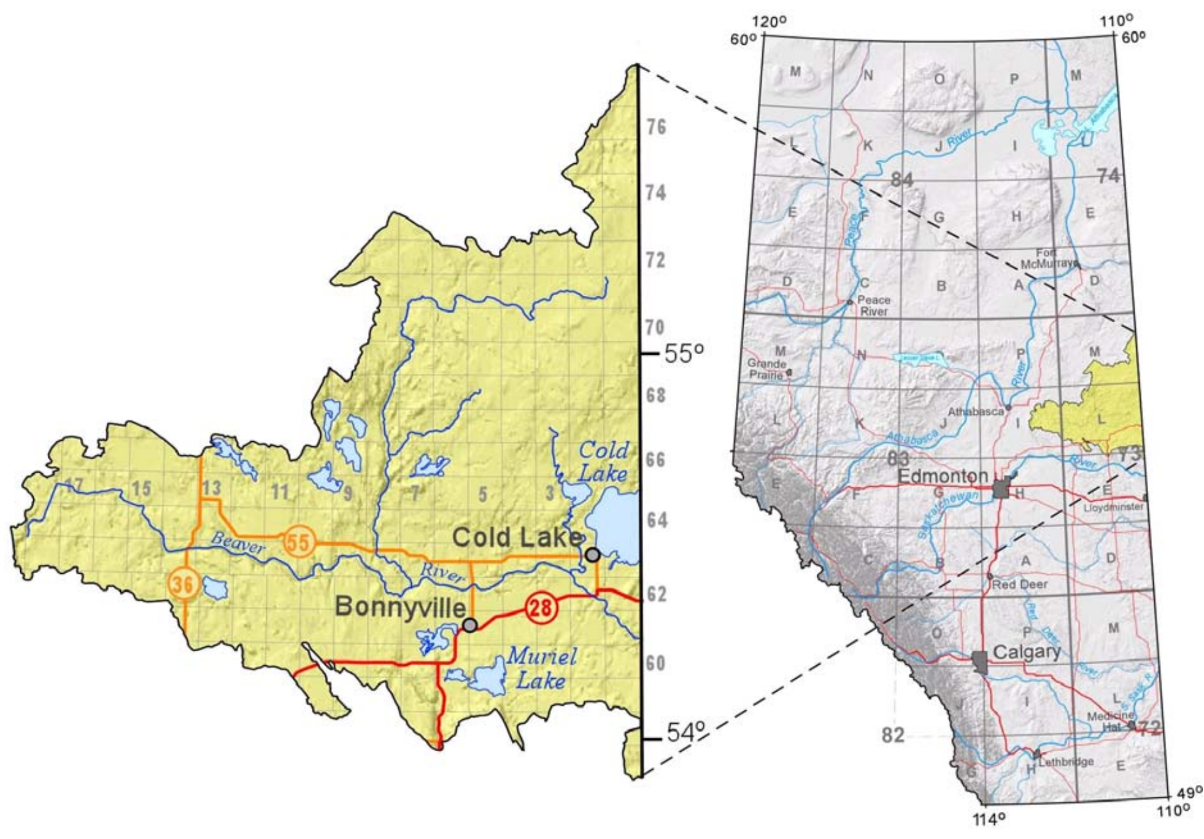
Figure 5.13. Piper plot for the Bronson Lake Formation.

most sample from the NEBR flow system. A northeast to southwest trending line can be drawn that separates samples from the SEBR flow system with calcium and magnesium as the dominant cations in solution from samples with sodium as the dominant cation in solution. The dominant anion in most of the samples from the SEBR is bicarbonate. Samples to the north and to the southeast of Moose Lake appear to have increasing concentrations of sulphate in solution. Chloride is the dominant anion in solution in the sample closest to the town of Bonnyville.

5.2.3 Muriel Lake Formation

The piper plot for the Muriel Lake Formation is shown in Figure 5.15. The data distributions in the Wiau, SWBR and NWBR flow systems do not allow for any definitive conclusions to be drawn regarding processes leading to the observed ion distributions. The plots for the SEBR and NEBR flow systems suggest that a process such as ion exchange is active and affects the dominant cation content of the water samples. Based on the plots, there also appear to be processes active that lead to increased concentrations of sulphate with respect to bicarbonate, and others that lead to increased concentrations of chloride with respect to bicarbonate.





Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

•	Sample location
〰	Major river
—	Major road
▬	Cold Lake Air Weapons Range Boundary
🟦	Lake
⬛	Town
▨	Approximate Formation extent
🟨	Beaver River basin drainage area (Alberta portion)

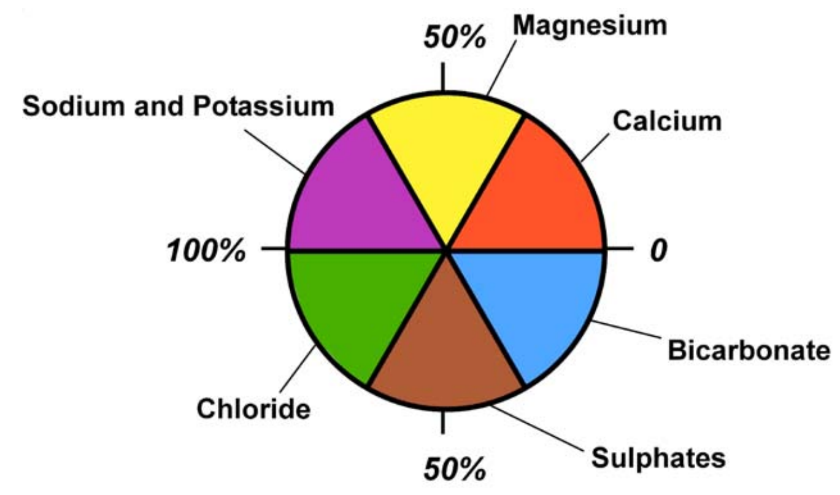


Figure 5.14. Major ion composition of water from the Bronson Lake Formation.

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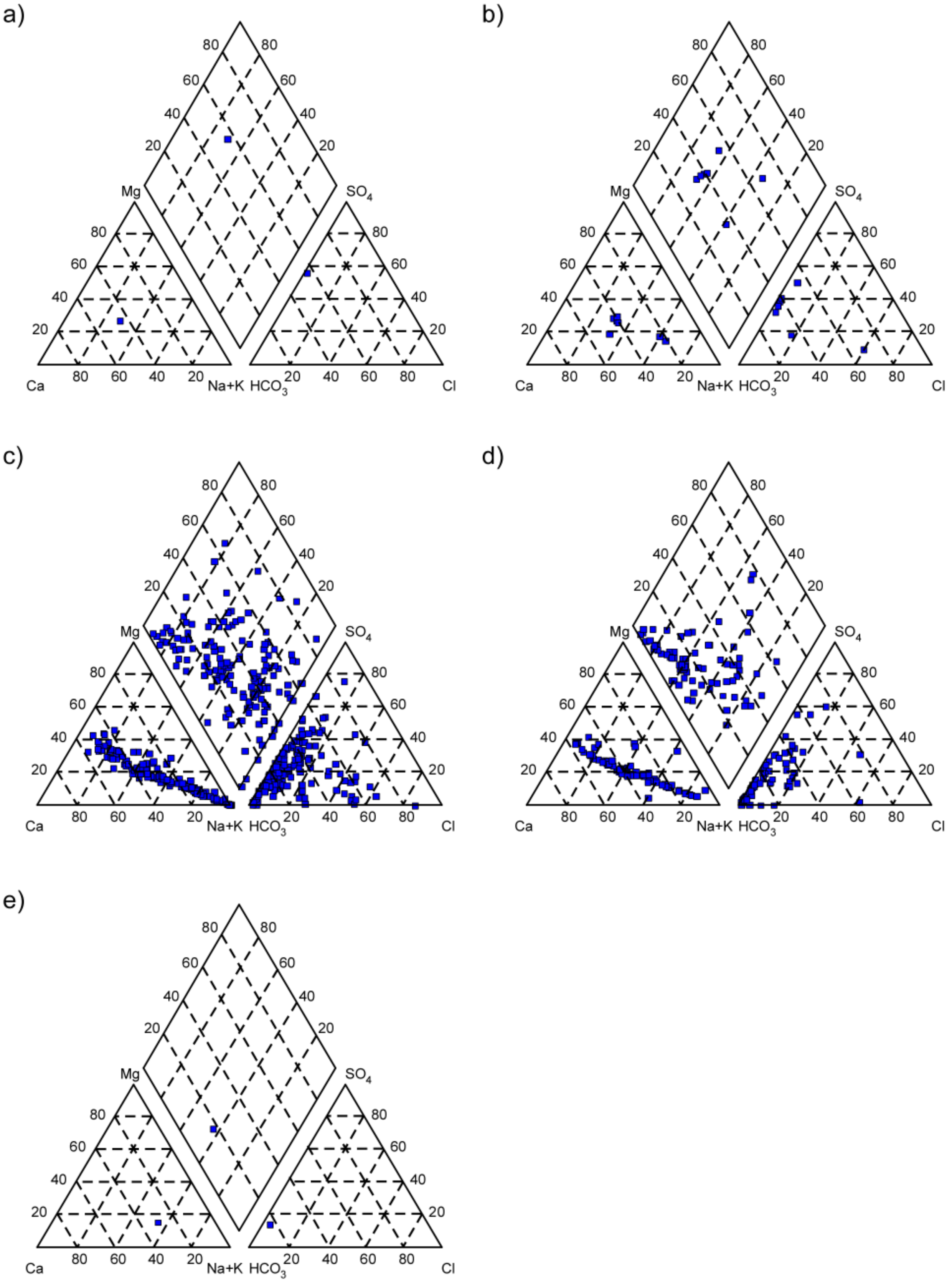


Figure 5.15. Piper plot for the Muriel Lake Formation.

The distribution of the major ions in the Muriel Lake Formation is presented in Figure 5.16. In general it appears that calcium and magnesium are the dominant cations in solution in the northern portions of the Muriel Lake Formation of the NEBR flow system. In the southern portion of the NEBR flow system, sodium becomes dominant. Bicarbonate is the dominant anion in solution at most of the locations, with occurrences of sulphate and chloride generally becoming more common in the southeastern corner of the flow system. In most cases, the dominant cation in solution in the SEBR flow system is sodium. While bicarbonate is the dominant anion in solution in most cases, there are a number of instances where either sulphate or chloride is the dominant anion. Chloride for instance appears most commonly as the dominant anion in the northwestern portion of the flow system. Sulphate becomes more important in the areas northeast of the town of Bonnyville and southwest of Moose Lake and in the vicinity of Muriel Lake. The majority of the samples in the NWBR flow system have calcium and magnesium as their dominant cations in solution, and bicarbonate as the dominant anion in solution. The concentration of sulphate in solution increases towards the south. The southern-most point has chloride as the dominant anion. This point has a similar composition to the samples from the adjacent SEBR flow system. The sample from the SWBR flow system has a composition similar to those samples from the adjacent SEBR flow system. The sample from the Wiau flow system has a composition similar to samples from the adjacent NEBR flow system.

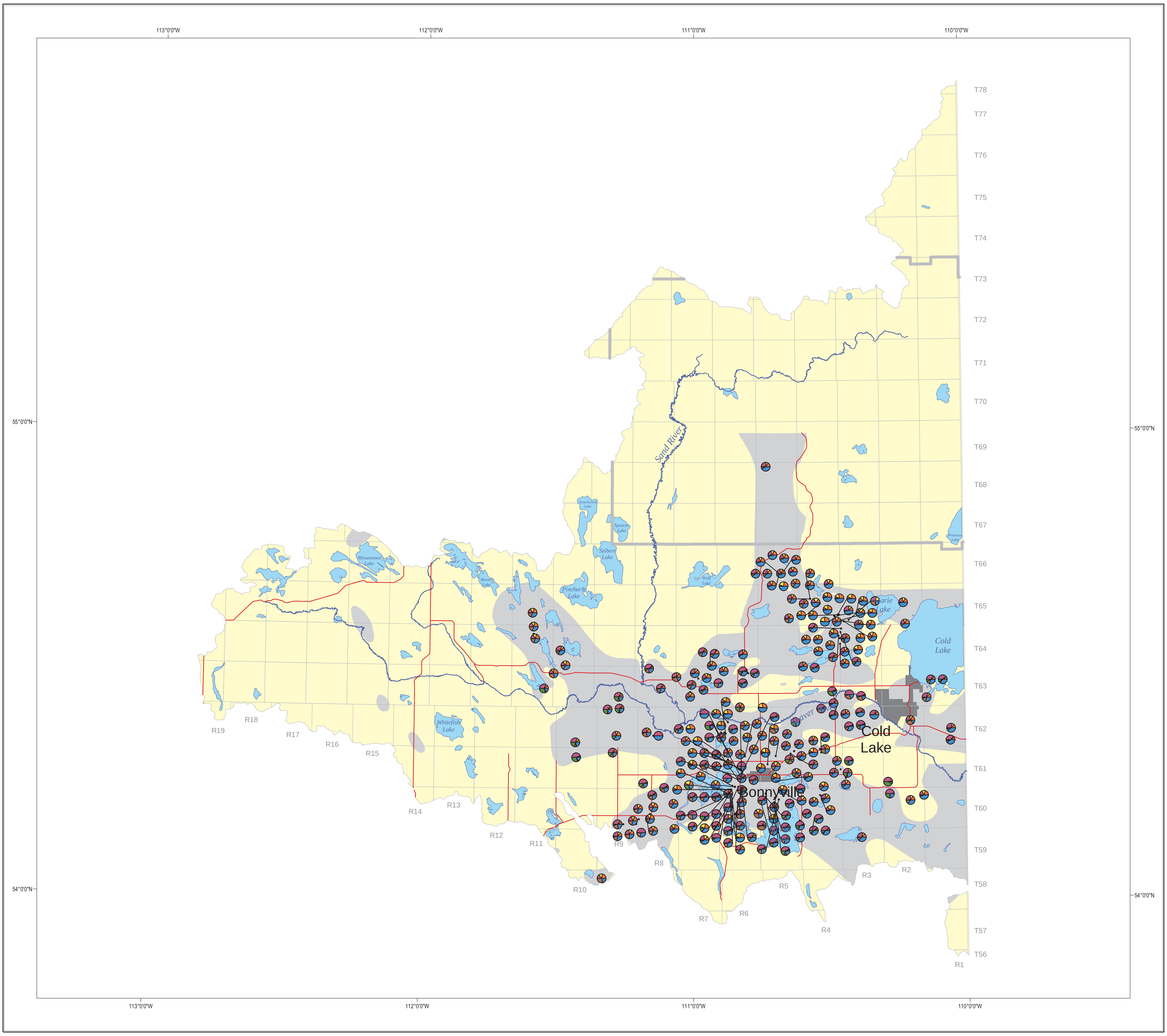
5.2.4 Bonnyville Formation

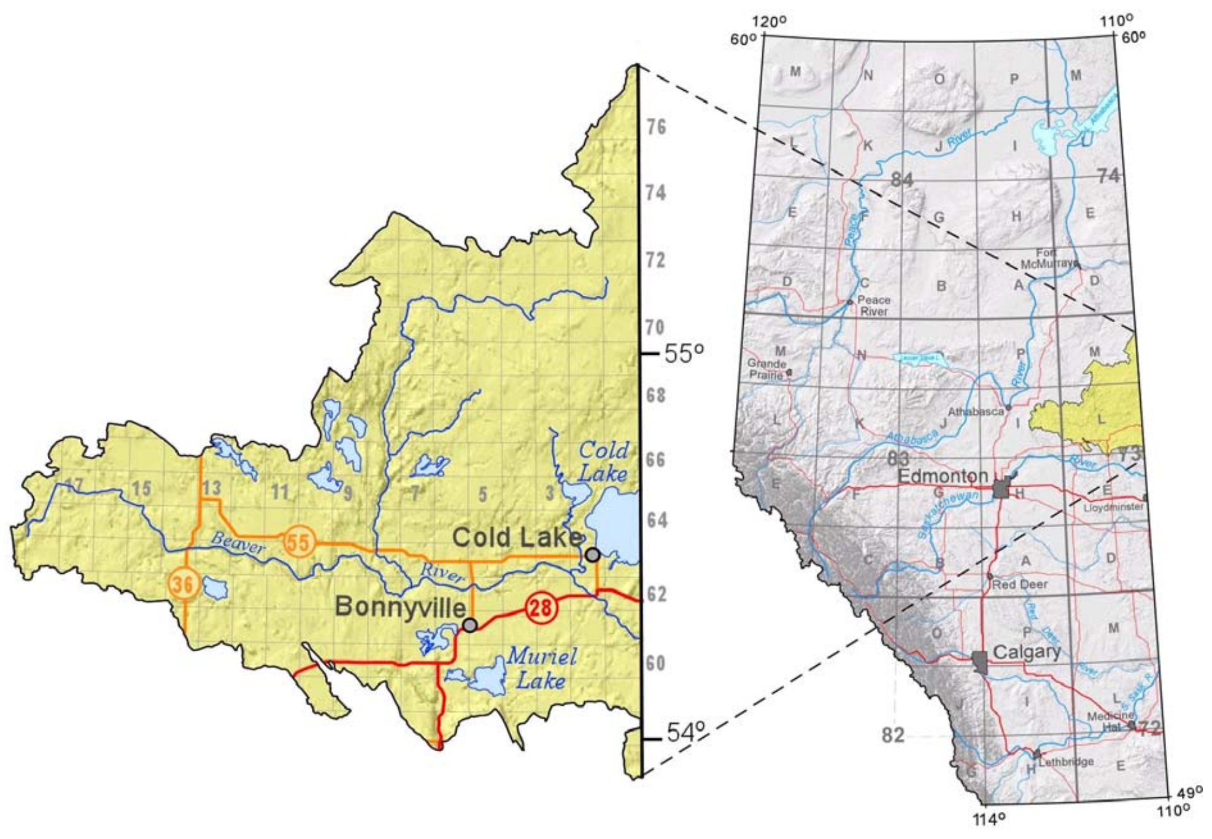
The piper plot for the Bonnyville Formation is shown in Figure 5.17. The data distributions for the NWBR, SEBR, NEBR and Wiau flow systems suggest that the process of ion exchange is occurring and producing the observed cation relationships. Relationships in the anion fields for these same flow systems suggest that certain processes are leading to the increase in sulphate or chloride in solution with respect to bicarbonate.

The major ion composition in the Bonnyville Formation is presented in Figure 5.18. The dominant cations in solution in the majority of the samples from the Wiau flow system are calcium and magnesium. Sodium concentrations appear to increase towards the west. The dominant anion in solution is bicarbonate. In the majority of the samples in the NEBR flow system, the dominant cations in solution are calcium and magnesium. The dominant anion in solution is generally bicarbonate. The sulphate concentrations become more important in the vicinity of the city of Cold Lake, southeast of Osborne Lake and to the southwest of Tucker Lake. The dominant ions in solution vary across the SEBR flow system. In the western-most portion of the flow system, to the north of Ernestina Lake, and in the vicinity of Charlotte, Muriel and Angling lakes, sodium is the dominant cation. The other sample locations have calcium and magnesium as the dominant cations in solution. Bicarbonate is the dominant anion in solution at most of the sample locations. In the western-most portion of the flow system, sulphate and chloride concentrations become more prominent. West and southwest of Sinking Lake sulphate becomes the dominant anion in solution in some of the samples. Calcium and magnesium are the dominant cations, and sulphate is the dominant anion in solution in the SWBR flow system. In the NWBR flow system, sodium is the dominant cation in the majority of the samples collected from southwest of Beaver Lake and southwest of Burnt Lake. Bicarbonate is the dominant anion in solution. Chloride concentrations appear to increase towards the northwest. Sulphate concentrations appear to generally increase along a line running west-southwest between Pinehurst and Kerr Lake.

5.2.5 Ethel Lake Formation

The piper plot for the Ethel Lake Formation is shown in Figure 5.19. The distribution of the major ion chemistries suggests that the process of cation exchange is occurring and affects the cation composition





Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

- • Sample location
- 〰 Major river
- — Major road
- — Cold Lake Air Weapons Range Boundary
- 🟦 Lake
- ■ Town
- ▨ Approximate Formation extent
- 🟨 Beaver River basin drainage area (Alberta portion)

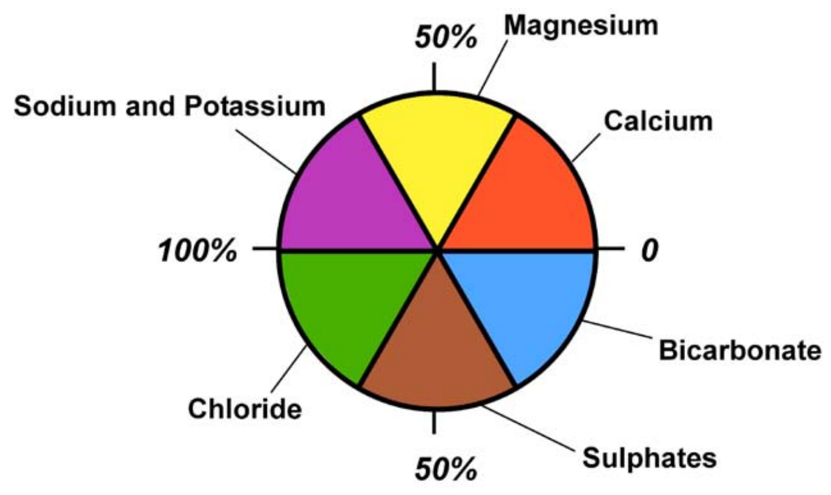


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Figure 5.16. Major ions composition of water from the Muriel Lake Formation.

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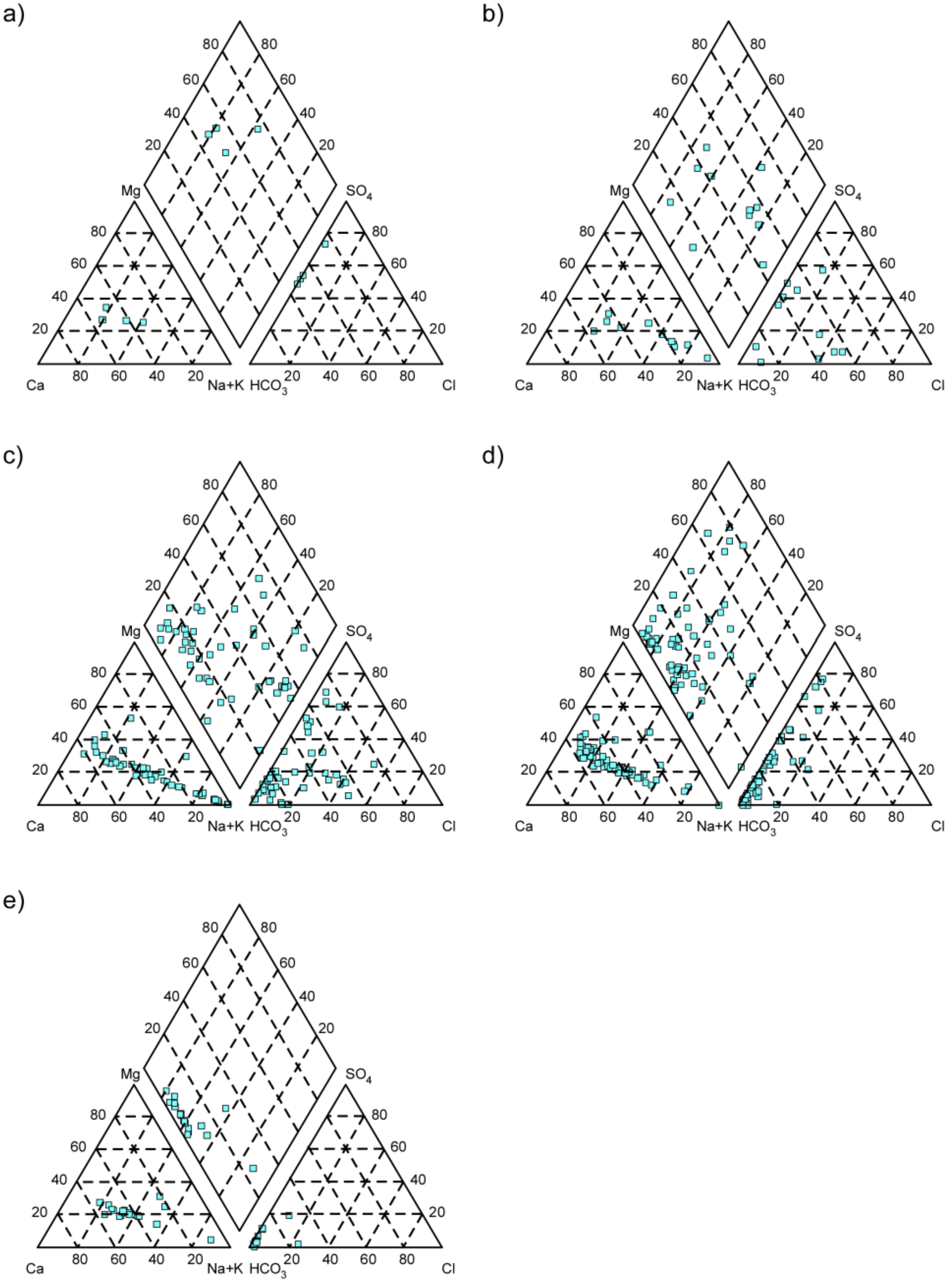
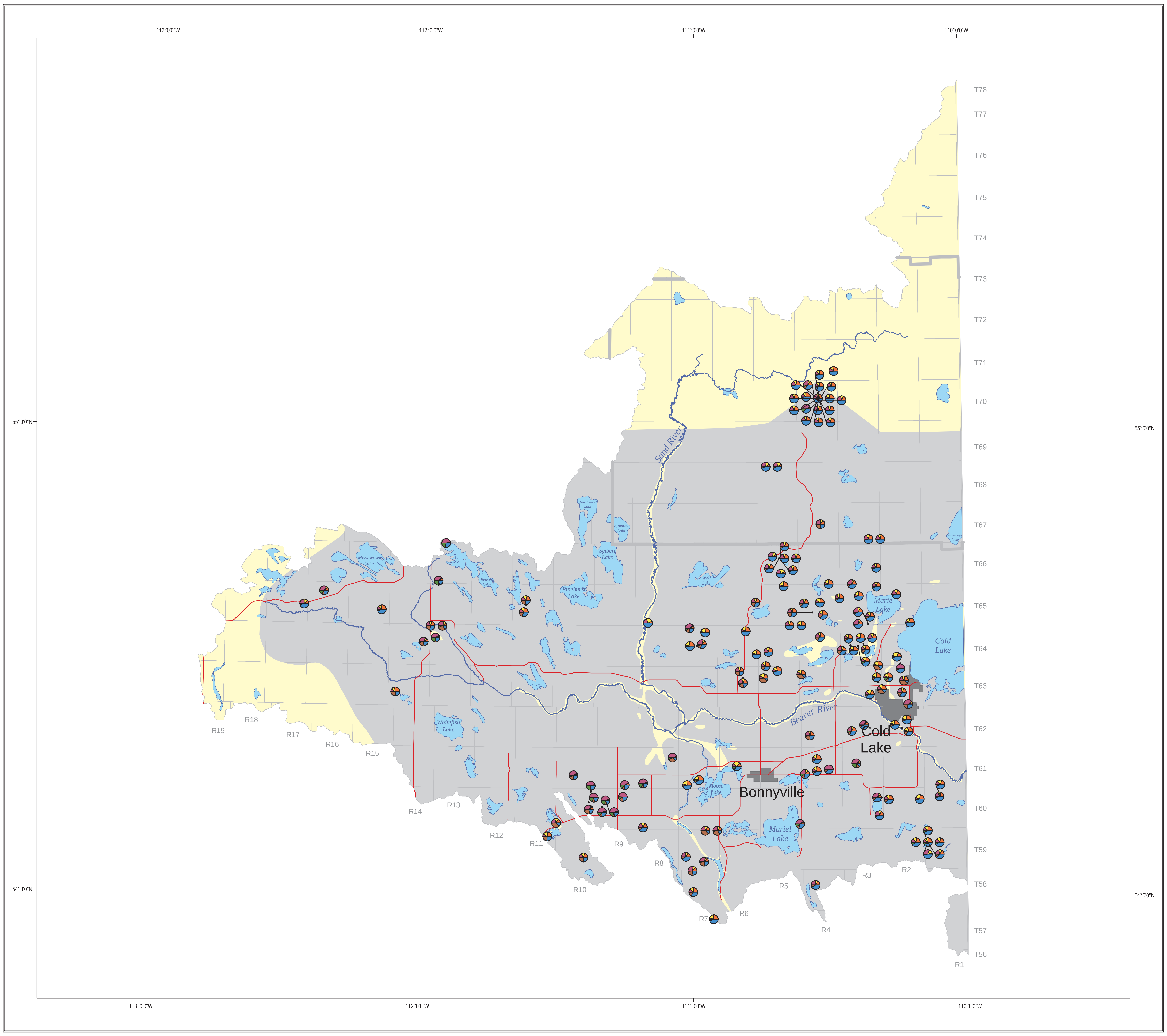
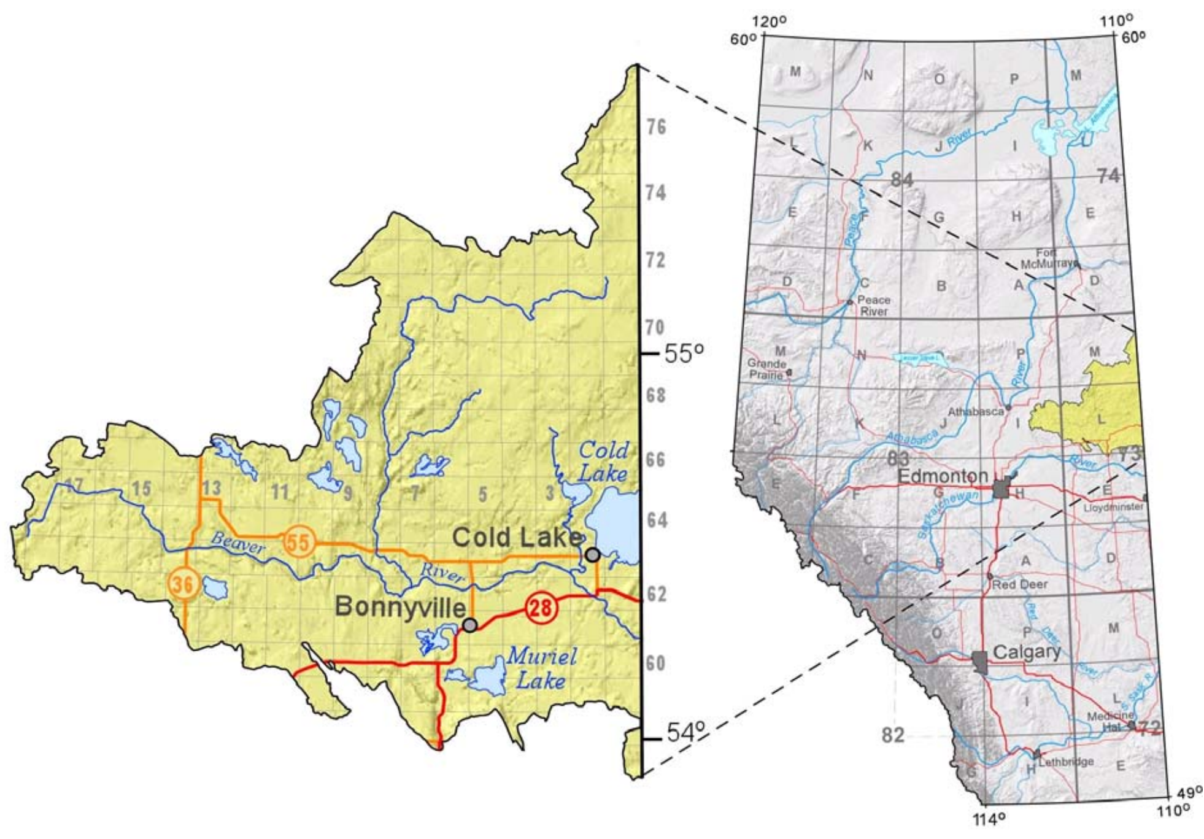


Figure 5.17. Piper plot for the Bonnyville Formation.





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5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

- • Sample location
- Major river
- Major road
- Cold Lake Air Weapons Range Boundary
- 🟦 Lake
- ⬛ Town
- ⬜ Approximate Formation extent
- 🟨 Beaver River basin drainage area (Alberta portion)

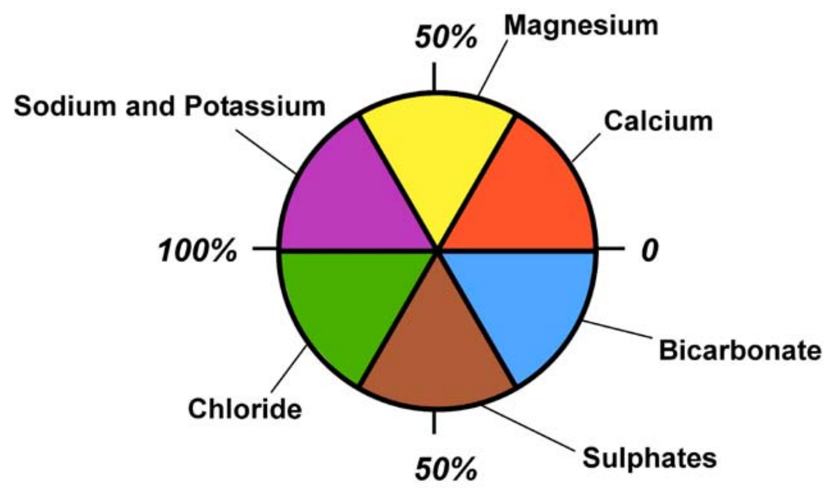

Figure 5.18. Major ion composition of water from the Bonnyville Formation.

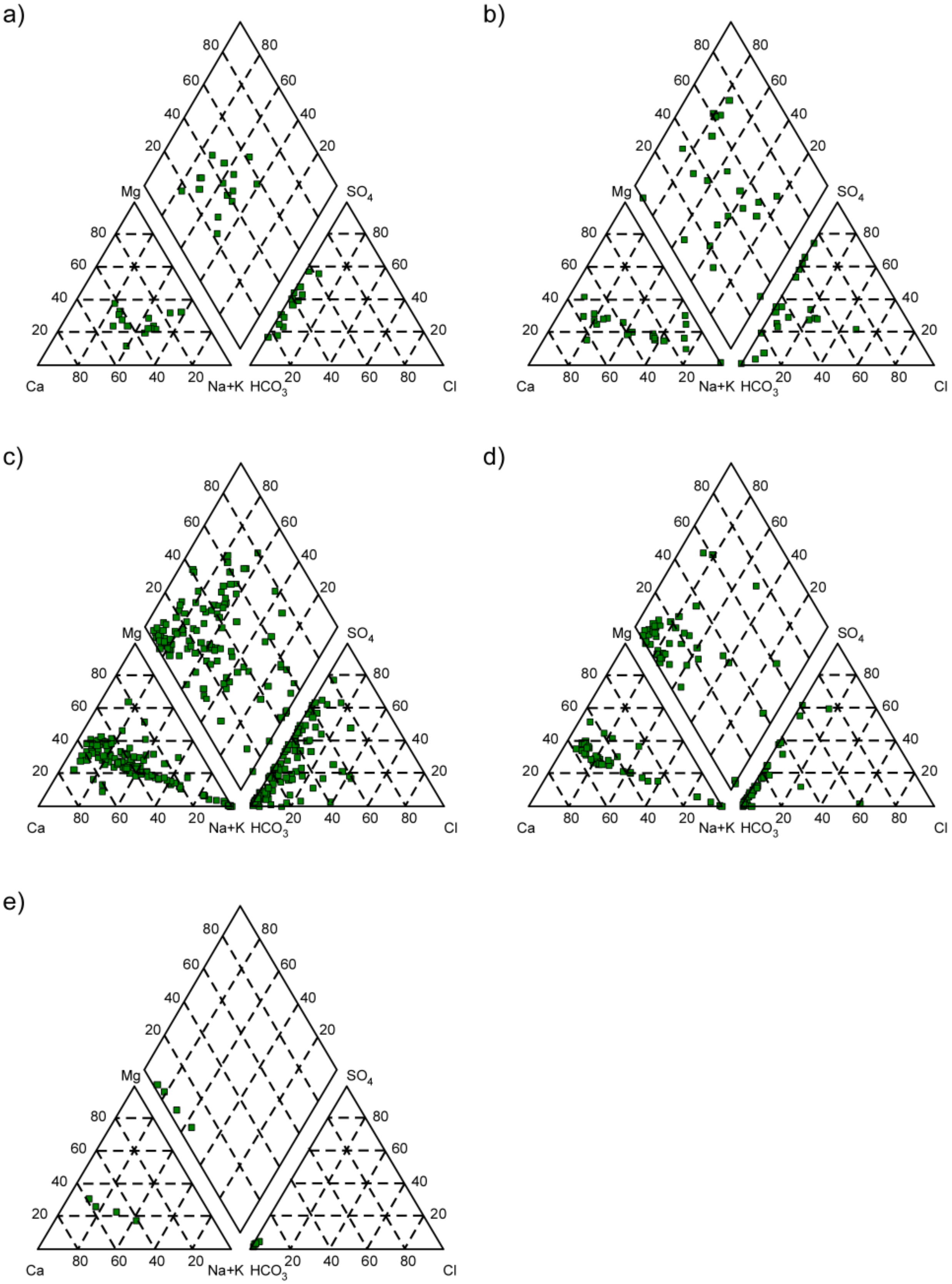

Figure 5.19. Piper plot for the Ethel Lake Formation.

of the water. The SWBR, NWBR, SEBR and NEBR flow systems indicate that certain processes have occurred to increase the concentration of sulphate in the samples with respect to bicarbonate, while other processes are introducing chloride. The Wiau flow system major anion composition appears generally stable.

The major ion composition in the Ethel Lake Formation is in Figure 5.20. The sodium concentration appears to be increasing towards the northwest within the Wiau flow system. The majority of the samples collected from the NEBR flow system have calcium and magnesium as the dominant cations in solution and bicarbonate as the dominant anion in solution. Sulphate concentrations are higher in the vicinity of Wolf and Ethel lakes as well as in isolated portions of the Formation. The cation composition doesn't appear to have any discernible spatial pattern within the SEBR flow system. Bicarbonate is the dominant anion in solution in the majority of the samples. Sulphate concentrations appear to increase west of Muriel Lake. The composition of water from the SWBR flow system is consistent across the flow system. The majority of the samples have calcium and magnesium as the dominant cations and bicarbonate as the dominant anion. The proportion of sulphate in the water samples appears to increase in the northwestern portion of the flow system. Calcium and magnesium are the dominant cations in just over half of the samples collected from the NWBR flow system. Bicarbonate is the dominant anion in the majority of the water samples. Sulphate makes up an increasing proportion of the anion component in the Ethel Lake within the central portion of the flow system.

5.2.6 Marie Creek Formation

The piper plot for the Marie Creek Formation is shown in Figure 5.21. The distribution of the major ion chemistries suggests that the process of cation exchange is occurring. The Wiau flow system major anion chemistry appears generally stable. The major anion distributions in the NEBR, SEBR, SWBR and NWBR flow systems indicate that processes are likely occurring that are introducing sulphate into solution in certain portions of the flow systems such that sulphate concentrations are increasing with respect to bicarbonate.

The major ion composition in the Marie Creek Formation is in Figure 5.22. The major ion concentrations in the Marie Creek Formation water samples within the Wiau flow system do not appear to vary significantly spatially. The Marie Creek Formation water samples are in close proximity to one another however. The dominant cations are calcium and magnesium, and the dominant anion is bicarbonate. The majority of the water samples from the NEBR flow system have calcium and magnesium as their dominant cation in solution. Sodium occurs as the dominant cation in the vicinity of Moore Lake, south of Cold Lake and northeast of Marie Lake. The dominant anion in solution in the majority of the samples is bicarbonate. Sulphate proportions within solution increase in the vicinity of the city of Cold Lake and in the area between Harold and Osborne lakes. Instances of higher chloride occur near Moore Lake. Calcium and magnesium are the dominant cations in solution in the majority of the samples in the SEBR flow system. Sodium is the dominant cation in some of the water samples in the vicinity of Moose and Muriel lakes. The dominant anion in solution in the majority of the samples is bicarbonate. Sulphate proportions increase in the samples east of Moose Lake, in the vicinity of Charlotte Lake, and in the vicinity of the city of Cold Lake. The dominant anion in solution in the SWBR flow system is generally bicarbonate, with the proportion of sulphate increasing towards the northwestern portion of the flow system. The dominant cations in solution in the majority of the samples are calcium and magnesium with sodium becoming more dominant towards the northwestern portion of the flow system. The proportion of sodium increases towards the western portion of the NWBR flow system. The dominant anion is bicarbonate in all but one sample where sulphate is the dominant anion in solution. The proportion of bicarbonate in solution appears to decrease towards the western portion of the flow system.

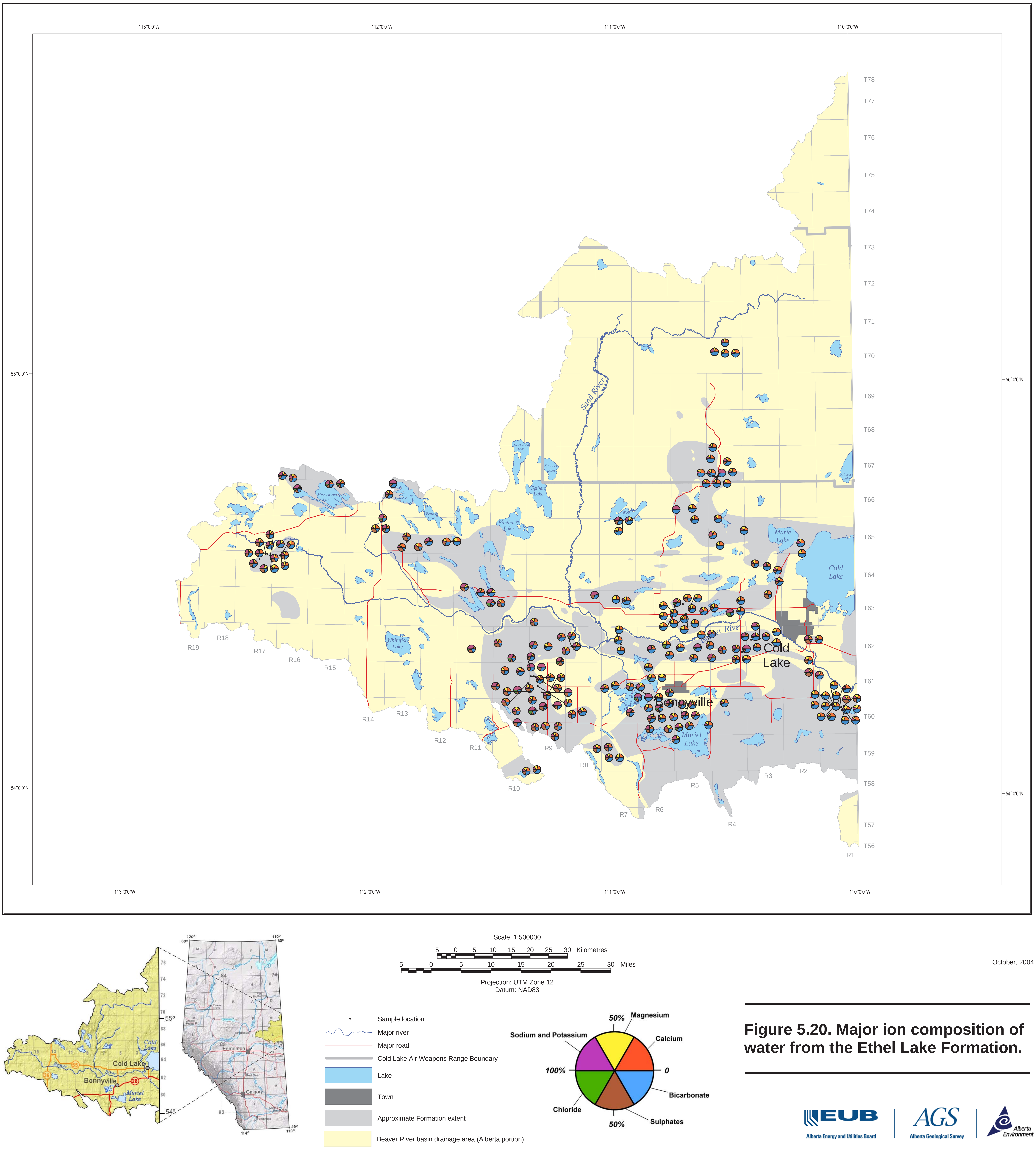

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Figure 5.20. Major ion composition of water from the Ethel Lake Formation.

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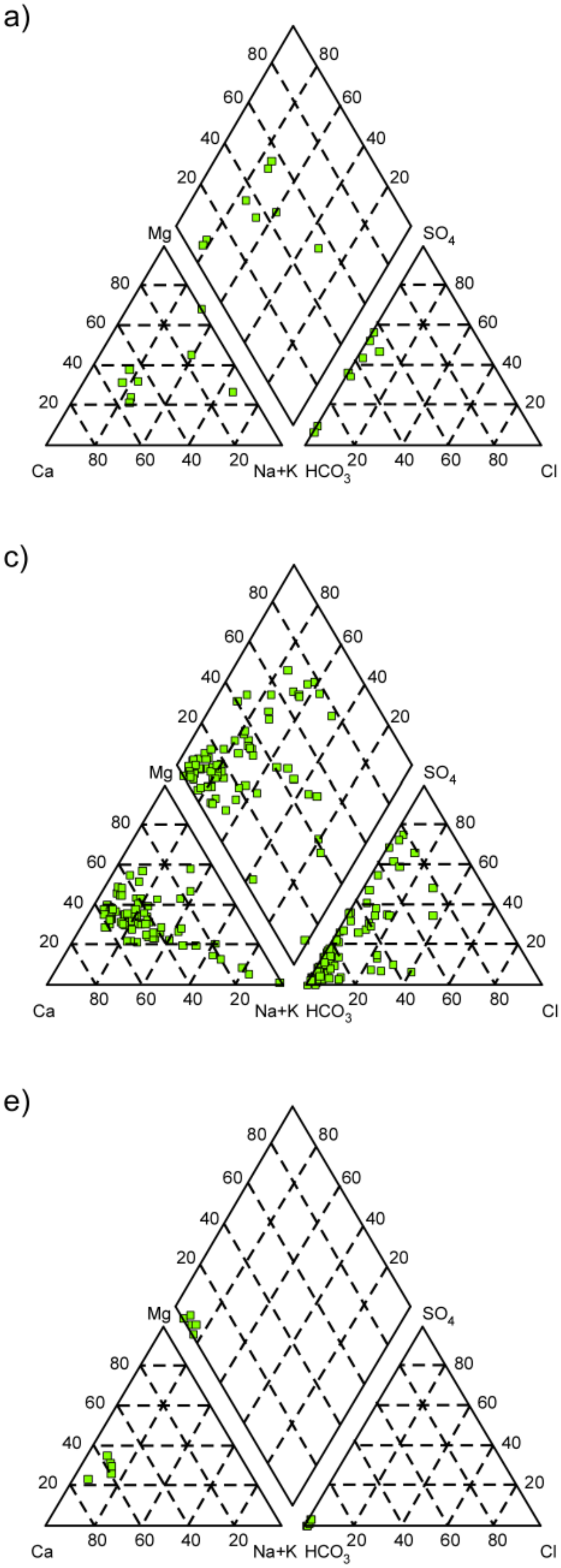
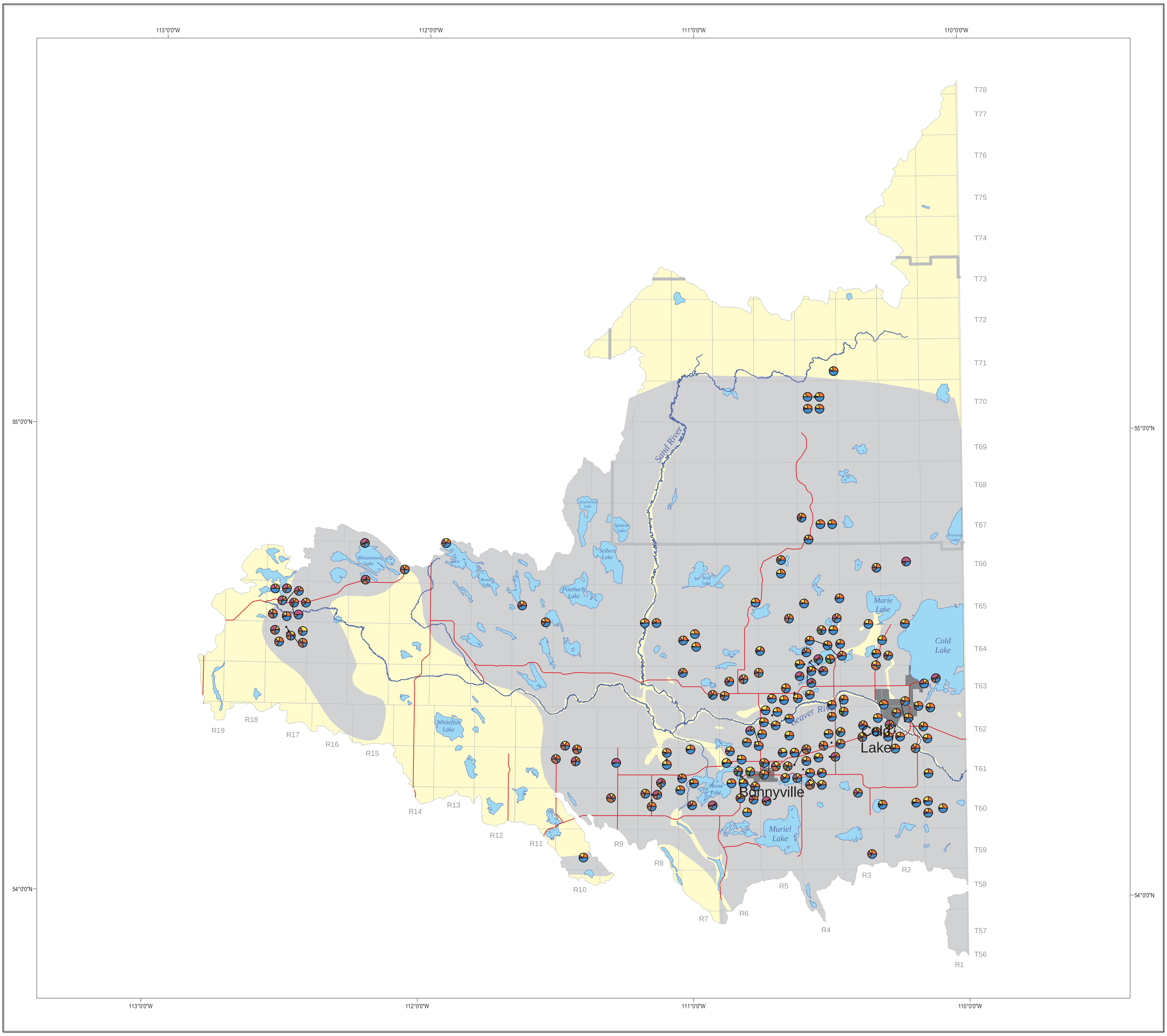
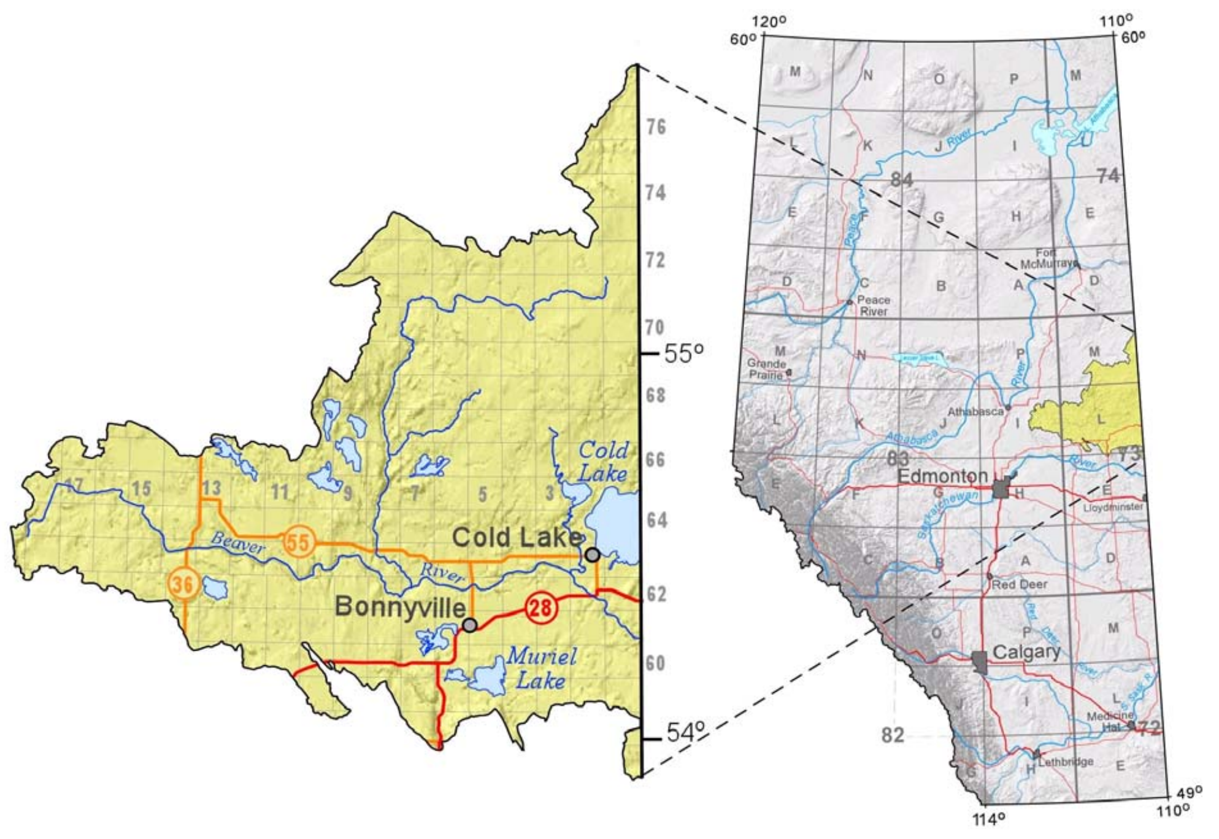


Figure 5.21. Piper plot for the Marie Creek Formation.





Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

•	Sample location
〰	Major river
—	Major road
▬	Cold Lake Air Weapons Range Boundary
▭	Lake
■	Town
▨	Approximate Formation extent
▭	Beaver River basin drainage area (Alberta portion)

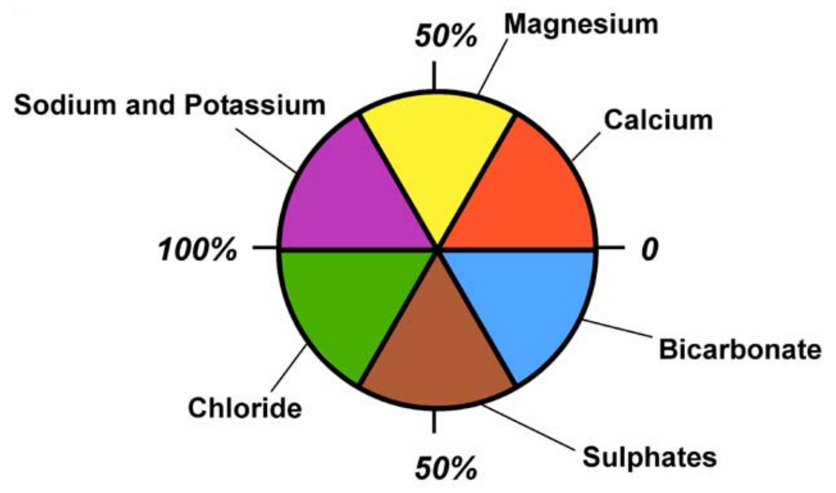


Figure 5.22. Major ion composition of water from the Marie Creek Formation.

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5.2.7 Sand River Formation

The piper plot of the water chemistry of the Sand River Formation is presented in Figure 5.23. Cation exchange processes appear active, as do processes that lead to the increase concentration of sulphate with respect to bicarbonate. There is also evidence to suggest that processes are active that increase the relative concentration of chloride with respect to bicarbonate.

The major ion composition in the Sand River Formation is in Figure 5.24. In the NEBR flow system, the dominant cations in the majority of the samples in solution are calcium and magnesium. Sodium is the dominant cation in solution in samples in the vicinity of some of the lakes in the region. The dominant anion in the majority of the samples is bicarbonate with the exception of some of the samples located near Cold Lake and Marie Lake where sulphate becomes the dominant anion in solution. The dominant cations in solution in the majority of the samples from the SEBR flow system are calcium and magnesium. Sodium is the dominant cation in some of the samples, particularly those in between Muriel and Moose lakes, and in the western portion of the flow system. Bicarbonate is the dominant anion solution in the majority of the samples within this flow system, with sulphate becoming dominant in the western portion of the flow system. While calcium and magnesium are the dominant cations, and bicarbonate is the dominant anion in solution in the majority of the samples in the SWBR flow system, sodium, sulphate and chloride are present as dominant species within certain samples. No trend appears obvious. The dominant ions in solution in the majority of the samples from the NWBR flow system are calcium and magnesium, and sulphate. Sodium is more prominent in the far-eastern and far-western portions of the flow system. Bicarbonate is more dominant in the eastern portion of the flow system.

5.2.8 Grand Centre Formation

The piper plot of the water chemistry of the Grand Centre Formation is presented in Figure 5.25. Cation exchange processes appear active based on the distributions within the cation fields. There is evidence to suggest that processes are active that increase the relative concentration of chloride with respect to bicarbonate in the NEBR, SEBR and Wiau flow systems. Processes appear active in the SWBR, NWBR and SEBR flow systems that increase the relative concentration of sulphate with respect to bicarbonate.

The major ion concentrations in the Grand Centre Formation water samples within the Wiau flow system do not appear to vary significantly spatially (Figure 5.26). The Grand Centre Formation water samples are in close proximity to one another however. The dominant cations are calcium and magnesium, and the dominant anion is bicarbonate. The dominant cations in solution in the majority of the samples from the NEBR flow system are calcium and magnesium. The proportion of sodium becomes higher in a few samples to the east of Wolf Lake, and to the northwest of the city of Cold Lake. The dominant anion in solution in the majority of the samples is bicarbonate. The dominant cations and the dominant anion in solution in the majority of the samples from the SEBR flow system are calcium and magnesium, and bicarbonate respectively. Sodium becomes the dominant cation in the general area between Moose, Charlotte and Muriel lakes and towards the western portion of the flow system. The dominant anion in solution is sulphate in portions of the western flow system and in the vicinity of Charlotte Lake. The dominant cations in solution in the majority of the water samples in the SWBR flow system are calcium and magnesium, while the dominant anion is generally bicarbonate. Sulphate is the dominant anion in samples in the southern portion of the flow system. The dominant cations in solution in the majority of the samples from the NWBR flow system are calcium and magnesium. Sodium is the dominant cation in solution in certain samples from the western portion of the flow system. The relative proportion of sodium appears to generally increase towards the west. Bicarbonate is the dominant anion in solution in the majority of the samples. Sulphate is the dominant anion in some of the samples from the western

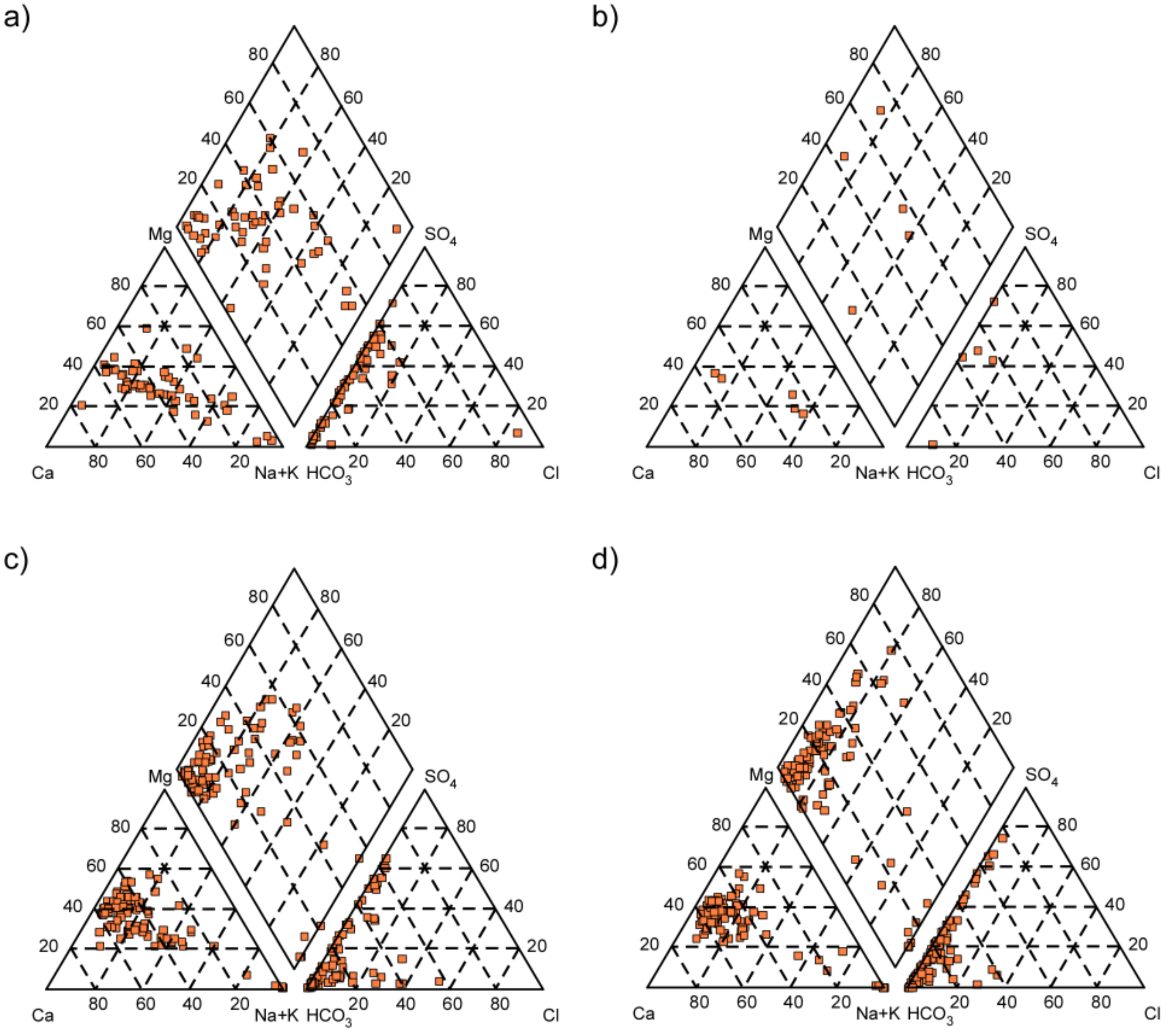
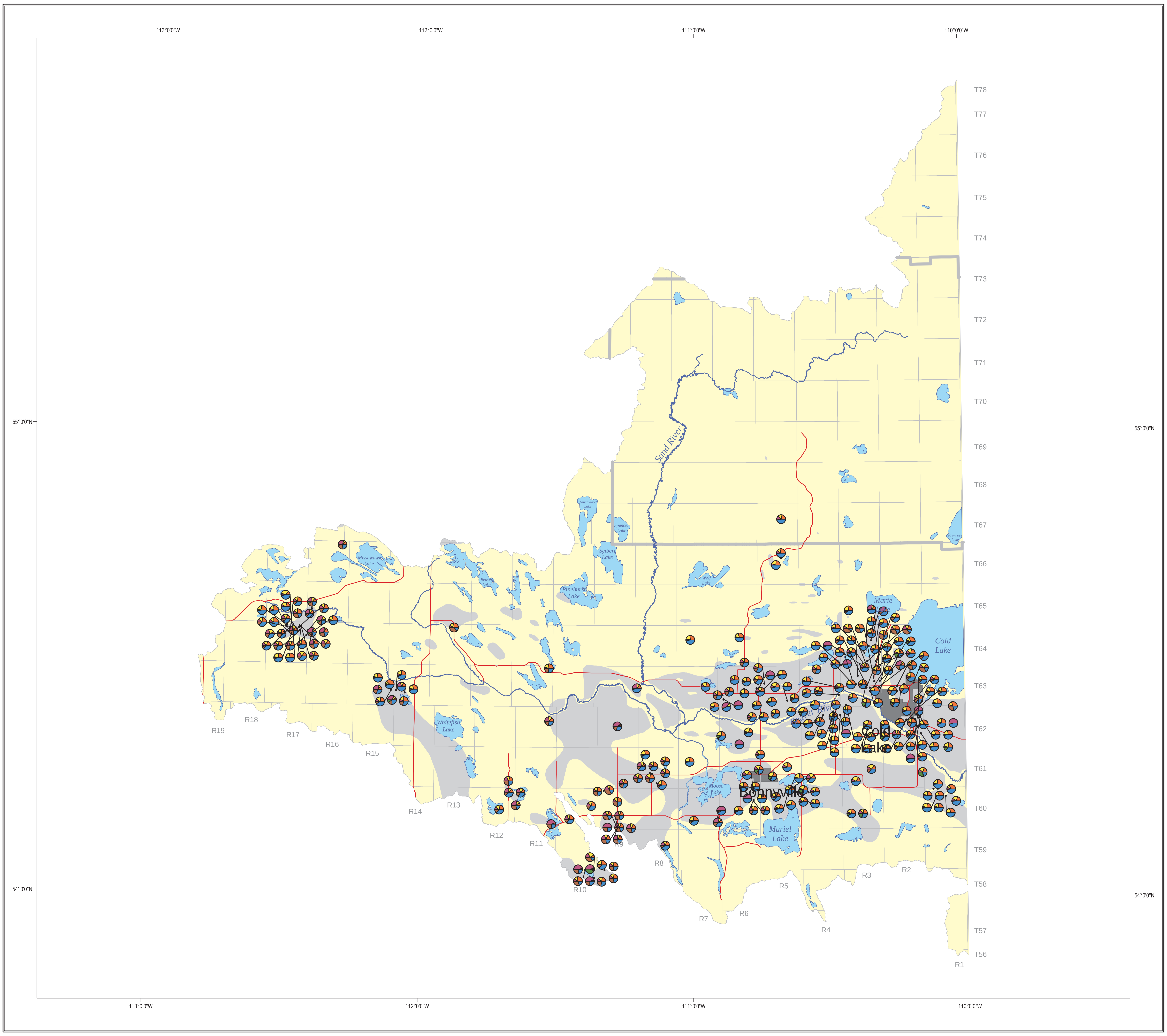
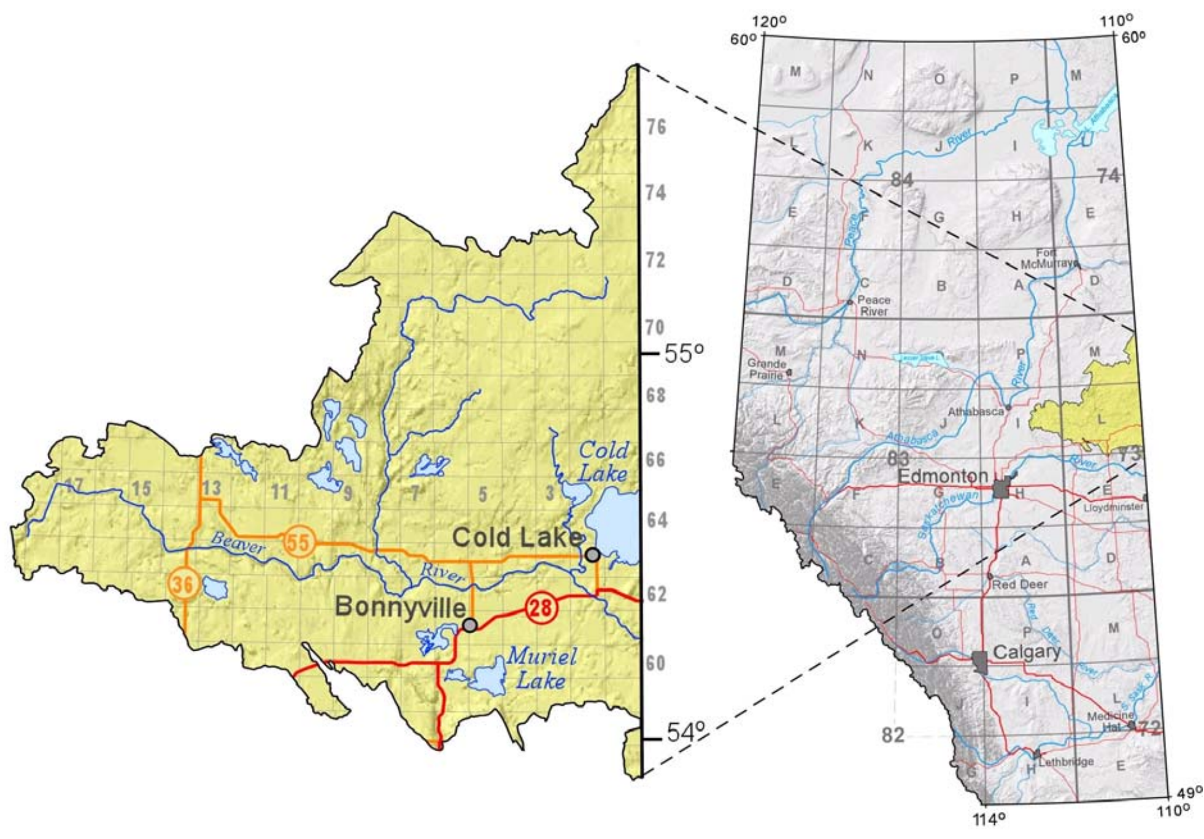


Figure 5.23. Piper plot for the Sand River Formation.





Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

- • Sample location
- 〰 Major river
- ― Major road
- ▬ Cold Lake Air Weapons Range Boundary
- 🟦 Lake
- ⬛ Town
- ▨ Approximate Formation extent
- 🟨 Beaver River basin drainage area (Alberta portion)

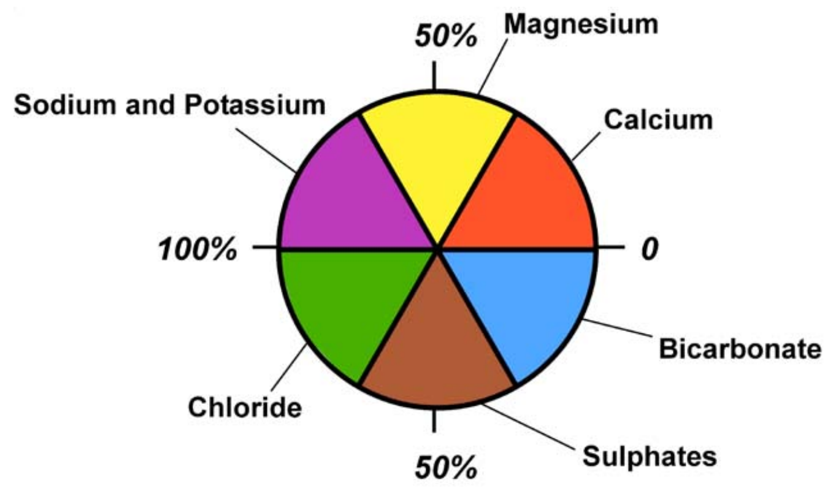


Figure 5.24. Major ion composition of water from the Sand River Formation.

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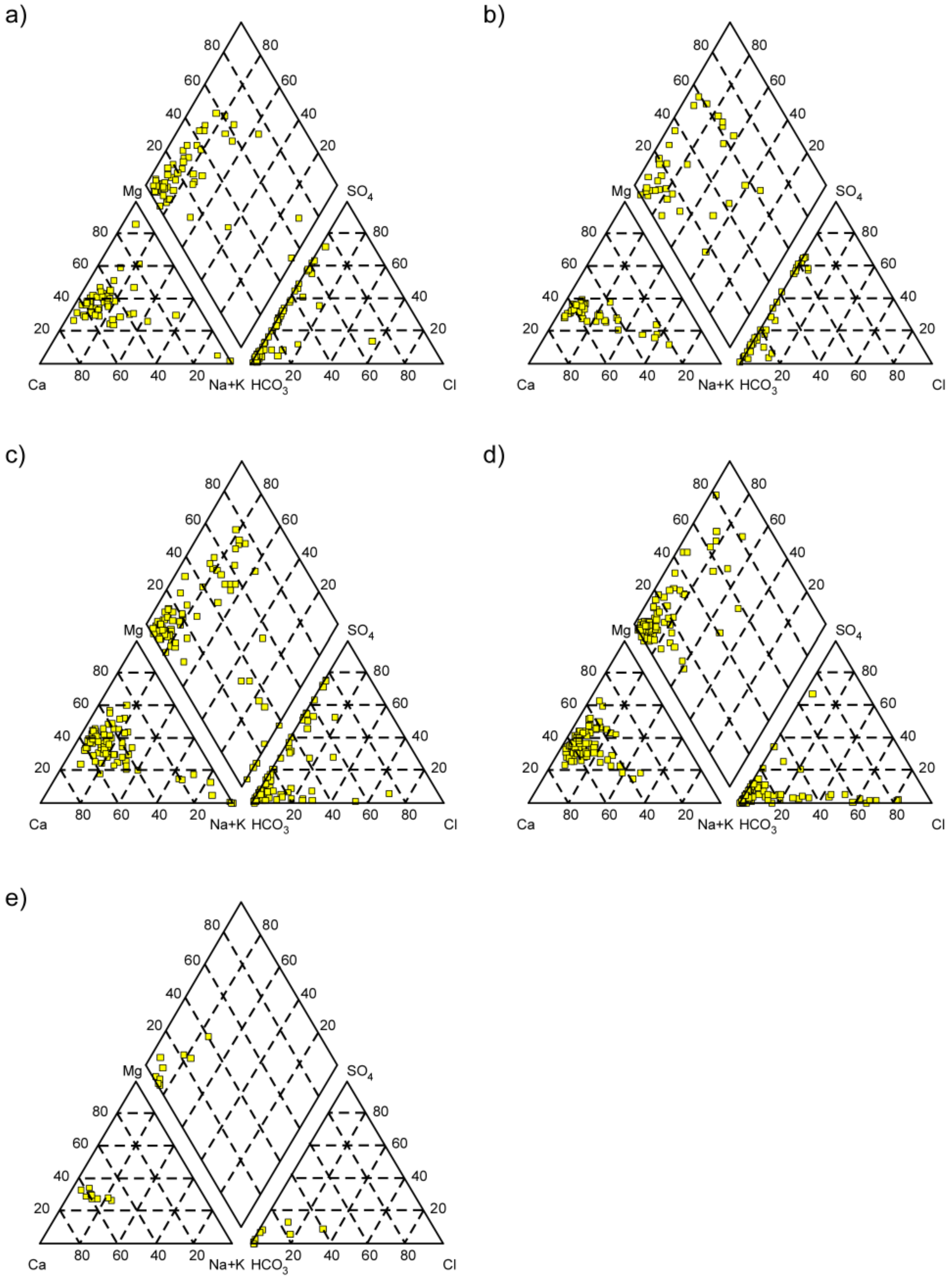
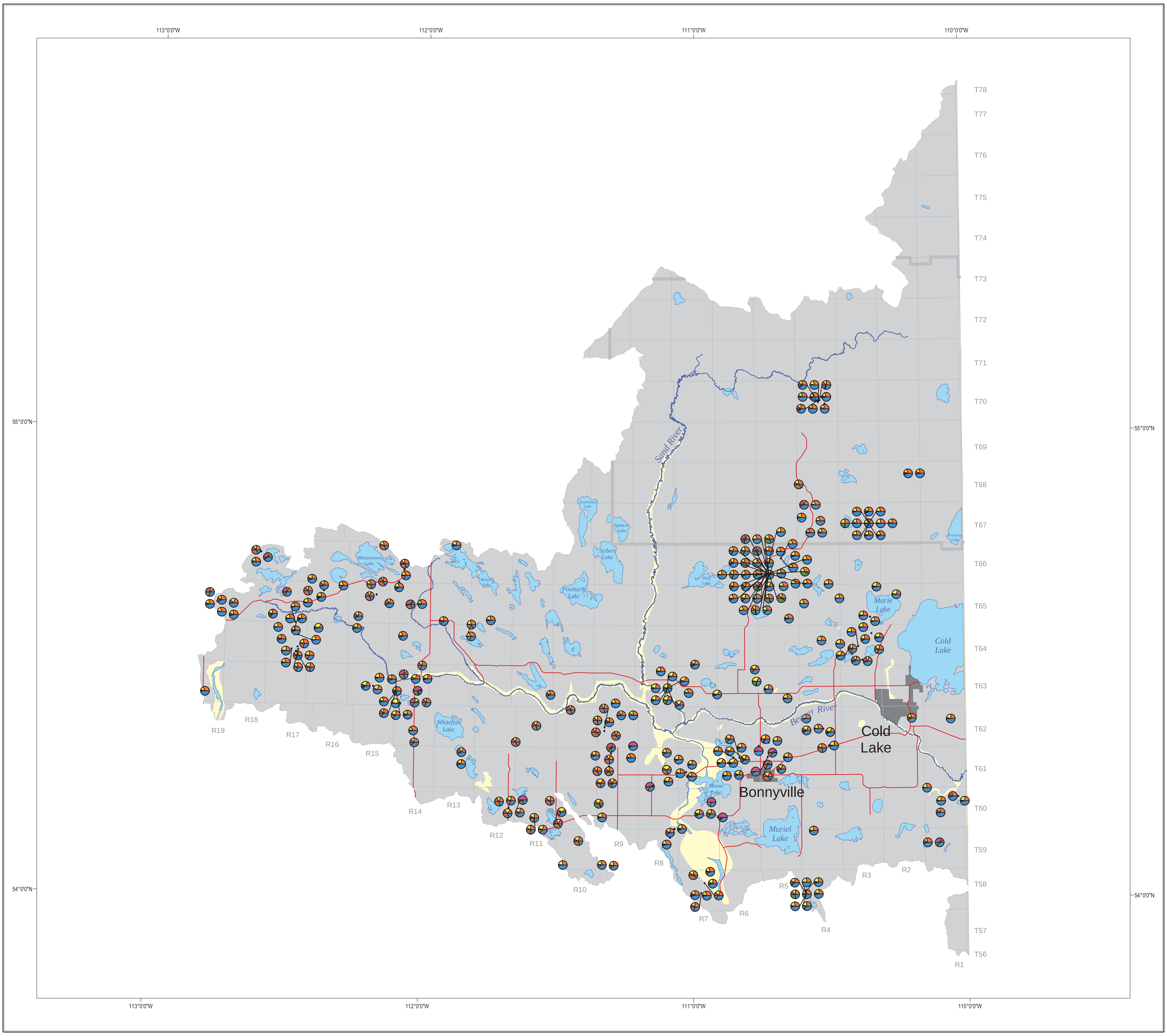
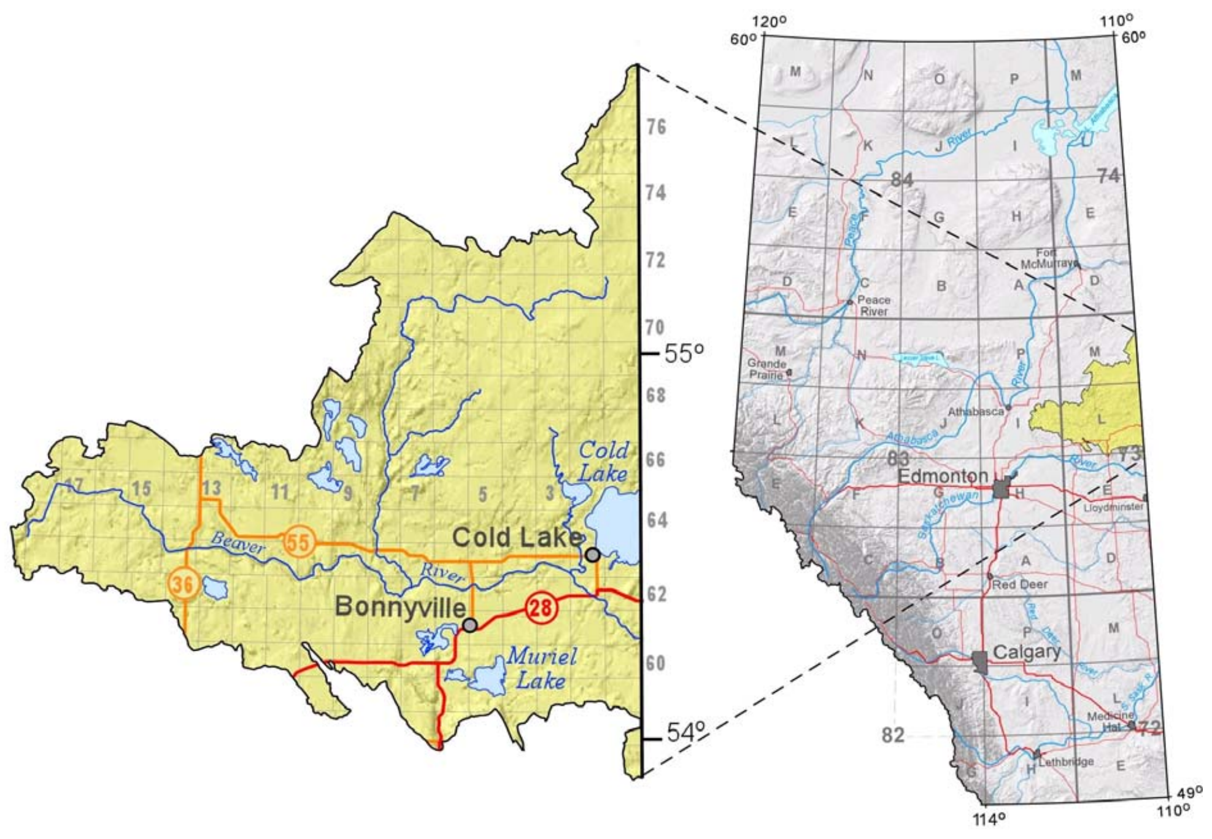


Figure 5.25. Piper plot for the Grand Centre Formation.





Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

• Sample location
〰 Major river
— Major road
— Cold Lake Air Weapons Range Boundary
🟦 Lake
⬛ Town
▨ Formation extent
🟨 Beaver River drainage basin area (Alberta portion)

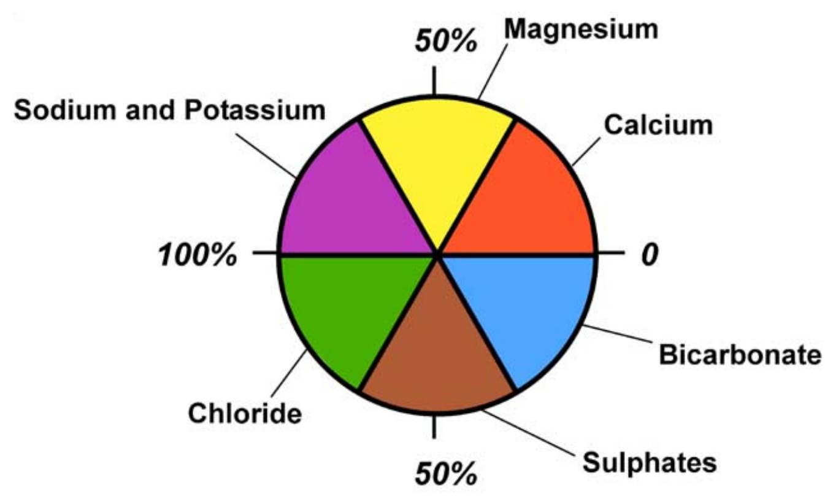


Figure 5.26. Major ion composition of water from the Grand Centre Formation.

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portion of the flow system. The relative proportion of sulphate appears to generally increase towards the west.

5.3 Distribution of Chloride

Chloride has both natural and anthropogenic sources. Potential natural sources are discussed in Section 3.2.3.2. The source of chloride in groundwater can be inferred through a number of techniques. Anion ratios such as Cl/Br have been used to determine potential sources of Cl in groundwater (Davis et al., 1998). The source of chloride in groundwater can also be inferred by examining potential water mixing scenarios. Analysis of formation waters in the area provides an end member Cl composition value. This coupled with a suitable second end member Cl concentration can be used in a mixing model to determine if the observed groundwater Cl concentrations are the results of mixing. Komex (1997) indicates that chloride is a major constituent in the formation water produced in association with Cold Lake bitumen, but is not a major constituent in drift aquifer water. Chloride is therefore considered an excellent contaminant tracer (Komex, 1997).

Environmental quality guidelines have been established for the chloride concentration in water for various uses and are presented in (Table 4) below.

Table 4. Canadian environmental quality guidelines for chloride in water (CCME, 2003, AENV, 1999).

Water – Community Use (CCME)		**Freshwater Aquatic Life (AENV)**		**Water – Agricultural Use (CCME)**		
		(Based on USEPA values)		Irrigation		Livestock
MAC, IMAC	AO	Chronic	Acute	Lower value	Upper value	
(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
-	≤ 250	230	860	100	700	-

Some of the chloride concentrations in the drift aquifers in the Basin exceed some or all of the environmental quality guidelines. The following table (Table 5) contains a summary of the exceedances of chloride concentrations captured in the water quality database. The first column (Formation) lists the drift formations. The second column (Range of Values) presents the minimum and maximum values for the Formation. The third column (N) presents the total number of records for a given Formation. The fourth column (ND) presents the number of records that were below the detection limit of the analysis. The fifth column (Water-Community Use) presents the number of records that exceed the water for community use guideline value where AO is the aesthetic objective. The sixth column (Freshwater Aquatic Life) presents the number of records that exceed the Alberta Environment surface water quality guideline values for the protection of freshwater aquatic life at the chronic an acute levels. The seventh column (Water-Agricultural Use) presents the number of records that exceed agricultural water use guideline values. In the case of water for irrigation use, a range of chloride values is presented. The column is split into two with the first subcolumn representing the number of records that exceed the lowest value of the range, and the second subcolumn representing the number of records that exceed the highest value of the range.

Table 5. Chloride exceedances summary.

Formation	Range of Values		N	ND	Water – Community Use	Freshwater Aquatic Life		Water – Agricultural Use		
								Irrigation		Livestock
	Min (mg/L)	Max (mg/L)			AO	Chronic	Acute	Lower value	Upper value	
Grand Centre	<0.5	1460	670	46	36	38	12	72	16	-
Sand River	<0.5	5500	357	30	5	6	1	16	1	-
Marie Creek	<0.5	550	319	43	5	6	0	17	0	-
Ethel Lake	<0.5	545	352	46	13	15	0	27	0	-
Bonnyville	<0.5	825	459	20	14	15	0	38	1	-
Muriel Lake	<0.5	1500	717	17	26	27	2	88	5	-
Bronson Lake	<0.5	1430	24	1	1	1	1	1	1	-
Empress	<0.5	2860	807	3	149	155	29	209	38	-

While the values above summarize the database contents, the following table (Table 6) describes the exceedances of the most recently collected data on chloride concentrations.

Table 6. Chloride exceedances summary - most recent values.

Formation	Range of Values		N	ND	Water – Community Use	Freshwater Aquatic Life		Water – Agricultural Use		
								Irrigation		Livestock
	Min (mg/L)	Max (mg/L)			AO	Chronic	Acute	Lower value	Upper value	
Grand Centre	<0.5	1350	276	24	16	17	4	29	5	-
Sand River	<0.5	5500	269	23	5	6	1	16	1	-
Marie Creek	<0.5	550	167	15	5	6	0	17	0	-
Ethel Lake	<0.5	545	207	17	9	11	0	22	0	-
Bonnyville	<0.5	825	144	5	12	13	0	25	1	-
Muriel Lake	<0.5	1475	241	5	22	23	1	47	3	-
Bronson Lake	<0.5	1430	14	1	1	1	1	1	1	-
Empress	1	2520	141	0	15	16	3	32	3	-

The distribution of the most recently collected data on chloride concentrations in the various formations is presented in Figure 5.27, Figure 5.28, Figure 5.29, Figure 5.30, Figure 5.31, Figure 5.32, Figure 5.33 and Figure 5.34.

5.3.1 Empress Formation

The chloride distribution in the Empress Formation is presented in Figure 5.27. Chloride values are generally less than the aesthetic objective throughout the aquifer. Some areas, in particular the area to the west of Cold Lake have higher concentrations of chloride in solution. All of these samples are located within the NEBR flow system.

5.3.2 Bronson Lake Formation

The chloride distribution in the Bronson Lake Formation is presented in Figure 5.28. Only one sample has a chloride concentration above the aesthetic objective (AO) for water quality for human use. It is located west of the town of Bonnyville along the shores of Moose Lake.

5.3.3 Muriel Lake Formation

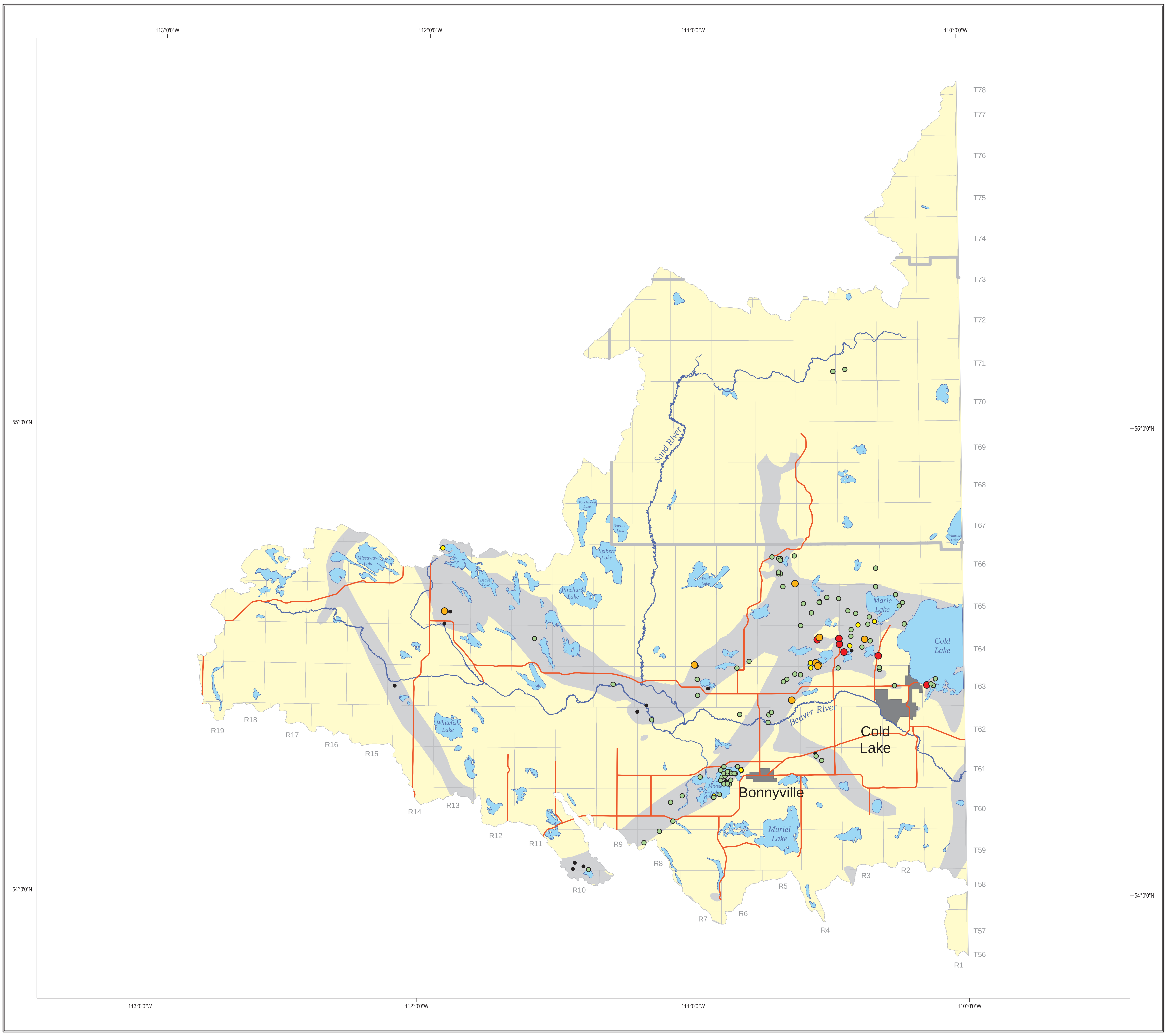
The chloride distribution in the Muriel Lake Formation is presented in Figure 5.29. The sample within the Wiau flow system has a chloride concentration below the AO for chloride and does not exceed the irrigation guidelines. The majority of the samples in the NEBR flow system have chloride concentrations below the AO and irrigation guidelines. Certain samples in the southern portion of the flow system exceed these guideline values. The greatest number of guideline exceedances appears to occur in the SEBR flow system. These exceedances do not appear to have any obvious spatial pattern. The majority of the samples in the NWBR flow system have chloride concentrations below the AO, but one sample on the shores of Fork Lake exceeds the AO and irrigation guidelines.

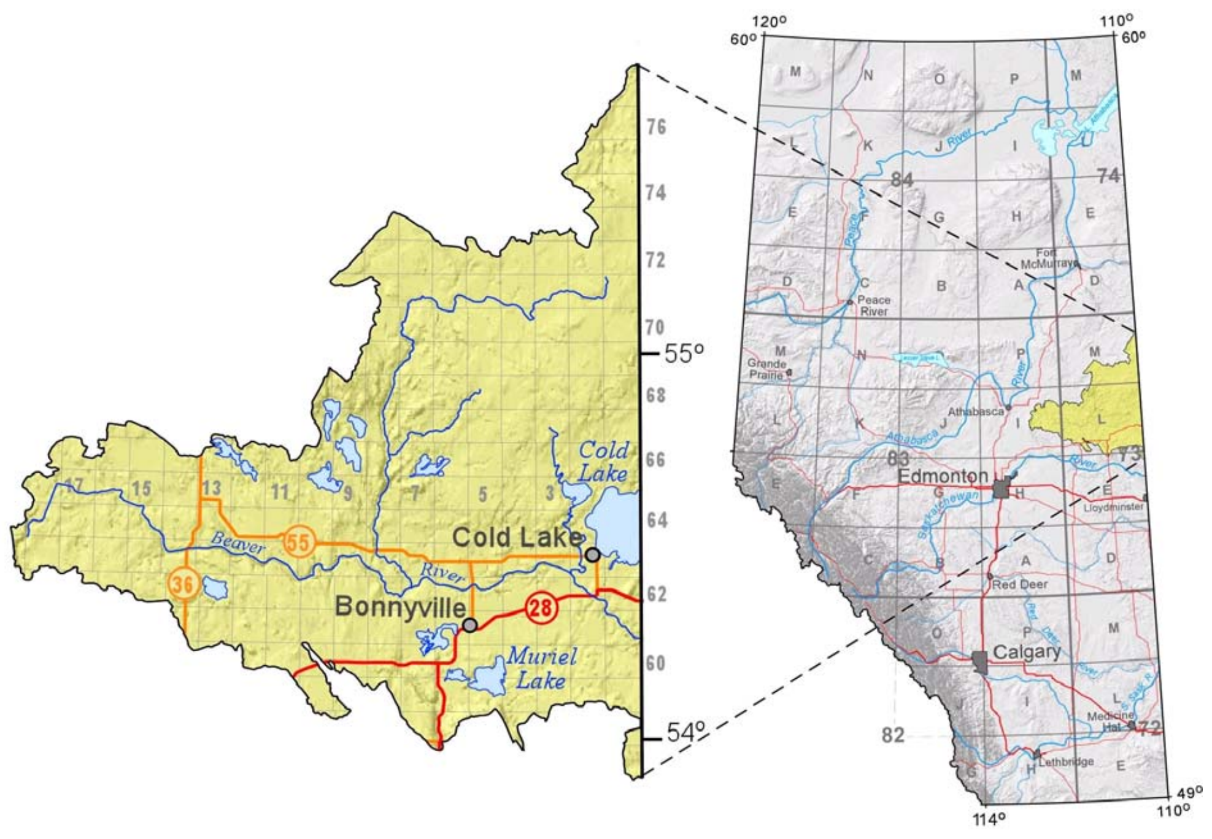
5.3.4 Bonnyville Formation

The chloride distribution in the Bonnyville Formation is presented in Figure 5.30. Samples within the Wiau and NEBR flow system have chloride values that are below the AO. One sample exceeds the lower limit of the irrigation water quality guidelines in the Wiau flow system and is located near the centre of the flow system. Five samples in the NEBR flow system exceed the lower limit of the irrigation water quality guidelines. These samples are located north of the city of Cold Lake and in the western portion of the flow system. The majority of the samples in the SEBR flow system have chloride concentrations that are below the AO and the irrigation guidelines. The majority of the samples that exceed the AO and irrigation water quality guidelines are found in the western portion of the flow system. Samples in the SWBR flow system have chloride values that are less than the AO and irrigation water quality guidelines. Proportionally, exceedances of the lower value of the irrigation water quality guideline is highest in the NWBR flow system where almost half of the samples exceed the guideline value. The highest chloride concentration values occur along a north-south line that passes through the central portion of the flow system.

5.3.5 Ethel Lake Formation

The chloride distribution in the Ethel Lake Formation is presented in Figure 5.31. Samples within the Wiau flow system have chloride concentrations below the AO and lower limit of the irrigation water quality guidelines. The majority of the samples within the NEBR flow system have chloride concentrations below the AO and the lower limit of the irrigation water quality guidelines. Only one sample exceeds the AO and is located in the southern portion of the flow system along the Beaver River. Two additional samples exceed the irrigation water quality guideline. They are also located in the southern portion of the flow system, one near the city of Cold Lake, and the other west of Harold Lake.





Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

- 〰 Major river
- — Major road
- ▬ Cold Lake Air Weapons Range Boundary
- 🟦 Lake
- ▨ Town
- ▨ Approximate Formation extents
- 🟨 Beaver River drainage basin area (Alberta portion)

Chloride concentration (mg/L)

- ● 0 - 125
- ● 125 - 250
- ● 250 - 500
- ● > 500
- ● Well completed in the Formation without chloride information or with suspect chemical analysis

Figure 5.27. Chloride concentrations in the Empress Formation.

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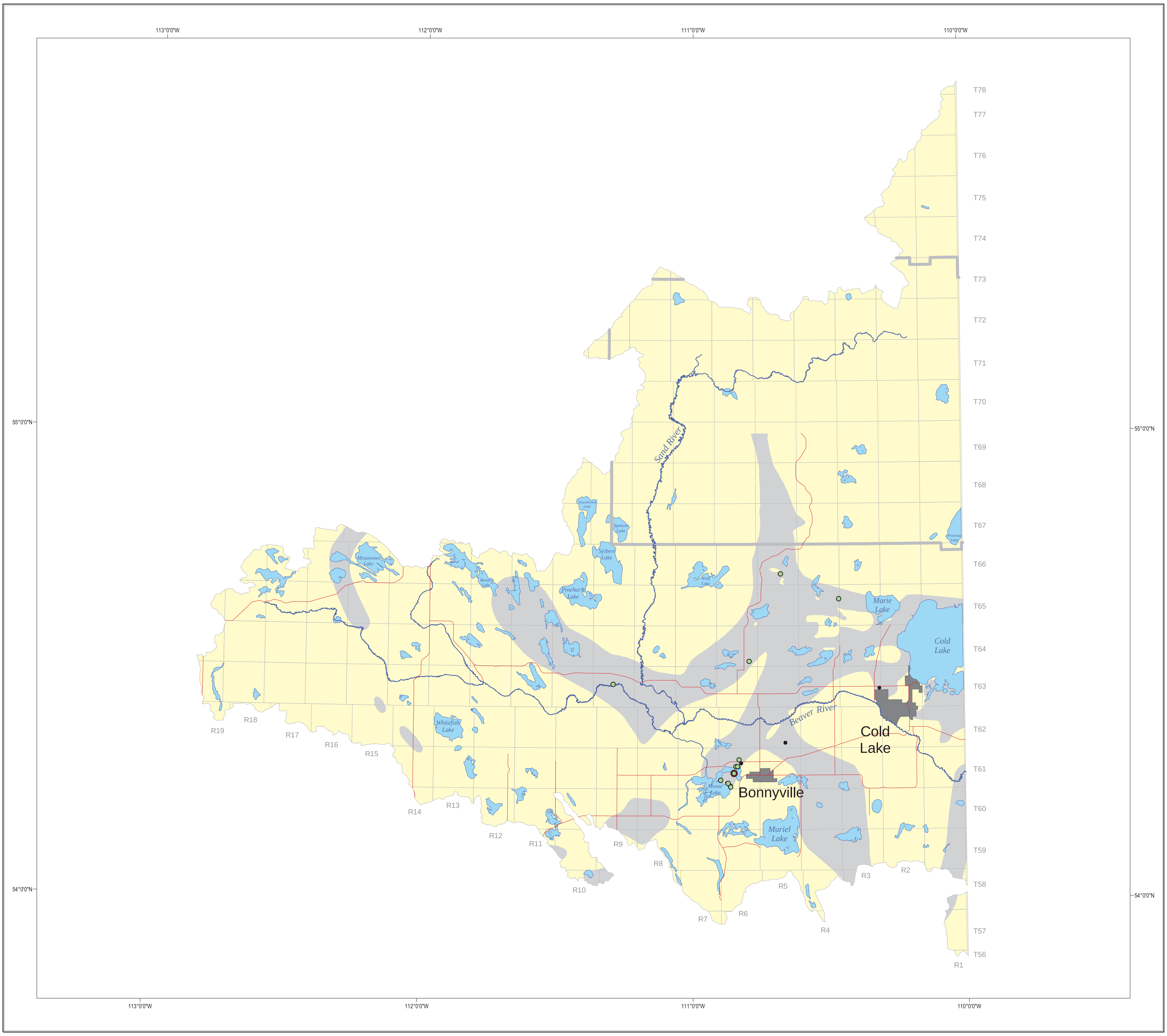

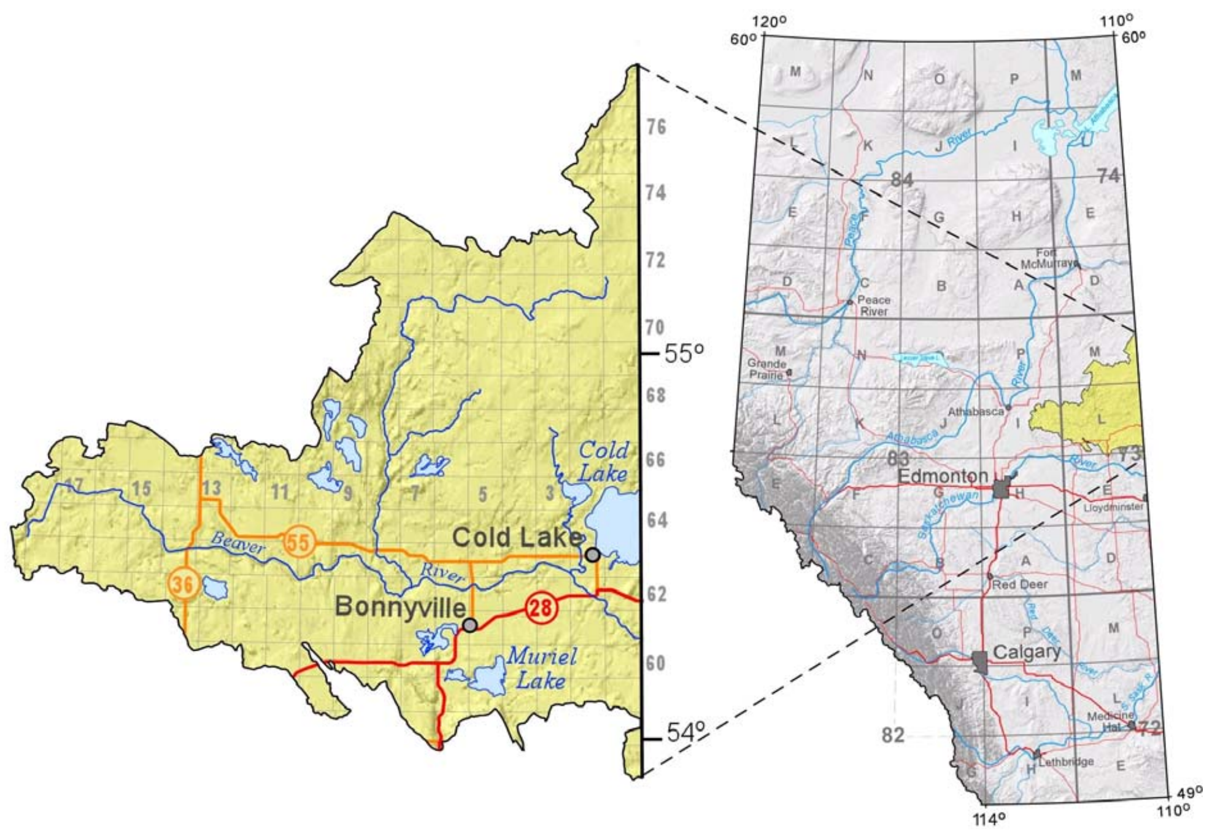

Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

Figure 5.28. Chloride concentrations in the Bronson Lake Formation.

〰	Major river
—	Major road
▬	Cold Lake Air Weapons Range Boundary
🟦	Lake
■	Town
▨	Approximate Formation extents
🟨	Beaver River drainage basin area (Alberta portion)

Chloride concentration (mg/L)

●	0 - 125
●	125 - 250
●	250 - 500
●	> 500
●	Well completed in the Formation without chloride information or with suspect chemical analysis

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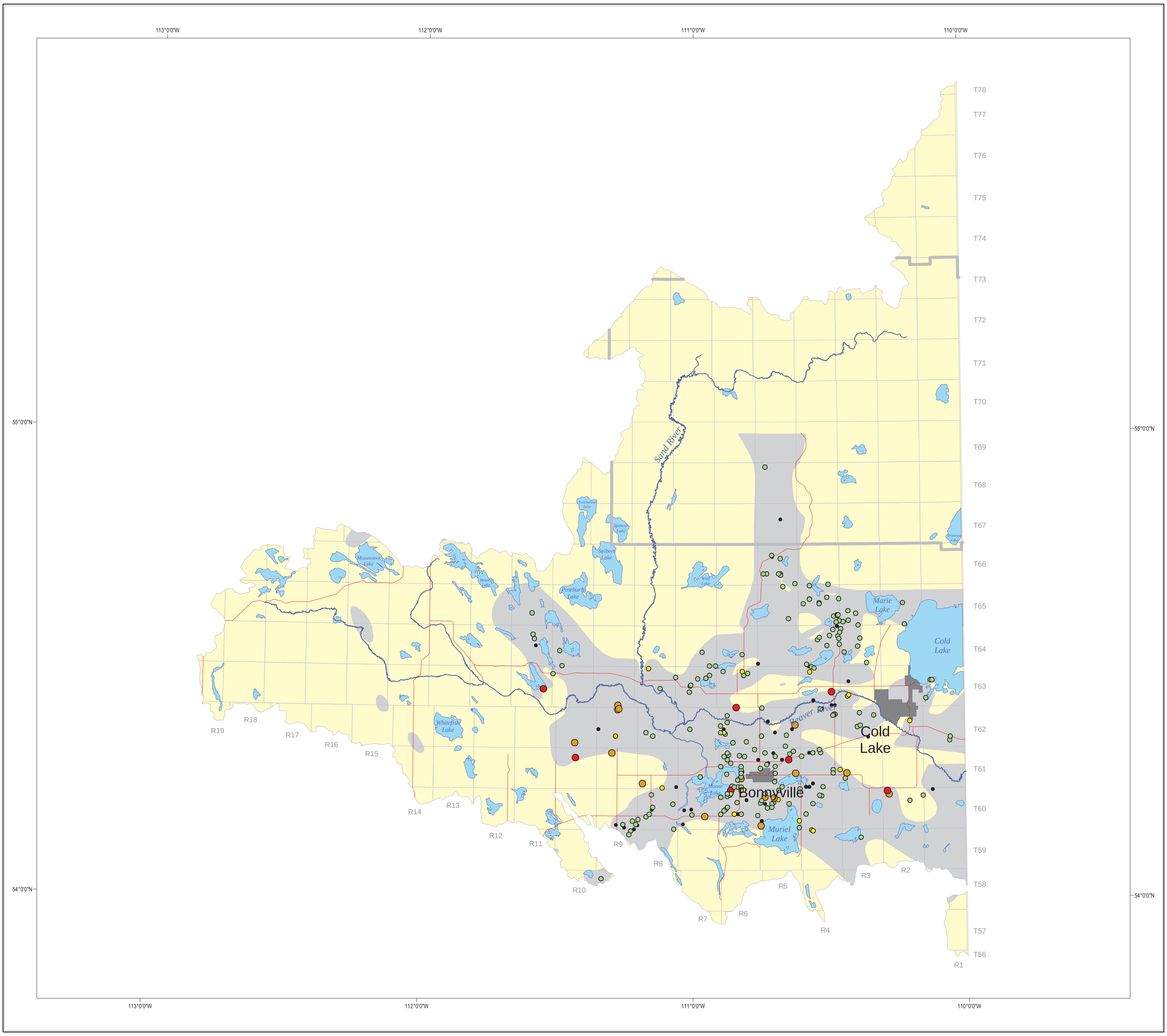

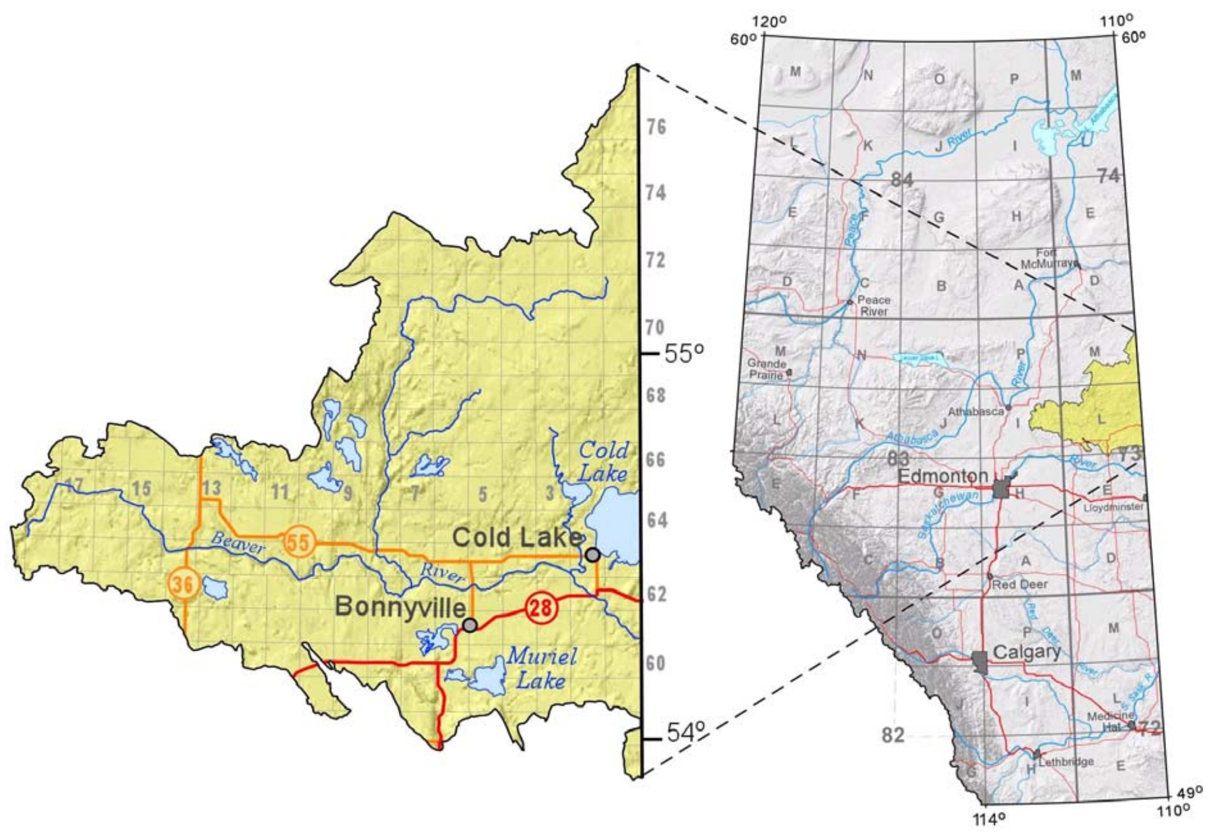

Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

〰	Major river
─	Major road
▬	Cold Lake Air Weapons Range Boundary
🟦	Lake
⬛	Town
▨	Approximate Formation extents
🟨	Beaver River drainage basin area (Alberta portion)

Chloride concentration (mg/L)

🟢	0 - 125
🟡	125 - 250
🟠	250 - 500
🔴	> 500
●	Well completed in the Formation without chloride information or with suspect chemical analysis

Figure 5.29. Chloride concentrations in the Muriel Lake Formation.

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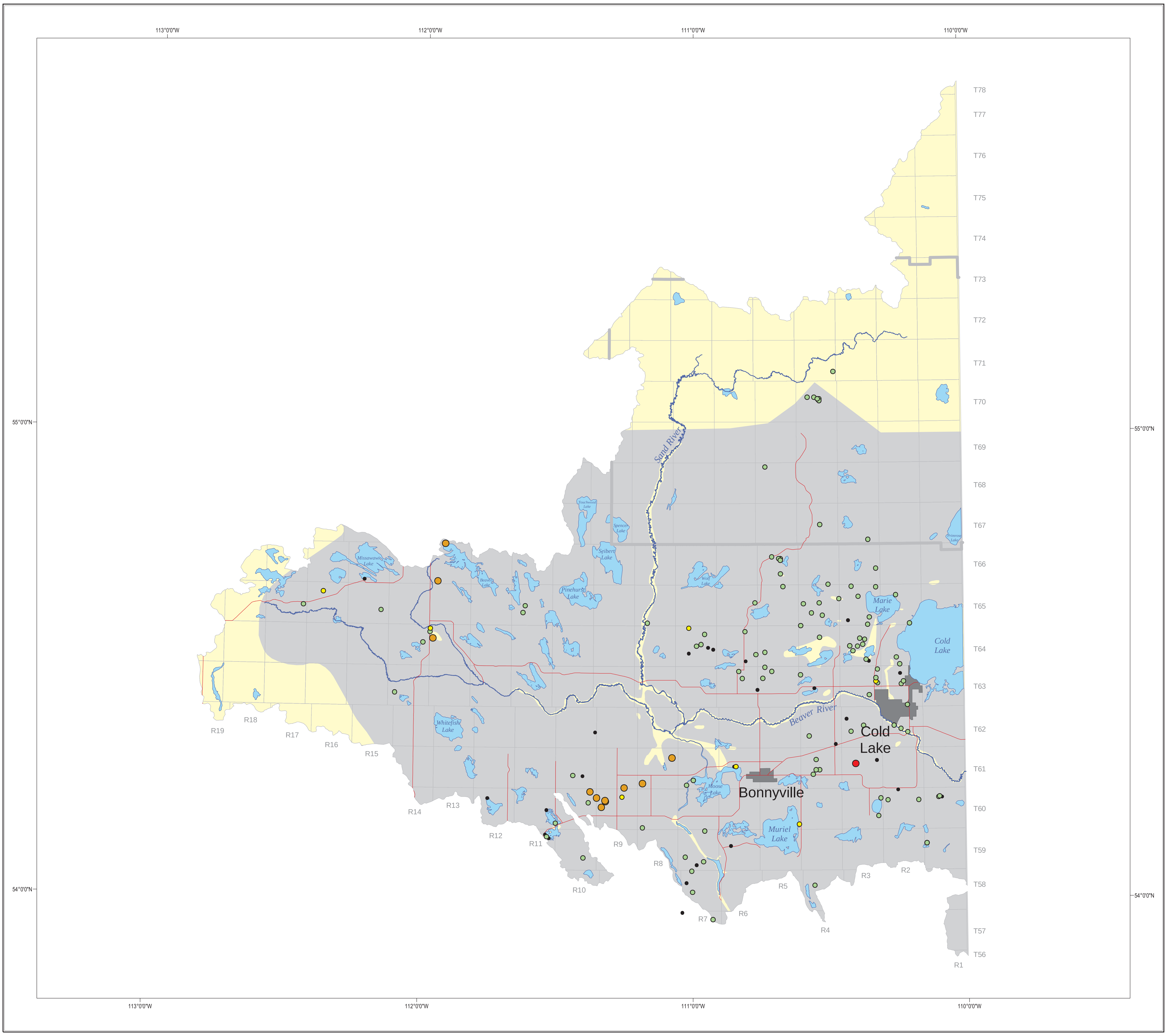

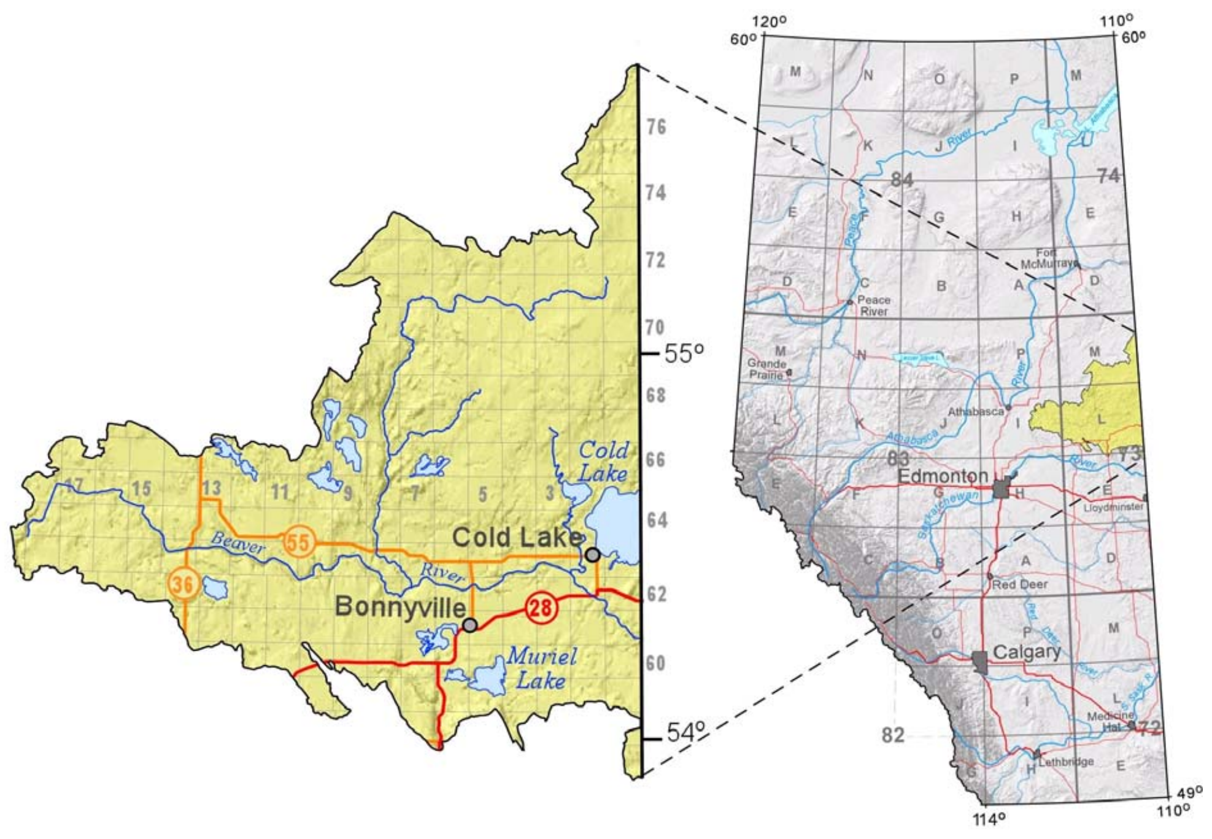

Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

〜 Major river
— Major road
— Cold Lake Air Weapons Range Boundary
🟦 Lake
⬛ Town
⬜ Approximate Formation extents
🟨 Beaver River drainage basin area (Alberta portion)

Chloride concentration (mg/L)

● 0 - 125
● 125 - 250
● 250 - 500
● > 500
● Well completed in the Formation without chloride information or with suspect chemical analysis

Figure 5.30. Chloride concentrations in the Bonnyville Formation.

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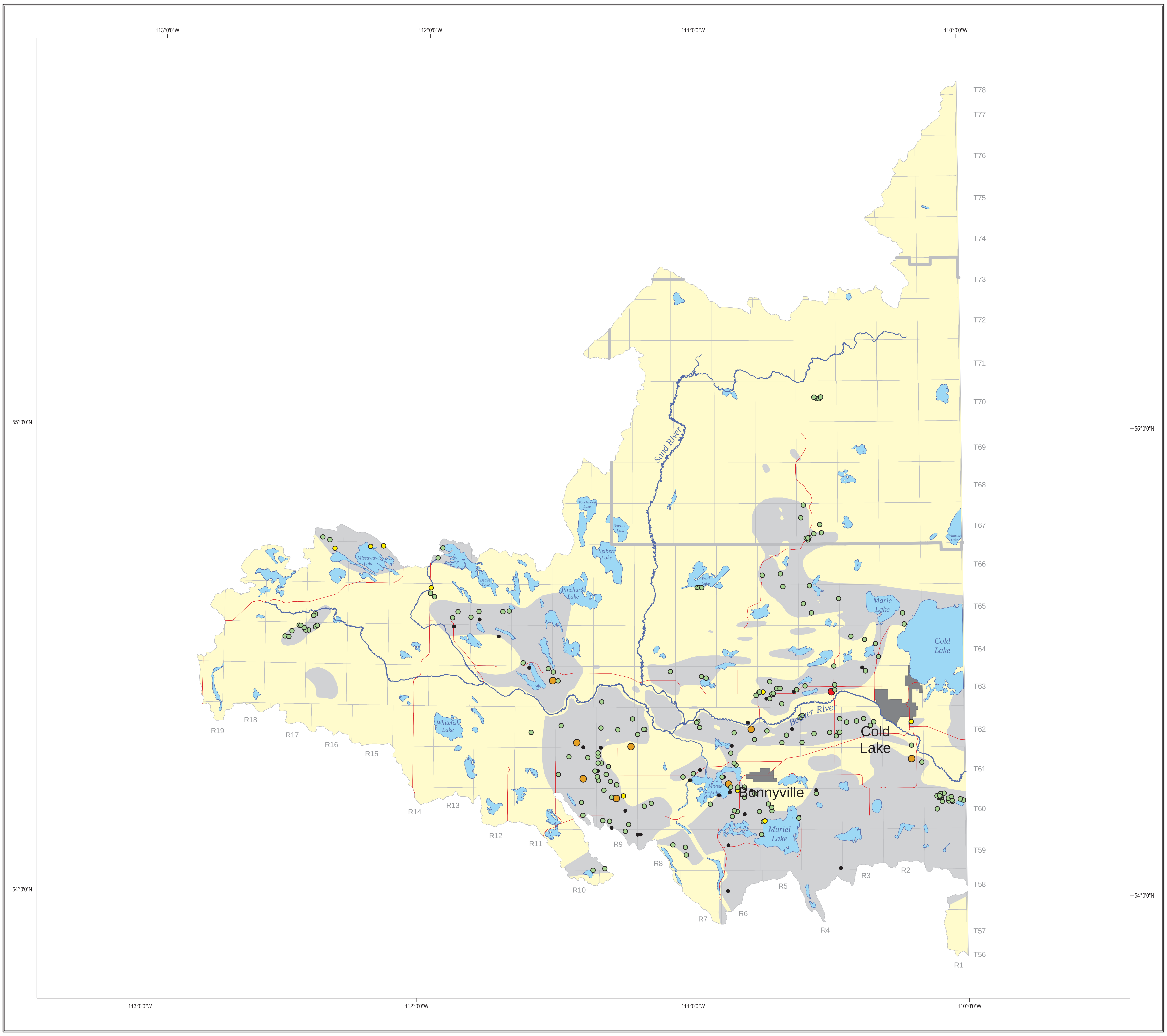

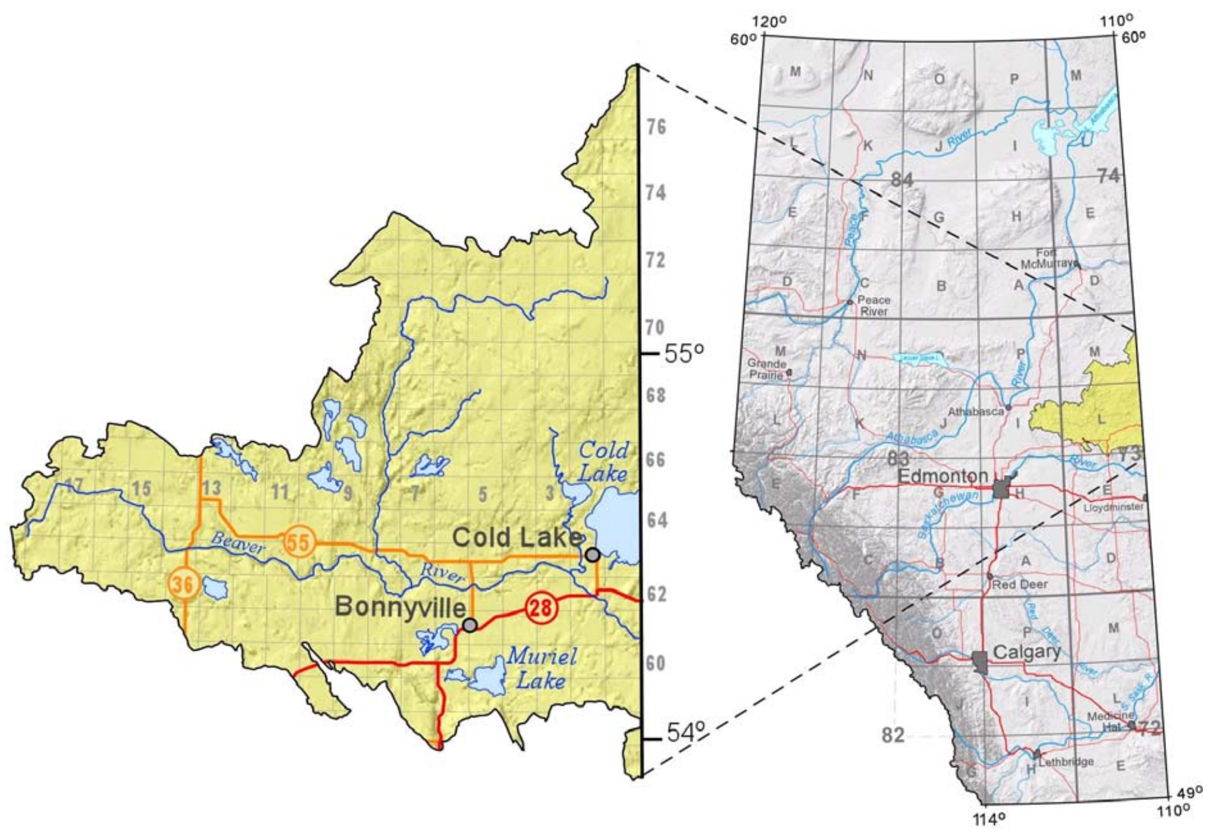

Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

〰	Major river
—	Major road
▬	Cold Lake Air Weapons Range Boundary
▨	Lake
▨	Town
▨	Approximate Formation extents
▨	Beaver River drainage basin area (Alberta portion)

Chloride concentration (mg/L)

○	0 - 125
○	125 - 250
○	250 - 500
○	> 500
●	Well completed in the Formation without chloride information or with suspect chemical analysis

Figure 5.31. Chloride concentrations in the Ethel Lake Formation.

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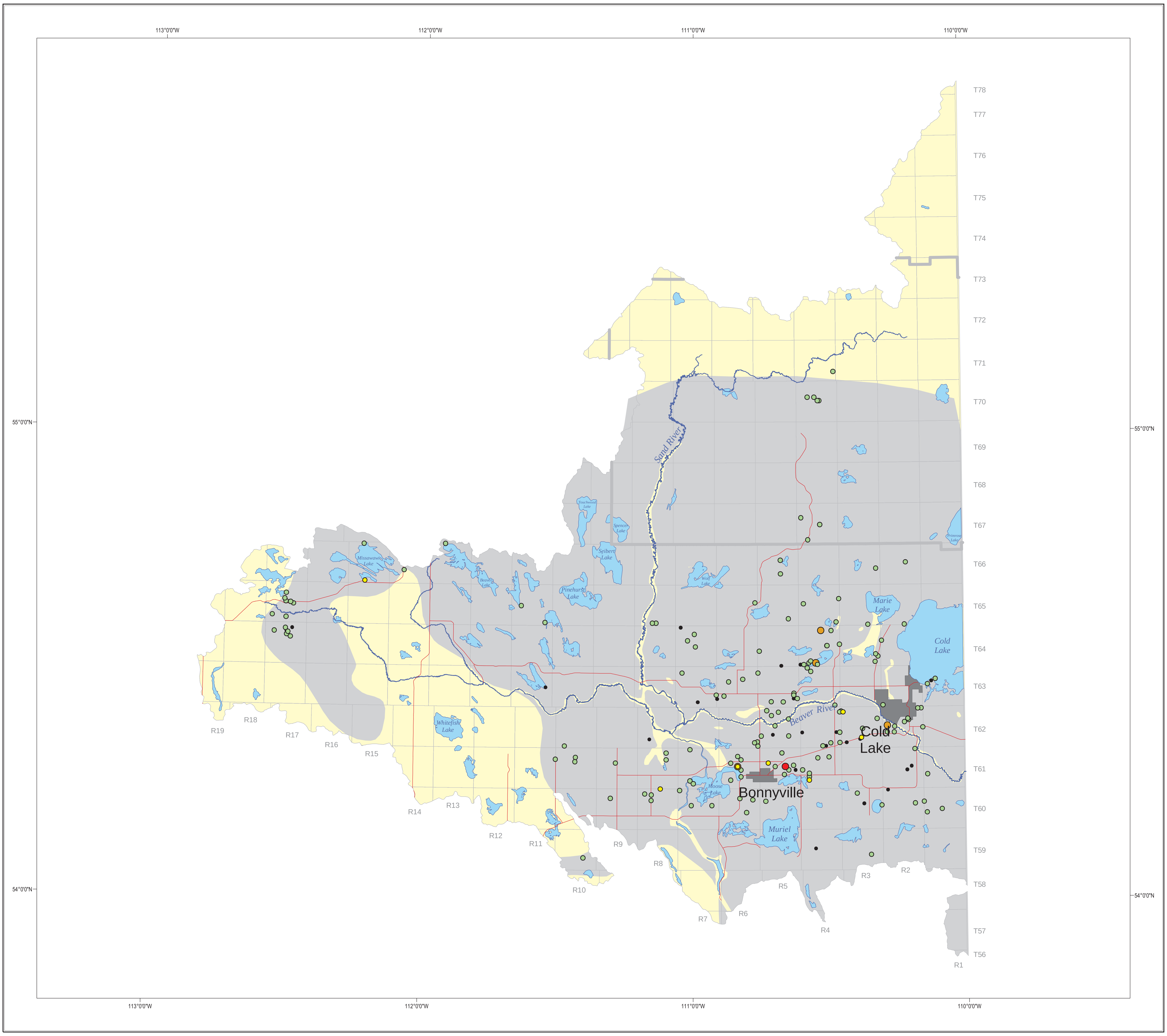
The majority of the samples in the SEBR flow system have chloride concentrations that are less than the AO and the lower limit of the irrigation water quality guideline. The samples that have exceedances of the AO water quality guideline are spread out across the flow system with the highest concentration of samples exceeding the guidelines occurring in the western portion of the flow system. The samples that exceed the lower limit of the irrigation water quality guidelines, like those that exceed the AO, are spread out across the flow system. The highest proportion of samples that exceed this value are generally located west of the town of Bonnyville. None of the samples in the SWBR flow system have chloride concentrations that exceed the water quality guidelines. Chloride concentrations are higher however in the northern portion of the flow system. Only one sample within the NWBR flow system has a chloride concentration that exceeds the AO and is located near Fork Lake. Five samples exceed the lower limit of the irrigation water quality guideline. They are mostly found in the northwestern portion of the flow system in the vicinity of Missawawi Lake.

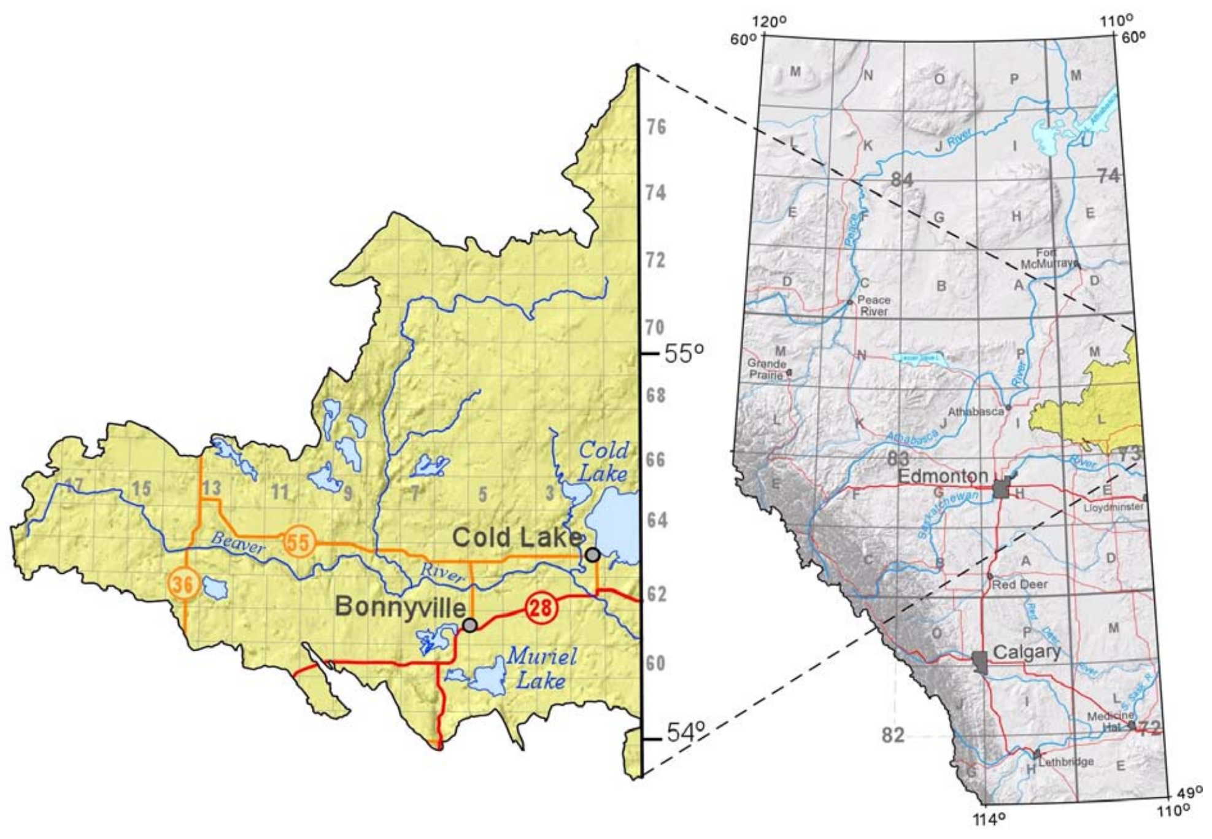
5.3.6 Marie Creek Formation

The chloride distribution in the Marie Creek Formation is presented in Figure 5.32. Samples within the Wiau flow system have chloride concentrations below the AO and the lower limit of the irrigation water quality guidelines. The majority of the samples within the NEBR flow system have chloride concentrations below the AO and the lower limit of the irrigation water quality guidelines. The two samples that exceed the AO are located to the northwest of Moore Lake. The remaining sample that exceeds the lower limit of the irrigation water quality guidelines is located in the southern portion of the flow system. The majority of the samples within the SEBR flow system have chloride values that are below the AO and lower limit of the irrigation water quality guidelines. Those samples that do exceed the AO are located near the town of Bonnyville and city of Cold Lake. The remaining samples that show exceedances of the lower limit of the irrigation water quality guidelines are located along the major road networks within the flow system. None of the samples from the SWBR flow system exceed the water quality guidelines. Higher concentrations of chloride are encountered in the northern portion of the flow system. The majority of the samples from the NWBR flow system have chloride concentrations that fall below the AO and irrigation water quality guidelines. Those that exceed AO, or irrigation water quality guidelines are located in the northern portion of the flow system in the vicinity of Missawawi Lake.

5.3.7 Sand River Formation

The chloride distribution in the Sand River Formation is presented in Figure 5.33. All of the samples within the NEBR have chloride concentrations below the AO. The majority of the samples have chloride concentrations below the lower limit of the irrigation water quality guidelines. Those three samples that exceed the irrigation water quality guideline are located in the vicinity of the city of Cold Lake. The majority of the samples from the SEBR flow system have chloride concentrations below the AO and lower limit of the irrigation water quality guidelines. Those samples that exceed the AO or the irrigation water quality guideline are located in the vicinity of the town of Bonnyville, or along the major road network within the flow system. Three main clusters of samples are found within the SWBR flow system. Most chloride concentrations within these samples are below the AO or irrigation water quality guidelines. The sample that exceeds the AO is located in the southern portion of the flow system. Those samples that exceed the irrigation water quality guideline are found in the central and northern cluster of wells. Only one of the samples in the NWBR flow system exceeds the lower limit of the irrigation water quality guideline value. It is located along the Beaver River in the western portion of the flow system.





Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

Figure 5.32. Chloride concentrations in the Marie Creek Formation.

〰	Major river
—	Major road
—	Cold Lake Air Weapons Range Boundary
🟦	Lake
■	Town
■	Approximate Formation extents
🟨	Beaver River drainage basin area (Alberta portion)

Chloride concentration (mg/L)

●	0 - 125
●	125 - 250
●	250 - 500
●	> 500
●	Well completed in the Formation without chloride information or with suspect chemical analysis

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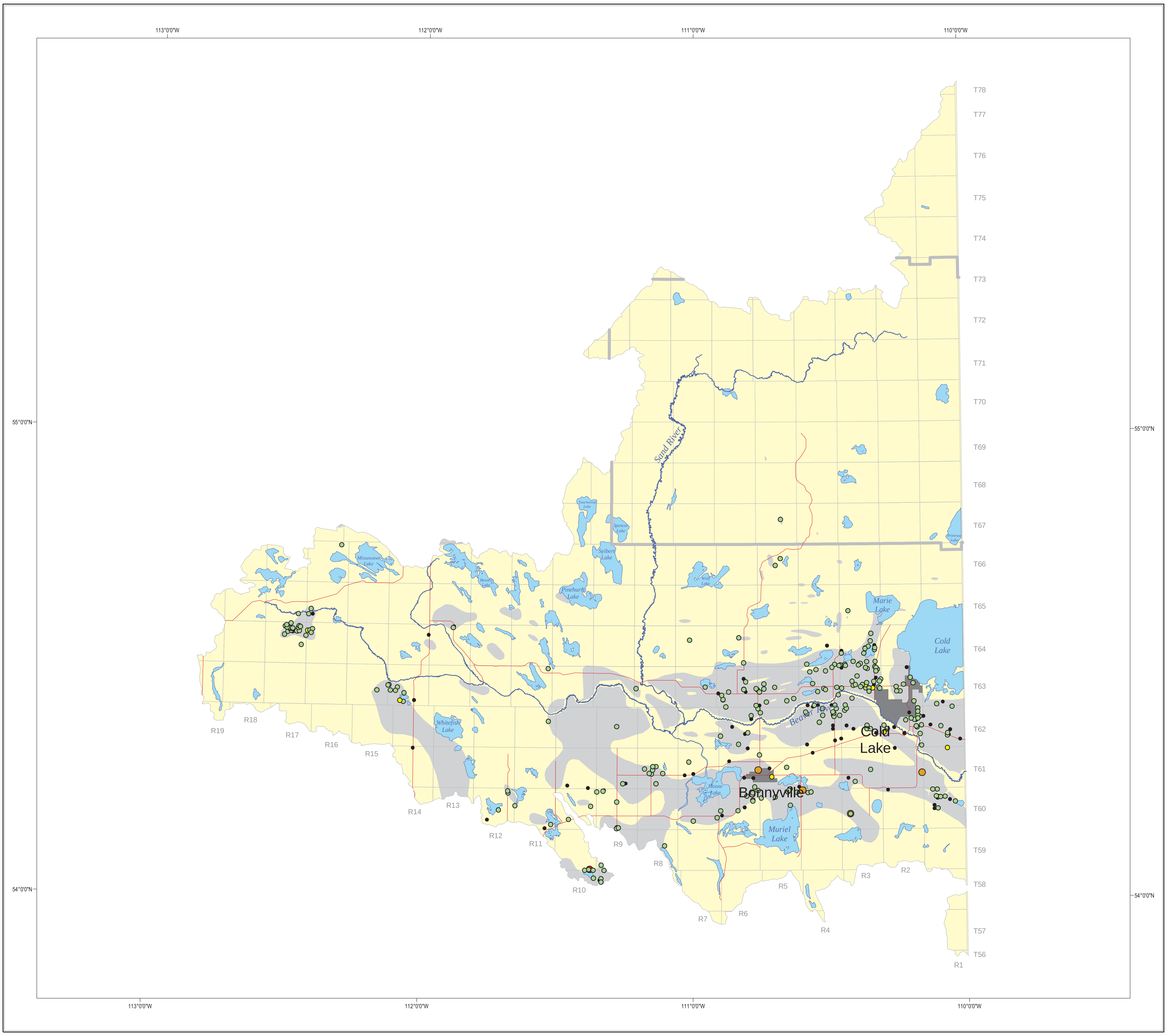

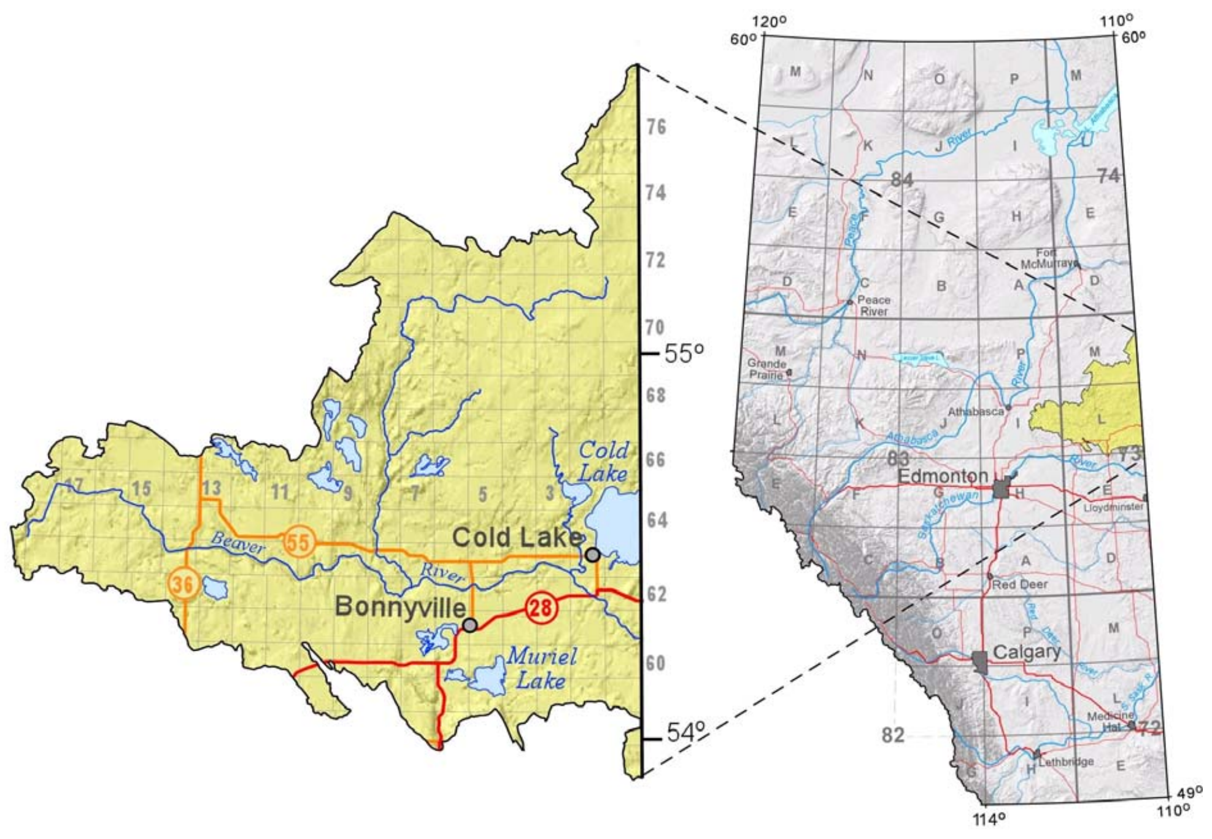

Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

- 〰 Major river
- ― Major road
- ▬ Cold Lake Air Weapons Range Boundary
- 🟦 Lake
- ■ Town
- ▨ Approximate Formation extents
- 🟨 Beaver River drainage basin area (Alberta portion)

Chloride concentration (mg/L)

- ● 0 - 125
- ● 125 - 250
- ● 250 - 500
- ● > 500
- ● Well completed in the Formation without chloride information or with suspect chemical analysis

Figure 5.33. Chloride concentrations in the Sand River Formation.

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5.3.8 Grand Centre Formation

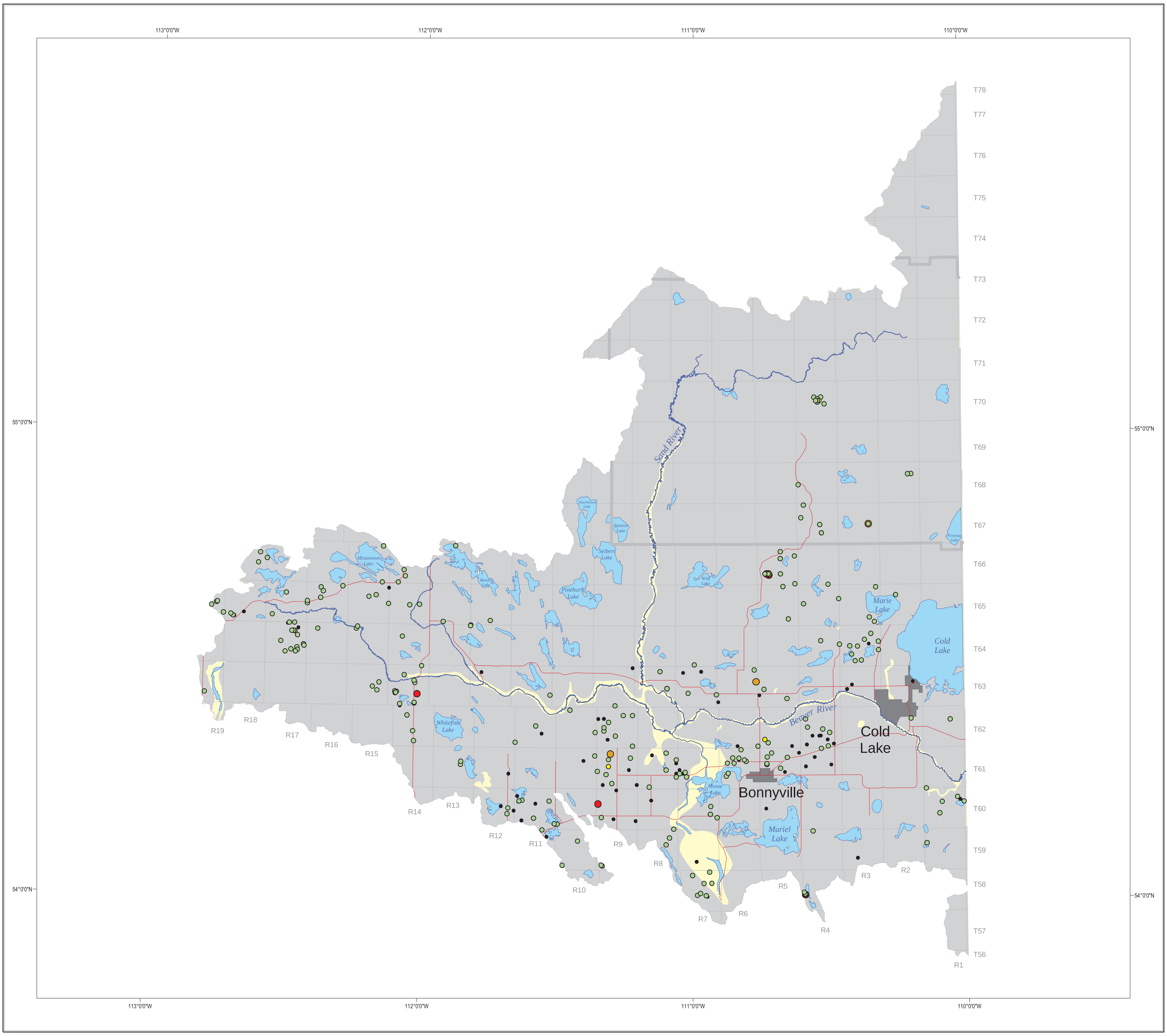
The chloride distribution in the Grand Centre Formation is presented in Figure 5.34. None of the samples in the Wiau flow system exceeds the AO, but two of the samples exceed the lower limit of the irrigation water quality guideline. The majority of the samples within the NEBR flow system have chloride concentrations below the AO and irrigation water quality guidelines. Samples that exceed the lower limit value of the irrigation water quality guideline are located east of Wolf Lake, east of Burnt Lake, southeast of Osborne Lake and in the southwestern corner of the flow system. The wells that exceed the AO are located east of Wolf Lake, east of Burnt Lake and southeast of Osborne Lake. The samples that exceed the upper limit value of the irrigation water quality guideline are located east of Wolf Lake. The majority of the samples in the SEBR flow system have chloride concentrations below the AO and irrigation water quality guideline values. Those samples that exceed the lower limit value of the irrigation water quality guideline are located north of the town of Bonnyville, south of Moose Lake, along the road network in the western portion of the flow system, and in the vicinity of the Garnier Lakes. The samples that exceed the AO are located in the vicinity of the Garnier Lakes and along the road network in the western portion of the flow system. The sample that exceeds the upper limit value of the irrigation water quality guideline is located along the road network in the western portion of the flow system. Three samples within the SWBR flow system exceed the lower limit value of the irrigation water quality guideline. These samples are located within the three main clusters of data points. One of those samples exceeds the AO and upper limit value for chloride in irrigation water as well. This sample is located along the Beaver River in the central portion of the flow system. None of the samples in the NWBR flow system exceed water quality guidelines. The higher chloride concentrations are located in the western portion of the flow system.

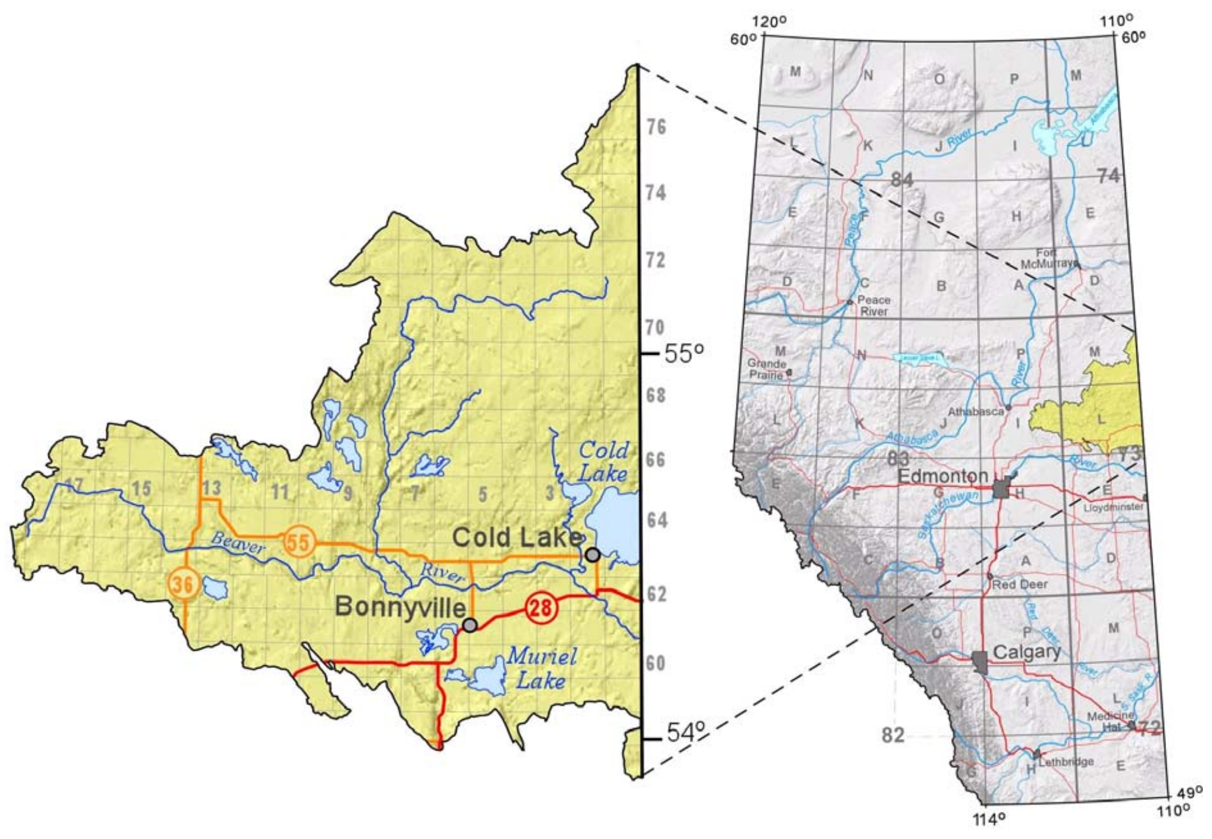
5.3.9 Changes in Chloride Concentrations Over Time

For historical comparisons, the available data that passed the quality screening were first segregated by flow system, aquifer group (the Empress 1 Formation alone, the channel group being the Empress 2 to Muriel Lake Formations; the intermediate group being the Bonnyville to Ethel Lake Formations; and shallow group being the Marie Creek to Grand Centre Formations), and by decade of analysis. These data were compared to each other and to the relevant Canadian drinking-water quality guideline over time and by flow system through the use of comparative notched box plots. The values used to make the box plots were the most recent by decade if multiple values or multiple sampling events existed for a given location. The box plot is a useful tool in describing the frequency distribution of data. The various elements of a notched box plot are presented in Figure 5.35. The results of this analysis show that the median concentrations of chloride has remained below the drinking water guidelines across the Basin and do not appear to be changing over time (Figure 5.36 and Figure 5.37). The number of incidents of detectable chloride above the drinking water guidelines in the NEBR flow system may be increasing over time in deep formations but so is the number of monitoring wells, so the significance of this observation is unknown. The spatial, temporal and geological variability between each sample site makes statistical analysis very challenging and may invalidate many statistical techniques. However, certain techniques could likely be applied at specific locations with appropriate data quality and quantity. Time series analysis as described by Box et al., (1994), is one such technique.

5.4 Distribution of Arsenic

The nature of the geological material in the Basin suggests that a natural source of arsenic is possible for the observed arsenic. Concerns have been raised over the possible connection between industrial activity and arsenic concentrations. The possible natural sources of arsenic in groundwater, and its geochemical





Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

- Major river
- Major road
- Cold Lake Air Weapons Range Boundary
- 🟦 Lake
- ▨ Town
- ▨ Approximate Formation extents
- 🟨 Beaver River drainage basin area (Alberta portion)

Chloride concentration (mg/L)

●	0 - 125
●	125 - 250
●	250 - 500
●	> 500
●	Well completed in the Formation without chloride information or with suspect chemical analysis

Figure 5.34. Chloride concentrations in the Grand Centre Formation.

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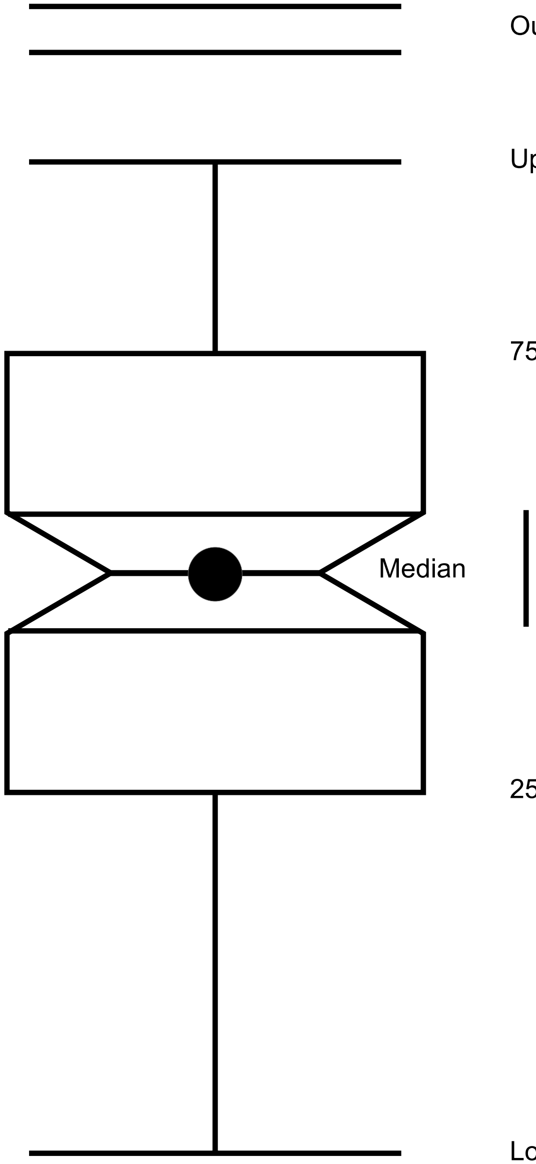

Outside values

Upper adjacent value = largest observation within one step of the 75th percentile

75th percentile

95% confidence limit about the median, where this interval overlaps between adjacent box plots, the medians are similar within the 95% confidence limit

25th percentile

Lower adjacent value = smallest observation within one step of the 25th percentile
A step is conventionally defined as 1.5 x (75th percentile value - 25th percentile value)

Figure 5.35. Explanation of the notched box plot.

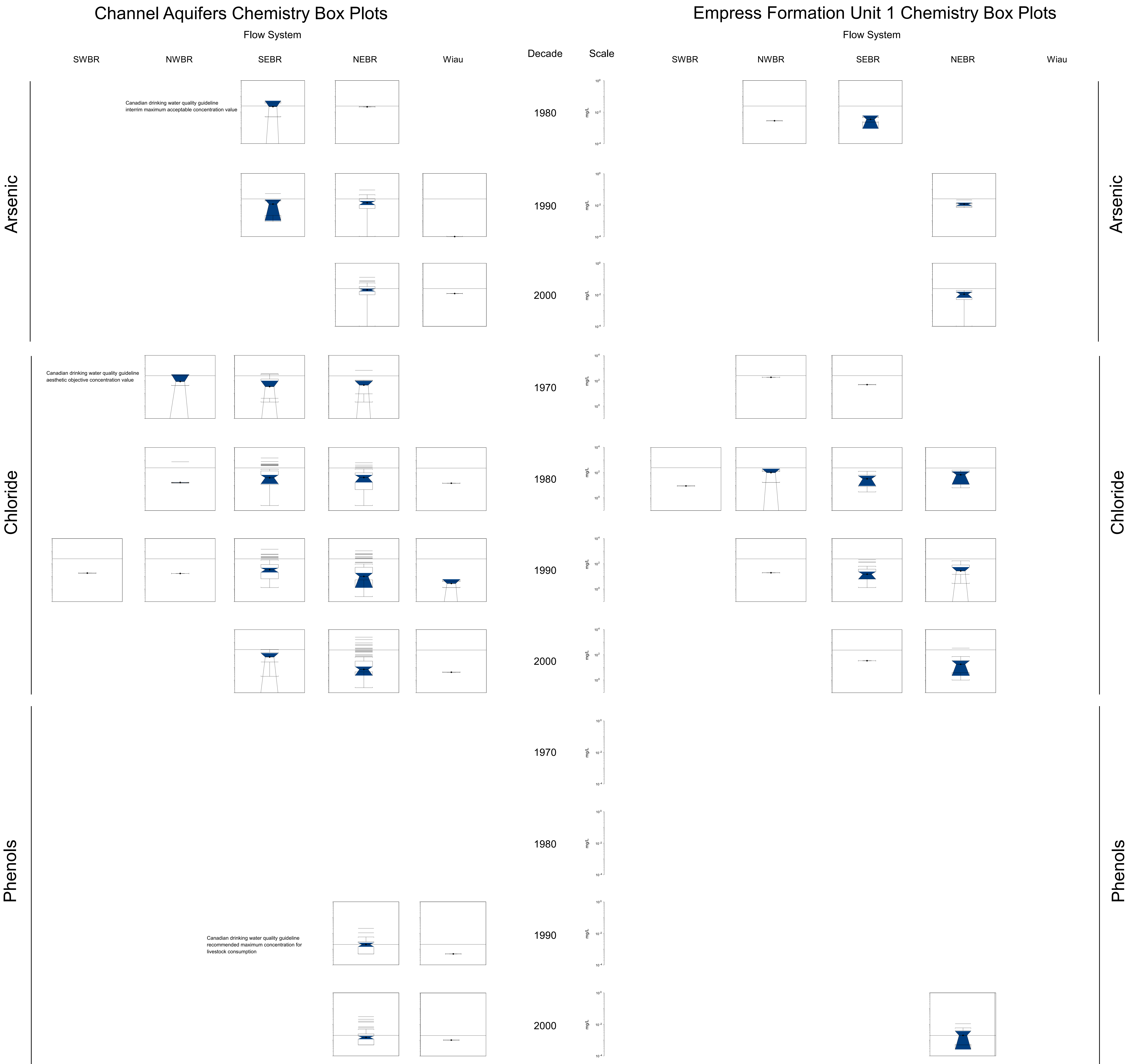

Figure 5.36. Notched box plots of arsenic, chloride and phenols for the Channel aquifers and Empress Formation Unit 1.

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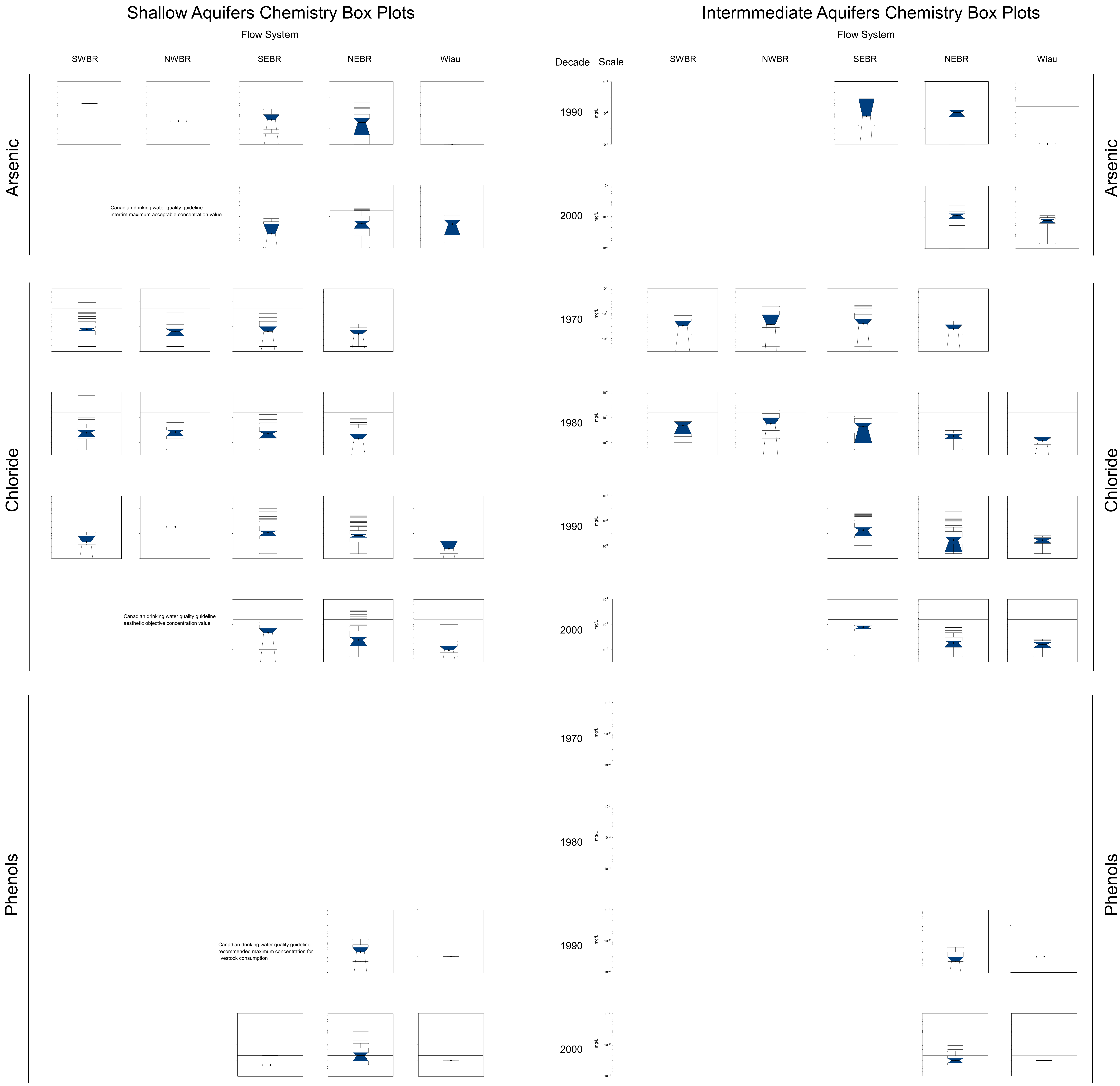


Figure 5.37. Notched box plots of arsenic, chloride and phenols for the Shallow and Intermmediate aquifers.

characteristics are discussed in Section 3.2.3.2. Environmental quality guidelines have been established for arsenic concentrations in water. These guidelines are presented below (Table 7).

Table 7. Canadian environmental quality guidelines for arsenic in water (CCME, 2003).

Water – Community Use		Freshwater Aquatic Life	Water – Agricultural Use	
			Irrigation	Livestock
IMAC	AO			
(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
0.025	-	0.005	0.1	0.025

Some of the arsenic concentrations in the drift aquifers in the Basin exceed some or all of the environmental quality guidelines. The following table (Table 8) contains a summary of the exceedances of arsenic concentration environmental water quality guidelines captured in the water quality database. The first column (Formation) lists the drift formations. The second column (Range of Values) presents the minimum and maximum concentration values for the Formation. The third column (N) presents the total number of records for a given Formation. The fourth column (ND) presents the number of records that were below the detection limit of the analysis. The fifth column (Water-Community Use) presents the number of records that exceed the water for community use guideline value where IMAC is the interim maximum acceptable concentration. The sixth column (Freshwater Aquatic Life) presents the number of records that exceed the freshwater aquatic life guideline value. The seventh column (Water-Agricultural Use) presents the number of records that exceed agricultural water use guideline values.

Table 8. Arsenic exceedances summary.

Formation	Range of Values		N	ND	Water – Community Use	Freshwater Aquatic Life	Water – Agricultural Use	
	Min (mg/L)	Max (mg/L)			IMAC		Irrigation	Livestock
Grand Centre	<0.0002	0.073	467	192	14	99	0	14
Sand River	0.0002	0.0452	107	2	10	84	0	10
Marie Creek	<0.001	0.061	287	16	39	201	1	39
Ethel Lake	<0.001	0.105	213	18	24	146	1	24
Bonnyville	<0.0002	0.077	582	35	117	411	0	117
Muriel Lake	<0.0002	0.145	730	26	214	611	6	214
Bronson Lake	0.0002	0.053	19	0	12	17	0	12
Empress	<0.001	0.361	1001	41	218	807	8	218

While the values above summarize the database contents, the following table (Table 9) describes the exceedances of the most recently collected data on arsenic concentrations.

Table 9. Arsenic exceedances summary - most recent values.

Formation	Range of Values		N	ND	Water – Community Use	Freshwater Aquatic Life	Water – Agricultural Use	
	Min (mg/L)	Max (mg/L)			IMAC		Irrigation	Livestock
Grand Centre	<0.001	0.04	68	16	2	20	0	2
Sand River	0.0002	0.0452	36	0	4	21	0	4
Marie Creek	0.0006	0.055	27	0	4	17	0	4
Ethel Lake	<0.001	0.0805	27	1	7	22	0	7
Bonnyville	0.0002	0.055	55	1	9	36	0	9
Muriel Lake	0.0009	0.129	57	0	23	45	1	23
Bronson Lake	0.0002	0.053	4	0	3	3	0	3
Empress	<0.001	0.078	55	2	12	42	0	12

The distribution of the most recently collected data on arsenic concentrations in the various formations is presented in Figure 5.38, Figure 5.39, Figure 5.40, Figure 5.41, Figure 5.42, Figure 5.43, Figure 5.44 and Figure 5.45.

5.4.1 Empress Formation

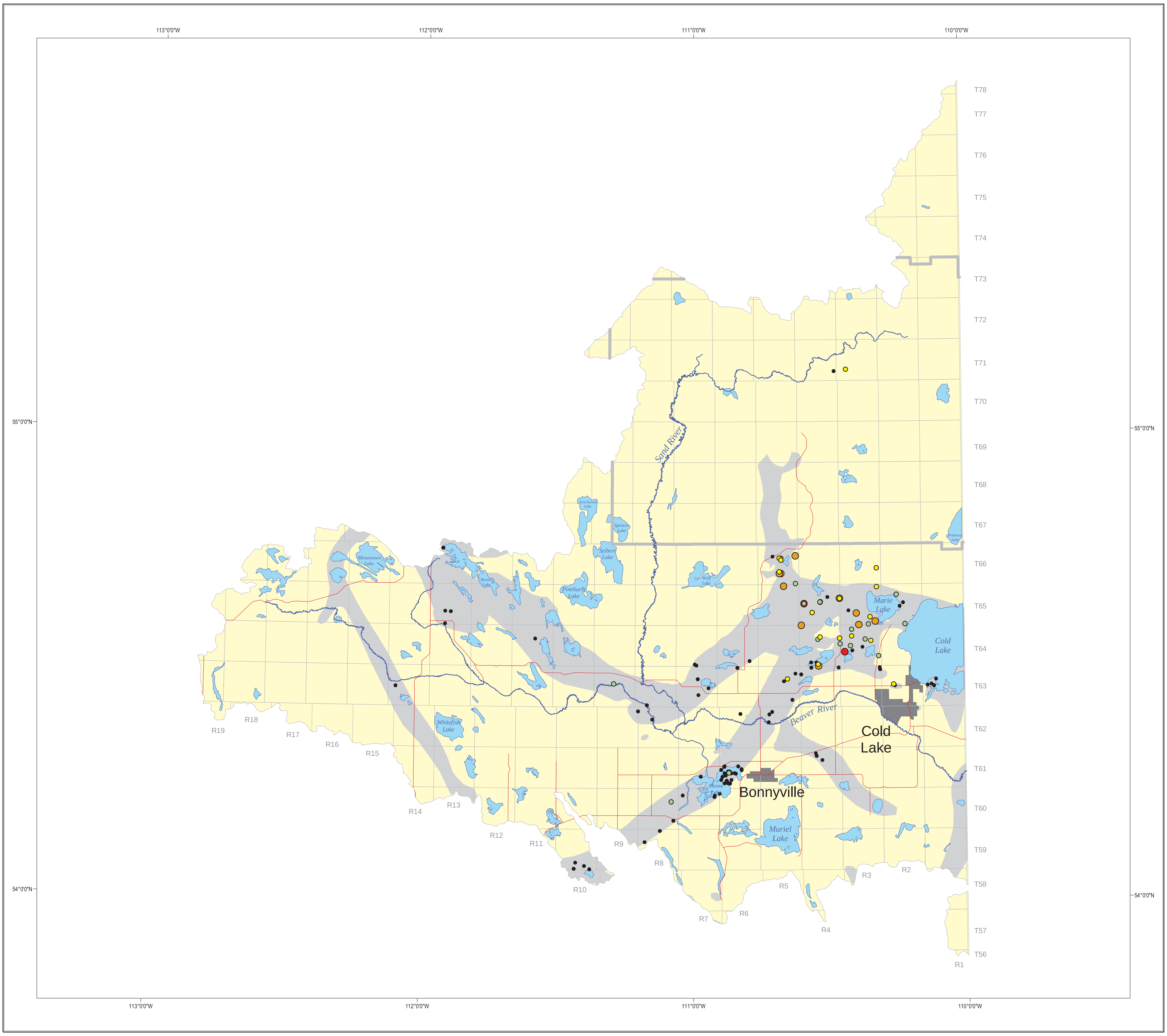
The arsenic concentration distribution is presented in Figure 5.38. The sample from the Wiau flow system only exceeds the freshwater aquatic life guideline value. All but nine of the samples in the NEBR flow system exceed the water quality guidelines for fresh water aquatic life. Twelve of the samples exceed the IMAC and livestock water quality guideline values. These samples are located in the central portion of the aquifer within the flow system. None of these samples exceed the irrigation water quality guidelines. The two samples from the SEBR flow system are below the established water quality guidelines. No obvious spatial relationship in arsenic concentration can be discerned from the data distribution. The concentration of arsenic in the sample from the NWBR flow system is below the established water quality guidelines.

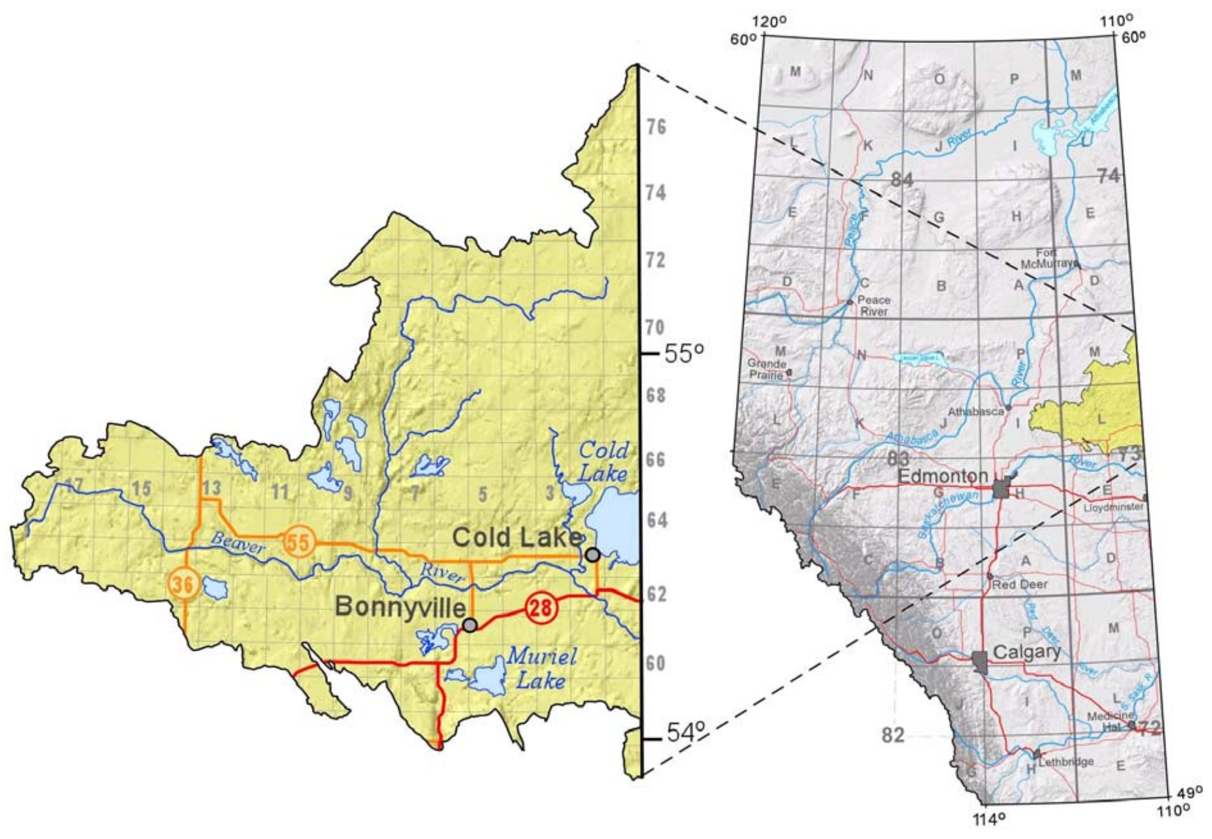
5.4.2 Bronson Lake Formation

The arsenic concentration distribution is presented in Figure 5.39. Two of the three samples from the NEBR flow system exceed the IMAC and freshwater aquatic life guideline values. The sample from the SEBR flow system exceeds the IMAC and freshwater aquatic life guideline values. No obvious spatial relationship can be discerned based on the data distribution.

5.4.3 Muriel Lake Formation

The arsenic concentration distribution is presented in Figure 5.40. All but eight of the samples in the NEBR flow system exceed the fresh water aquatic life guideline values. Twenty-two of the samples exceed the IMAC water quality guideline. One of the samples exceeds the irrigation water quality guideline value. Six of the samples in the SEBR exceed the fresh water aquatic guideline values. One of the samples exceeds the IMAC water quality guideline. No obvious spatial relationships are visible in the arsenic concentrations within the various flow systems.





Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

〰	Major river
―	Major road
▬	Cold Lake Air Weapons Range Boundary
▨	Lake
▨	Town
▨	Approximate Formation extent
▨	Beaver River drainage basin area (Alberta portion)

Arsenic concentration (mg/L)

●	0.000 - 0.010
●	0.010 - 0.025
●	0.025 - 0.050
●	> 0.050
●	Well completed in the Formation without arsenic information or with suspect chemical analysis

Figure 5.38. Arsenic concentrations in the Empress Formation.

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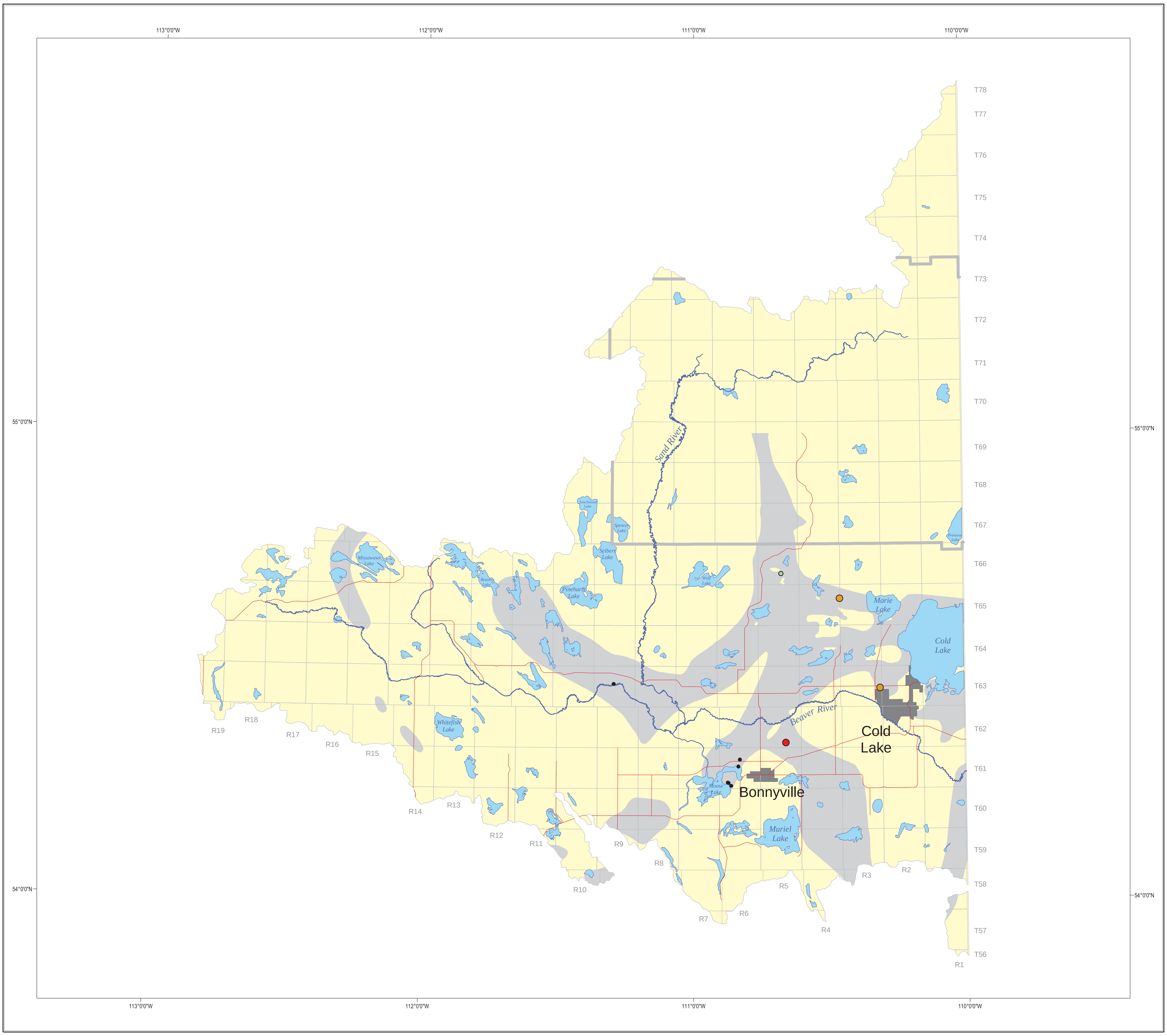

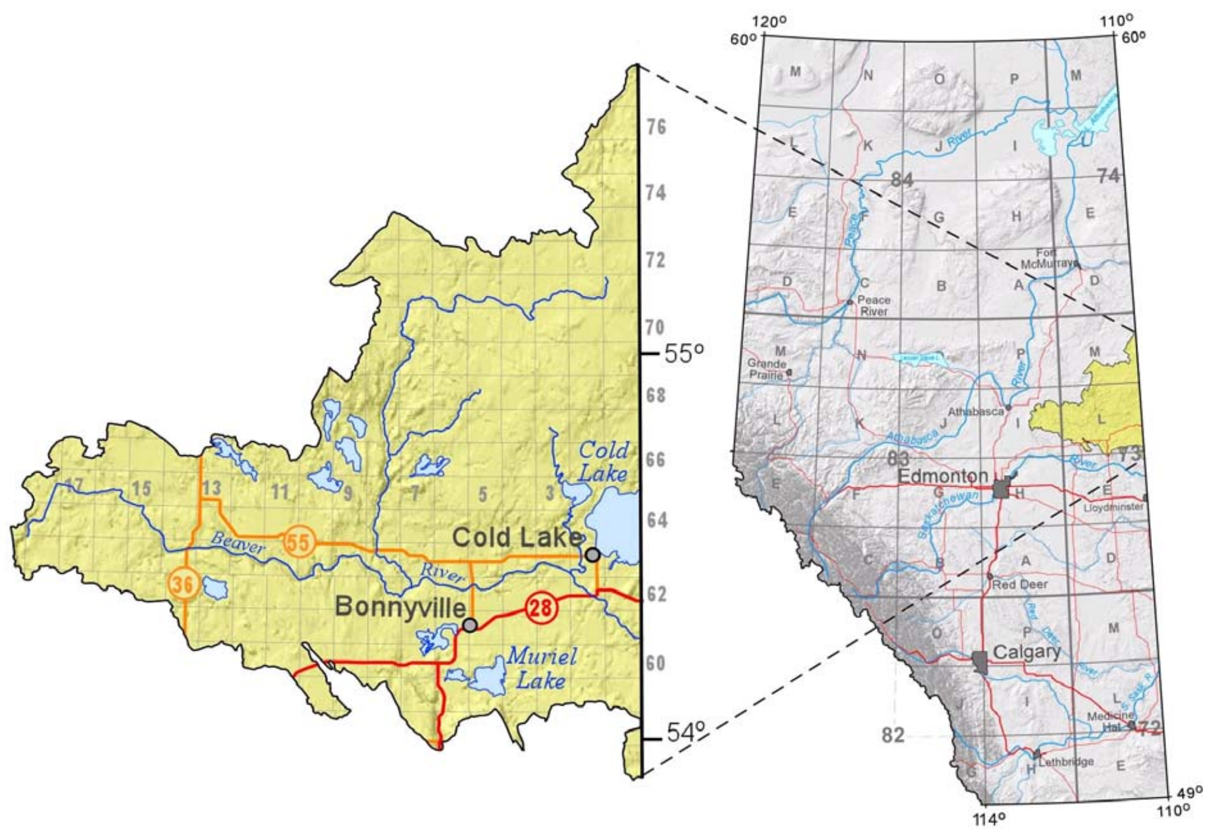

Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

〰	Major river
—	Major road
—	Cold Lake Air Weapons Range Boundary
▨	Lake
▨	Town
▨	Approximate Formation extent
▨	Beaver River drainage basin area (Alberta portion)

Arsenic concentration (mg/L)

●	0.000 - 0.010
●	0.010 - 0.025
●	0.025 - 0.050
●	> 0.050
●	Well completed in the Formation without arsenic information or with suspect chemical analysis

Figure 5.39. Arsenic concentrations in the Bronson Lake Formation.

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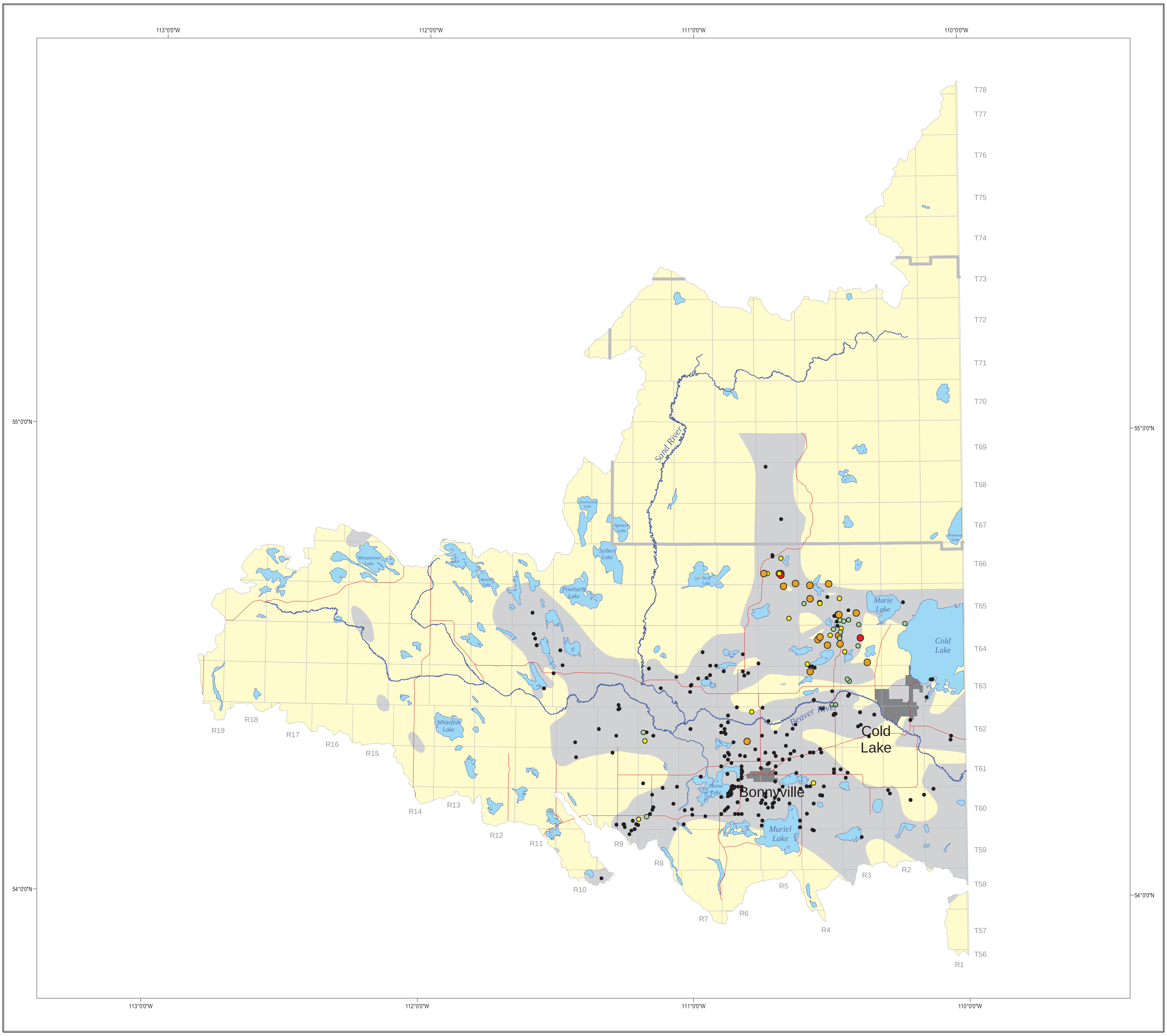

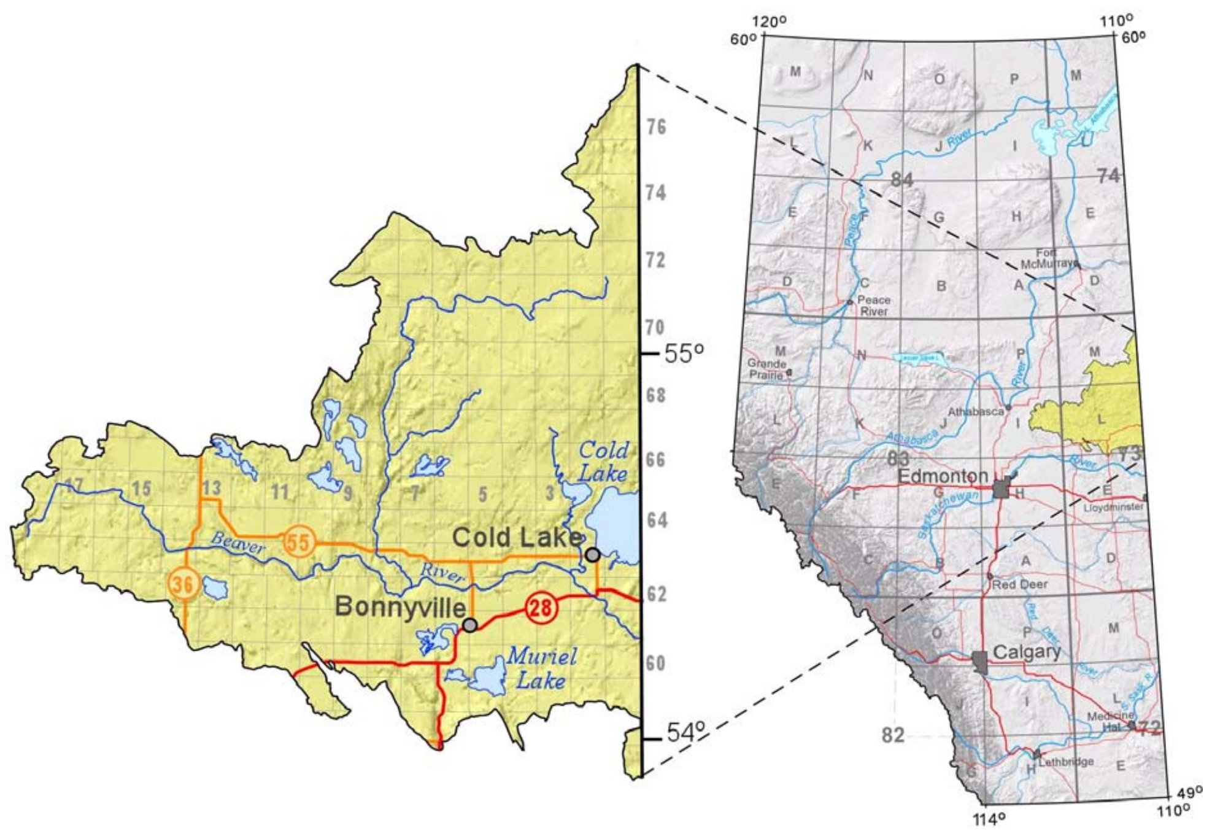

Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

〰	Major river
—	Major road
▬	Cold Lake Air Weapons Range Boundary
🟦	Lake
■	Town
▨	Approximate Formation extent
🟨	Beaver River drainage basin area (Alberta portion)

Arsenic concentration (mg/L)

●	0.000 - 0.010
●	0.010 - 0.025
●	0.025 - 0.050
●	> 0.050
●	Well completed in the Formation without arsenic information or with suspect chemical analysis

Figure 5.40. Arsenic concentrations in the Muriel Lake Formation.

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5.4.4 Bonnyville Formation

The arsenic concentration distribution is presented in Figure 5.41. The majority of the samples in the Wiau flow system exceed the freshwater aquatic life guideline, but not the IMAC guideline. The data distribution precludes any conclusions regarding spatial distribution of arsenic concentrations. The majority of the water samples in the NEBR flow system have arsenic concentrations that exceed the freshwater aquatic life guidelines. The distribution of the arsenic concentrations does not appear to have a spatial relationship. The one sample from the SEBR flow system is below the freshwater aquatic life guideline value.

5.4.5 Ethel Lake Formation

The arsenic concentration distribution is presented in Figure 5.42. Two of the four samples in the Wiau flow system exceed the fresh water aquatic life guideline value. None of the samples exceed the IMAC value. The majority of the samples from the NEBR flow system exceed the fresh water aquatic life guideline value. Six of the samples exceed the IMAC value. No obvious spatial relationship in arsenic concentrations is visible. Both of the samples from the SEBR flow system exceed the fresh water aquatic life guideline value and one exceeds the IMAC value. The value that exceeds the IMAC value is along the Beaver River.

5.4.6 Marie Creek Formation

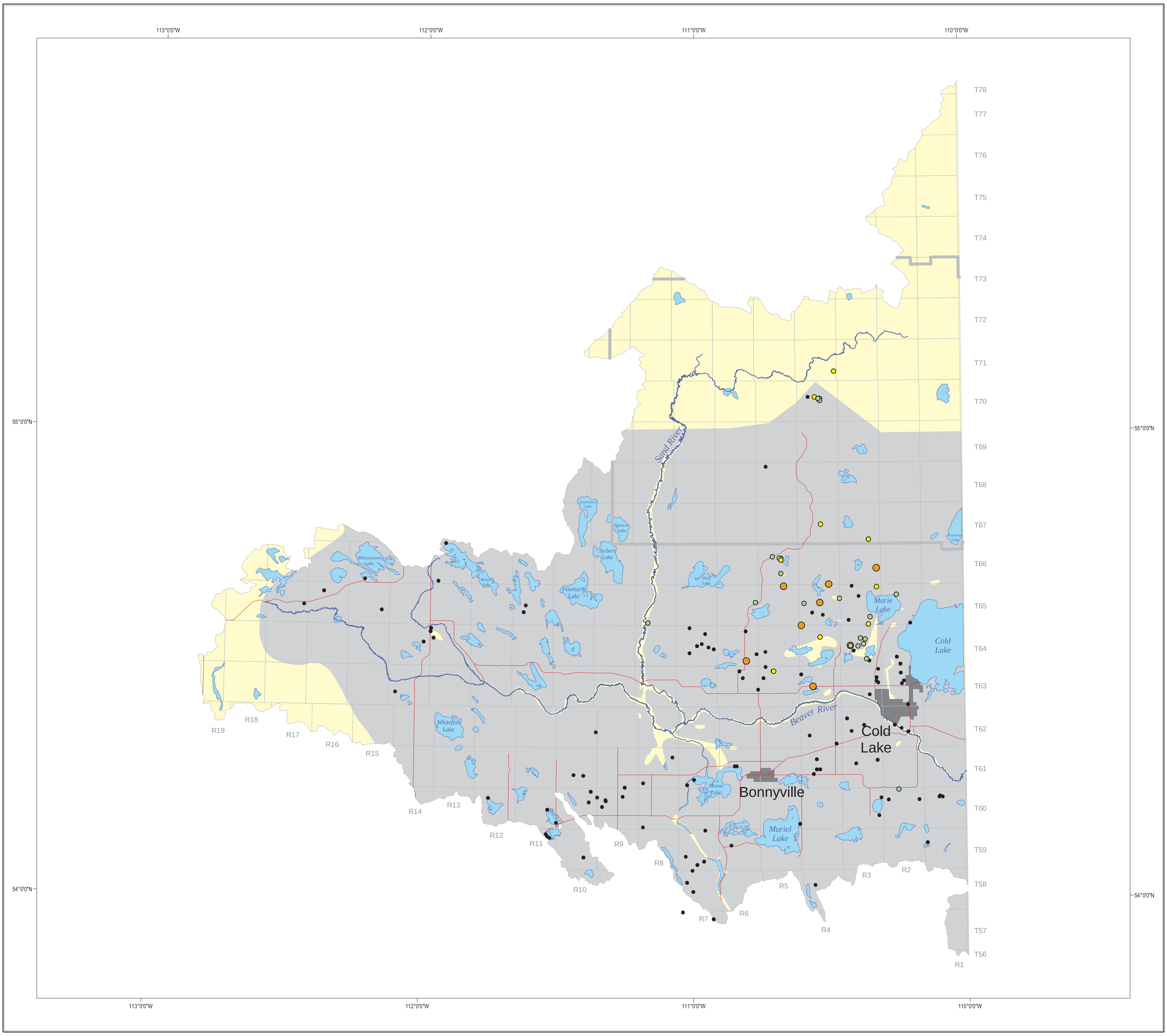
The arsenic concentration distribution is presented in Figure 5.43. The majority of the samples in the Wiau flow system exceed the fresh water aquatic life guideline value. These samples occur in the large cluster of sample points. The majority of the samples in the NEBR flow system exceed the fresh water aquatic life guideline value. The samples that exceed the IMAC values are located within the southern portion of the data region. One of the samples from the SEBR flow system exceeds the fresh water aquatic life guideline. The higher arsenic concentration occurs in the sample adjacent to the Beaver River.

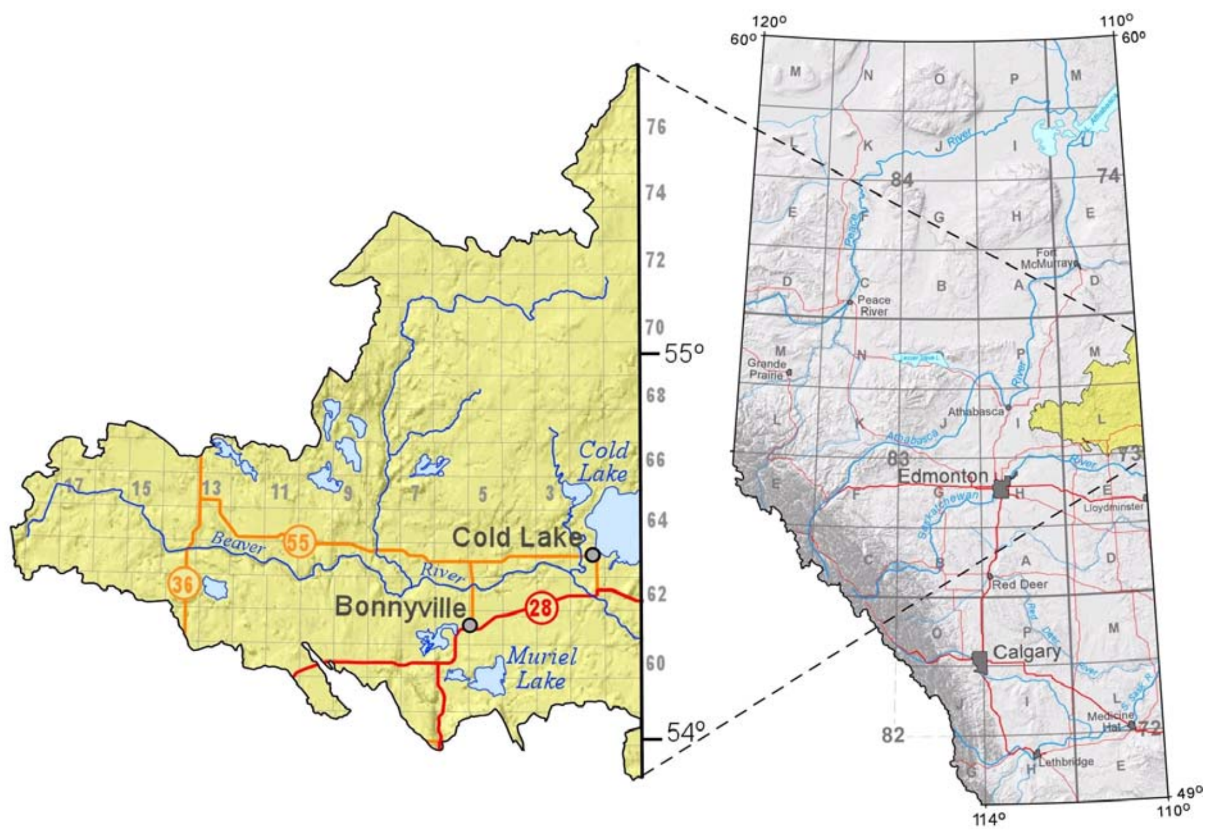
5.4.7 Sand River Formation

The arsenic concentration distribution is presented in Figure 5.44. The majority of the samples in the NEBR exceeded the fresh water aquatic life guidelines. Those samples exceeding the IMAC value are located north of Ethel Lake, and south of Moore Lake. One of the two samples in the SEBR flow system exceeds the fresh water aquatic life value.

5.4.8 Grand Centre Formation

The arsenic concentration distribution is presented in Figure 5.45. Thirteen of the samples in the NEBR flow system exceeded the fresh water aquatic life guideline value. These samples are located along the periphery of the data region. The sample that exceeds the IMAC value is located within the northern portion of the flow system. Three of the samples in the SEBR exceeded the fresh water aquatic life guideline. These samples are located in the southern portion of the flow system. The sample in the SWBR flow system exceeds the fresh water aquatic life and IMAC values. The sample from the NWBR flow system doesn't exceed the guideline values.





Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

- Major river
- Major road
- Cold Lake Air Weapons Range Boundary
- Lake
- Town
- Approximate Formation extent
- Beaver River drainage basin area (Alberta portion)

Arsenic concentration (mg/L)

- ● 0.000 - 0.010
- ● 0.010 - 0.025
- ● 0.025 - 0.050
- ● > 0.050
- ● Well completed in the Formation without arsenic information or with suspect chemical analysis

Figure 5.41. Arsenic concentrations in the Bonnyville Formation.

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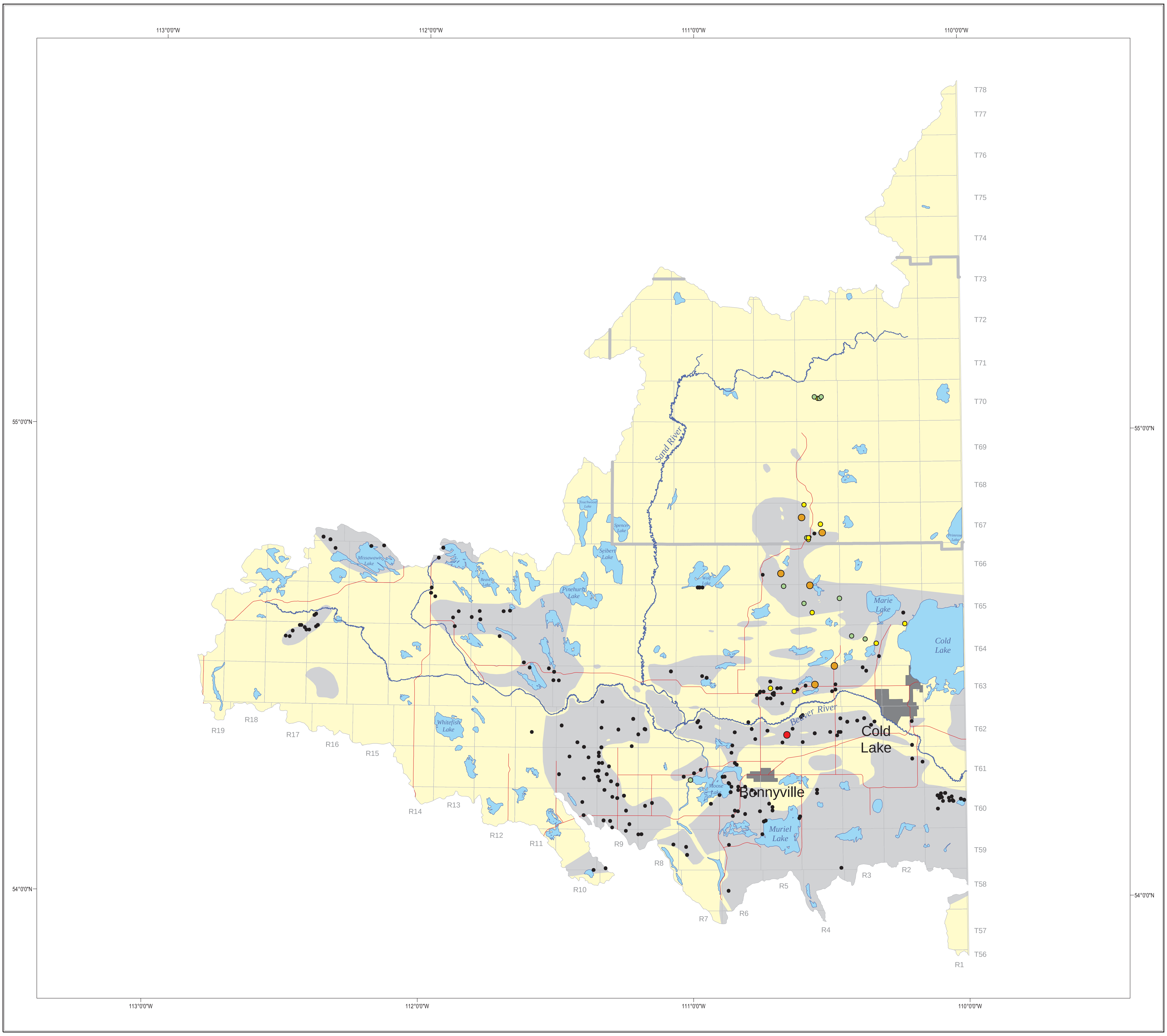

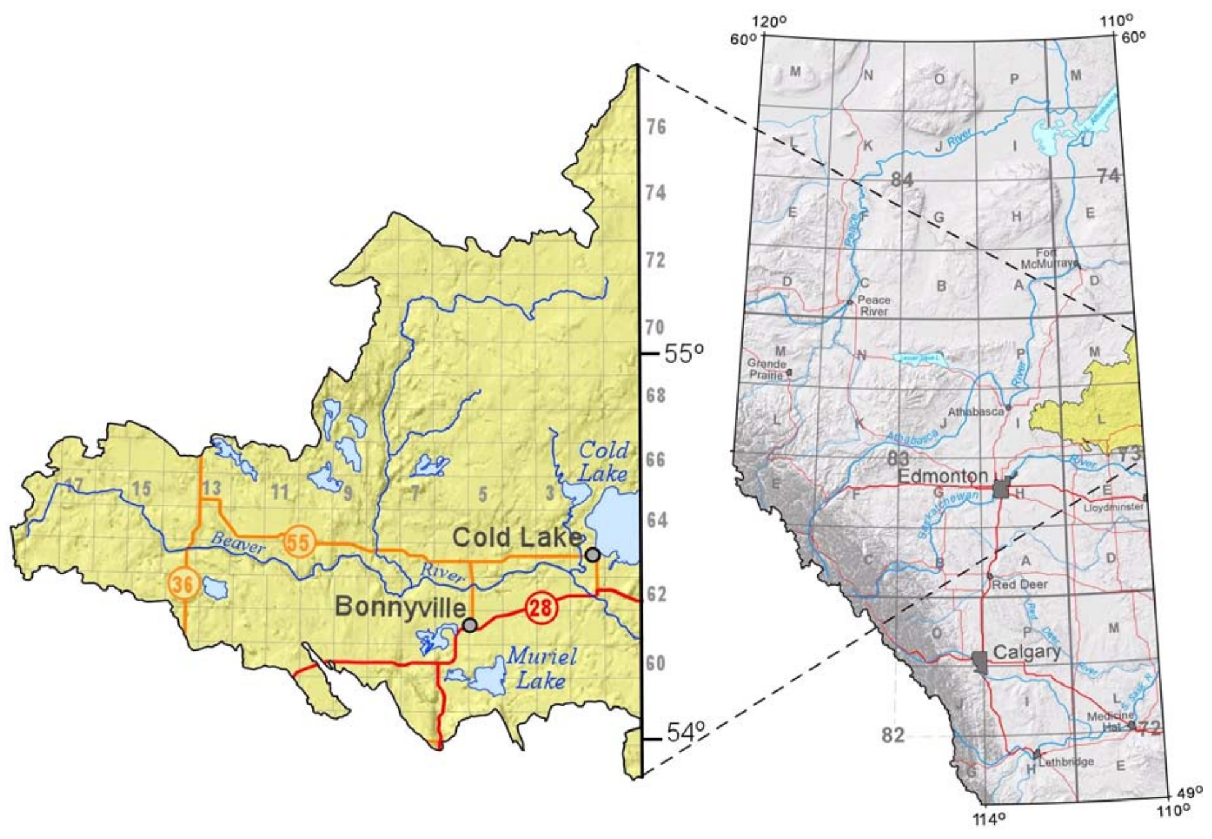

Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

〰 Major river
— Major road
▬ Cold Lake Air Weapons Range Boundary
🟦 Lake
⬛ Town
▨ Approximate Formation extent
🟨 Beaver River drainage basin area (Alberta portion)

Arsenic concentration (mg/L)

●	0.000 - 0.010
●	0.010 - 0.025
●	0.025 - 0.050
●	> 0.050
●	Well completed in the Formation without arsenic information or with suspect chemical analysis

Figure 5.42. Arsenic concentrations in the Ethel Lake Formation.

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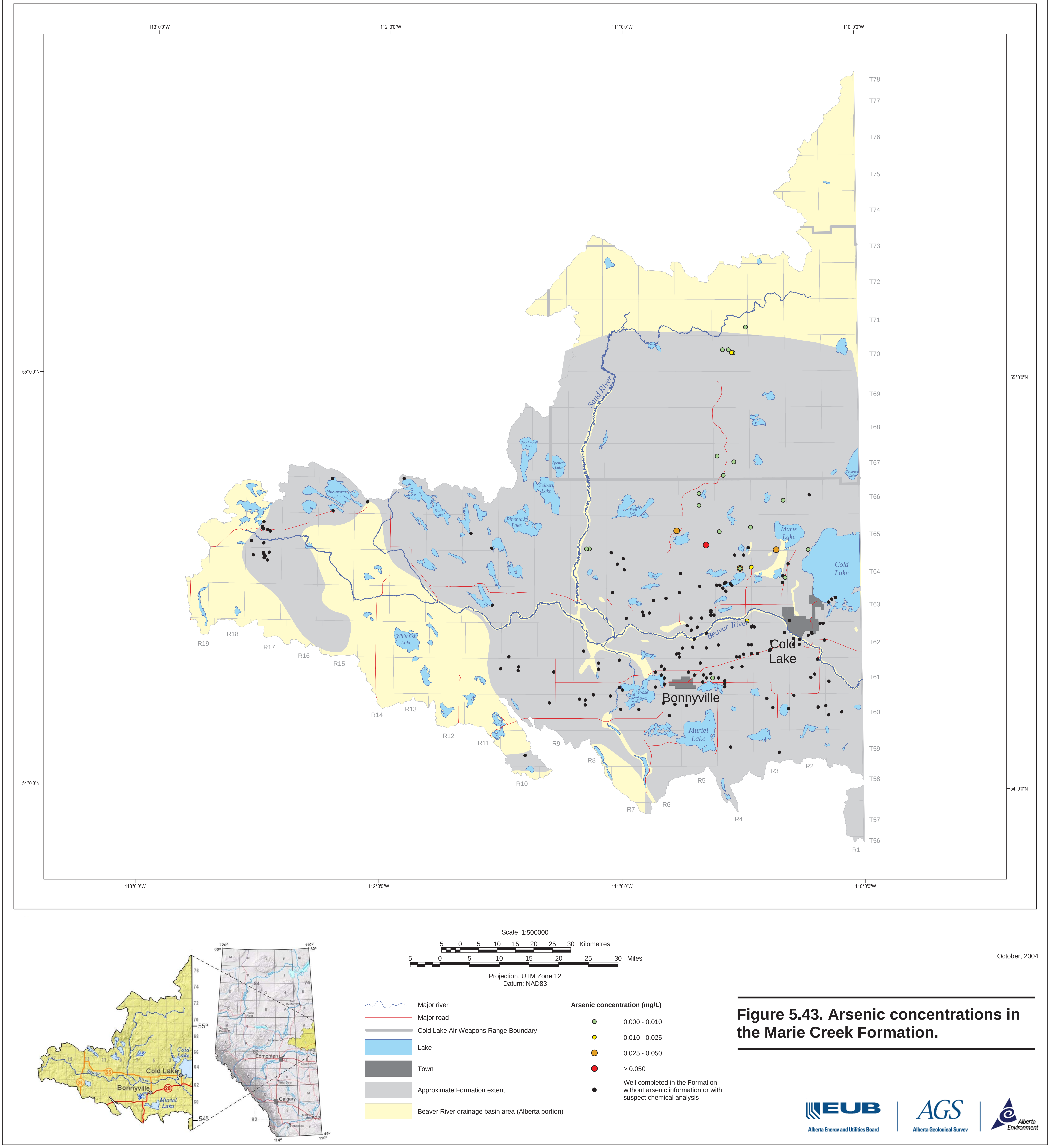

Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

〰	Major river
—	Major road
▬	Cold Lake Air Weapons Range Boundary
🟦	Lake
■	Town
▨	Approximate Formation extent
🟨	Beaver River drainage basin area (Alberta portion)

Arsenic concentration (mg/L)

🟢	0.000 - 0.010
🟡	0.010 - 0.025
🟠	0.025 - 0.050
🔴	> 0.050
●	Well completed in the Formation without arsenic information or with suspect chemical analysis

Figure 5.43. Arsenic concentrations in the Marie Creek Formation.

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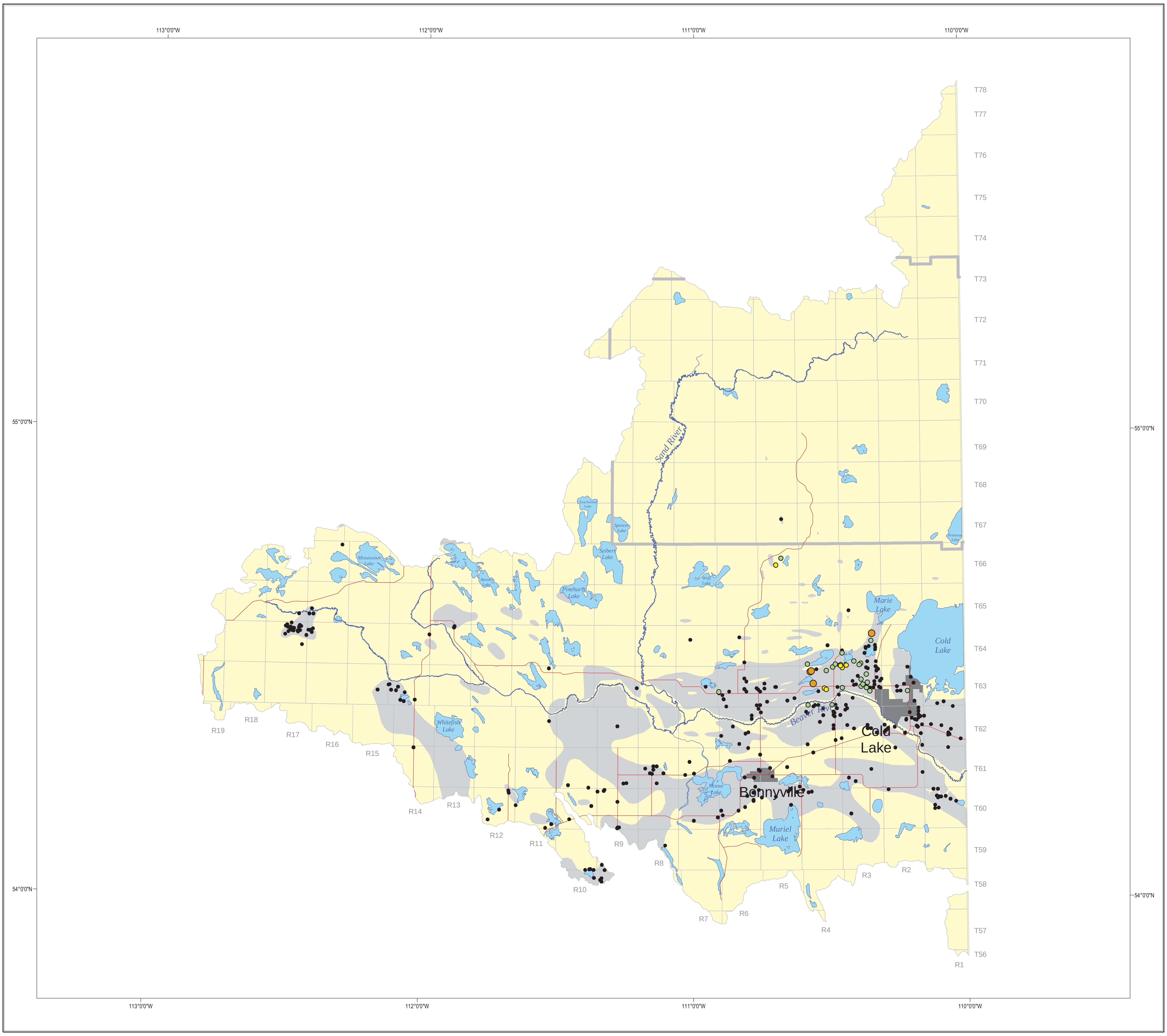
Alberta Environment



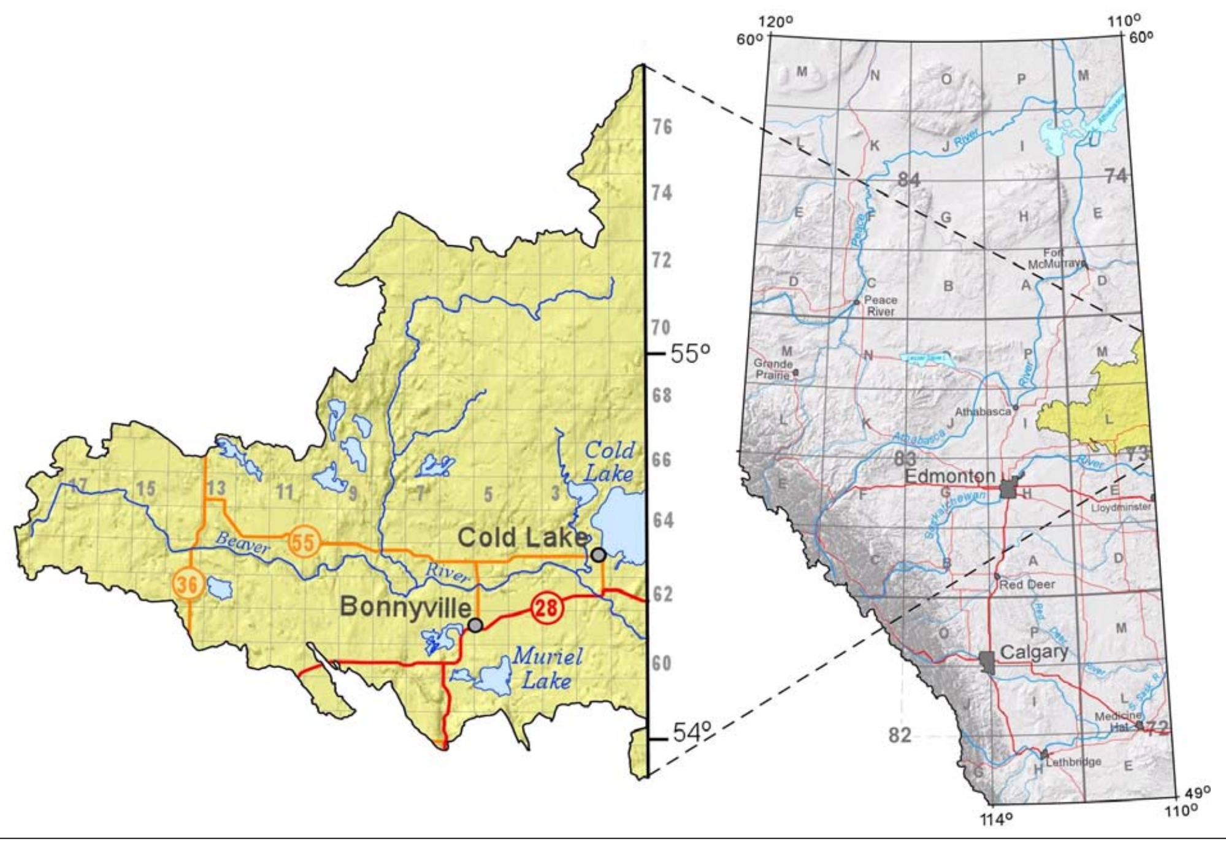
Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004



〰	Major river
―	Major road
▬	Cold Lake Air Weapons Range Boundary
🟦	Lake
■	Town
▨	Approximate Formation extent
🟨	Beaver River drainage basin area (Alberta portion)

Arsenic concentration (mg/L)

🟢	0.000 - 0.010
🟡	0.010 - 0.025
🟠	0.025 - 0.050
🔴	> 0.050
●	Well completed in the Formation without arsenic information or with suspect chemical analysis

Figure 5.44. Arsenic concentrations in the Sand River Formation.

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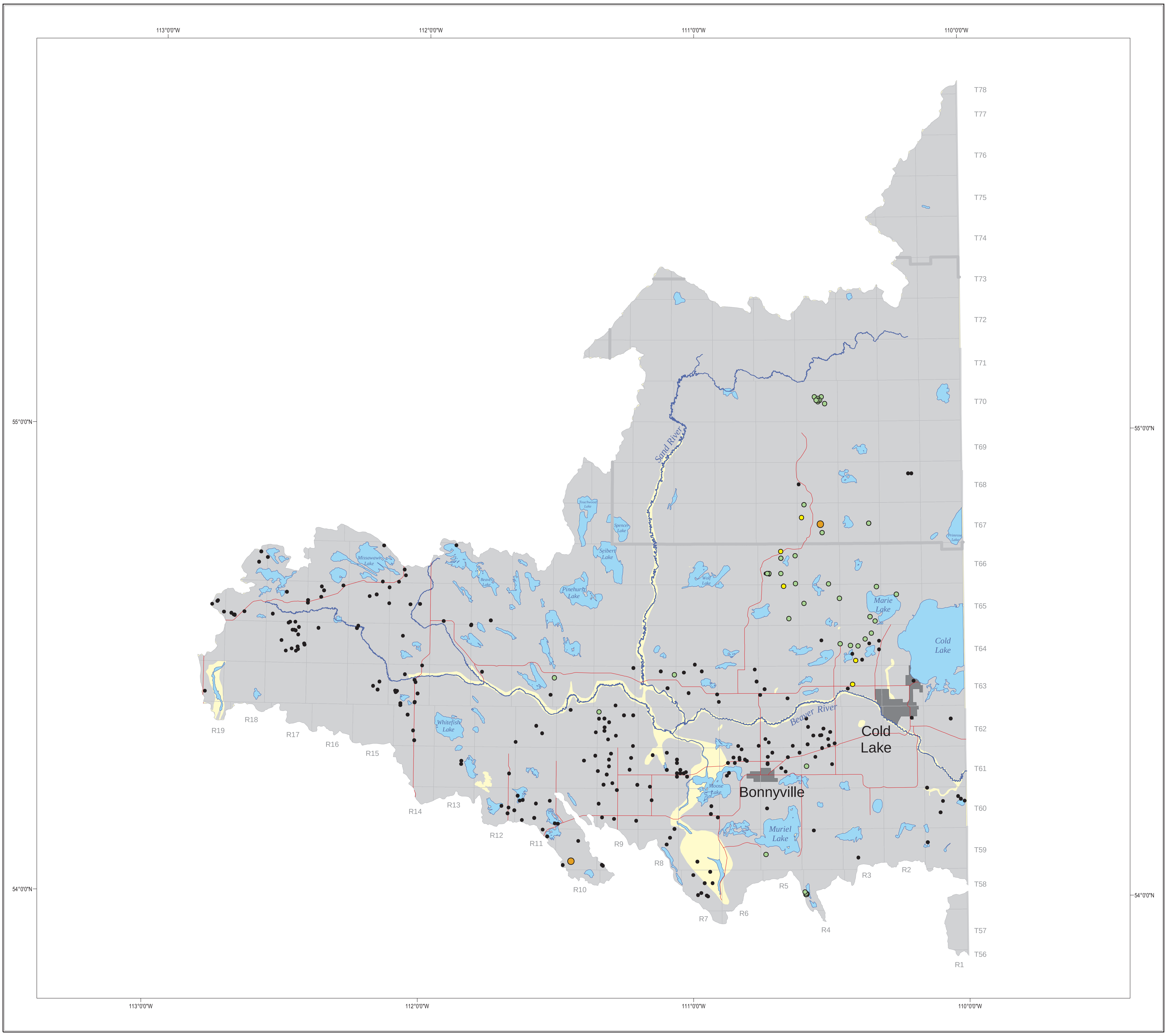

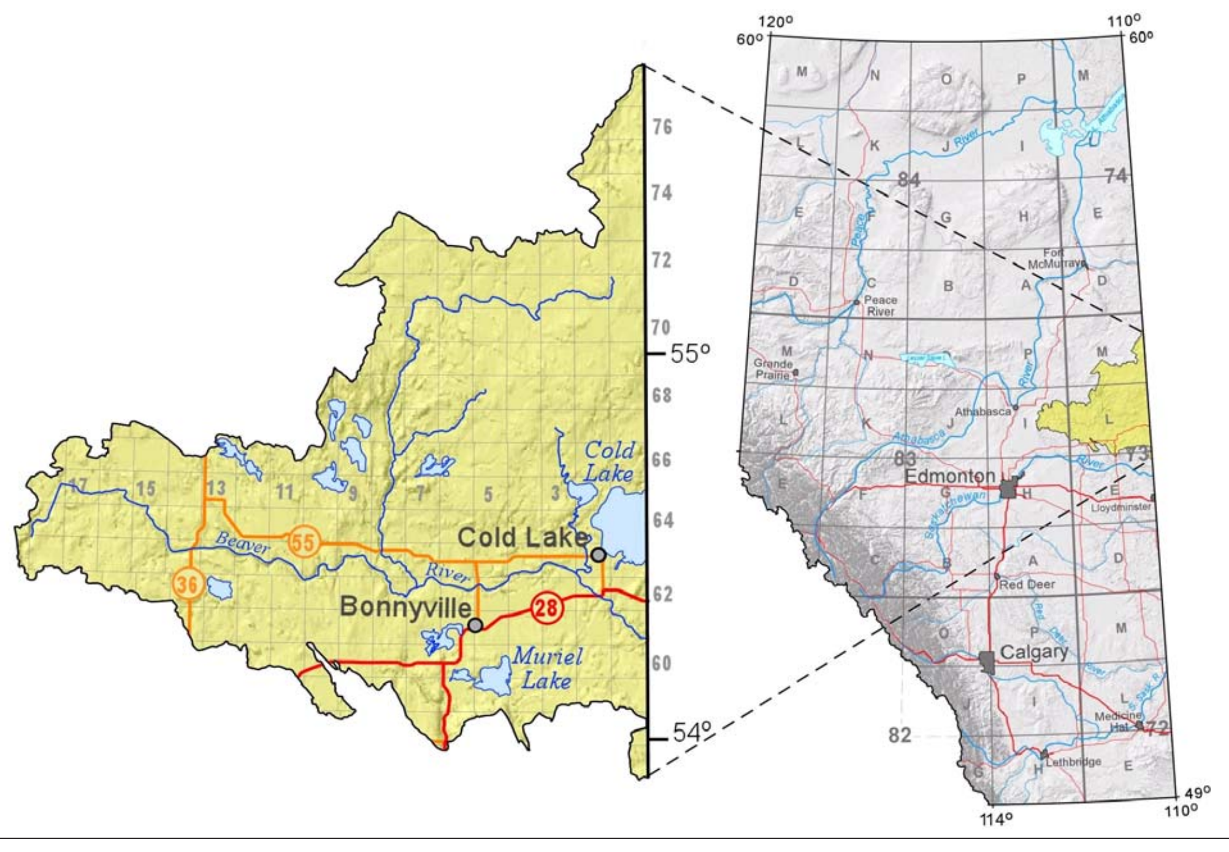

Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

〜	Major river
—	Major road
▬	Cold Lake Air Weapons Range Boundary
🟦	Lake
■	Town
▨	Approximate Formation extent
🟨	Beaver River drainage basin area (Alberta portion)

Arsenic concentration (mg/L)

🟢	0.000 - 0.010
🟡	0.010 - 0.025
🟠	0.025 - 0.050
🔴	> 0.050
●	Well completed in the Formation without arsenic information or with suspect chemical analysis

Figure 5.45. Arsenic concentrations in the Grand Centre Formation.

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5.4.9 Changes in Arsenic Concentrations Over Time

The median concentration of arsenic in channel and intermediate aquifers in the SEBR and NEBR flow systems has at times not been significantly different than the drinking water guideline. Individual reports of arsenic above the drinking water guidelines have been reported for shallow aquifers in the NEBR flow system. In all other aquifers, times, and flow systems for which data are available, the median arsenic concentration of compiled samples has remained below the drinking water guideline (Figure 5.36 and Figure 5.37) and has remained relatively stable within each flow system based on the 95% confidence limit about the median. The spatial, temporal and geological variability between each sample site makes statistical analysis very challenging and may invalidate many statistical techniques. However, certain techniques could likely be applied at specific locations with appropriate data quality and quantity. Time series analysis as described by Box et al., (1994), is one such technique.

5.5 Distribution of Phenols

Phenols can be produced through the decay of organic matter and are associated with petroliferous rocks. Drift aquifers likely contain organic matter and observational evidence suggests that Quaternary materials in the Basin can contain petroleum products. Komex (1997) indicated that given the biodegradable nature of phenols, concentrations in excess of the baseline they determined within a portion of the Basin, generally less than 0.005 mg/L could suggest a contaminant source. Komex (1997) also indicated that phenols have been measured in formation water associated with produced bitumen. Environmental quality guidelines have been established for phenols concentrations in water. These guidelines are presented below (Table 10).

Table 10. Canadian environmental quality guidelines for phenols in water (CCME, 2003).

Water – Community Use		Freshwater Aquatic Life	Water – Agricultural Use	
			Irrigation	Livestock
MAC, IMAC	AO			
(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
-	-	0.004	-	0.002

Some of the phenols concentrations in the drift aquifers in the Basin exceed some or all of the environmental quality guidelines. The following table (Table 11) contains a summary of the exceedances of phenols concentration environmental water quality guidelines captured in the water quality database. The first column (Formation) lists the drift formations. The second column (Rand of Values) presents the minimum and maximum concentration values for the Formation. The third column (N) presents the total number of records for a given Formation. The fourth column (ND) presents the number of records that were below the detection limit of the analysis. The fifth column (Water – Community Use) presents the number of records that exceed the water for community use guideline value. The sixth column (Freshwater Aquatic Life) presents the number of records that exceed the freshwater aquatic life guideline value. The seventh column (Water – Agricultural Use) presents the number of records that exceed the agricultural water use guideline values.

Table 11. Phenols exceedances summary.

Formation	Range of Values		N	ND	Water – Community Use	Freshwater Aquatic Life	Water – Agricultural Use	
	Min (mg/L)	Max (mg/L)					Irrigation	Livestock
Grand Centre	<0.001	1.45	243	105	-	48		113
Sand River	<0.001	0.01	41	23	-	3		12
Marie Creek	<0.001	0.012	153	71	-	10		61
Ethel Lake	<0.001	0.166	129	65	-	9		43
Bonnyville	<0.001	0.151	308	164	-	20		94
Muriel Lake	<0.001	0.087	437	158	-	78		205
Bronson Lake	<0.001	0.002	9	4	-	0		3
Empress	<0.001	0.126	581	180	-	140		303

While the values above summarize the database contents, the following table (Table 12) describes the exceedances of the most recently collected data on phenols concentrations.

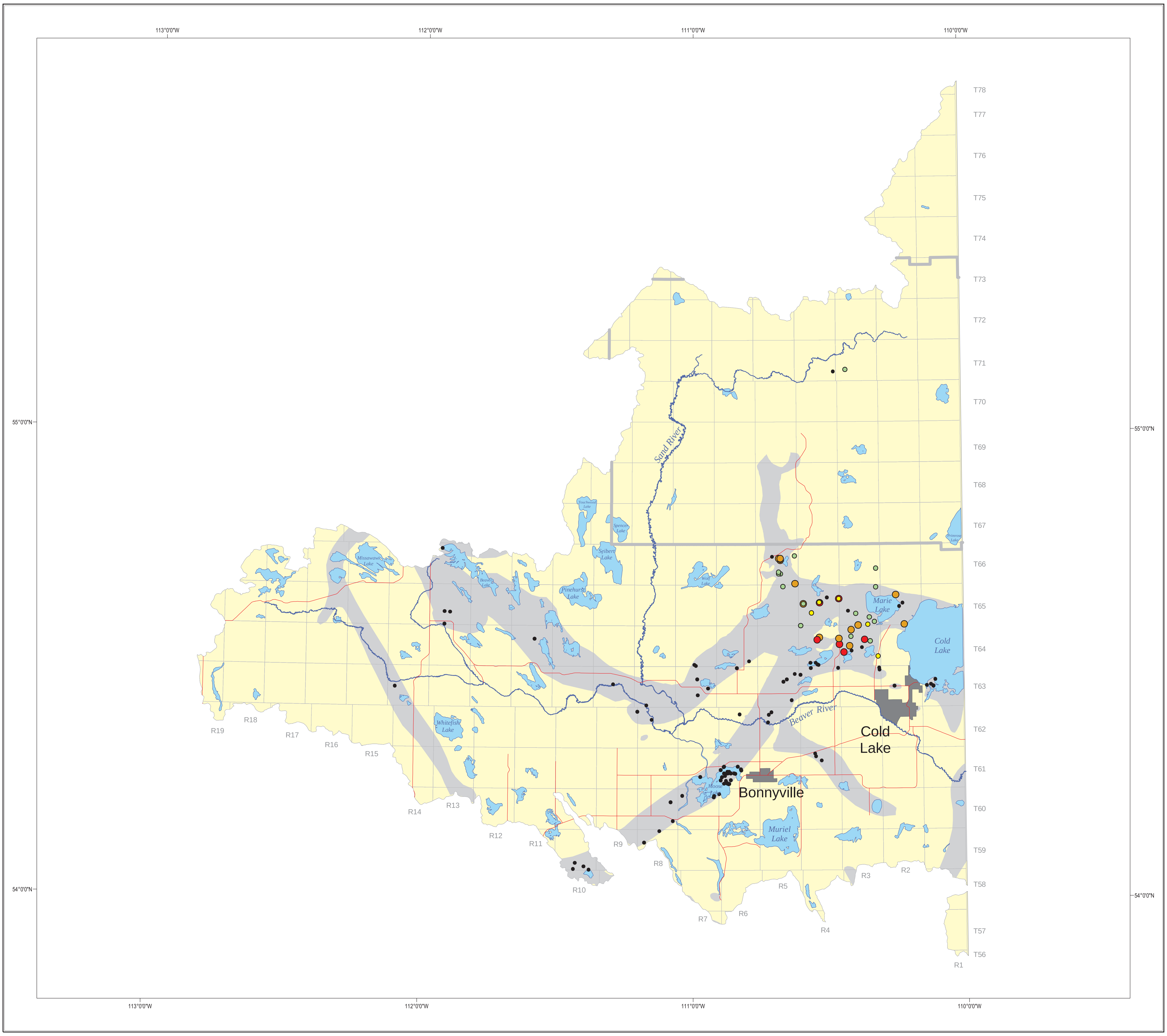
Table 12. Phenols exceedances summary - most recent values.

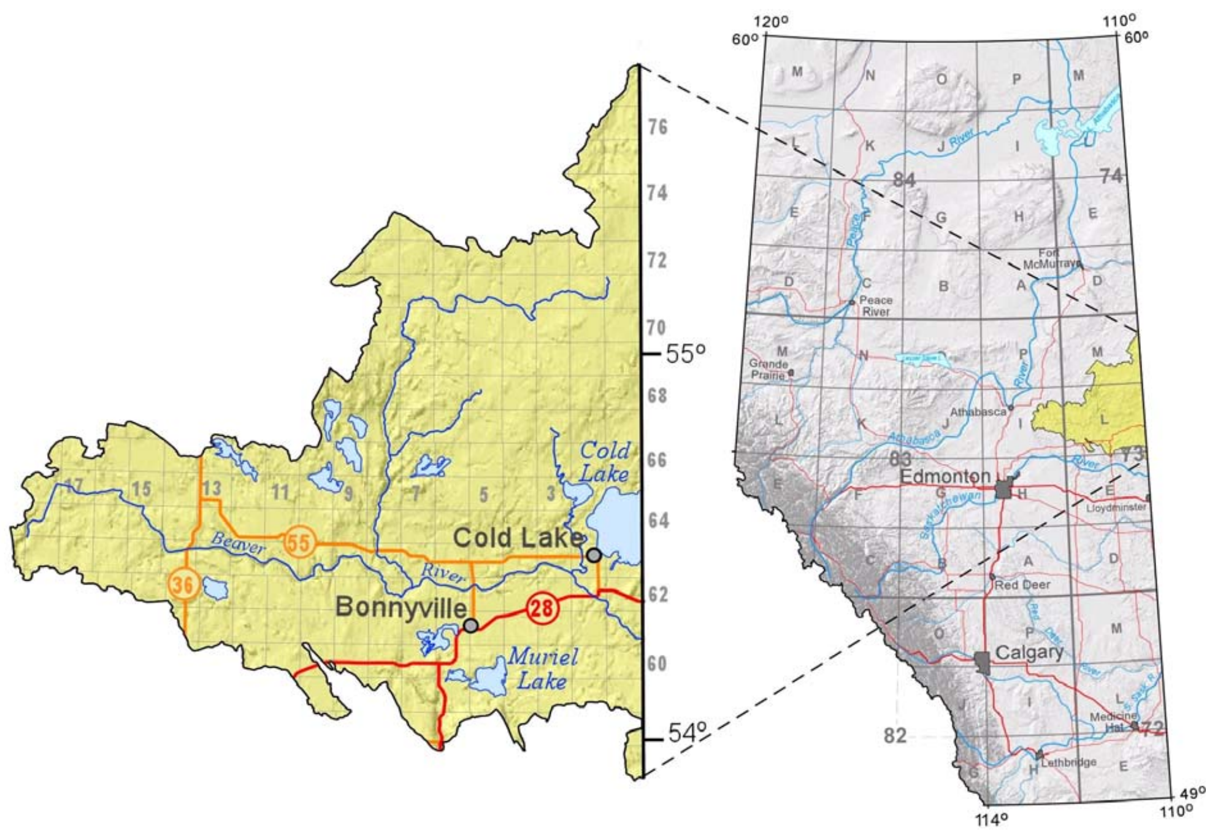
Formation	Range of Values		N	ND	Water – Community Use	Freshwater Aquatic Life	Water – Agricultural Use	
	Min (mg/L)	Max (mg/L)					Irrigation	Livestock
Grand Centre	<0.001	0.175	53	24	-	16	-	27
Sand River	<0.001	0.01	5	1	-	1	-	3
Marie Creek	<0.001	0.012	24	13	-	2	-	10
Ethel Lake	<0.001	0.003	21	15	-	0	-	4
Bonnyville	<0.001	0.009	48	27	-	3	-	15
Muriel Lake	<0.001	0.016	42	18	-	4	-	19
Bronson Lake	<0.001	-	2	2	-	0	-	0
Empress	<0.001	0.031	48	14	-	13	-	29

The distribution of the most recently collected data on phenols concentrations in the various formations is presented in Figure 5.46, Figure 5.47, Figure 5.48, Figure 5.49, Figure 5.50, Figure 5.51, Figure 5.52 and Figure 5.53.

5.5.1 Empress Formation

The phenols concentration distribution is presented in Figure 5.46. The sample from the Wiau flow system has a phenols concentration below established guidelines. The majority of the samples from the NEBR flow system exceed the livestock water quality guideline value. Thirteen of the samples exceed the fresh water aquatic life guideline value. Although a spatial distribution of exceedances is difficult to assess, more exceedances appear to occur in the southern portion of the data region.





Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

- Major river
- Major road
- Cold Lake Air Weapons Range Boundary
- Lake
- Town
- Approximate Formation extent
- Beaver River drainage basin area (Alberta portion)

Phenols concentration (mg/L)

- ● 0.000 - 0.001
- ● 0.001 - 0.002
- ● 0.002 - 0.004
- ● > 0.004
- ● Wells completed in the Formation without phenols information or with suspect chemical analysis

October, 2004

Figure 5.46. Phenols concentrations in the Empress Formation.

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Alberta Environment

5.5.2 Bronson Lake Formation

The phenols concentration distribution is presented in Figure 5.47. The samples from the NEBR flow system are both below established guideline values.

5.5.3 Muriel Lake Formation

The phenols concentration distribution is presented in Figure 5.48. Samples are only available within the NEBR flow system. Exceedances of the water quality guidelines appear more common in southern portion of the data area.

5.5.4 Bonnyville Formation

The phenols concentration distribution is presented in Figure 5.49. None of the samples in the Wiau flow system exceed the water quality guideline values. The majority of the samples in the NEBR flow system have phenols concentrations below the water quality guideline values. Those samples that exceed the livestock water quality guideline values are located predominantly in the southern portion of the data region. The samples that exceed the freshwater aquatic life guideline value do not appear to be spatially correlated. The samples with the highest phenols concentrations are located east of Wolf Lake. One of the samples is located in the far western portion of the flow system along the Sand River. The two samples in the SEBR flow system both exceed the livestock water quality guideline value, but not the fresh water aquatic life value.

5.5.5 Ethel Lake Formation

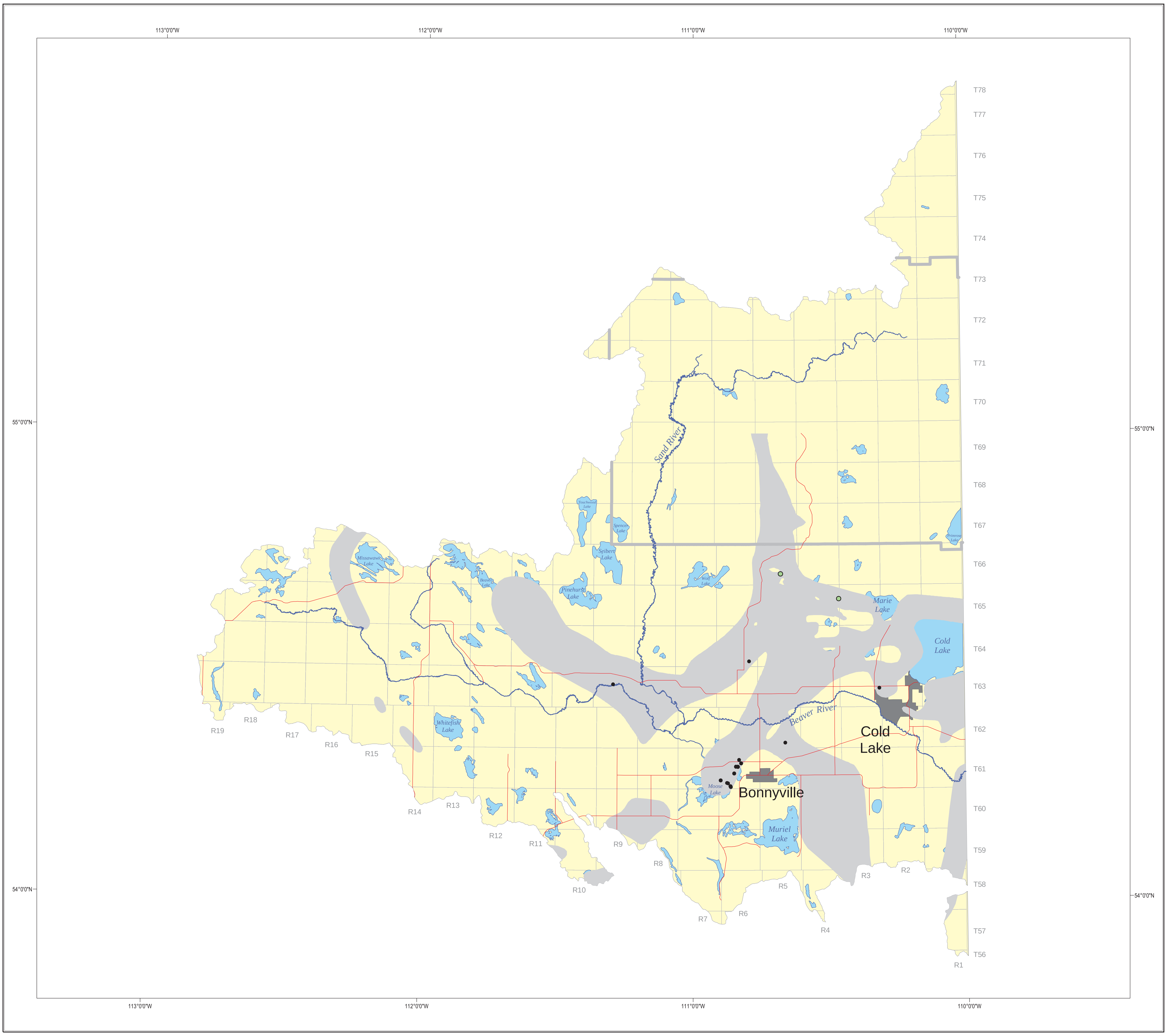
The phenols concentration distribution is presented in Figure 5.50. None of the samples in the Wiau flow system exceed the water quality guideline values. The majority of the samples in the NEBR flow system have phenols concentrations below the established water quality guidelines. Four of the samples exceed the livestock water quality guidelines. Most of these samples are located within the southern portion of the data region. None of the samples exceed the fresh water aquatic life guideline values.

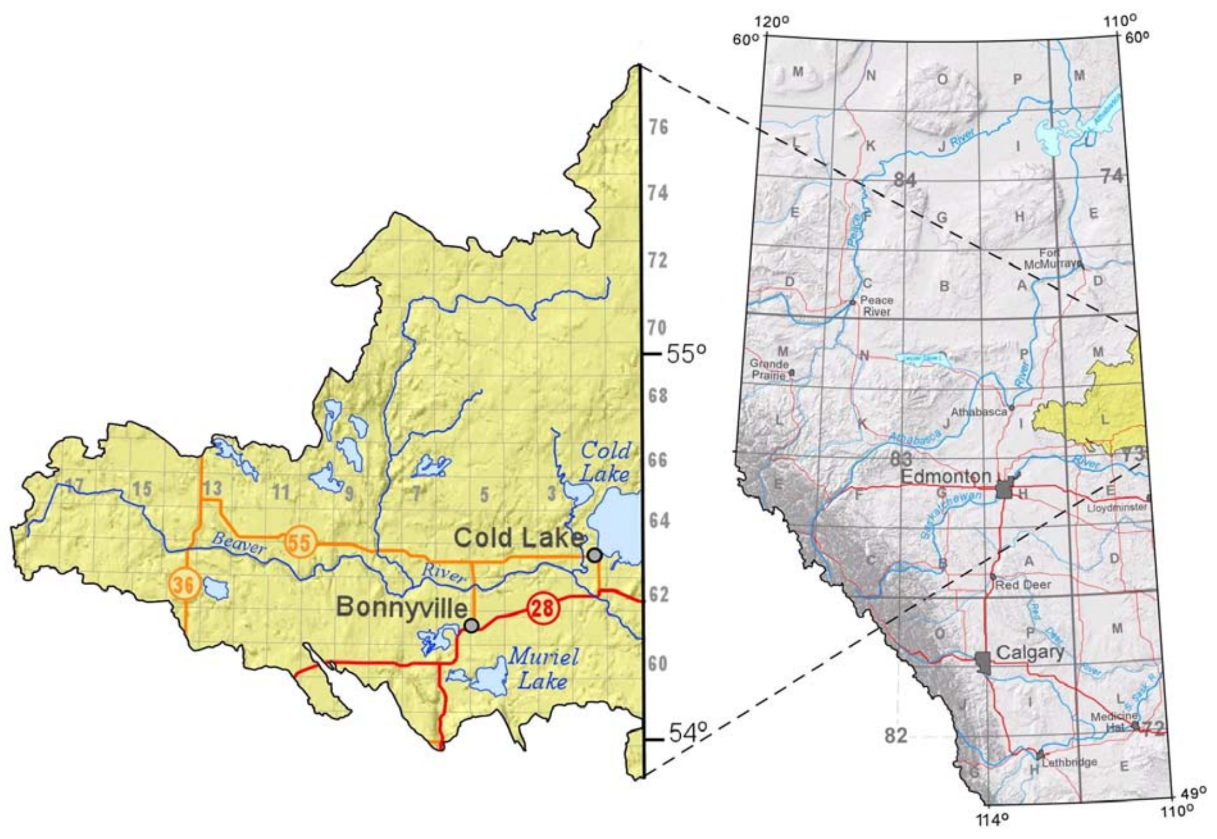
5.5.6 Marie Creek Formation

The phenols concentration distribution is presented in Figure 5.51. None of the samples in the Wiau flow system exceed the water quality guideline values. The majority of samples within the NEBR flow system have phenols concentration below the established water quality guidelines. The samples that exceed the livestock water quality guideline values are scattered throughout the flow system with a number of them concentrated in the vicinity of Marie Lake and Cold Lake. The samples that exceed the fresh water aquatic life guideline value are located to the west of Cold Lake, and along the Sand River in the western portion of the flow system.

5.5.7 Sand River Formation

The phenols concentration distribution is presented in Figure 5.52. The majority of the samples in the NEBR flow system exceed the livestock water quality guideline value. Two of the samples are located south of Marie Lake and the other is located to the west of Sinclair Lake. The sample west of Sinclair Lake also exceeds the fresh water aquatic life guideline value.





Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

Major river
Major road
Cold Lake Air Weapons Range Boundary
Lake
Town
Approximate Formation extent
Beaver River drainage basin area (Alberta portion)

Phenols concentration (mg/L)

●	0.000 - 0.001
●	0.001 - 0.002
●	0.002 - 0.004
●	> 0.004
●	Wells completed in the Formation without phenols information or with suspect chemical analysis

Figure 5.47. Phenols concentrations in the Bronson Lake Formation.

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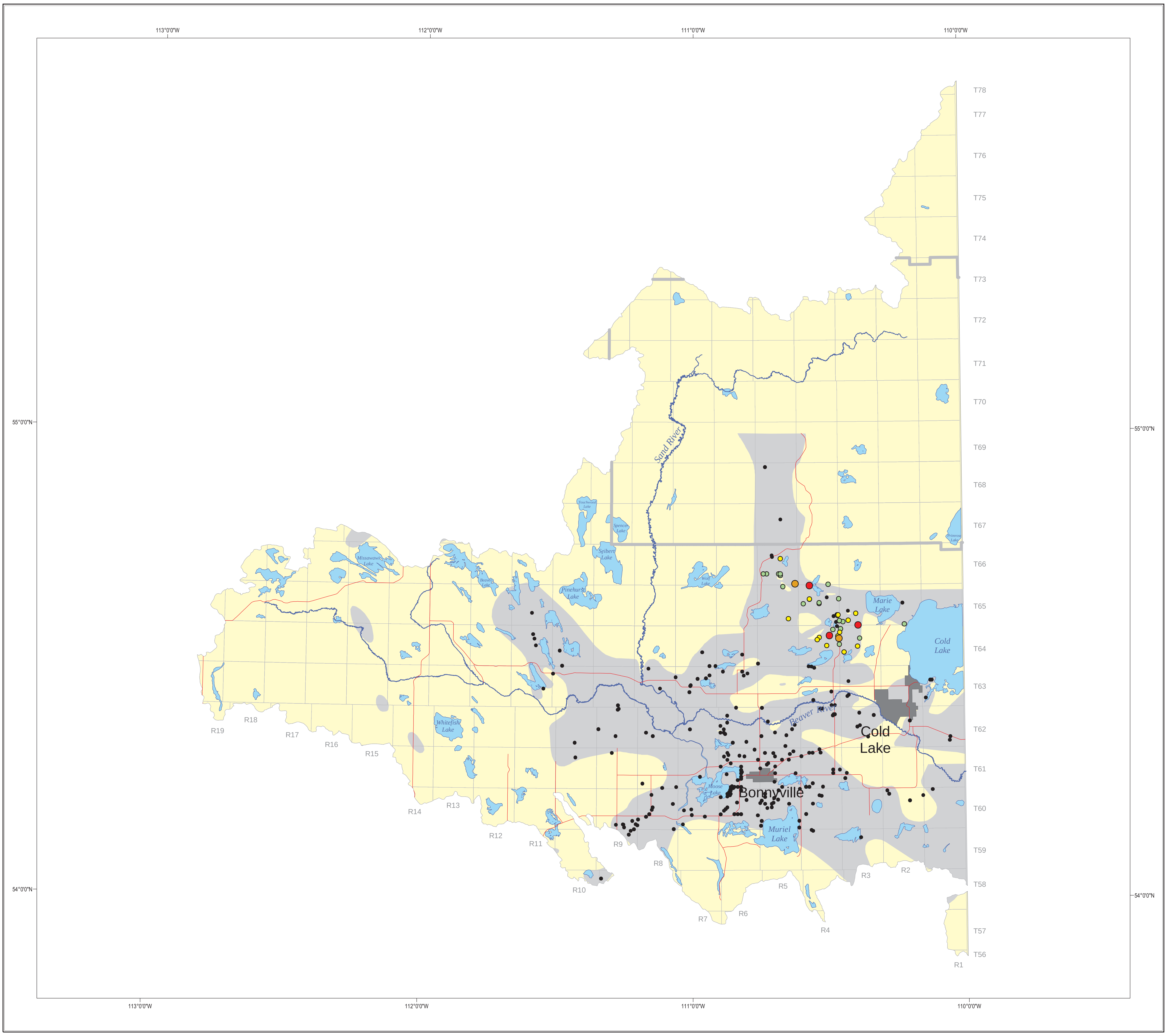

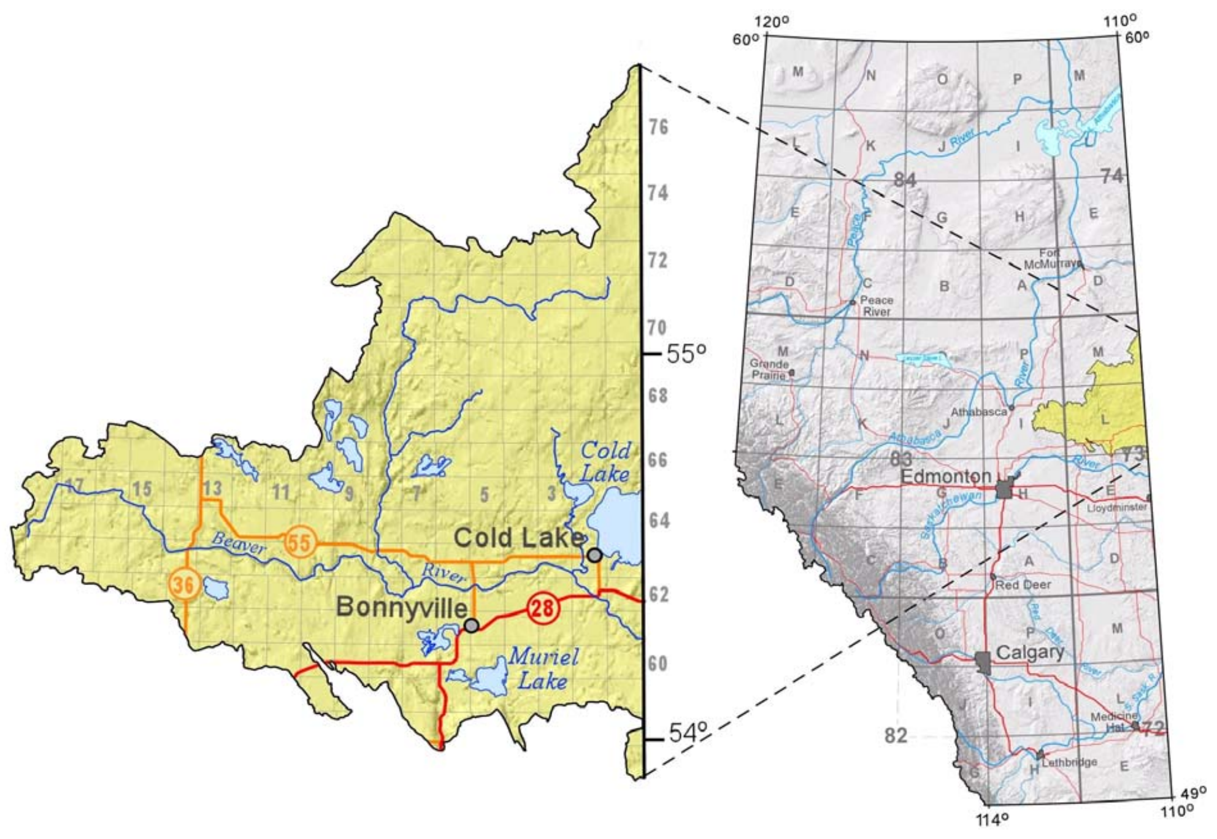

Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

Major river
Major road
Cold Lake Air Weapons Range Boundary
🟦 Lake
■ Town
▨ Approximate Formation extent
▨ Beaver River drainage basin area (Alberta portion)

Phenols concentration (mg/L)

● 0.000 - 0.001
● 0.001 - 0.002
● 0.002 - 0.004
● > 0.004
● Wells completed in the Formation without phenols information or with suspect chemical analysis

Figure 5.48. Phenols concentrations in the Muriel Lake Formation.

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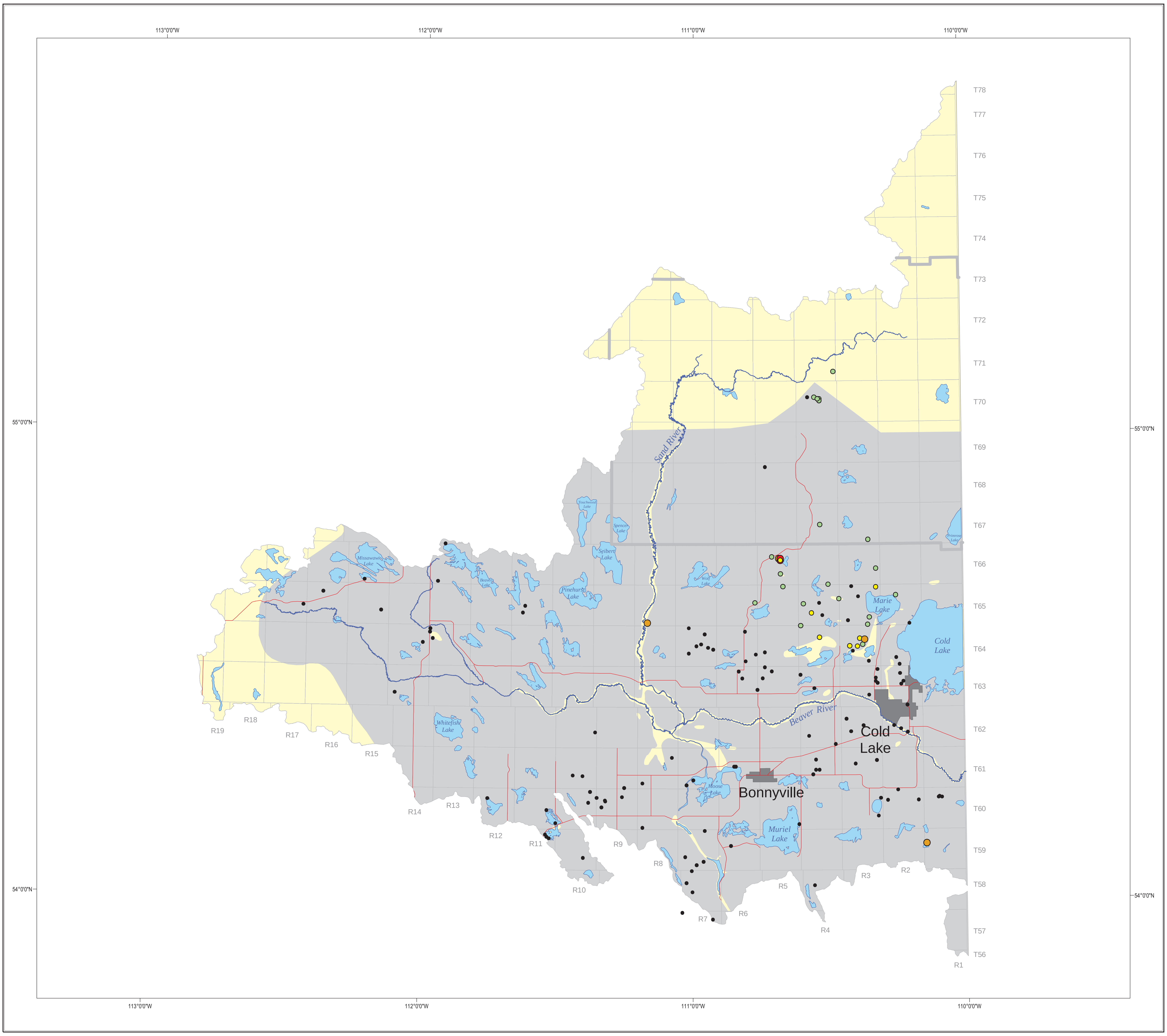

Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

- Major river
- Major road
- Cold Lake Air Weapons Range Boundary
- 🟦 Lake
- ⬛ Town
- ▩ Approximate Formation extent
- 🟨 Beaver River drainage basin area (Alberta portion)

Phenols concentration (mg/L)

- 🟢 0.000 - 0.001
- 🟡 0.001 - 0.002
- 🟠 0.002 - 0.004
- 🔴 > 0.004
- ● Wells completed in the Formation without phenols information or with suspect chemical analysis

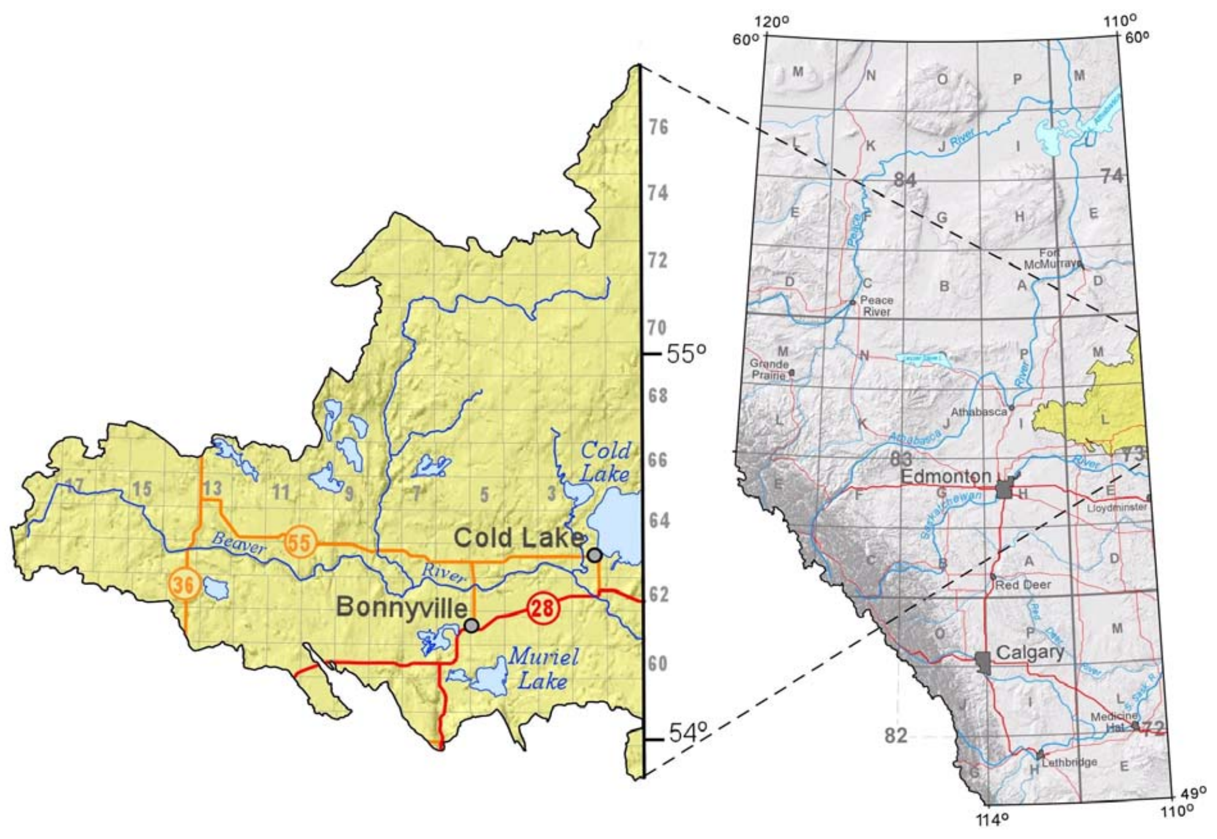

Figure 5.49. Phenols concentrations in the Bonnyville Formation.

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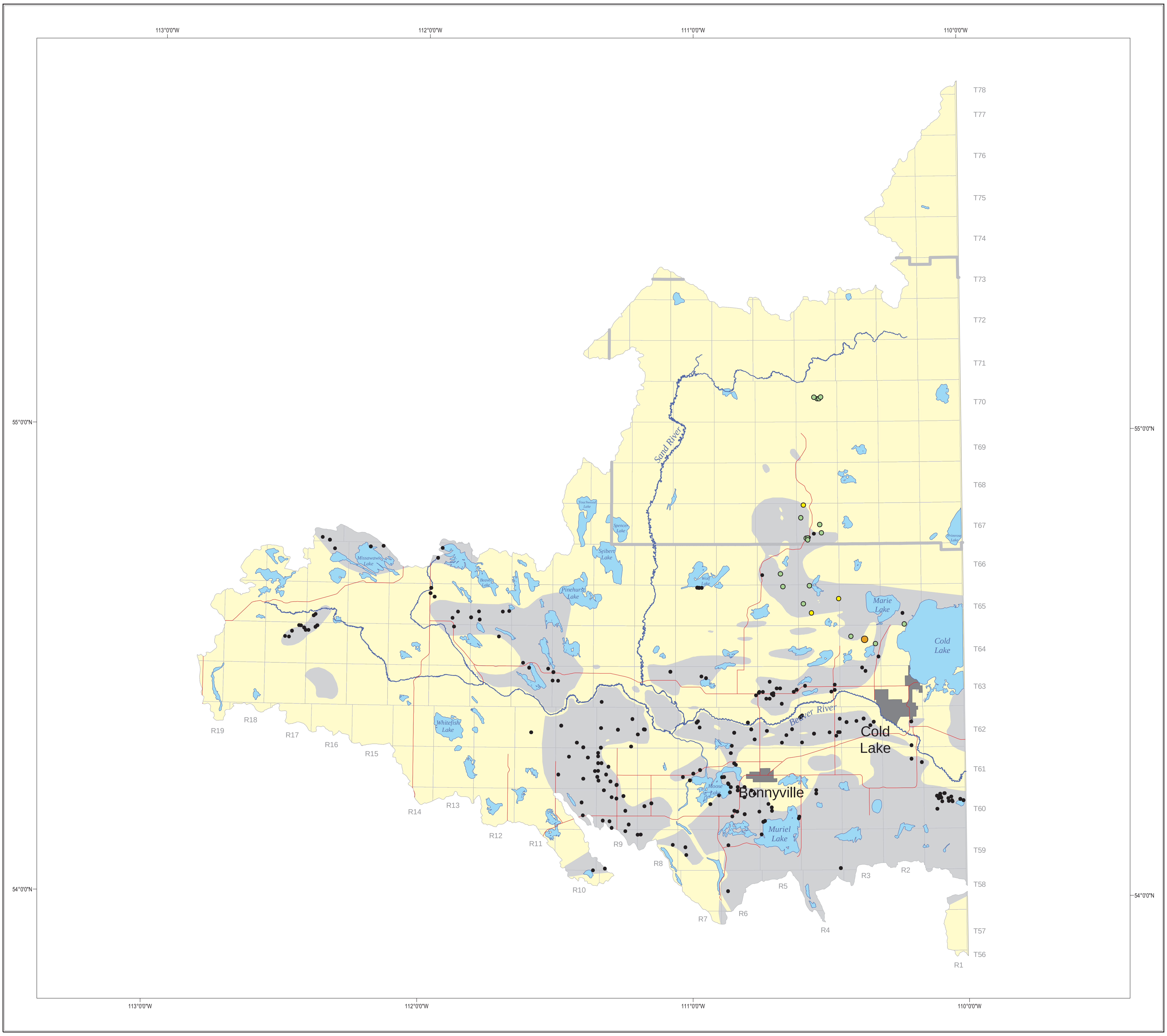

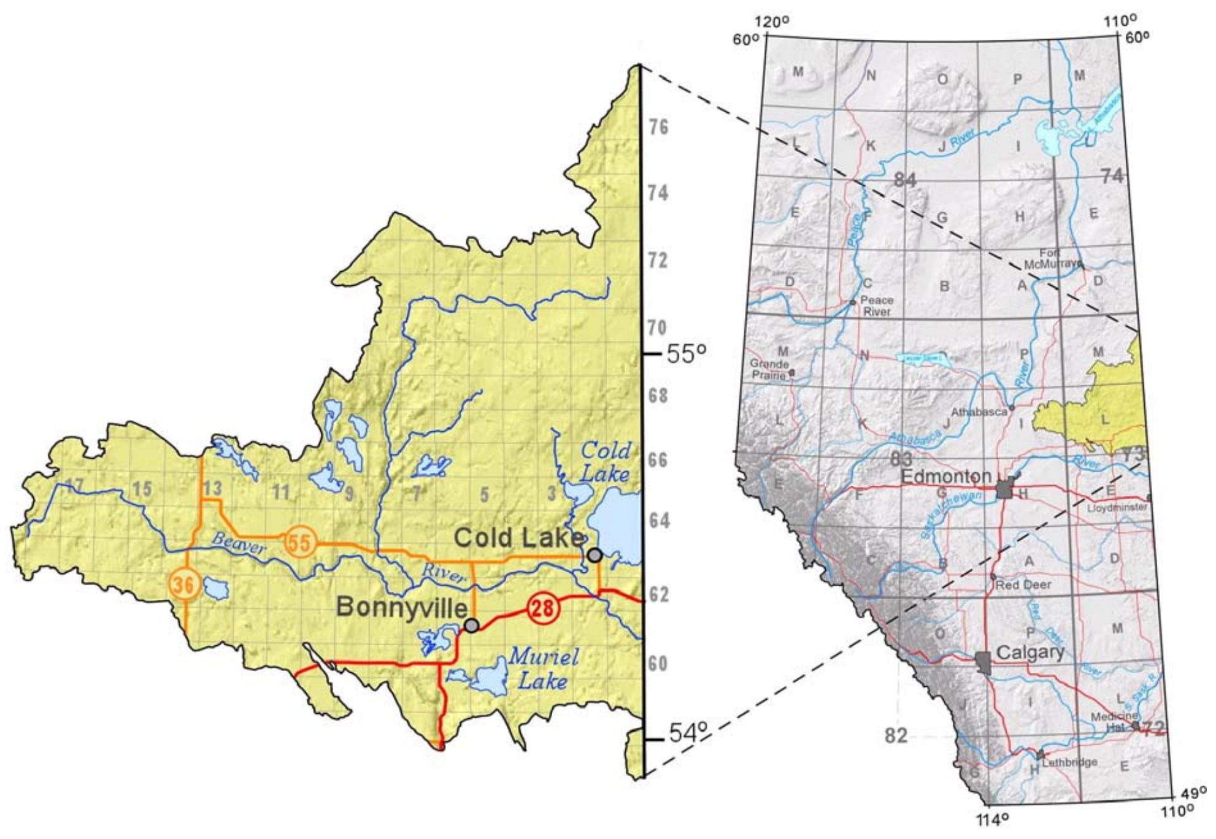

Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

〰	Major river
—	Major road
▬	Cold Lake Air Weapons Range Boundary
🟦	Lake
■	Town
▨	Approximate Formation extent
🟨	Beaver River drainage basin area (Alberta portion)

Phenols concentration (mg/L)

🟢	0.000 - 0.001
🟡	0.001 - 0.002
🟠	0.002 - 0.004
🔴	> 0.004
●	Wells completed in the Formation without phenols information or with suspect chemical analysis

Figure 5.50. Phenols concentrations in the Ethel Lake Formation.

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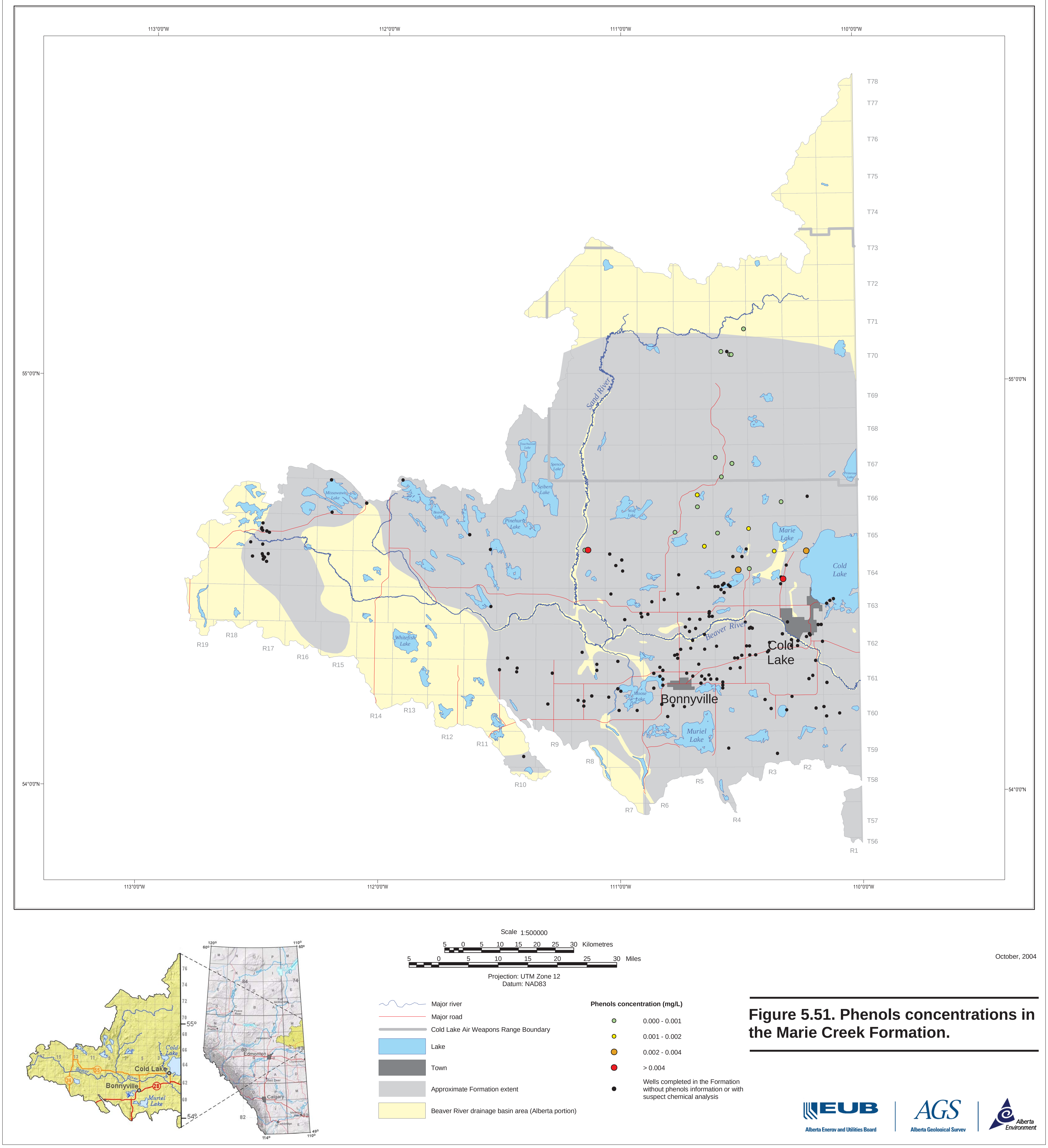

October, 2004

Figure 5.51. Phenols concentrations in the Marie Creek Formation.

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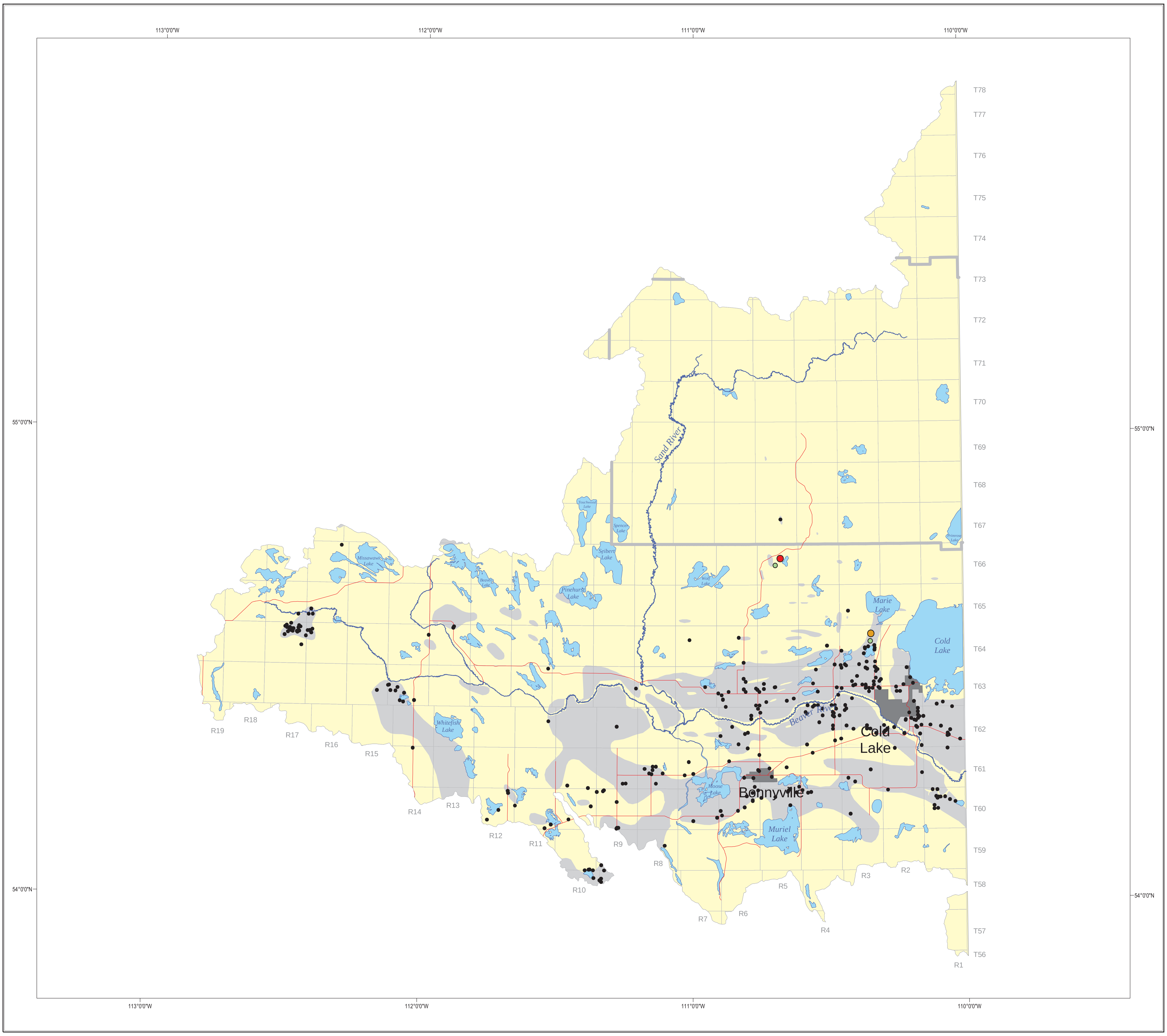


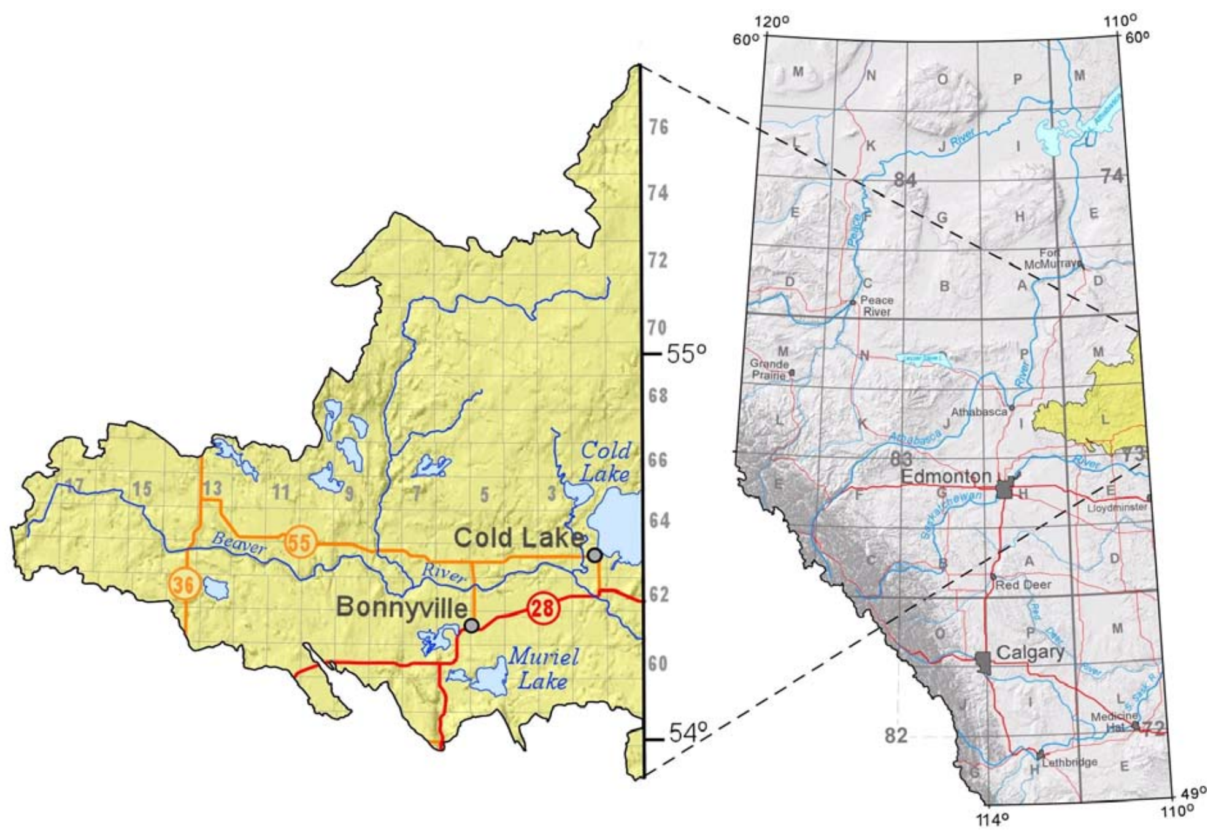
Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004



〰	Major river
—	Major road
▬	Cold Lake Air Weapons Range Boundary
▭	Lake
■	Town
▨	Approximate Formation extent
▭	Beaver River drainage basin area (Alberta portion)

Phenols concentration (mg/L)

●	0.000 - 0.001
●	0.001 - 0.002
●	0.002 - 0.004
●	> 0.004
●	Wells completed in the Formation without phenols information or with suspect chemical analysis

Figure 5.52. Phenols concentrations in the Sand River Formation.

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Alberta Geological Survey
Alberta Environment

5.5.8 Grand Centre Formation

The phenols concentration distribution is presented in Figure 5.53. The highest recorded phenols values are within the Grand Centre Formation samples. The majority of the samples in the Wiau flow system have phenols concentration below the established water quality guideline values. One of the samples exceeds both the livestock and fresh water aquatic life guideline. The majority of the samples in the NEBR flow system have phenols concentrations above the livestock water quality guideline value. Fifteen of the samples have phenols concentrations above the fresh water aquatic life guideline value. The majority of these samples are located in northern portion of the data region.

5.5.9 Changes in Phenols Concentrations Over Time

Phenols information is available for the NEBR and Wiau flow systems for the 1990's and for the SEBR, NEBR and Wiau flow systems for the first few years of 2000 (Figure 5.36 and Figure 5.37). The median concentrations within the various flow systems during the different decades of sampling generally overlap at the 95% confidence level. The median concentrations are also generally below the established water quality guideline value for consumption of water by livestock. The exceptions occur in samples from the NEBR flow system in the Empress Formation Unit 1 during the first few years of 2000, the Channel Aquifers during the 1990's, and in the Shallow Aquifers during the 1990's and the first few years of 2000. Some exceedances of the guideline values are present in the NEBR and Wiau flow systems. The number of exceedances increased in the various aquifer groups present in the NEBR flow system between the 1990's and the first few years of 2000. The number of monitoring wells within this flow system has also increased during that time, so the significance of this observation is unknown. Some of the observed concentrations exceed the value proposed as a background phenols concentration of approximately 0.005 mg/L (Komex, 1997). The spatial, temporal and geological variability between each sample site makes statistical analysis very challenging and may invalidate many statistical techniques. However, certain techniques could likely be applied at specific locations with appropriate data quality and quantity. Time series analysis as described by Box et al., (1994), is one such technique.

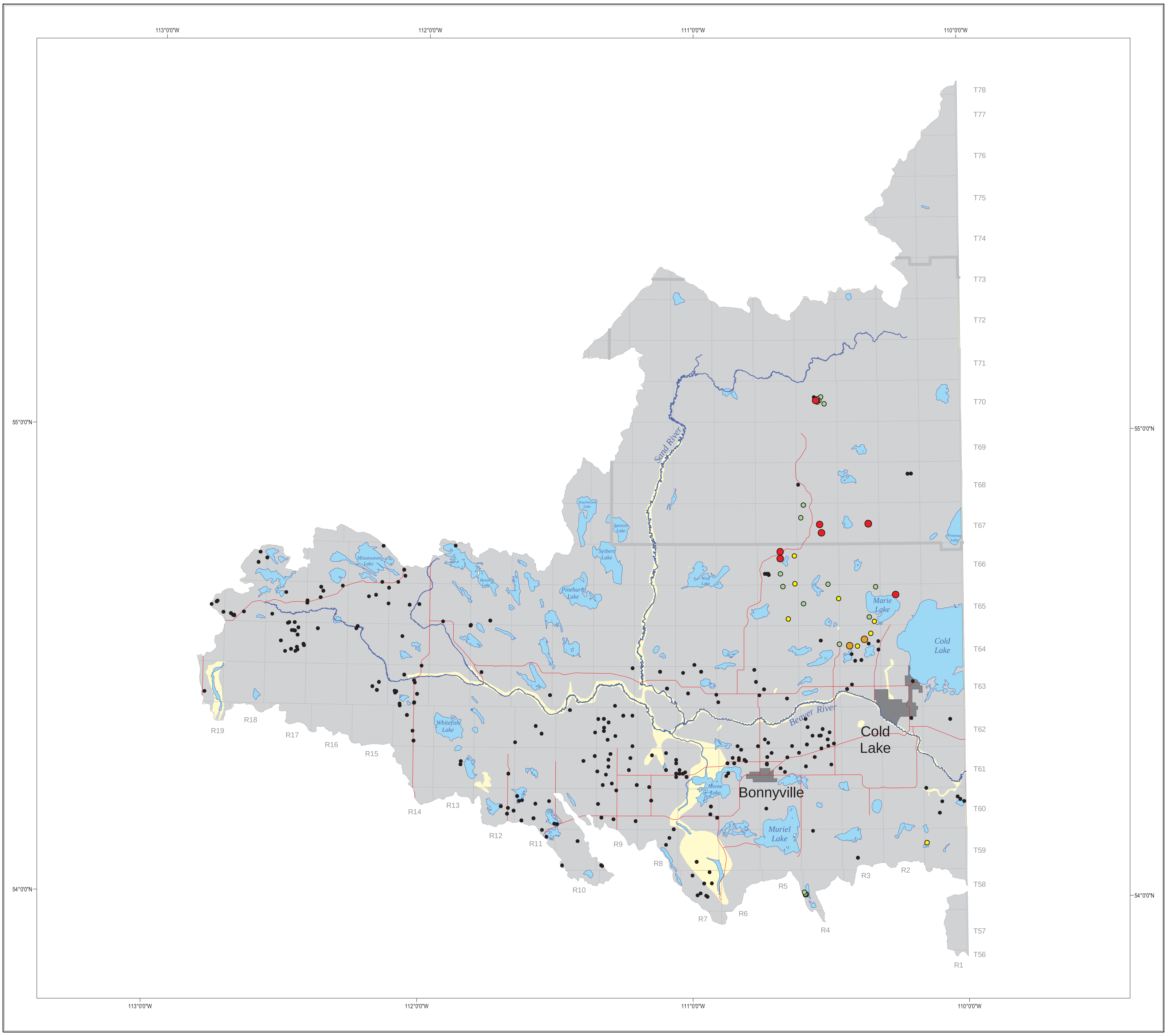
6 Aquifer Sensitivity Assessment of the Cold Lake-Beaver River Basin

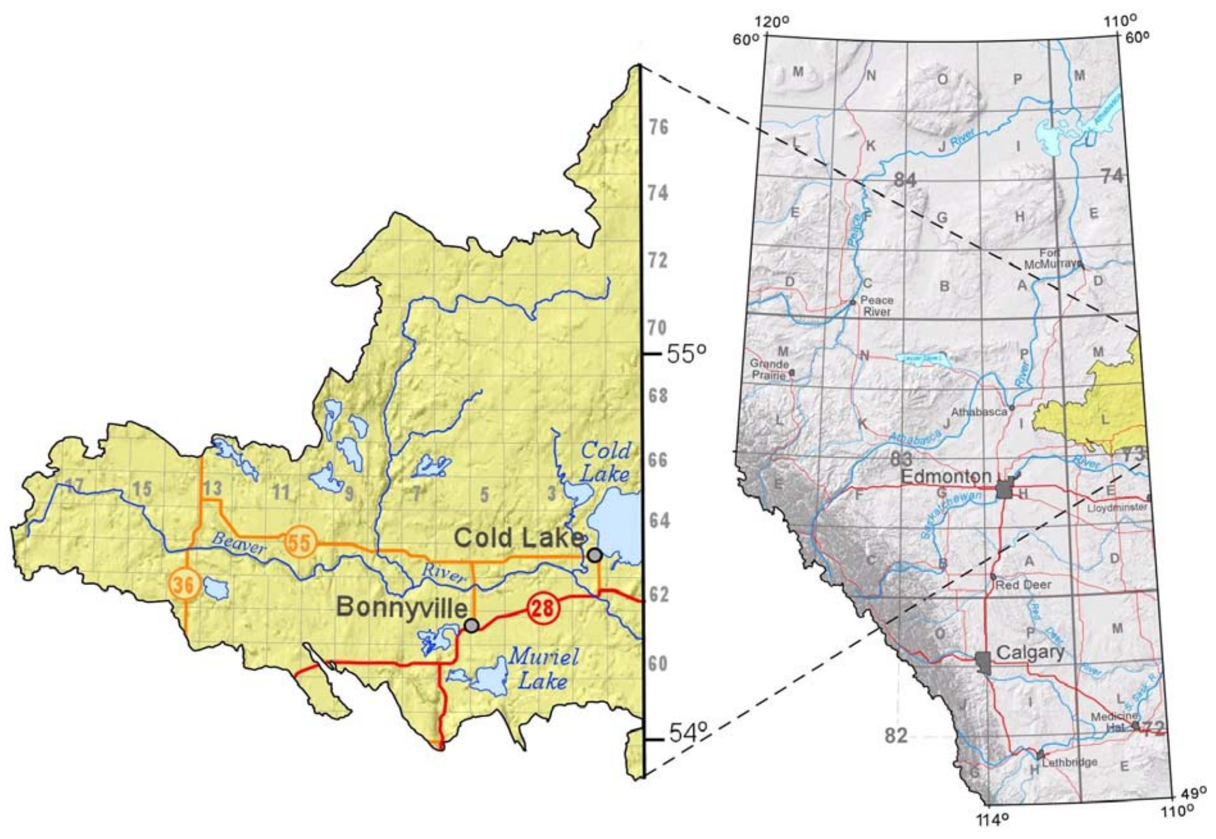
The method chosen for the assessment of intrinsic sensitivity is a subjective rating system (Focazio et al., 2002). This method will be applied to the uppermost layers of the geology, the surface materials and the Grand Centre Formation, and will be applicable in the case of a surface release and the potential for migration into underlying aquifers.

6.1 Aquifer Sensitivity Assessment - Process

Aquifer sensitivity was assessed using a GIS-based approach. Information from various layers was combined to create a hybrid layer that possessed the characteristics of all of the layers used to create it. This hybrid layer was then queried in the GIS environment to determine the areas potentially sensitive to contamination in the Cold Lake-Beaver River Basin. The information incorporated into the sensitivity assessment included the

- Surficial geology mapped by Andriashek (2003), Shetsen (1990), Andriashek and Fenton (1989) and Fenton and Andriashek (1983)
- Sand on sand contacts mapped by Andriashek and Fenton (1989)





Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

〰 Major river
— Major road
▬ Cold Lake Air Weapons Range Boundary
🟦 Lake
⬛ Town
⬜ Approximate Formation extent
🟨 Beaver River drainage basin area (Alberta portion)

Phenols concentration (mg/L)

🟢 0.000 - 0.001
🟡 0.001 - 0.002
🟠 0.002 - 0.004
🔴 > 0.004
● Wells completed in the Formation without phenols information or with suspect chemical analysis

October, 2004

Figure 5.53. Phenols concentrations in the Grand Centre Formation.

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- Grand Centre sand and clay content measurements determined by Andriashek and Fenton (1989)
- Location of lakes within the study area
- Regional extents and characteristics of the various drift formations mapped by Parks et al. (2005).

Not all of the layers covered the entire study area. As such, there are areas where no or limited assessment could be carried out. The information in the hybrid layer was queried according to the following flow chart (Figure 6.1). This systematic approach helped focus the assessment of the aquifer sensitivity and allowed for the tracking of the various steps required in the process. The assessment benefited greatly from the availability of information on the extent and characteristics of the surficial and subsurface materials present within the Basin. Without this information, the assessment would have been much less detailed and less useful. The current assessment though subjective is useful is determining the areas with the highest potential sensitivity to contamination and will enable more informed decisions on matters regarding groundwater management in the Basin. This assessment is based on regional scale mapping of surficial and subsurface geology and therefore will inherently contain any of the associated errors of these regional studies. This does not affect its usefulness as a regional assessment, but limits its specific applicability. Field confirmation of this assessment must be carried out for specific site assessments.

6.2 Aquifer Sensitivity Assessment – Results

The result of the process outlined in Figure 6.1 is presented in Figure 6.2. The most sensitive areas to contamination are the areas in red. These areas are generally located in the vicinity of the major river channels. However, some are also located where geologic processes have created sand on sand contacts between aquifers within different formations. The areas in orange represent areas where coarse-grained surficial material, wetlands, or organic material is present and either the underlying material is considered to be relatively impermeable, or not enough information was available for the underlying material to assess its potential connection to underlying formations. The latter materials are located within the far northern and far western portions of the Basin where information on the sand and clay content of the Grand Centre Formation was not available. The orange category of materials is considered sensitive to contamination and is common throughout the study area. The areas in yellow represent instances where the material beneath the surficial material is likely permeable, but the surficial material is considered relatively impermeable and so the relationship between the two is uncertain. These areas are likely sensitive to contamination. The areas in green represent the area where the geological characteristics of the subsurface materials suggest that they are relatively impermeable and therefore would have the lowest potential for contamination of the materials encountered in the Basin. This is the dominant category in the Basin. The areas in gray represent the areas within the Basin where not enough information was available on the Grand Centre Formation sand and clay composition to complete the aquifer sensitivity assessment.

6.3 Aquifer Sensitivity Assessment – Applicability

The definition of aquifer sensitivity based on geological materials is the first step in determining the vulnerability of the groundwater system to contamination. Focazio et al. (2002) state that

> "The vulnerability of a ground-water resource to contamination depends on intrinsic susceptibility as well as the locations and types of sources of naturally occurring and anthropogenic contamination, relative location of wells, and fate and transport of the contaminants. Water-resource decision makers are often faced with a choice on deciding whether to manage a resource based on knowledge of intrinsic susceptibility or to target more comprehensive and contaminant-specific assessments of vulnerability."

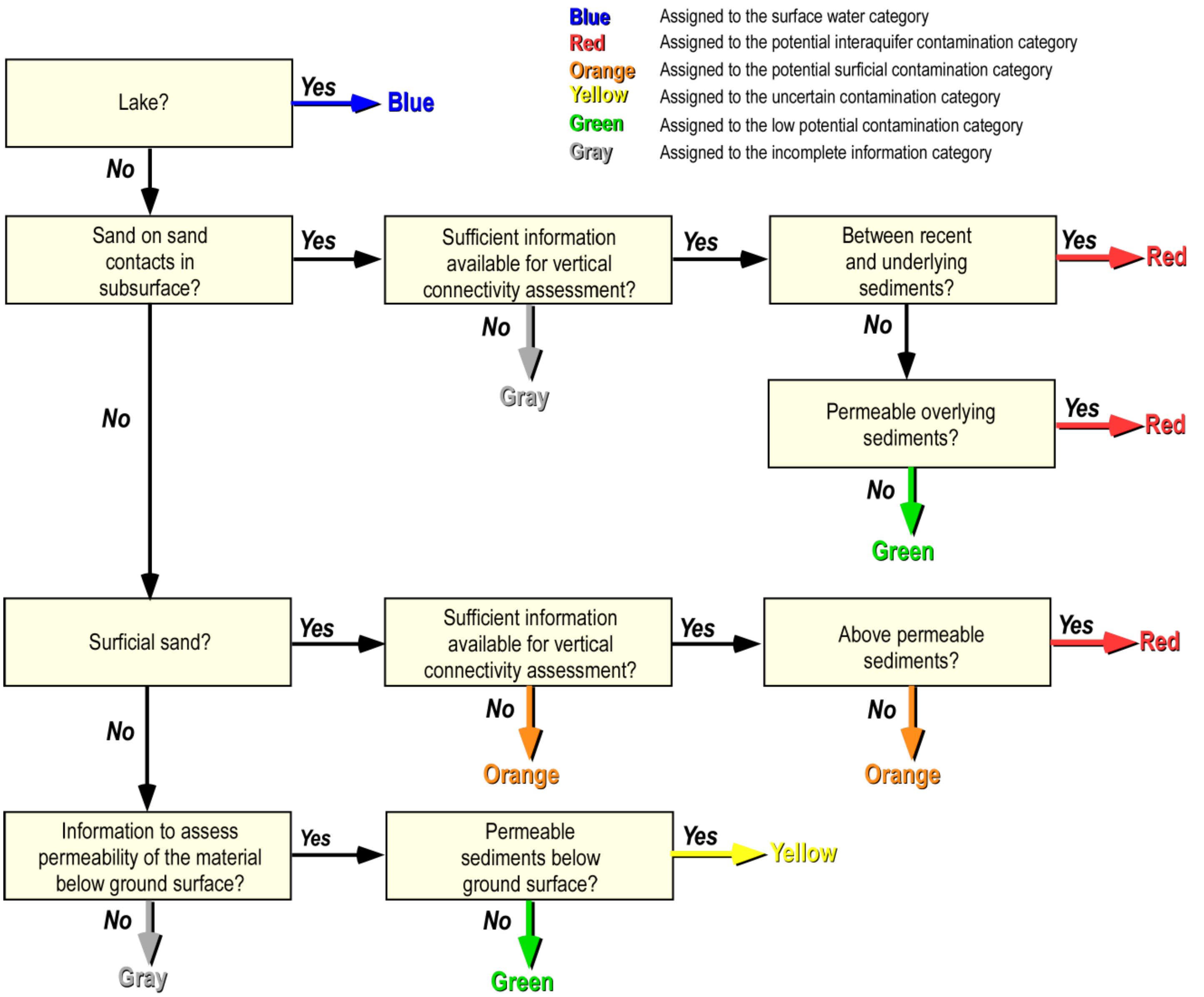
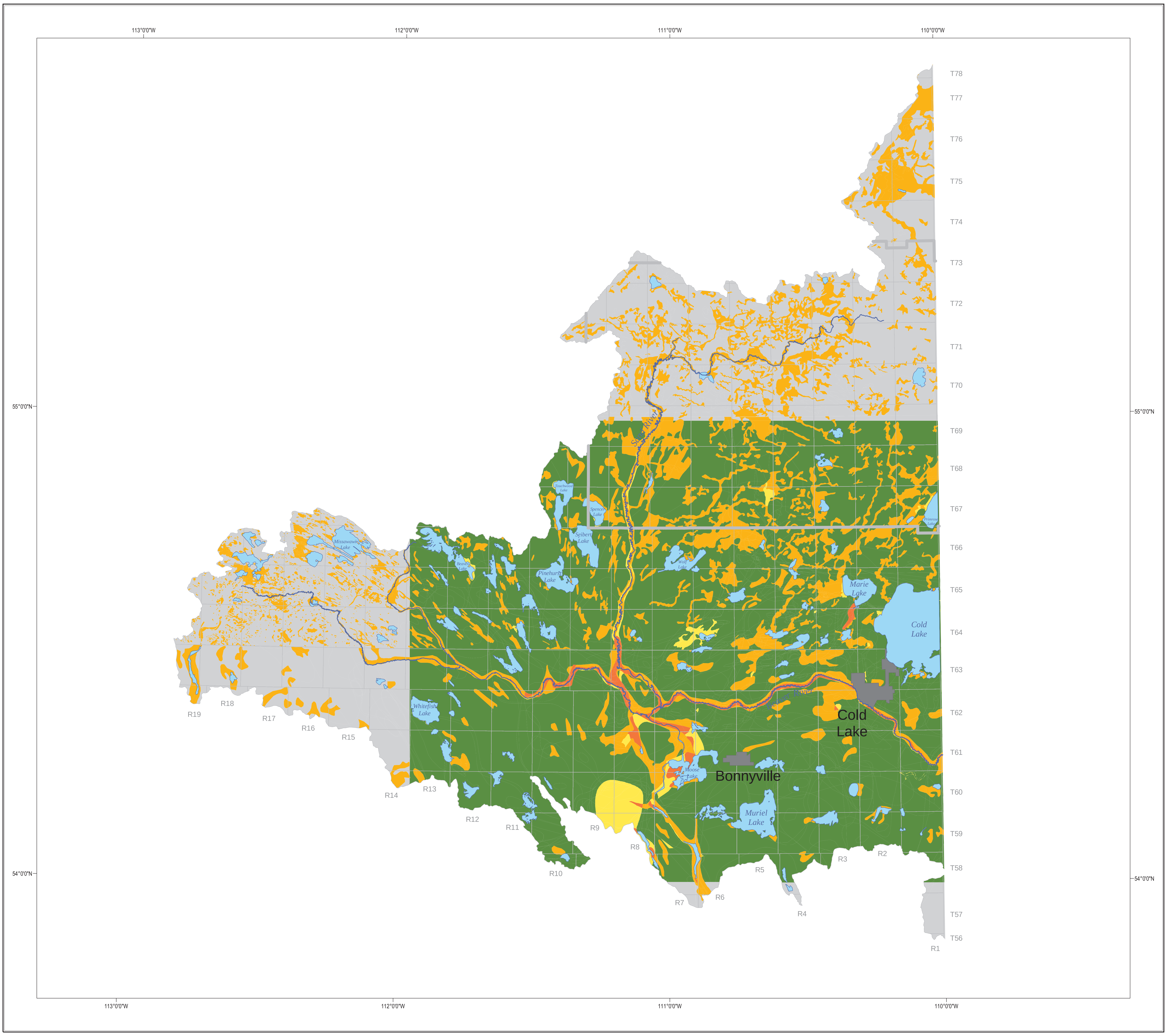
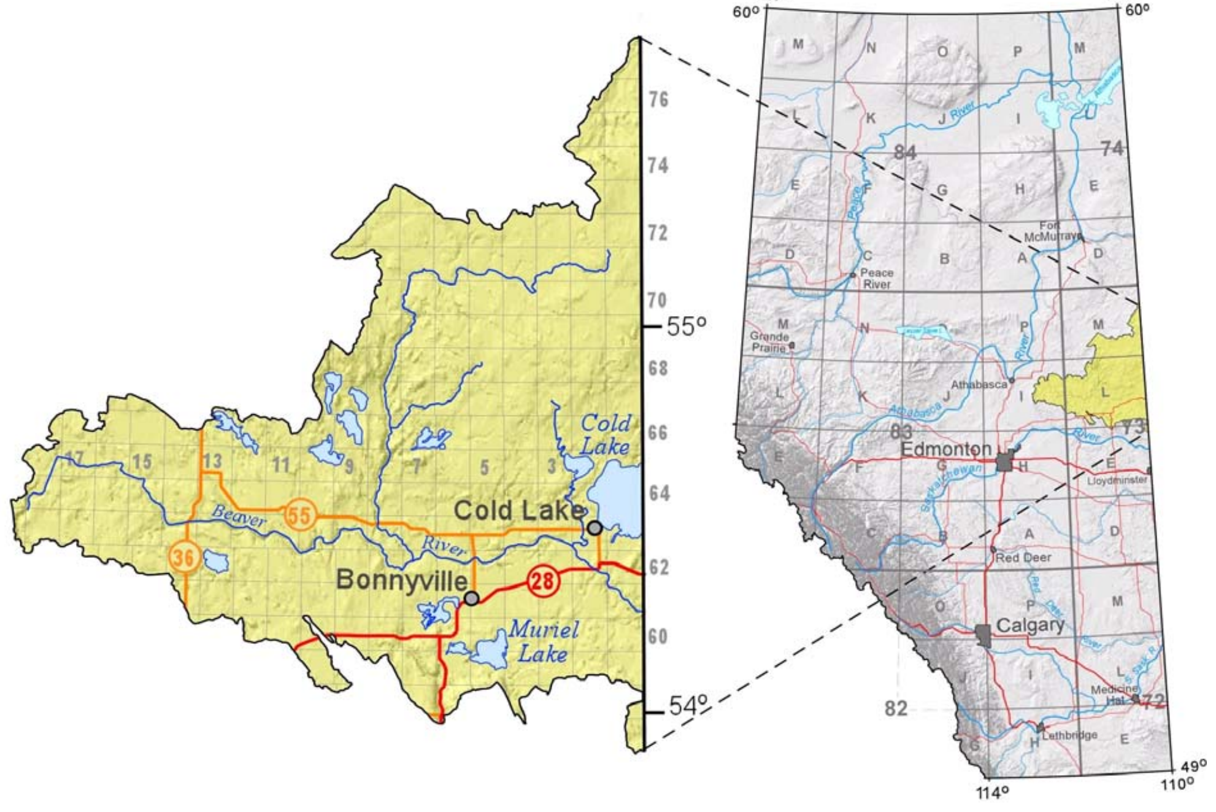


Figure 6.1. Aquifer sensitivity determination flow chart.





Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

〰	Major river
▬	Cold Lake Air Weapons Range Boundary
🟦	Lake
⬛	City or town

Aquifer sensitivity classes

🟥	High sensitivity to interaquifer contamination
🟧	High sensitivity to surficial aquifer contamination
🟨	Uncertain sensitivity to contamination
🟩	Low sensitivity to contamination
⬜	Insufficient information available

Figure 6.2. Aquifer sensitivity to contamination.

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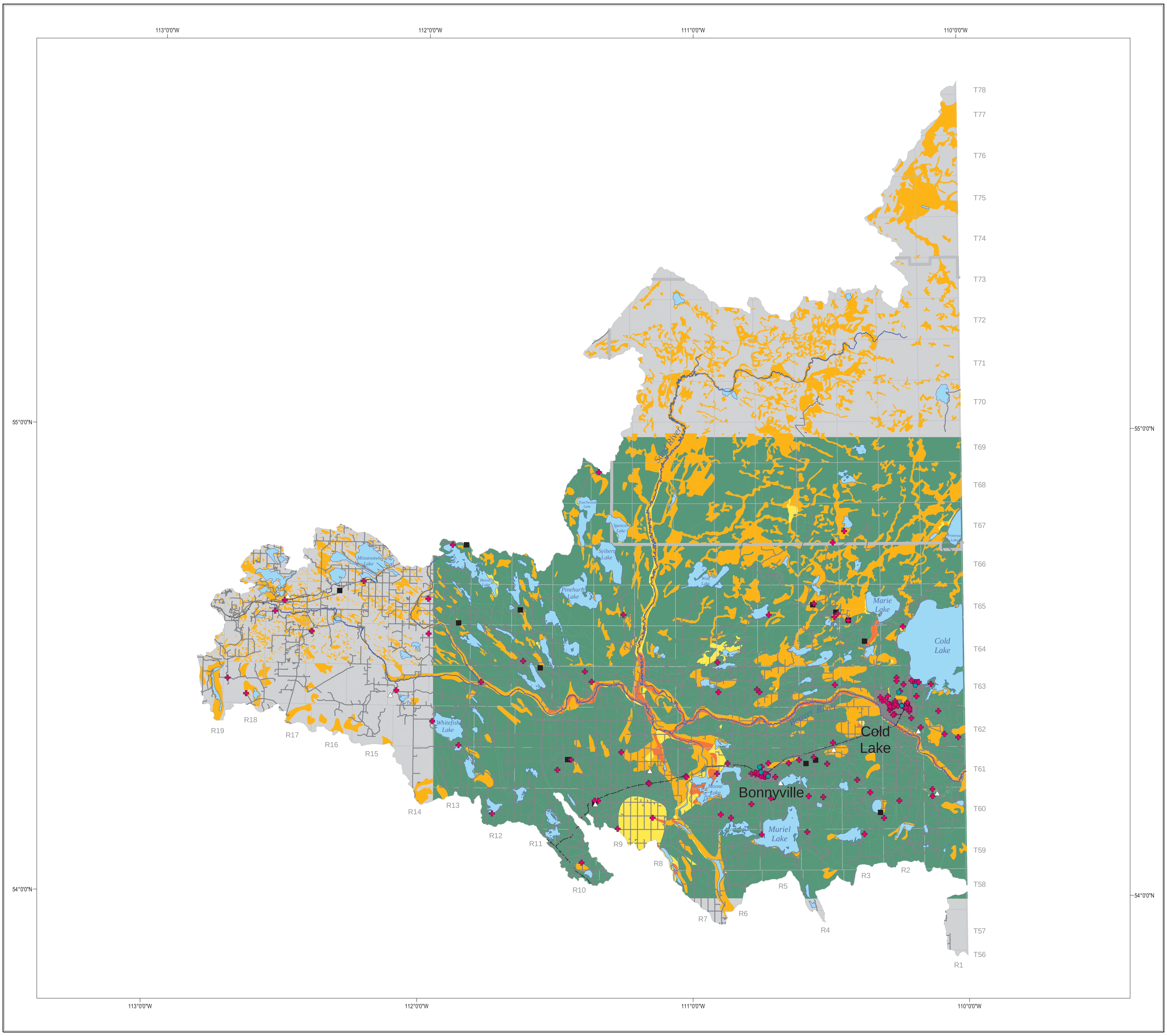
As outlined in Section 4, there are a number of potential sources of contamination in the Basin. The location of these sources in relation to the defined aquifer sensitivities is presented in Figure 6.3, Figure 6.4, Figure 6.5, Figure 6.6, Figure 6.7, Figure 6.8 and Figure 6.9. The vulnerability of the aquifers to the various point and non point sources of contamination can be visually assessed from these figures. Though beyond the scope of this report, the determination of the vulnerability to various sources of contamination could be accomplished in a more rigorous manner by combining the sensitivity information with the density of the various point and non point sources and querying the results. By located the existing monitoring wells in relation to these areas of vulnerability and sensitivity, the ability of the wells to assess any impacts on the groundwater quality can be determined. The existing network of wells can then either be reduced, or supplemented in order to more efficiently determine any changes in groundwater quality.

7 Conclusions and Recommendations

A number of conclusions and recommendations can be made regarding the regional groundwater quality in the Cold Lake-Beaver River Basin. It must be noted however that a regional groundwater quality appraisal is different than a human health assessment of drinking-water quality or investigation of groundwater contamination. In the former, there would be much more emphasis on the type and nature of the drinking-water source and treatment technology rather than emphasis on the geological formation of origin. In the latter, there would be much stricter attention to sampling methodology, laboratory analysis, and the methods used to normalize or “level” data to facilitate comparison of results from different methods or different sampling events, mainly because the concentrations in question are in the part-per-billion or part-per-trillion range (1 mg/l roughly equates to one part-per-million). Thus the results of this analysis should not be interpreted in terms applied to investigations of drinking-water quality or groundwater contamination. Although a comparison of the available chemical analyses of groundwater samples to existing water quality guidelines was undertaken, the nature of the conclusions drawn from those comparisons must be consistent with the possible sources of error associated with a partially scrutinized data set. The comparison to water quality guidelines was undertaken to identify elements or compounds that might be of concern in groundwater within the Basin.

In discussions with Alberta Environment, certain parameters, elements and organic compounds were identified as being of particular concern. These included, TDS, chloride, arsenic and phenols. The distribution of these parameters, elements or compounds varied throughout the five flow systems within the Basin as well as by Formation. However, the median concentrations varied little through time, or across flow systems or aquifer groups. General trends of increased chloride and TDS concentrations were observed in the vicinity of discharge areas. However, not all higher concentrations of chloride and TDS may be related to natural processes. These samples are in proximity to various industrial, transportation or agricultural sites that have the potential to affect groundwater quality. Arsenic and phenols concentration information was localized primarily in the vicinity of industrial development in the area. Some of the reported concentrations exceeded water quality guidelines. Without similar well control in other portions of the Basin, it is difficult to establish any direct link to industrial operations and arsenic or phenols concentrations, especially since evidence exists to support the natural occurrence of these constituents in the Basin. The natural versus anthropogenic nature of these constituents is an issue that should be resolved to the satisfaction of decision makers.



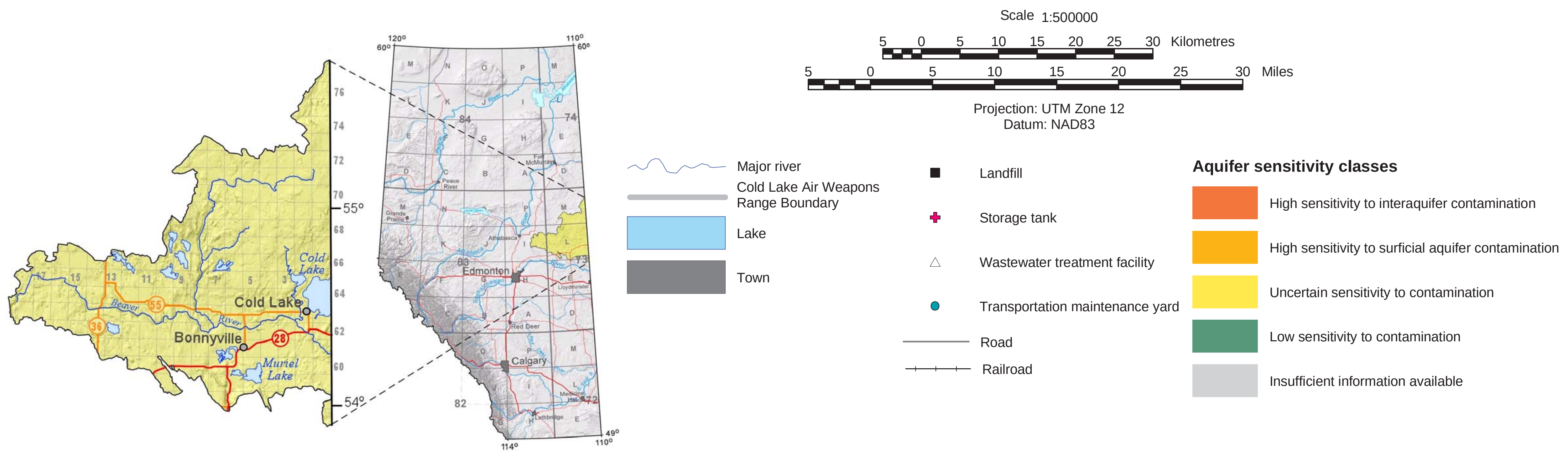


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Figure 6.3. Locations of urban areas, wastewater treatment sites, landfills, transportation infrastructure and storage tanks with respect to aquifer sensitivities.

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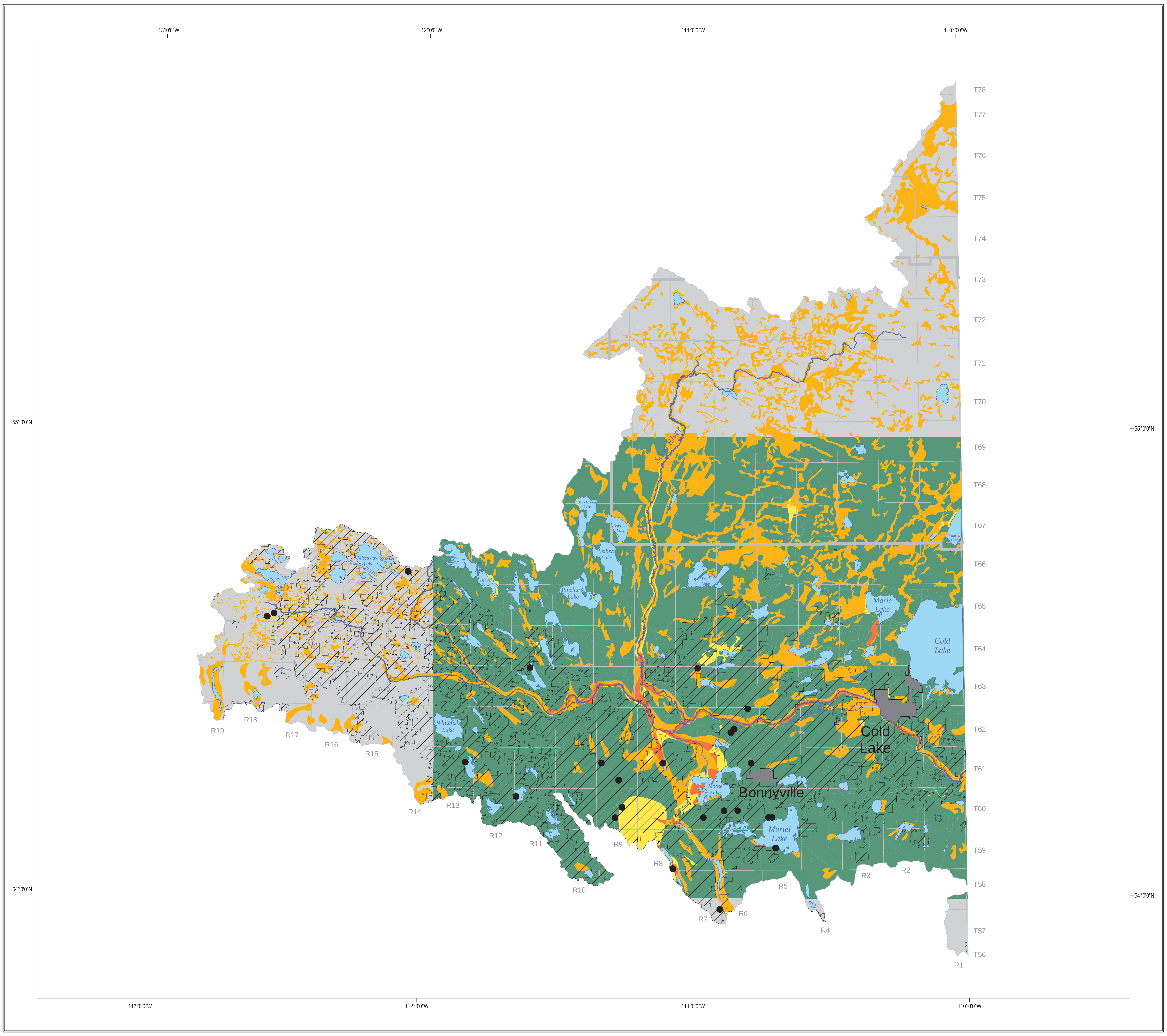


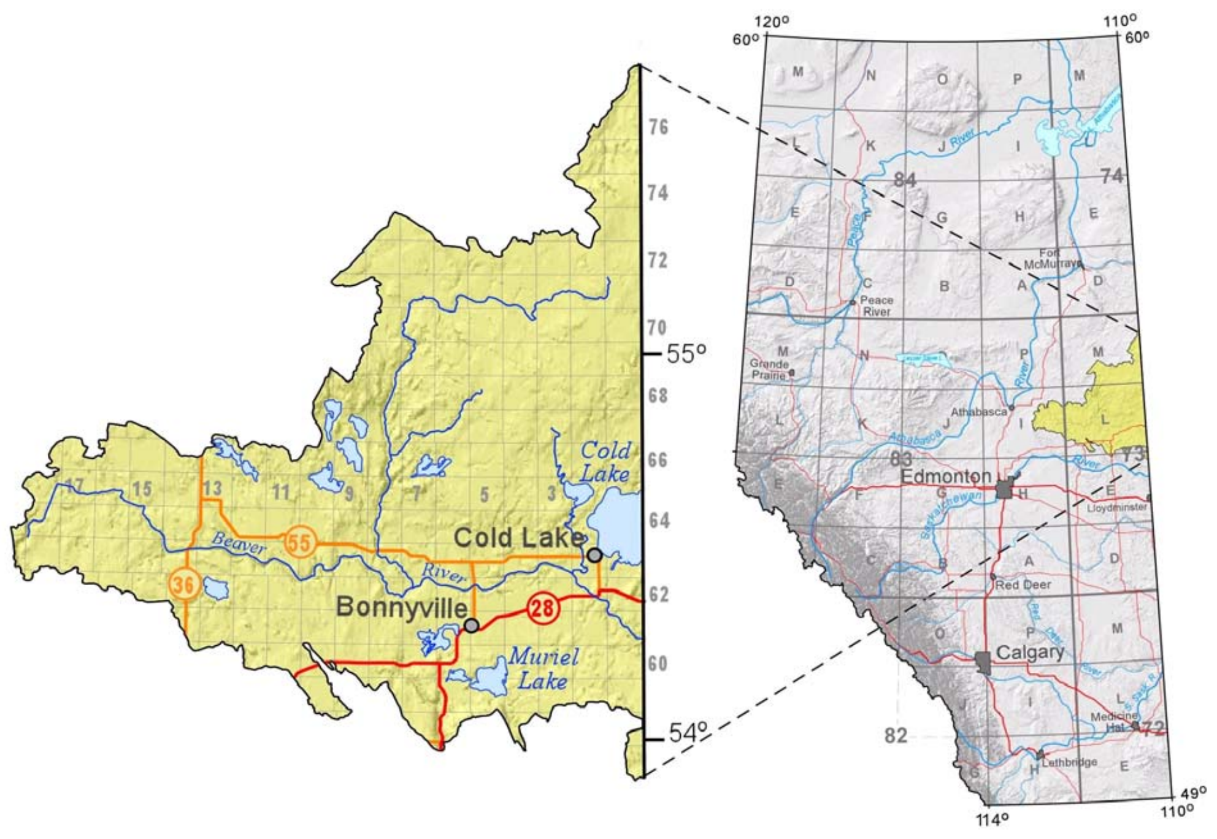
Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004



- 〰 Major river
- ▬ Cold Lake Air Weapons Range Boundary
- 🟦 Lake
- ⬛ Town
- ● Confined feeding operation
- ▨ Agricultural land use

Aquifer sensitivity classes

- 🟥 High sensitivity to interaquifer contamination
- 🟧 High sensitivity to surficial aquifer contamination
- 🟨 Uncertain sensitivity to contamination
- 🟩 Low sensitivity to contamination
- ⬜ Insufficient information available

Figure 6.4. Agricultural land use and the location of confined feeding operations with respect to aquifer sensitivities.

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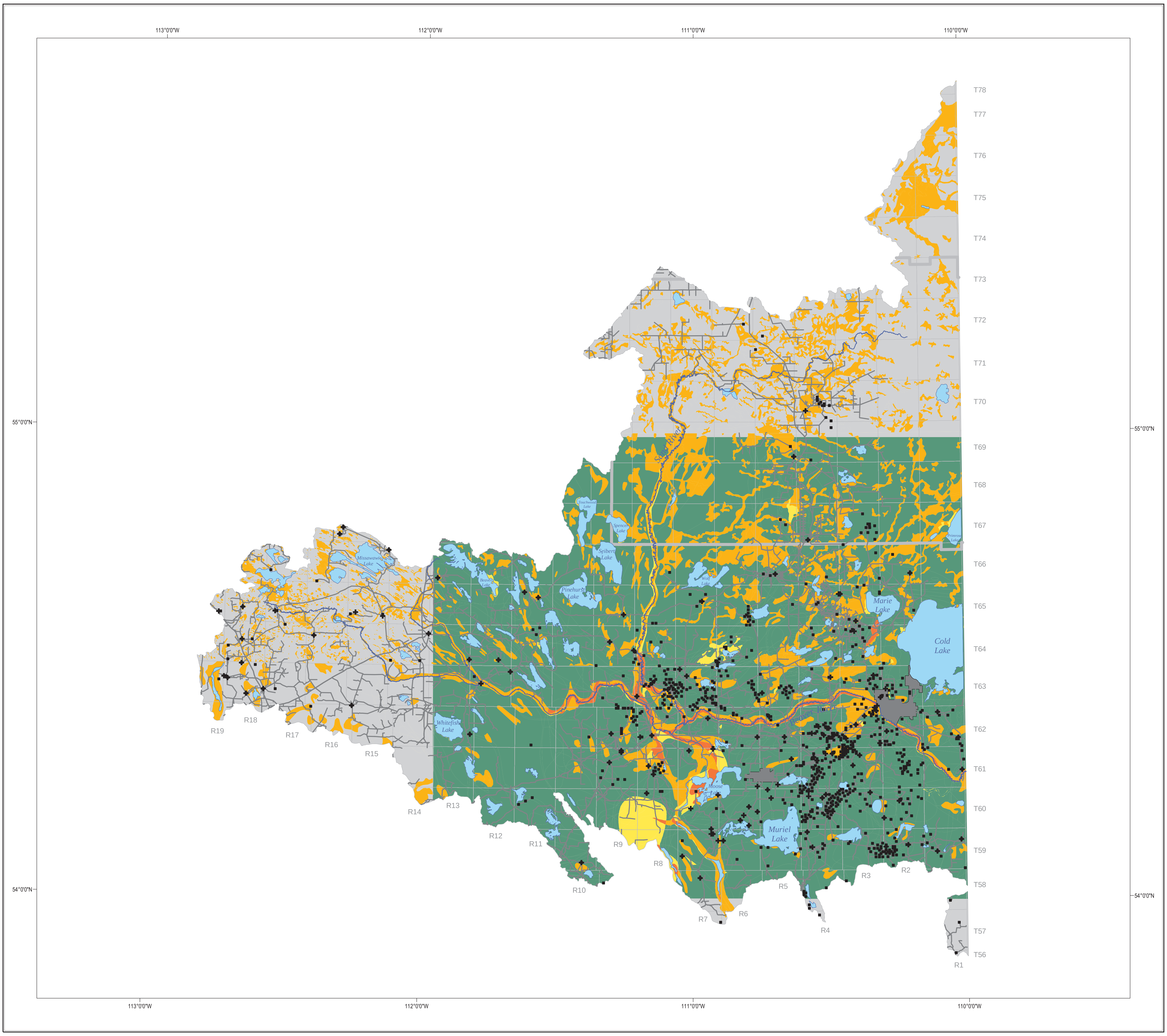
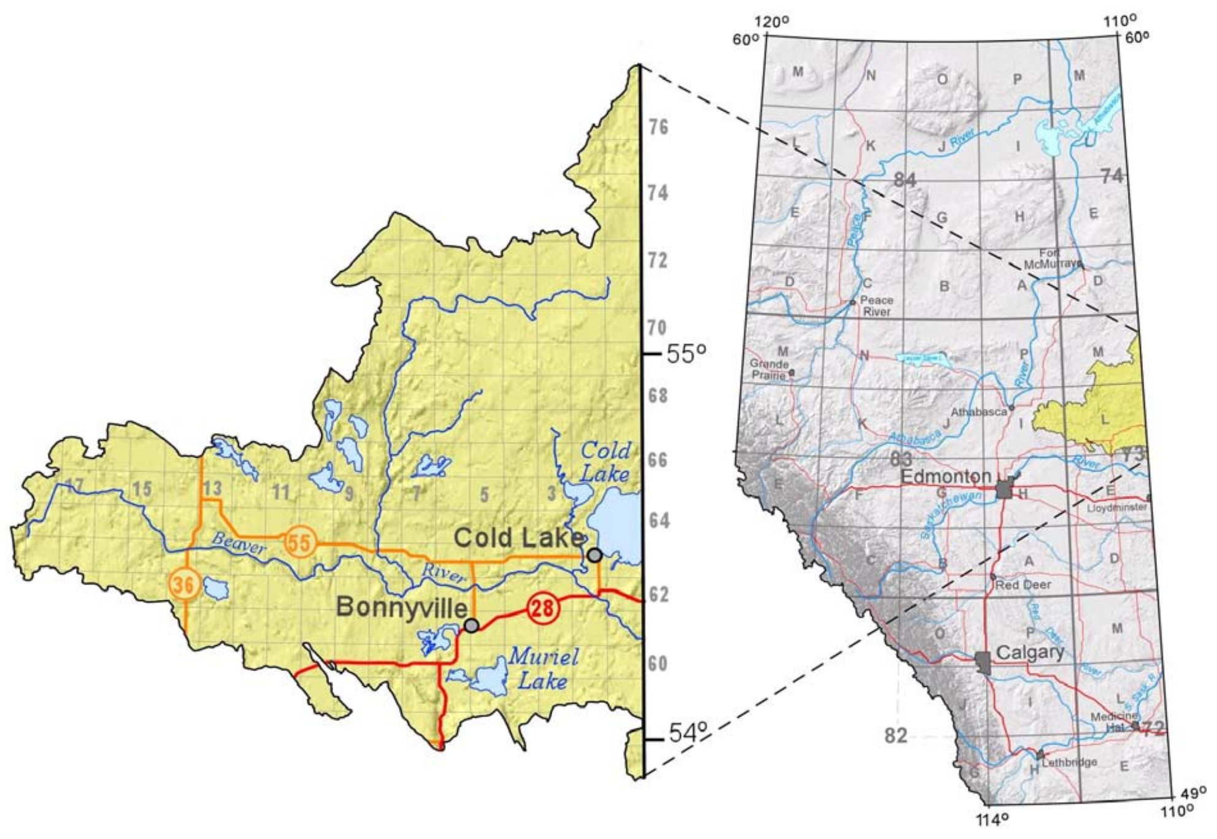
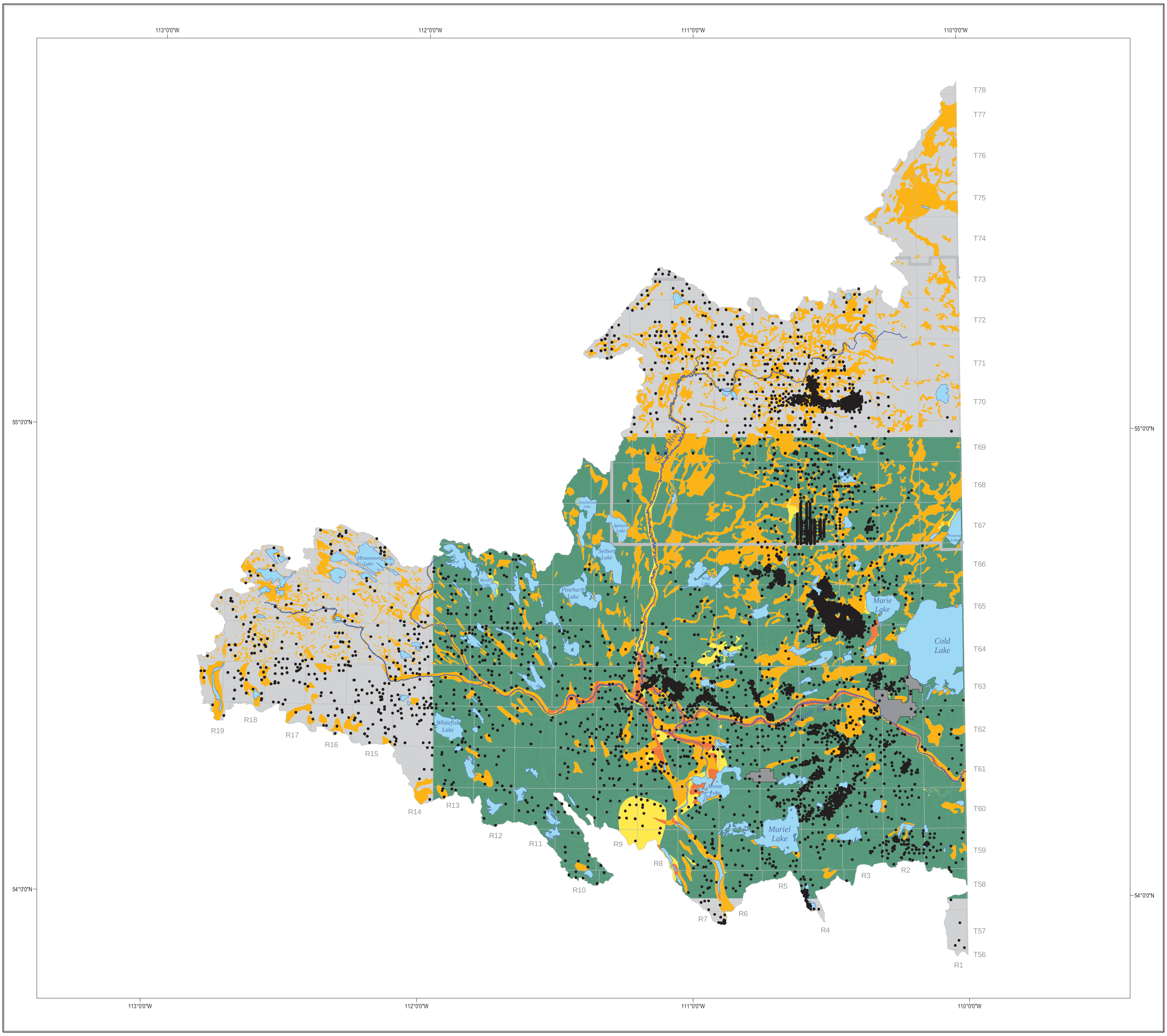
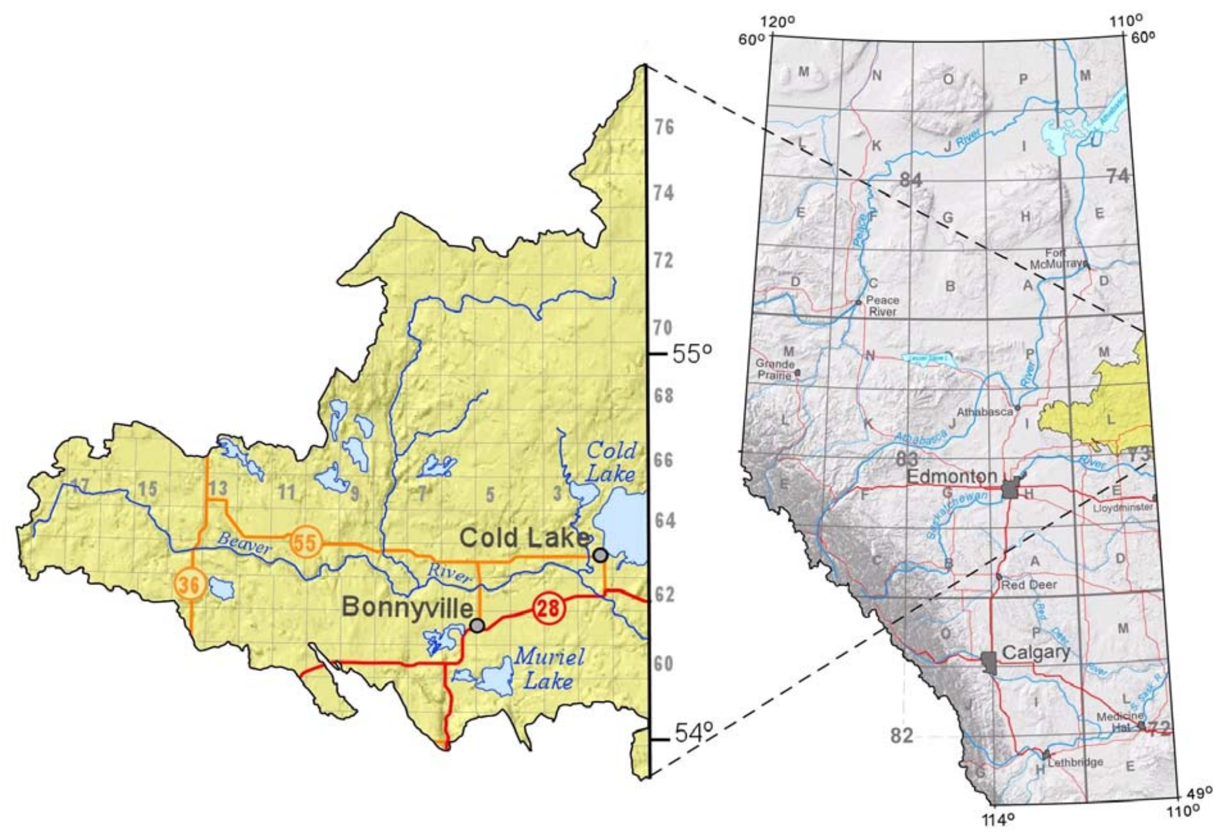




October, 2004

Figure 6.5. Oil and gas infrastructure with respect to aquifer sensitivities.





Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

〰	Major river
▬	Cold Lake Air Weapons Range Boundary
🟦	Lake
⬛	Town
•	Oil or gas well

Aquifer sensitivity classes

🟥	High sensitivity to interaquifer contamination
🟧	High sensitivity to surficial aquifer contamination
🟨	Uncertain sensitivity to contamination
🟩	Low sensitivity to contamination
⬜	Insufficient information available

Figure 6.6. Active oil and gas wells with respect to aquifer sensitivities.

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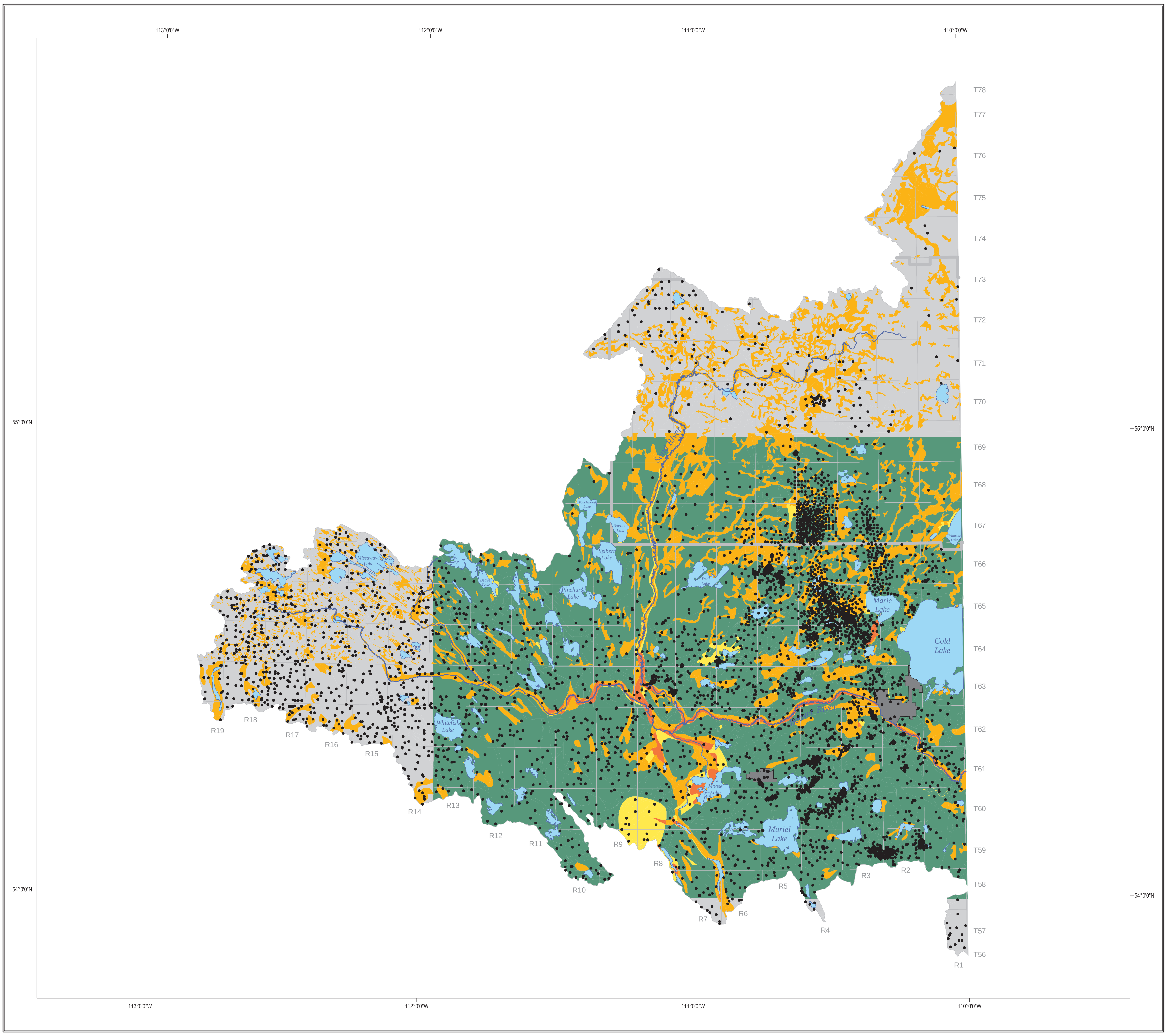


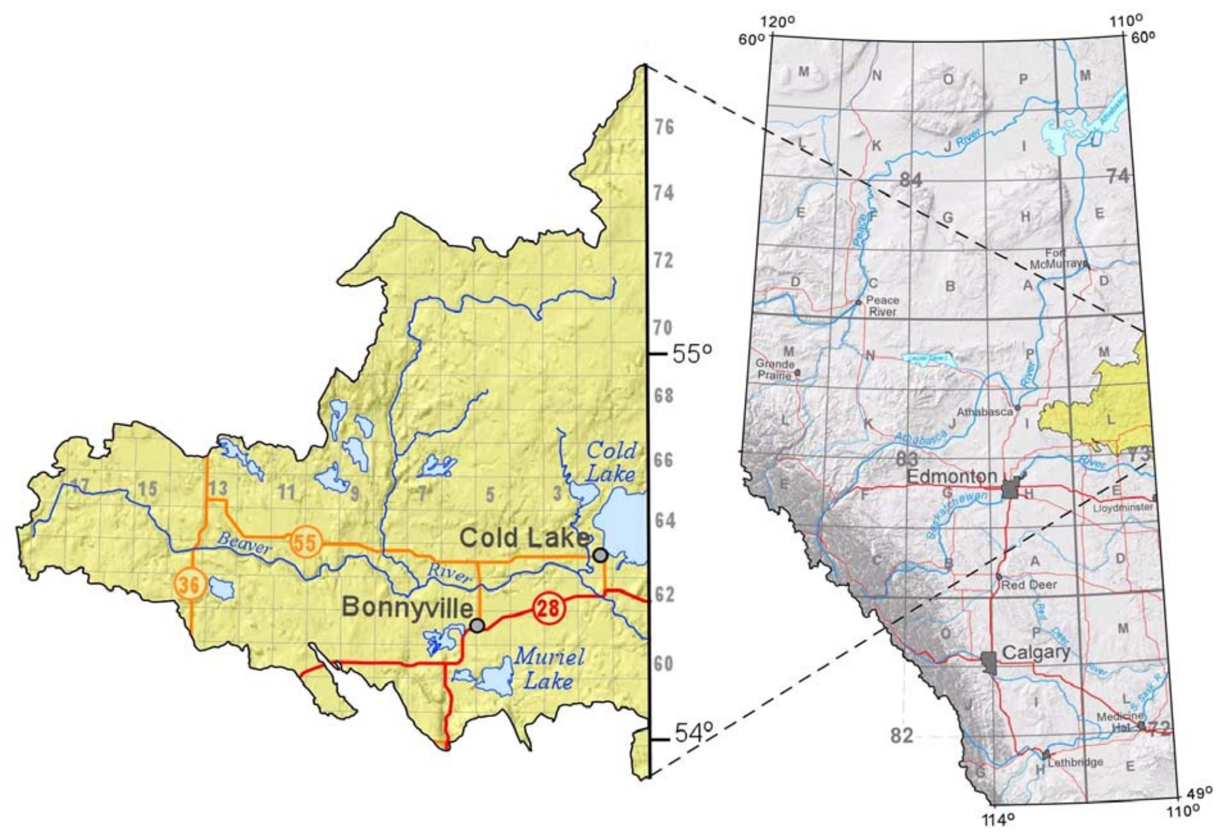
Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004



～ Major river

▬ Cold Lake Air Weapons Range Boundary

🟦 Lake

⬛ Town

● Oil or gas well

Aquifer sensitivity classes

🟥 High sensitivity to interaquifer contamination

🟧 High sensitivity to surficial aquifer contamination

🟨 Uncertain sensitivity to contamination

🟩 Low sensitivity to contamination

⬜ Insufficient information available

Figure 6.7. Inactive oil and gas wells with respect to aquifer sensitivities.

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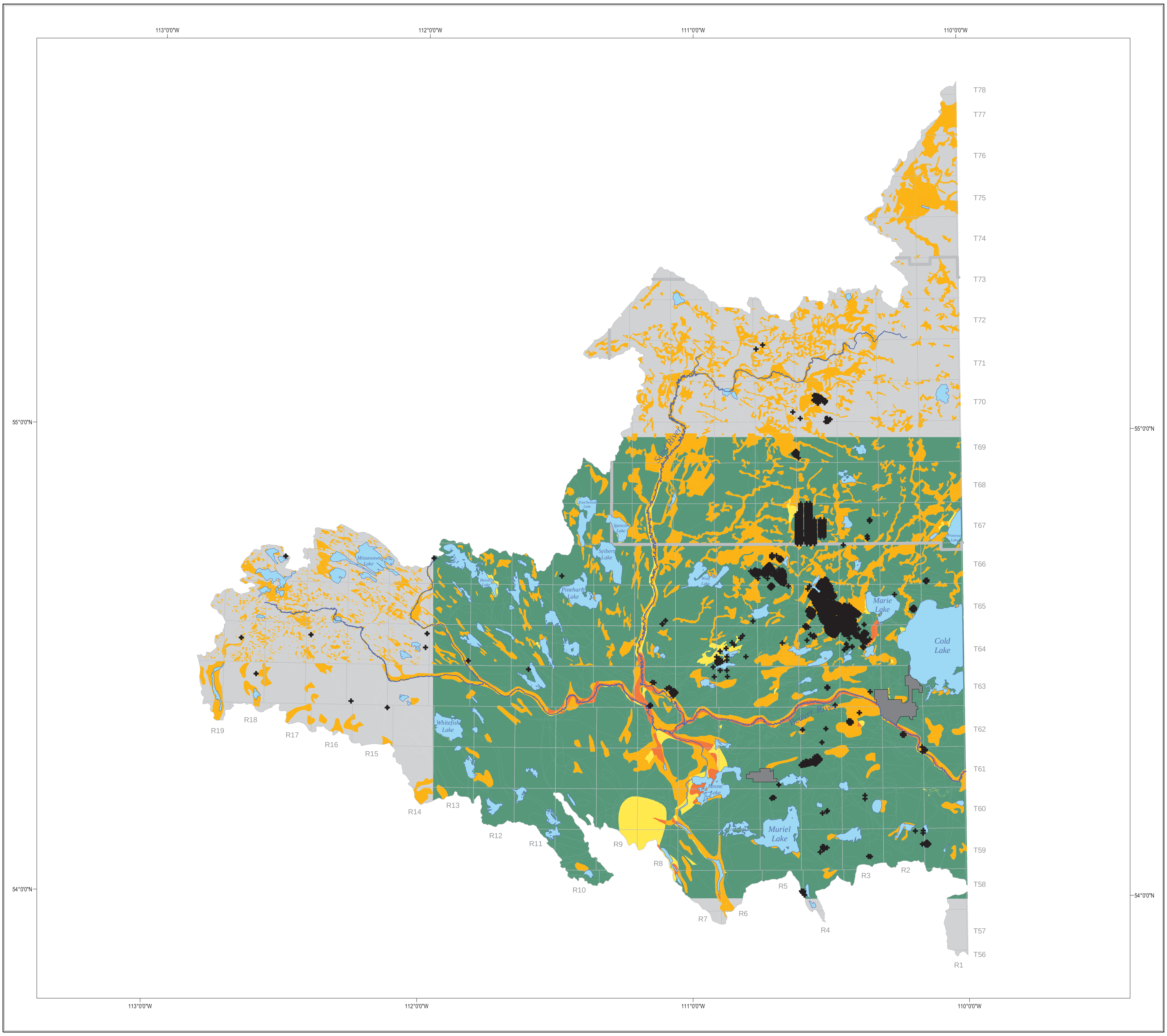

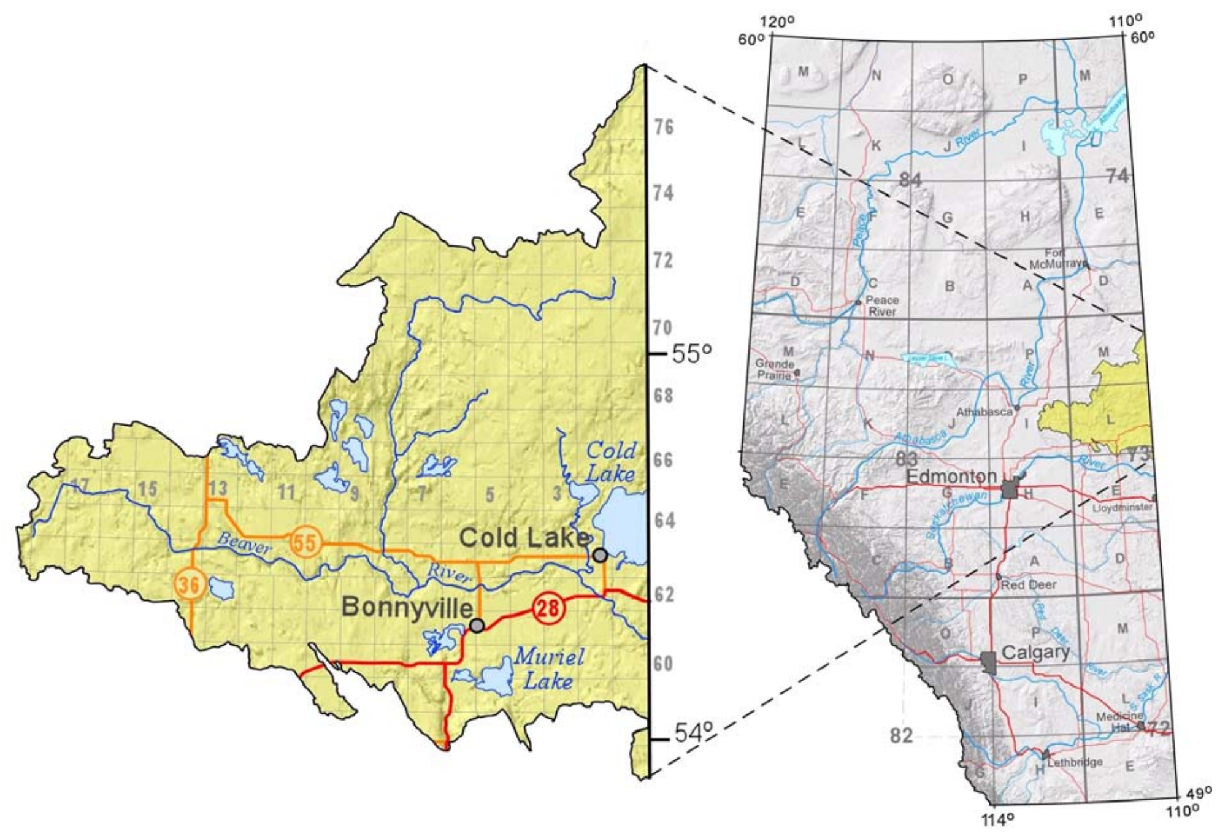

Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

October, 2004

Figure 6.8. Injection and disposal wells with respect to aquifer sensitivities.

〰	Major river
▬	Cold Lake Air Weapons Range Boundary
🟦	Lake
⬛	Town
■	Well currently used for injection or disposal
✚	Well previously used for injection or disposal

Aquifer sensitivity classes

🟥	High sensitivity to interaquifer contamination
🟧	High sensitivity to surficial aquifer contamination
🟨	Uncertain sensitivity to contamination
🟩	Low sensitivity to contamination
⬜	Insufficient information available

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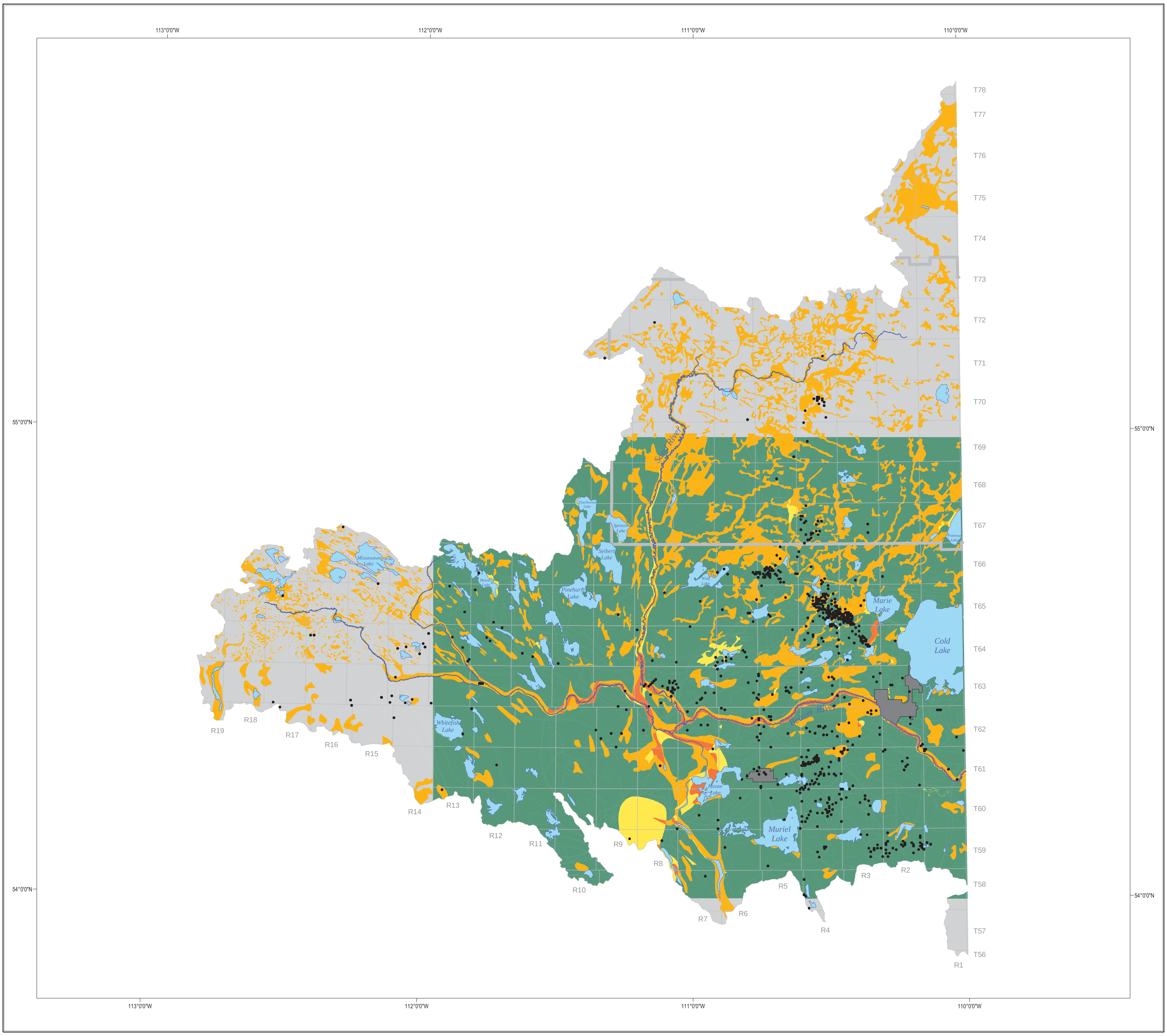

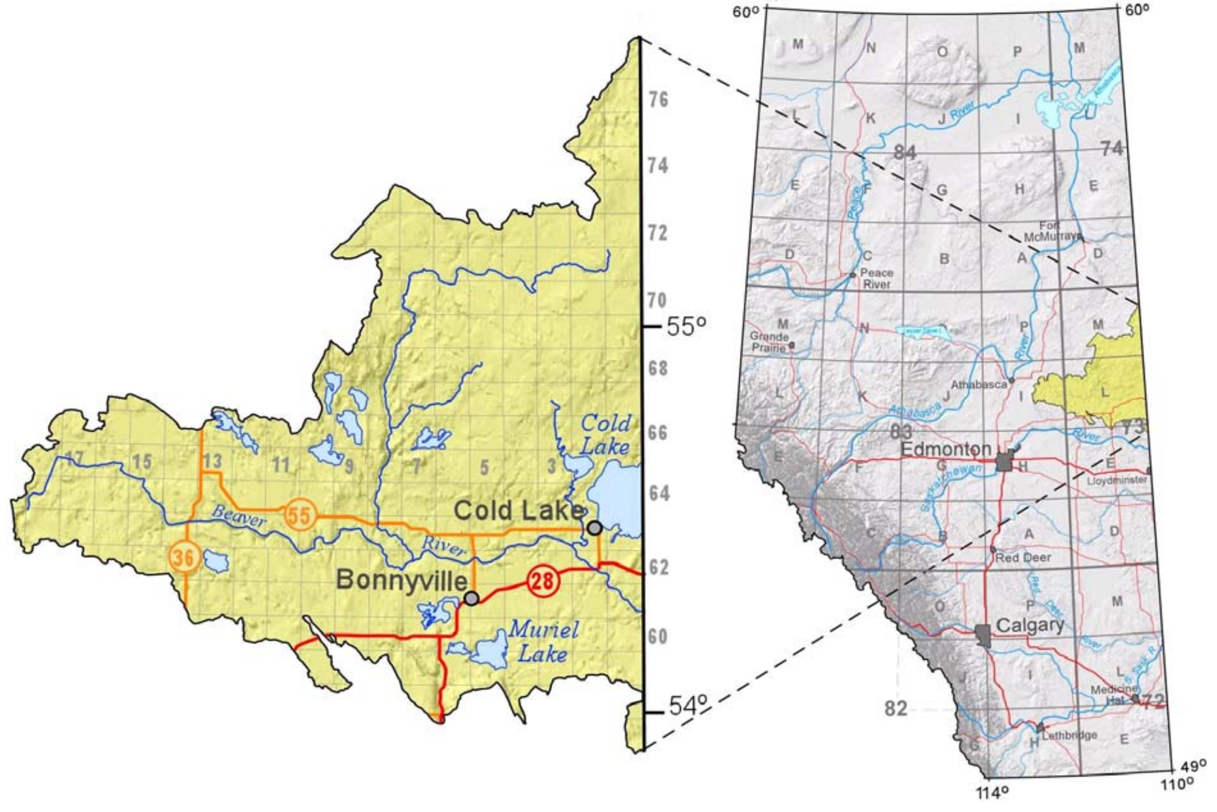

Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

Major river

Cold Lake Air Weapons Range Boundary

🟦 Lake

⬛ Town

● Environmental release location

Aquifer sensitivity classes

🟥 High sensitivity to interaquifer contamination

🟧 High sensitivity to surficial aquifer contamination

🟨 Uncertain sensitivity to contamination

🟩 Low sensitivity to contamination

⬜ Insufficient information available

October, 2004

Figure 6.9. Locations of environmental releases associated with oil and gas activities with respect to aquifer sensitivities.

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A cursory analysis of the collected data identified other constituents that exceed established guidelines including

Major constituents

Sulphate

Minor constituents

Boron, fluoride, iron and nitrate

Trace constituents

Aluminum, antimony, barium, cadmium, chromium, cobalt, copper, lead, manganese, mercury, molybdenum, nickel, selenium, silver, thallium, uranium, vanadium and zinc

Organic compounds

Petroleum distillates

Many of these constituents have both natural and anthropogenic sources. The availability of the data in a database that is compatible with GIS applications allows for the assessment of the potential risk associated with the concentrations of these constituents in groundwater. Depending on the future goals of groundwater quality assessment in the Basin these constituents should be assessed to present a more thorough state of the groundwater quality. The presence of these constituents suggests that additional groundwater quality monitoring should include at least these elements.

The statistical analysis of the changes in concentration of arsenic, chloride and phenols over time by flow system involved the construction of notched box plots. Box plots allow for a rapid visual inspection of the distribution of data. When compared to samples from different locations or from different time periods or against water quality guidelines, similarities and differences between sample sets are quickly revealed and guideline exceedances can be visualized. This type of statistical analysis was chosen because it is a robust and proven statistical technique that shows changes in data distributions. More detailed statistical analyses are likely possible such as time series analysis as described by Box et al. (1994). However, the spatial, temporal and geological variability between sample site makes statistical analysis very challenging and may invalidate many statistical techniques. If more detailed analysis is warranted, careful assessment of such factors must be considered.

Additional analyses can be carried out on the chemical characteristics of the groundwater with respect to land use to try and determine the natural versus anthropogenic contribution of constituents of concern to groundwater quality. Statistical techniques exist that allow for the comparison of a number of parameters with the most important characteristics affecting the observed chemical make-up receiving the highest score. These statistical tests could help resolve the issue of natural versus anthropogenic source for many of the constituents of concern.

The collection of information on the geological material in the Basin allowed for the assessment of aquifer sensitivity to a near-surface contamination event. The level of detail available on the geological materials within the Basin is absolutely fundamental in developing aquifer sensitivity maps. Sensitivity assessments based on less detailed geological data could provide decision makers with general classes of aquifer sensitivity, but would not provide the level of detail available for the Cold Lake-Beaver River Basin. Information compiled on land use, industrial activity, environmental releases, landfills, wastewater treatment plants, transportation infrastructure and urban development can be combined with the above sensitivity analysis to develop aquifer vulnerability maps that can be used to guide decisions regarding monitoring requirements, site construction requirements, and the future development options for certain portions of the Basin.

The vulnerability of aquifers can also be assessed with respect to certain contaminants. Based on the available knowledge of the transport characteristics of contaminants in the subsurface, site-specific assessments of the effect of introducing constituents of concern into certain portions of the Basin can be carried out. This type of analysis relies on groundwater flow models developed for the area. A detailed flow model was developed for the Basin as part of the groundwater quantity assessment detailed in Parks et al. (2005). Careful construction resulted in a model that closely matched observed conditions within the Basin. Opportunities exist to better define certain characteristics of the model through a better chemical understanding of the groundwater within the Basin. The use of groundwater age-dating techniques allows for the clarification of recharge and discharge relationships within the Basin and can also be used to validate the conclusions made by the model regarding sustainability of the groundwater resource and connectivity of various portions of the groundwater flow system. With an improved model comes an improved assessment of groundwater transport of contaminants in the subsurface.

Focazio et al. (2002) state, “Ultimately, successful ground-water-vulnerability assessments blend scientifically defensible analyses used to meet science objectives with additional interpretations by water-resource decision makers to meet management or policy objectives.” A more complete assessment of vulnerability will therefore require the definition of the groundwater quality management objectives for the CLBRB.

The assessment of the state of the groundwater quality within the Basin is dependent on groundwater quality data and water well completion information. The minimum amount of information required is a location, a completion interval, a sample date and the results of the analyses for the major ions. The sample selection process revealed that many water well drillers’ reports were incomplete and in some instances incorrect. These omissions or errors likely resulted in a significant decrease in the available water quality data that could have been used to characterize the groundwater quality within the Basin. Many of the submissions used different chemical names for certain constituents making them difficult to compare. In many instances no information is available on sampling methodology or analytical methods. If a future goal is to conduct a more thorough assessment of water quality with respect to drinking water quality or contamination of aquifers, much of the data may prove unusable because of the uncertainty associated with its collection.

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